The Vulnerability of Broad Vegetation Community Types to Climate and Land Use Change within Northumberland National Park

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Abstract

Future climate and land use change are predicted to have a concomitant impact on ecological communities. Some sources have proposed that at global scales, and for particular regions, land use change will have a greater impact than changes in climate. This research aimed to test this assertion for the semi-natural landscape of Northumberland National Park (NNP) in the north east of England.

The methodology applied a simple habitat suitability model to simulate changes in the distribution of relevant vegetation communities through changes in land use occurring under two future land use scenarios formulated for the study area. Appropriate landscape metrics were then applied to the results to gauge how the associated changes in patch characteristics impacted on the sensitivity and adaptive capacity of the communities. A relatively simple bioclimatic envelope model was also applied to the results of the land use modelling to estimate the sensitivity of vegetation communities to changes in climate predicted under the UKCP09 Medium emissions scenario. Together the applied measures offer a simple and accessible method for estimating the current and future vulnerability of Broad Vegetation Communities (BVCs) within the study area.

Results were analysed at the landscape level for NNP, as well as the five National Character Areas (NCAs), which wholly or partially coincide with its area. Class level results were analysed for nine Priority Broad Vegetation Communities (PBVCs) for NNP and each of the NCAs. Overall the results strongly suggest that the climate changes predicted to affect the park in the future are likely to have a notably greater impact on the vulnerability of the PBVCs than the simulated changes in land use. Landscape level results suggest that vulnerability is likely to be notably reduced in the future under both land use scenarios. This is due the majority of PBVCs exhibiting significant reductions in overall vulnerability in the future, largely due to significant reductions in their levels of climate stress. However, two PBVCs (Blanket Bog and Raised Bog) exhibited considerable increases in vulnerability, due to the increases in the climate stress that they experience. These PBVCs may be regarded as a potential focus for future conservation efforts.

The approach adopted within this research has allowed a number of relevant management recommendations to be made for NNP and for individual PBVCs and NCAs. PBVCs most at risk have been identified and relevant causes investigated. The characteristics of the methodology (simplicity, accessibility, robustness) mean that it provides a useful framework for providing meaningful vulnerability assessments for whole ecological communities across entire landscapes with comparative ease and speed.

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Finally, I would like to thank my friends and family, particularly my wife Shafia, for supporting me throughout my studies.

Declaration

I declare that the work contained in this thesis is entirely my own work and has not been submitted for any other award. Information sources have been acknowledged and all quotations are distinguished and referenced in the text.

Any ethical clearance for the research presented in this thesis has been approved. Approval has been sought and granted by the School Ethics Committee on April 2009.

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List of Acronyms

ATEAM	Advanced Terrestrial Ecosystem Analysis and Modelling
BB	Blanket Bog
BEF	Biodiversity and Ecosystem Functioning
BLCC	British Land Capability Classification
BLW	Broadleaved Woodland
BLWP	Broadleaved Woodland: Priority
BLWNP	Broadleaved Woodland: Non-Priority
BMF	Border Moors and Forests
Br	Bracken
BVC	Broad Vegetation Community Type
CAP	Common Agricultural Policy
CEH	Centre for Ecology and Hydrology
CF	Conservation First
CFGM	Coastal and Floodplain Grazing Marsh
CFr	Cheviot Fringe
CG	Calcareous Grassland
Ch	Cheviot
CW	Coniferous Woodland
DA	Degree of Agreement
DEM	Digital Elevation Model
EU	European Union
FLUFP	Foresight Landuse Futures Project
F&S	Flush & Spring
FMS	Fen, Marsh and Swamp
FSMF	Fuzzy Set Membership Function
GEO-3	Global Environmental Outlook
GFG	Going for Growth
GIS	Geographic Information System
GHG	Green House Gas

GSG	Global Scenarios Group Futures
GV	Geometric Vulnerability
HSI	Habitat Suitability Index
IDW	Inverse-Distance Weighting
IG	Improved Grassland
IGP	Improved Grassland: Priority
IGNP	Improved Grassland: Non-Priority
JNCC	Joint Nature Conservation Committee
LBAP	Local Biodiversity Action Plan
LCM2000	Land Cover Map 2000
LO	Lower Optimum
MB	Modified Bog
MCE	Multi-Criteria Evaluation
ME	Medium Emissions
MOLA	Multiple-Objective Land Allocation Model
MV	Matrix Vulnerability
NCA	National Character Area
NG	Neutral Grassland
NGP	Neutral Grassland: Priority
NNP	Northumberland National Park
NNPA	Northumberland National Park Authority
NPBVC	Non-Priority Broad Vegetation Community Type
NSH	Northumberland Sandstone Hills
NVC	National Vegetation Classification
OS	Ordinance Survey
P1HS	Phase One Habitat Survey
PBVC	Priority Broad Vegetation Community Type
PO	Probability of Occurrence
RB	Raised Bog
SC	Shape Complexity
SRES	Special Report on Emissions Scenarios

TG	Tyne Gap and Hadrian's Wall
TIB	Theory of Island Biogeography
UKBAP	United Kingdom Biodiversity Action Plan
UKCIP	United Kingdom Climate Impacts Programme
UO	Upper Optimum
VM	Vulnerability Measure
WC	Wetness Class

Chapter 1: General Introduction

1.1 General Background

Pressures on existing ecosystems, related to anthropogenic activities, are numerous, unprecedented and in many cases are expected to increase notably throughout the 21st century (CBD, 2010; Haines-Young & Potschin, 2010; MA, 2005a**;** 2005b). These pressures include introduced or invasive species, land use and land use change, over exploitation of resources, pollution, and climate change (MA, 2005a). Although each of these pressures may affect ecosystems individually, in many cases they can interact to further exacerbate ecological impacts (MA, 2005a**;** 2005b). Their relative influence for different ecosystem types and environmental contexts are likely to be varied (MA, 2005a; 2005b). For terrestrial ecosystems land use and climate change are generally regarded as the most significant threats (CBD, 2010; Haines-Young, 2009; IPCC, 2007a; MA, 2005a; 2005b; Sala *et al*., 2000). However, there is uncertainty over which of these pressures is likely to be the most important for terrestrial ecosystems over particular spatial and temporal scales.

These various pressures may not necessarily induce negative ecological effects. However, overall, across local and global scales, they are strongly linked with notable species' extinctions, increased biotic homogenisation and degradation and disruption of the structure, properties and functioning of existing ecosystems (Keller *et al*., 2011; Lui *et al*., 2010; Rabalais *et al*., 2002; CBD, 2010; MA, 2005a; 2005b). These issues are of particular concern, not only for wildlife conservation, but also for human populations generally because of the interrelationship between biodiversity, ecological properties and functions and the vital goods and services existing ecosystems provide to humans largely for free (CBD, 2010; MA, 2005a; 2005b; Hooper *et al*., 2005). Although much is still to be achieved in understanding the relationship between biodiversity and ecosystem functioning, there is general consensus that biodiversity is essential for ecological functioning and can act to stabilise or maintain ecosystem functions (and therefore the goods and services they are associated with) in the face of environmental change (Cardinale *et al*., 2011; Botkin *et al*., 2007; Hooper *et al*., 2005; Scherer-Lorenzen, 2005; MA, 2005a; 2005b).

There is, therefore, an imperative need for research, methods and techniques which seek to investigate and communicate the potential impacts of environmental change and anthropogenic pressures on ecological phenomena in order to better manage the 'biodiversity crisis' that we currently face (Preston *et al*., 2011; IPCC, 2007a; Hooper *et al*., 2005; Scherer-Lorenzen, 2005). The complexity and dynamism inherent within many natural ecosystems, as well as current limitations in human knowledge and understanding means that producing accurate predictions of potential impacts remains a significant challenge (Cardinale *et al*., 2011; Tremblay-Boyer & Anderson, 2007; Hooper *et al*., 2005; Pearson & Dawson, 2003; Guisan & Zimmerman, 2000; Zimmerman & Keinast, 1999). Nevertheless, the scale, magnitude and potential urgency of the problem means that, despite this uncertainty, efforts to predict potential impacts and identify relevant causes are likely to be more valuable for effective management and planning than delaying efforts until greater certainty is achieved; as long as the uncertainties associated with predictions are adequately acknowledged, understood and conveyed (Morecroft *et al*., 2012; Klausmeyer *et al*., 2011; Preston *et al*., 2011; IPCC, 2007a; Hooper *et al*., 2005). Spatially-explicit assessments are likely to be particularly valuable for conservation efforts (Preston *et al*., 2011; Klausmeyer *et al*., 2011; Brzeziecki *et al*., 1993).

Previous research has tended to concentrate assessments at either small (local) or large (national to global) levels for a single, or limited number of, species, partly because of the relative simplicity of conducting assessments at these spatial and thematic scales (Trivedi *et al*., 2008; Mitchell *et al*., 2007; Holman *et al*., 2005a; Pearson & Dawson, 2003; Guisan & Zimmerman 2000; Peng, 2000; Zimmerman & Kienast*.,* 1999; Brzeziecki *et al.,* 1995; Brzeziecki *et al*., 1993). However, the literature strongly suggests that assessments of impacts on whole ecological communities at sub-regional, landscape scales should be a focus of future research, despite the methodological challenges that this presents, in order to provide more holistic and relevant information to biodiversity managers and the public (Morecroft *et al*., 2012; Griffiths *et al*., 2011; Klausmeyer *et al*., 2011; Preston *et al*., 2011; Berry, 2008; Trivedi *et al*., 2008; Botkin *et al*., 2007; Holman *et al*., 2005a; CBD, 2003; Zimmerman & Kienast, 1999; Burnett *et al*., 1998).

Concepts such as vulnerability are useful for a better understanding and communication of the potential impacts of environmental pressures and change on ecological phenomena from a broader more holistic perspective (Morecroft *et al*., 2012; Preston *et al*., 2011; Klausmeyer *et al*., 2011; De Lange *et al*., 2010; IPCC, 2007a). As such, their potential for providing spatially-explicit assessments for whole communities and ecosystems at intermediate (landscape) scales is increasingly recognised (Morecroft *et al*., 2012; Preston et al., 2011). Although the use of the vulnerability concept has increased notably in recent years there are number issues associated with its application. A variety of detailed species-specific assessments have been undertaken (Klausmeyer *et al*., 2011). However, despite the relative ease of conducting assessments at this thematic level the costs, levels of expertise and time required often mean that assessments, even at local scales, are only feasible for a few biodiversity managers with adequate resources and technical capacity (Klausmeyer *et al*., 2011; Tremblay-Boyer & Anderson, 2007). The costs and requirements associated with conducting comprehensive assessments for all of the species over larger areas make them highly impractical (Klausmeyer *et al*., 2011).

Ambiguities surrounding the definition and application of the vulnerability concept are apparent (Preston *et al*., 2011; De Lange *et al*., 2010; Berry, 2008; Botkin *et al*., 2007; Thuiller *et al*., 2005). Often vulnerability is assessed (either implicitly or explicitly) by simulating impacts of environmental change (particularly climate change) on species or community distributions or suitable climate space (Preston *et al*, 2011; Berry, 2008; Botkin *et al*., 2007). Such approaches, though undoubtedly valid, do tend to define (and therefore treat) vulnerability in a somewhat simplistic or restricted manner (Berry, 2008; Botkin *et al*., 2007; Thuiller *et al*., 2005). Other factors that are also vital components of the vulnerability concept, such as a system's capacity to adapt to or cope with environmental pressures and change, are often neglected. Increasingly, attention is being given to the 'endogenous' aspects of a system that influence its potential to adapt and/or cope with change (Preston *et al*., 2011; Hooper *et al*., 2005; Scherer-Lorenzen, 2005). However, assessments of the inherent or 'endogenous' vulnerability of more natural ecological systems are often lacking (Preston *et al*., 2011). Also, many previous assessments have been restricted to investigating vulnerability in terms of single exogenous pressures (e.g. climate change) (Cardinale et al., 2011; Preston *et al*., 2011; Berry, 2008; Hooper *et* al., 2005; Scherer-Lorenzen, 2005). Considering the number of pressures ecological systems face, such research is likely to misestimate the vulnerability of these systems.

There is therefore good scope for simple and accessible methods and research which facilitate reasonably comprehensive, relatively rapid, less costly and spatially-explicit vulnerability assessments for ecological communities across entire landscapes in terms of a number of different exogenous pressures. Such work should help provide much needed investigation into the relative significance of different drivers of vulnerability (e.g. climate and land use change) on ecological phenomena at these scales, thus helping managers to identify those most at risk (as well as relevant causes and specific areas of concern) (Preston *et al*., 2011; Klausmeyer et al., 2011; Tremblay-Boyer & Anderson, 2007; Hooper *et al*., 2005). Such work should also contribute to increased understanding and engagement amongst a broader range of stakeholders (including the public) regarding environmental management, change and risk at scales (i.e. local - sub-regional/landscape) that are highly relevant for those with which humans more commonly interact, and at which much of the policy response can and should be developed and implemented (Preston *et al*., 2011; Holman et al., 2005a; Hooper *et al*., 2005).

1.2 General Research Aims & Objectives

The primary aim of the research was to investigate the relative roles of climate and land use change in determining the ecological vulnerability of vegetation communities at the landscape scale, with NNP as a case study. However, an additional goal when developing the methodology to achieve this was to create a framework with the potential to be easily understood and readily adapted and/or applied in other contexts. To meet these aims the research objectives are:

1. To investigate, through literature review and other appropriate methods, the potential influence of climate (and other factors) on ecological phenomena at the landscape scale.

2. To develop a model capable of producing reliable land use simulations relatively simply and quickly for entire landscapes, for an array of land cover/community types relevant for the UK.

3. To develop regionally relevant land use scenario storylines for NNP that reflect the major uncertainties regarding land use change and are indicative of the broad range of potential land use futures that may affect the park.

4. Using the formulated land use model, to simulate the potential impacts of land use change on the distribution of vegetation communities within NNP under the scenarios.

5. To review the ecological literature with regard to the influence of the spatial characteristics of communities at the landscape scale on ecological processes, functions and vulnerability.

6. Based on objectives 1 and 5, to develop as series of vulnerability indicators that are relevant for assessing community vulnerability in terms of climate and land use change and may be easily understood and readily applied.

7. To provide more detailed and targeted management recommendations for relevant decision makers to elucidate the usefulness of the model for identifying vulnerable communities (as well as relevant causes and specific areas of concern).

1.3 General Methods

The research draws upon a range of relevant theories, concepts and techniques, many of which are rooted in the related fields of biogeography and landscape ecology. For instance, the correlative approaches used to investigate relevant environmental tolerances and make assessments of potential impacts are common to the field of biogeography generally (Guisan & Thuiller, 2005; Pearson & Dawson, 2003; Guisan & Zimmerman, 2000). Due to its landscape level focus, many aspects of the research owe much to the discipline of landscape ecology. This discipline, which developed from the study of island biogeography, seeks to apply many of the principles and concepts used in the study of oceanic islands, to understand the ecological properties and functioning of habitat 'islands' (patches) within a terrestrial, landscape context (Forman, 2001; Begon *et al*., 1996; 1990).

The island biogeography approach provides a useful conceptual framework for understanding the relationship between spatial pattern and ecological functioning within landscapes (McGarigal, 2006; Forman, 2001; Farina, 1998; Begon *et al*., 1996; 1990). However, the role, properties and processes of terrestrial islands within a landscape are not directly analogous to those of more readily identifiable, water-locked islands (McGarigal, 2006; Begon *et al*., 1996; 1990). Additional concepts and models have been subsequently developed within the discipline of landscape ecology specifically, to provide a more realistic and accurate picture of ecological properties, processes and functions within terrestrial contexts (McGarigal, 2006; Forman, 2001; Farina, 1998; Begon *et al*., 1996; 1990). The models, associated issues and considerations, which inform and underpin this field, have been used extensively within this research. They have proved useful for gauging the vulnerability of relevant vegetation communities, particularly in terms of the potential impacts of land use change on their spatial characteristics, and relevant ecological properties and processes.

Other research areas that are relevant for the study include the current understanding and developments regarding the related concepts of vulnerability and resilience, which are increasingly utilised within predictive research to provide more holistic assessments of ecological impacts (Morecroft *et al*., 2012; Preston *et al*., 2011; De Lange *et al*., 2010; Scherer-Lorenzen, 2005; Brooks, 2003). Also, due to the inherent relationship between humans and their environment, methods common within the field of scenario development, such as the establishment and analysis of key socio-economic drivers, are employed to investigate potential land use futures for NNP. It is therefore recognised that the research draws upon several strands of research in achieving its aims.

In general, the study adopts an independent desktop-based approach and relies heavily on the use of various Geographic Information System (GIS) data, tools and techniques to achieve its aims. The use of GIS methods can require a fair degree of technical expertise. However, the way in which they are utilised within this research to assess vulnerability is relatively simple, straightforward and accessible. For instance, in most cases, the underlying data used within the GIS to establish relevant environmental tolerances and make predictions are generally readily available and inexpensive for most biodiversity managers. Additionally the various methods, concepts and techniques used within the model are relatively straightforward and easy to implement, requiring only a minimum level of expertise.

Although the research presented here uses the landscape of NNP to provide a detailed case study of the adopted approach, it has good potential to be adapted and/or applied in other contexts. It is hoped that the method(s) presented here offer(s) a robust and accessible approach for investigating the vulnerability of ecological communities across whole regions or landscapes, which is pertinent for a range of relevant stakeholders and may be readily applied in a variety of contexts.

1.4 Outline of Thesis

The thesis is divided into seven chapters and is largely arranged according to the objectives of this study. This chapter, Chapter One, introduces the thesis.

Chapter Two provides a more detailed background to the research based on a review of the literature. It covers the main anthropogenic pressures facing ecosystems both now and in the future, current understanding regarding the relationships between biodiversity and ecosystem functioning, as well as the concept of vulnerability and its use within previous research. General issues which are relevant for impact assessments, such as spatial scale, thematic scale and common modelling approaches are also discussed. The chapter then reiterates the aim of the research in light of this information and concludes with details of the study area.

Chapter Three gives an account of the research undertaken to investigate the role of climate in influencing community distributions at the landscape scale within NNP. This was important, due to the uncertainty regarding the role climate plays in influencing biological distributions and impacts at these scales. This investigation, along with some of the discussion from Chapter Two, strongly points to the significance of land use and land use change in influencing ecological impacts at the landscape scale both now and in the future. This information was used to inform further stages of the research

Chapters Four, Five and Six describe the approach to modelling both climate and land use change vulnerability. The approach is organised into three elements covered separately in each of the chapters. Chapter Four describes the formulation of appropriate land use change scenario storylines for the study area and the development and application of a model for simulating future community distributions as influenced by land use change.

Chapter Five, building upon some of the information in Chapter Two and the findings of Chapter Three, discusses the potential role of climate in influencing community vulnerability and explains the modelling of current and future community vulnerability due to Climate Stress.

Chapter Six describes the modelling of current and future community vulnerability due to land use change, through the application of two metrics, 'Geometry' and 'Matrix', used to measure specific attributes of community patches deemed important in determining vulnerability. The relevance of these measures was investigated through a review of the landscape ecology literature which is presented at the beginning of the chapter and also refers back to some of the discussion in Chapter Two.

Chapter Seven covers the methods used to integrate the measures of climate and land use vulnerability to provide a measure of Overall Vulnerability. Relevant issues and trends are discussed with particular reference to the relative influence of climate and land use change on community vulnerability. This information is then used to provide targeted management recommendations for NNP before summarising the major findings of the research and offering a critique of the adopted approach.

Chapter 2: Background

Anthropogenic activities exert a variety of pressures on ecological systems. These pressures have increased notably in intensity in recent decades, have been associated with significant declines in biodiversity and are predicted to continue to increase in the future. This has greatly heightened concerns regarding the potential effects of these changes on ecosystem functioning and services and the consequences for human health and wellbeing. Predictive research investigating the potential impact of these changes is therefore vital for effective planning and sustainable ecosystem management. The concept of ecological vulnerability is increasingly recognised as useful for predictive research in order to provide a better understanding of overall risks and impacts. These topics are discussed in this chapter before reiterating the aims of the thesis and describing the study area.

2.1 Environmental Pressures and Impacts

Human activities are inherently linked to environmental change across all scales (Gerard *et al*., 2010; IPCC, 2007a; MA, 2005a; Hooper *et al*., 2005). Anthropogenically-induced environmental change in the past 50 years has been more rapid and widespread than in any comparable period in history (MA, 2005a). Species introductions or invasions, pollution, over-exploitation of resources, the loss and degradation of ecosystems and the rate and magnitude of climate change, have all increased in recent decades (Haines-Young & Potschin, 2010; IPCC, 2007a; MA, 2005a). These changes are closely related to levels of human population growth, increased consumption, technological development and industrialisation, and have lead to significant, potentially irreversible, losses and declines in biodiversity (Butchart *et al*., 2010; Mooney & Mace, 2009; MA, 2005a**;** 2005b). It is likely that the pressures and impacts from each of these factors will increase significantly in the future (MA, 2005a). In many cases, however, these factors are also likely to interact to further exacerbate ecological impacts (MA, 2005a).

2.1.1 Introduced/Invasive Species

The incidence of invasions and introductions of species outside of their natural range, largely due to increased human transport, is extremely high and has increased significantly, particularly in the last 50 years (Keller *et al*., 2011; CBD, 2010; MA, 2005b; Lovejoy, 1996). For instance, Lambdon *et al*. (2008) report an exponential increase in the rate of establishment of non-native plant species in Europe since the beginning of the 20^{th} century. Such changes are not necessarily always associated with significant impacts. In most cases introductions are unsuccessful (Keller *et al*., 2011; MA, 2005b) and there are a number of examples where introduced species have had a negligible effect on the receptive ecological community (Keller *et al*., 2011; Manchester & Bullock, 2000). For instance, the non-native grassland plant species Slender speedwell (*Veronica filiformis*) is widespread throughout the UK but is regarded as having no negative effect on native biodiversity (Manchester & Bullock, 2000). Other non-native species that Manchester & Bullock (2000) report as having negligible impacts in the UK include: the Rose-ringed parakeet (*Psittacula krameri);* the Cynipid gall wasp (*Andricus quercuscalicis);* the Mandarin duck (*Aix galericulata)* and the Roman snail (*Helix pomatia*).

In a number of instances, however, introduced species have led to significant ecological impacts through interactions and processes such as predation, herbivory, competition, habitat alteration, disease transmission and genetic effects (Keller *et al*., 2011; CBD, 2010; MA, 2005b; Manchester & Bullock, 2000). These factors can significantly alter the dynamics of native systems and have been associated with extinctions and considerable homogenising effects on biodiversity (CBD, 2010; MA, 2005a, 2005b; Mckinney & Lockwood, 1999). For instance, MA (2005b, pp. 104) reports that of the 27 documented global extinctions over the past 20 years, 12 have been plants and are at least partially attributable to the impacts of 'alien invasive species'. Although these impacts on many terrestrial ecosystems (e.g. temperate forests and grasslands) over the past century have generally been low, they are likely to increase in the near future, particularly as other pressures (e.g. climate change, land use change and habitat loss) are likely to have a further exacerbating effect (CBD, 2010; MA, 2005a).

2.1.2 Pollution

In general terms, pollution typically refers to the presence of minerals, chemicals or physical properties in the environment which cause harm to the organisms that live in it (UNEP, no date). Pollution is therefore a broad issue and refers to many substances and processes arising from a diverse range of sources (MA, 2005a). A particularly important issue in relation to ecosystem processes and functioning is that of nutrient loading; particularly high levels of nitrogen and phosphorus (CBD, 2010; MA, 2005a). In terrestrial ecosystems, flows of biologically available nitrogen have doubled whilst flows of phosphorus have tripled since 1960, largely related to agricultural practices (CBD, 2010; MA, 2005a). The significant increases in levels of biospheric phosphorus and nitrogen that have occurred in the last fifty years are mainly due to inputs associated with the conversion of land for agricultural purposes and changing land use practices (e.g. agricultural intensification) (CBD, 2010; MA, 2005a). Although the presence of such elements is necessary for biological systems (e.g. for plant growth) and increased levels can have beneficial effects (e.g. increased crop yields), adverse effects such as acidification and eutrophication can also occur. Such processes are problematic because they can lead to species loss, changes in species dominance and composition, and toxicity effects (CBD, 2010; MA, 2005a; 2005b). For instance, anthropogenic eutrophication of water bodies can notably increase phytoplankton productivity leading to the local decline and extinction of populations of more complex flora and fauna through the effects of competition and changes in the physical environment (e.g. available light, levels of oxygen and toxic compounds) with significant homogenising effects (Begon *et al*., 1990). The Gulf of Mexico 'dead zone' off the coast of Louisiana and Texas is a notable example (Lui *et al*., 2010; MA, 2005b; Rabalais *et al*., 2002). High nutrient runoff, primarily from agricultural inputs from the Mississippi basin, has led to the loss of fish, shrimp and crab populations and increased stress on benthic infaunal organisms due to the reduced oxygen levels associated with an increase in phytoplankton growth and subsequent increase in the decomposition of this organic matter (Lui *et al*., 2010; MA, 2005b; Rabalais *et al*., 2002). Adverse effects have also been associated with terrestrial ecosystems. MA (2005a) suggest that globally, increased nutrient loading over the last 50 years has had *moderate* and *very high* impacts on temperate forests and grasslands respectively. In the UK, Smart *et al*. (2003) report significant increases in the fertility of sites of moorland, woodland, heath and bog between 1978 and 1998. These changes have been associated with a notable overall decrease in the frequency of occurrence of individual species in woodland and 'infertile grassland' plots (Smart *et al*. 2005; 2003). Observed changes in other habitats are regarded as 'consistent with the impact of eutrophication' (Smart *et al*. 2005, pp. 367). For instance, shifts in the species composition of moorland, heath and bog, linked to excessive nutrient deposition, include a much greater proportion of generalist plant species (e.g. *Festuca rubra*, *Holcus lanatus* and *Agrostis stolonifera*) with moderate to high nutrient demands, more typical of semi-improved or improved grasslands (Smart *et al*. 2005). A decrease in the proportion of stress-tolerant species (e.g. *Nardus stricta, Erica tetralix* and *Agrostis capillaris*) more commonly associated with these community types was also reported (Smart *et al*. 2005). Generally, impacts on terrestrial ecosystems from nutrient loading up to 2050 are likely to increase (MA, 2005a).

2.1.3 Over-exploitation

Over-exploitation refers to the excessive harvesting of renewable resources (e.g. individuals from a population or biomass) at rates beyond the natural limits for long-term sustainable and economic development (Moxnes, 1998, Begon *et al*., 1996; 1990; UNEP, no date). Over-exploitation is particularly linked to increasing demand for/use of particular ecosystem goods and services (e.g. food and fibre provision), primarily due to an increasing human population (MA, 2005a). Examples of over-exploitation include the over-harvesting of marine and freshwater populations (e.g. fish and invertebrates), over-harvesting of terrestrial plant crops without allowing soils to restore levels of fertility, excessive deforestation, extraction of water from lakes, rivers and aquifers that exceeds recharge rates and over-exploitation of wild bush-meat (CBD, 2010; MA, 2005a; 2005b; Moxnes, 1998; Clark, 1998; Begon *et al*., 1996; 1990).

Historic and projected impacts on different types of ecosystems are variable. Some ecosystem types (e.g. marine and coastal ecosystems and tropical forests, grasslands and savannas) have experienced high to very high impacts due to over-exploitation. Marine populations in particular have experienced severe impacts due to over-fishing, especially since the 1950s. In these ecosystems, current practices have led to significant depletion of stocks and services and are regarded as largely unsustainable (MA, 2005a). In some cases this has already been associated with the collapse of ecosystem services with highly negative impacts on the human economies, communities and infrastructures reliant upon their continued supply. A notable example of this is the collapse of Atlantic cod stocks off the east coast of Newfoundland in 1992 due to over-fishing, leading to the closure of the commercial fisheries in the area (MA, 2005a). Despite the closure of the industry there have been ‘few signs of recovery’ in the intervening years (MA, 2005a, pp. 91). In general, the impacts of over-exploitation on marine and coastal ecosystems and tropical forests, grasslands and savannas are predicted to increase notably up to 2050.

Alternatively, many temperate ecosystems (e.g. temperate wetlands, forests and grasslands) have experienced low to moderate impacts (MA, 2005a). In all cases, impacts from over-exploitation on these ecosystems are not predicted to increase up to 2050 (MA, 2005a), suggesting that, in general, over-exploitation is likely to be much less of an issue for these ecosystems in the future compared to coastal, marine and tropical systems.

2.1.4 Habitat Loss/Degradation (Land Conversion/Land Use Change)

Between one half and two thirds of the area of six of the world’s 14 major terrestrial biomes (including temperate grasslands and broadleaved forests), had been converted, primarily to agriculture, by 1990 (MA, 2005a). A significant proportion of this change occurred during the latter half of last century (MA, 2005a; 2005b). Land conversion not only leads to ecosystem changes through increased inputs of potential pollutants but also leads to the direct loss or displacement of the habitats and species originally occupying the area on which conversion takes place (MA, 2005a; 2005b). Habitat conversion has been identified as the single most important anthropogenic driver of change and biodiversity loss within terrestrial ecosystems, and is currently regarded as the primary cause of declines in species' ranges and populations (CBD, 2010; MA, 2005a; 2005b). Wetland and temperate grassland ecosystems specifically have experienced very high impacts due to habitat conversion over the past 50-100 years. Impacts are likely to increase up to 2050 (MA, 2005a).

In addition to the direct loss of species, land conversion also influences the structure and functioning of ecosystems through habitat fragmentation (CBD, 2010; MA, 2005a; 2005b; CBD, 2003; Gurevitch *et al*., 2002). This is problematic because the areas of habitat remaining, following conversion, are typically smaller, more isolated and exhibit different physical properties to the original habitat. Smaller areas of remnant habitat will only be able to support smaller populations and will likely exhibit decreased habitat heterogeneity than the original continuous habitat (MA, 2005b; Gurevitch *et al*., 2002). Smaller populations are inherently more vulnerable to extinction due to the influence of random demographic variations (Gurevitch *et al*., 2002; Begon *et al*., 1990). Also, smaller populations tend to exhibit decreased genetic variation which means that they will be less able to evolve, and therefore persist, in response to environmental change (Gurevitch *et al.*, 2002; Begon *et al*., 1990). The decreased habitat heterogeneity associated with patches following fragmentation means that populations occupying such patches will also be at greater risk of extinction from environmental change (particularly stochastic events) due to the reduced opportunities for survival and subsequent recovery that the remaining, fragmented habitat provides (Botkin *et al*., 2007).

Additionally, fragmentation within an area generally leads to an increase in 'edge-effects' (i.e. systematic differences between conditions close to the edges of areas of habitat compared to those of the interior) (Gurevitch *et al.*, 2002). Fragmentation, therefore, potentially reduces the amount of suitable or optimum habitat available to organisms originally occupying the area and also creates opportunities for increases in the populations of less specialised or more edge adapted species, including alien invasive species, either *in situ* or through invasion (MA, 2005b). Overall such changes tend to lead to lower levels of biodiversity and increasing homogeneity as the original species 'are replaced by a much smaller number of expanding species that thrive in human-altered environments' (MA, 2005a, pp. 35; 2005b; CBD, 2003).

MA (2005a) predicts that, as a result of habitat loss, the number of plant species, globally, will have decreased by approximately 10-15% during the period 1970-2050. Habitat loss through land conversion is likely to continue to be the major direct driver of change in terrestrial ecosystems in the future (MA, 2005a). Habitat loss and fragmentation are also likely to interact with the other drivers of change, particularly climate change, to negatively impact on ecosystems and increase biodiversity loss (CBD, 2010; MA, 2005a).

2.1.5 Climate Change

It is widely recognised that human activities such as fossil fuel consumption and the associated release of greenhouse gases (GHGs) are affecting atmospheric and terrestrial systems and are contributing to global climate change (CBD, 2010; IPCC, 2007b; Cunningham & Saigo 1990). Between 1750 and 2000 the atmospheric concentrations of CO_2 and CH_4 increased by roughly 30% and 150% respectively, primarily due to the combustion of fossil-fuels and land use change (IPCC, 2007b; CBD, 2003). Due to these increases, average global temperatures have already risen by approximately 1^{o}C in the last 150 years (IPCC, 2007b). Other observed changes include an increase in precipitation, particularly in mid and high latitudes, an increase in extreme weather and climate events (e.g. heat waves) and sea level rise (IPCC, 2007b; CBD, 2003). Projected increases in average global temperature, over the period 1990 to 2100 related to anthropogenic GHG emissions, are between 1.4 and 5.8^{o}C (IPCC, 2007b; MA, 2005b; CBD, 2003; IPCC, 2002). Other *likely* to *very likely* changes projected for 2100 include: further increases of 5-20% in average annual precipitation, especially in the winter and at northern mid-latitude areas; a reduction in very cold winters in temperate regions; increases in extreme weather and climate events and mean sea level rises of between 0.09 and 0.88m (CBD, 2003).

Niche theory (Hutchinson, 1957) states that species are adapted to survive, grow, reproduce and maintain viable populations within the limits of a range of suitable environmental conditions and resources that their environment provides. Climatic factors (e.g. temperature) comprise part of the conditions that species require for survival (Begon *et al.*, 1996; 1990). Climate broadly determines the distribution of species and the structure and functioning of ecosystems (Huggett, 1998; Begon *et al.*, 1996; Woodward, 1987). As a result, notable impacts on ecosystems from climate change are expected (CDB, 2010; MA, 2005a; 2005b; CBD, 2003; IPCC, 2002).

Because of the relationships between climate, species and ecosystems, it is likely that, as climate shifts further from current conditions, existing ecological phenomena will increasingly experience direct (potentially negative) effects (CBD, 2010). For instance, higher maximum temperatures and the incidence of hot days and heat waves are likely to lead to increasing heat stress for many taxa, particularly plants (CBD, 2003). Such changes, in themselves, may cause significant declines in productivity and increase local extinctions (CBD, 2003). However ecosystems are also likely to experience indirect effects from climate change. For instance, changes in phenology (e.g. the timing of bud break in plants and the hatching and migration of insects, birds and mammals) have already been observed and are likely to continue (CBD, 2010; IPCC, 2007a; CBD, 2003). Such changes can have beneficial or detrimental effects. For instance, changes in plant phenology, such as lengthening of the growing season, can increase the susceptibility of plants to the early or late onset of frost and pest or disease outbreak (IPCC, 2007a). The decoupling of established ecological relationships (e.g. plant-pollinator, plant-herbivore and predator-prey) due to different phonological responses of closely associated species is a possibility with potentially detrimental impacts (CBD, 2010; Hegland *et al*., 2009; IPCC, 2007a; CBD, 2003).

Geographic shifts in the ranges of many species are one of the consequences of climate change (Davis & Shaw, 2001). Since the beginning of the Pleistocene epoch (approximately 1.8 million years ago), climate change has resulted in major shifts in species' geographical ranges and notable reorganisations of ecological communities (CBD, 2003). For many species, future climate changes (particularly levels of atmospheric warming) are likely to lead to a shift in suitable climate into areas of higher latitude and elevation (CBD, 2010; MA, 2005a; CBD, 2003). This may represent a positive change for some, at least in the short term (MA, 2005a; CBD, 2003). However, climate change is likely to have negative impacts overall, particularly over longer time scales, with greater rates and magnitudes of change and for particular regions and ecosystem types (IPCC, 2007a; CBD, 2010; MA, 2005a). Although temperate forests, wetlands and temperate grasslands have generally experienced low impacts from climate change over the last 50-100 years, impacts on these ecosystems are predicted to increase very rapidly up to 2050 (MA, 2005a; 2005b).

Because of predicted future climate change, by 2100, the 'climate zones of temperate and boreal plant species may be displaced by 200-1200 km poleward' compared to the 1990s distribution, based on a projected rate of atmospheric warming of 1.4-5.8^{o}C (CBD, 2003, pp. 38). The level of warming at the upper end of this range is notably greater than that experienced at any time during the Pleistocene (including the present interglacial period), where the highest average global temperatures were roughly 3^{o}C above current levels (CBD, 2003). Furthermore, the change in temperature projected between 1990 and 2100 is broadly equivalent to the change experienced in the previous 10,000 years since the end of the last ice age (Begon *et al*., 1996). These rates and levels of change are likely to have significant impacts. Extinctions are more likely to occur with increasing rapidity of climate change. For instance, Joachimski *et al*. (2012) suggest that the mass extinction of terrestrial and marine species that marks the boundary between the Permian and Triassic periods was at least partly caused by the significant global warming that preceded this change. They also suggest that the very warm climate that continued into the early Triassic period was a major factor responsible for delaying the subsequent recovery of life on earth. More recently, the last notable period of extinctions and biodiversity loss in northern temperate floras occurred during the relatively rapid climate change that marked the initiation of the Pleistocene epoch (CBD, 2003). Also, paleoecological studies of past climate change have demonstrated that the composition of many temperate forest ecosystems is still being affected by the delayed colonisation response of many floristic species to the atmospheric warming that marks the beginning of the present interglacial period (Begon *et al*., 1996). It is likely, that for many species, particularly those with relatively low mobility and migratory capacity (e.g. many plant species), the unprecedented levels and rates of climate change predicted to occur over the next century will represent a significant challenge (CBD, 2010; MA, 2005b; CBD, 2003, pp. 23).

2.1.6. Interaction of Drivers, Potential for Abrupt, Non-linear Change and Key Drivers for Terrestrial Ecosystems

In the absence of other human pressures, climate change may be unlikely to cause major extinctions, particularly if changes in climate are within the Pleistocene range (CBD, 2003). However, the ability of species to migrate through landscapes has been greatly diminished due to the influence of other drivers, particularly habitat loss and fragmentation related to human land use (CBD, 2010; MA, 2005b). These drivers alone have been associated with extinction rates between 50-500 times higher than background levels over the last 100 years (CBD, 2010; MA, 2005a; CBD, 2003). Habitat fragmentation is a particular issue in Europe, where conversion rates have typically been highest (CBD, 2003). As a result, and considering the vital ecological role plant species assume as primary producers (Pimm, 1982), widespread extinctions, and changes in community structure are expected (McCarty, 2001; Begon *et al.,* 1996).

The impacts of climate and land use change on existing ecosystems are likely to exacerbate the potential threat posed from other direct drivers (Berry, 2008). For instance, the fragmentation of existing ecosystems creates the opportunities and conditions for the dispersal and subsequent establishment of populations of 'weedy (i.e. those that are highly mobile and can establish quickly) and invasive species' (CBD, 2003, pp. 38). If existing systems and their biological components are already stressed because of the direct impact of changes in climate, weedy or invasive species are likely to be afforded a notable advantage and have a greater ecological impact, particularly if changes in climate have also allowed such species to further expand their climatic range.

These pressures may also further interact with the threat posed from the other pressures. As suggested, habitat fragmentation, climate change and nutrient loading have the potential to facilitate the spread of non-native or invasive species outside of their natural range and so increase their contact and interactions with native species or communities. Whilst in themselves these changes are potentially problematic, climate change, habitat fragmentation, pollution and over-exploitation may also increase the susceptibility of native systems to invasion and therefore subsequent effects. For instance, these pressures have the potential to increase the stress of populations originally occupying an area by reducing the size of native populations and/or creating conditions that are nearer to the limits of their environmental tolerances. Furthermore, native species may be less likely to avoid interactions with invasive species (e.g. competition, allelopathy, herbivory), or move to more suitable areas, due to their reduced capacity to migrate through fragmented landscapes. Because of the combined effects of climate, land use change, pollution and over-exploitation, native populations may therefore be less able to resist and/or recover from the effects of invasion.

A full discussion of the potential interactions between the main pressures and possible impacts on various different ecosystem types is beyond the scope of this thesis. However, a particular issue of concern is the potential for abrupt, non-linear changes in ecosystem properties, processes and functions to occur. Such changes may occur due to the effects of individual pressures; the collapse of the Newfoundland cod populations mentioned above provides a notable example (MA, 2005a). However, the potential for abrupt changes in ecosystem properties, processes, functions and services is likely to be greatly increased if pressures affect ecosystems concomitantly (MA, 2005a; 2005b).

Although the above mentioned pressures are likely to interact, the above discussion suggests that specific pressures (i.e. climate and land use change) are likely to be particularly important for terrestrial ecosystems. For instance, a number of sources generally concur that climate change and land use change are likely to represent the two greatest future pressures on terrestrial ecosystems (CBD, 2010; Haines-Young, 2009; Sala *et al*., 2000). Haines-Young (2009) and Sala *et al*. (2000) suggest that the major factors influencing terrestrial ecosystems globally, by 2100, are likely to be land use change *followed by* climate change. The IPCC (2007a) and MA (2005a; 2005b) make similar general assertions for the year 2050. However, there is some uncertainty over which of these pressures is likely to be the most significant at different spatial and temporal scales. For instance, MA (2005a) suggests that climate change, rather than land use change, could become the major direct driver of biodiversity loss globally, by 2100. Berry (2008, pp. 4) proposes that, although land use change is likely to have a greater impact on ecosystem vulnerability over short time scales (e.g. 1-10 years), at smaller (e.g. local) spatial scales, climate change will 'increasingly contribute to longer-term stresses on plants and ecosystems'. CBD (2010) make similar assertions. This suggests that, by 2050, climate change may have already replaced land use change as the main pressure affecting ecosystems, at least at larger (regional to global) spatial scales.

2.2 Biodiversity Loss, Ecosystem Services and Human Wellbeing

Human cultures, societies and populations depend heavily on the services that ecosystems provide (MA, 2005a; CBD, 2003). These services not only include provisioning services (e.g. food, water, timber) but also: regulating services, where benefits are gained from the regulation of ecosystem processes (e.g. waste treatment and the regulation of climate, floods, disease and water quality); cultural services, regarded as the non-material benefits that humans gain from ecosystems (e.g. recreation, education, cultural heritage, spiritual fulfilment); and supporting services, which are those services (e.g. soil formation, water and nutrient cycling) that are necessary for the provision of all the other ecosystem services and often impact on people less directly and over longer timescales (MA, 2005a).

Because of the intrinsic interconnectedness of ecosystems, in many cases, modifications of an ecosystem to alter one service, leads to changes to other ecosystem services (MA, 2005a). For instance, actions to increase food provision, such as the conversion of forest to agriculture, can result in significant changes in flood regulation, water quality and water use, which potentially affect flood frequency and magnitude, as well as water availability and supply, in other locations and/or over longer timescales (MA, 2005a). It is often the case that 'most changes to regulating services are inadvertent results of actions taken to enhance the supply of provisioning services' (MA, 2005a, pp. 39).

Because of human reliance on the provision of ecosystem services and the innate ability of humans to modify them, the functioning and well-being of human populations is inherently related to that of ecosystems. As stated, the general impact of human activities and drivers of ecosystem change has been a reduction in biodiversity. Through changes in biodiversity, such as the loss of species in a particular location or introduction of species to a new location, the various ecosystem services associated with those species are also changed (MA, 2005a; Hooper *et al*., 2005; CBD, 2003). This is particularly pertinent to habitat conversion (MA, 2005a). MA (2005a, pp. 46-47) point out that with the conversion of habitat from one type to another 'an array of ecosystem services associated with the species present in that location is changed, often with direct and immediate impacts on people'. Although it is relatively well accepted that ecosystem functions are sensitive to changes in biodiversity, the specific relationship between biodiversity and ecosystem properties, services and functioning is complex and, in many cases, understanding of the effects of changes in biodiversity is currently limited (Cardinale *et al*., 2011; Botkin *et al*., 2007; Hooper, *et al*., 2005; CBD, 2003).

2.2.1 Biodiversity and Ecosystem Functioning (BEF): Theory

The concept of complementarity is commonly used in support of a causal relationship between biodiversity and ecosystem function (Scherer-Lorenzen, 2005). This incorporates ideas on the ecological mechanisms commonly used to explain the coexistence of species in communities, and suggests that diversity is related to the continuation and enhancement of particular ecosystem properties and functions. For instance, 'niche complementarity' refers to the process whereby ecosystem functioning (e.g. productivity, resource use efficiency) is sustained and enhanced due to the partitioning of resources (in type, space, or time) amongst coexisting species (Cardinale *et al*., 2011; Hooper *et al*., 2005; Hooper & Vitousek, 1997; Begon *et al*., 1990). Where resources limit growth, such partitioning is predicted to increase the efficiency of resource capture and biomass production of the community as a whole, compared to that of any component species by itself, because the diversity of mixed communities allows 'niche space' to be filled, and resources to be utilised more completely (Cardinale *et al*., 2011; Scherer-Lorenzen, 2005; Hooper *et al*., 2005; Tilman, 1999). Biodiversity is therefore believed to be actively involved in maintaining ecosystem properties and functioning (Cardinale *et al*., 2011; Scherer-Lorenzen, 2005; Hooper *et al*., 2005). Other complementary interactions between species (e.g. facilitation and mutualisms) are also likely to generate a positive relationship between biodiversity and ecosystem processes. The positive influence that legumes have on nutrient availability and production across the wider community in agricultural systems provides a notable example (Cardinale *et al*., 2011; Scherer-Lorenzen, 2005; Hooper *et al*., 2005). The 'redundancy hypothesis' (Scherer-Lorenzen, 2005) assumes that more than one species fulfils a specific function within an ecosystem (Walker, 1992). From this perspective, differing environmental responses (i.e. niche differentiation) between species performing similar ecological roles act to stabilise particular ecosystem functions (e.g. productivity and nutrient cycling) under changing environmental conditions, due to a 'compensatory effect' between these species (Scherer-Lorenzen, 2005; Hooper *et al*., 2005; Lawton, 1994). Increased diversity within the community therefore increases the likelihood that it will contain at least some species tolerant of changing conditions and capable of sustaining ecosystem functioning and can therefore act as insurance in carrying out ecological processes (Hooper *et al*., 2005; Yachi & Loreau, 1999).

Other hypotheses focus more on the extent to which individual species drive and maintain ecosystem functioning. The 'sampling effect hypothesis' regards species within a community as relatively specialised in their roles, with only one or a few species having a large effect on particular functions (Hooper *et al*., 2005). It is proposed that the statistical probability of randomly including ('sampling') these key species is greater in more diverse communities, as they have a larger pool of species to draw upon (Scherer-Lorenzen, 2005; Cardinale *et al*., 2011). As such, increasing diversity is thought to increase the likelihood that particular ecosystem functions will be maintained through an indirect effect on species composition (Simova *et al*., 2013; Hooper *et al*., 2005; Hector *et al*., 1999).

The 'rivet hypothesis' compares the role of species in a community to that of rivets on an aeroplane wing (Cardinale *et al*., 2011; Scherer-Lorenzen, 2005**;** Lawton, 1994). Some species may be redundant in their function which increases the overall reliability of the system (Scherer-Lorenzen, 2005). However with increased species loss, or where species' roles are inherently more specialised, there is decreased redundancy and compensatory effects. In such instances more or less all of the species within the community are actively involved in sustaining ecosystem function at any given time (Lawton, 1994). A minimum set of functional groups are required for the maintenance of ecosystem functioning (Scherer-Lorenzen, 2005; Hooper *et al*., 2005). The loss of any species is therefore far more critical to the performance of the ecosystem (Lawton, 1994). Further species loss potentially leads to exponential effects on ecosystem functioning, increasing the likelihood of subsequent collapse (Cardinale *et al*., 2011; Scherer-Lorenzen, 2005; Lawton, 1994).

2.2.2 BEF: Evidence, Issues and Limitations

Although these hypotheses suggest a generally positive relationship between biodiversity and ecosystem functioning, in many cases the relationship is not a simple one (Cardinale *et al*., 2011; Hooper *et al*., 2005; Scherer-Lorenzen, 2005). For instance, ecosystem properties, such as productivity, are expected to show a 'saturating response' to increasing species richness due to sampling effects, complementarity and facilitation (Hooper *et al*., 2005). Increasing the numbers of species within a community is therefore likely to have progressively less effect on ecosystem functions as available niches or roles are filled and redundancy increases (Cardinale *et al*., 2011; Scherer-Lorenzen, 2005). This 'positive but decelerating' relationship, implies that there is a limit to the positive effects of species richness (biodiversity) on ecosystem function, represented by the level at which the relationship saturates (Cardinale *et al*., 2011).

Much of the empirical evidence, at least until the mid-1990s, regarding a potential BEF relationship was primarily based on observational field studies comparing communities with different levels of diversity, e.g. species-rich forests of East Asia with species poor temperate forests in Europe (Scherer-Lorenzen, 2005). Generally these studies demonstrated a unimodal relationship between species diversity and particular ecosystem properties, such as productivity, disturbance regime or resource availability (Hooper *et al.*, 2005; Fridely, 2001). Although this indicated a correspondence between higher levels of species richness at intermediate levels of resource availability, stress, productivity, or disturbance (Scherer-Lorenzen, 2005, Kahmen *et al*., 2005; Dodson *et al*., 2000; Connell, 1978), in some instances, a negative relationship was also exhibited, with relatively low levels of species diversity associated with higher levels of productivity, for example (Hooper *et al.*, 2005). The validity of such findings has been questioned, however. Earlier comparative approaches typically focused on biodiversity (often represented by, and deemed synonymous with species richness or composition) as the response variable affected by different abiotic factors (e.g. nutrient availability, climate, disturbance) (Hooper *et al*., 2005;

Scherer-Lorenzen, 2005). However, these factors themselves often covary with, and have a strong mediating effect on, the relationship between biodiversity and ecosystem properties, such as productivity (Hooper *et al*., 2005; Scherer-Lorenzen, 2005; Begon *et al*., 1990; 1996). The confounding effect of these underlying factors means that such comparative studies, although useful for establishing correlations between biodiversity (e.g. species richness) and ecological properties (e.g. productivity), cannot be used to prove a causal relationship (Scherer-Lorenzen, 2005; Kahmen *et al*., 2005).

Recent experimental approaches have attempted to address this issue by conducting studies, often within the same site, where environmental conditions are kept as constant as possible whilst manipulating species richness (either through species removal or random allocation of diversity treatments) (Duffy *et al*., 2007; Scherer-Lorenzen, 2005). Only by using these methods can 'within-habitat effects of biodiversity be detected unequivocally' (Scherer-Lorenzen, 2005, pp. 7). In general such work tends to support the idea of a positive but decelerating ('asymptotic') BEF relationship and both sampling effects and complementarity have been invoked as explanatory mechanisms (Cardinale *et al*., 2011; Scherer-Lorenzen, 2005). However, issues concerning the validity and relevance of these studies remain (particularly for interpreting biodiversity loss in natural systems), largely because of the highly controlled or artificial conditions under which they are conducted (Hooper *et al*., 2005; Scherer-Lorenzen, 2005; Kahmen *et al*., 2005).

Many experimental studies, for sound practical reasons, tend to focus on particular types of ecosystem or artificial systems (e.g. grasslands or microbial communities), at specific single trophic levels (e.g. producers), over relatively small temporal and spatial scales and often make explicit or implicit assumptions regarding the way in which communities are assembled or disassembled, which may or may not be relevant to natural communities (Cardinale *et al*., 2011; Duffy *et al*., 2007; Scherer-Lorenzen, 2005; Thebault & Loreau, 2005; Hooper *et al*., 2005; Huston, 1997; Lawton, 1994). For instance, experiments have commonly studied diversity effects on 'fast growing, small sized early successional model systems such as grasslands' (Scherer-Lorenzen, 2005, pp. 3) over a single year or a generation (Hooper *et al*., 2005; Cardinale *et al*., 2011). These studies generally showed a positive but asymptotic relationship, with ecosystem properties such as productivity generally saturating at 5-10 species (Hooper *et al*., 2005). There are often 'positive short term effects of species richness on aboveground productivity with higher resource availability, such as…fertilizer enrichment' (Hooper *et al*., 2005, pp. 14). Hooper *et al*. (2005) suggest that the generally positive results from these grassland experiments are mainly due to facilitation among legume and non-legume species. Grime (2001, cited in Hooper *et al*., 2005) suggests, however, that these results are likely to be skewed because plots have insufficient time for biodiversity to reach equilibrium with the higher fertility induced by the legumes. Fertility and productivity are often positively correlated (Hooper *et al*., 2005). There is also a 'well known phenomena of decreasing plant diversity with increasing fertilisation' (Hooper *et al*., 2005, pp. 14), as highlighted by the 'humpbacked' relationship from observational studies. Additionally, some experimental studies involving longer-lived perennial plants showed that ecosystem responses, such as productivity and nutrient retention, were maximised with only one or two species (Hooper *et al*. 2005). It is therefore quite possible that, given sufficient time, a new equilibrium would have been reached, within the short-term experiments, involving higher levels of productivity at lower species richness.

The apparently contradictory results between observational and experimental studies are reconcilable, and are largely due to differences between the two approaches, in terms of questions posed and scales assessed (Hooper *et al*., 2005; Hector, 2005; Scherer-Lorenzen, 2005; Fridely, 2001). The 'macro-ecological' perspective that typically underpins observational research (Hooper *et al*., 2005), often focuses on understanding patterns of diversity (e.g. species richness), in response to variation in abiotic factors (e.g. resource availability, disturbance regime), either across or within sites (Hooper *et al*., 2005; Hector, 2005; Scherer-Lorenzen, 2005). As suggested, these factors themselves interact with species' traits to determine ecosystem properties such as productivity (Hooper *et al*., 2005; Scherer-Lorenzen, 2005). Local diversity is mainly a 'function of local environmental conditions, most notably fertility and disturbance levels' (Fridely, 2001, pp. 519) and 'represents the species functional traits for which that environment selects' (Hooper *et al*., 2005, pp. 19). Because of the issue of decreasing plant diversity with increasing fertilization, the high productivity at low levels of species richness associated with some sites within observational studies is therefore likely due to the more extreme conditions characterising such sites (e.g. high fertility) and therefore the opportunities they represent for particular types of species or species traits. In other words, because of their characteristics, observational studies highlight the high degree of variation in local diversity among habitats due to differing site conditions, manifest as differences in ecosystem properties such as productivity (Fridely, 2001).

Because of their aims, experiments have sought to keep environmental conditions as constant as possible in order to avoid the potentially confounding effect of underlying abiotic variables (Scherer-Lorenzen, 2005; Hector, 2005; Hooper *et al*., 2005). They therefore focus exclusively on the 'within-site effects of diversity' (Scherer-Lorenzen, 2005, pp. 13), which represents a small portion of the observed overall variance in productivity and is largely 'explained by local species composition, determined in part by the size of the species pool via the sampling effect' (Fridely, 2001, pp. 519). Fridley (2001) suggests that experiments, because of their characteristics, focus on the relationship between local productivity and the diversity of the species pool, rather than that between local diversity and productivity *per se*. These studies are therefore unable to account for the variation in local diversity among habitats which, as stated, largely explains the apparently negative correlation between species richness and productivity on the descending part of the unimodal diversity-productivity curve from observational studies. These points highlight that environmental context and the characteristics of the species involved largely determine the particular shape of the diversity-ecosystem function relationship locally (Hooper *et al*., 2005; Fridley, 2001), but do not undermine the idea of a generally positive relationship between the two.

Diversity is also likely to become increasingly important with increasing spatial and temporal scale due to the greater variety of biotic and abiotic conditions that are experienced (Cardinale *et al*., 2011; Hooper *et al*., 2005). It has been suggested that the small temporal and spatial scales that characterise many experiments 'may underestimate the impacts of diversity loss on ecosystem processes in natural ecosystems' because they do not account for the greater heterogeneity and therefore the increased opportunities for niche differentiation that natural systems offer due to their greater spatial and temporal variation (Cardinale *et al*., 2011, pp. 586; Hillebrand & Mathiessen, 2009). A number of longer-term experiments involving grasslands demonstrate that the effects of species richness on ecosystems properties (i.e. biomass) and the 'magnitude of complementarity effects' increased with the length of experiments (Cardinale *et al*., 2011). Relatively few studies have been conducted over multiple spatial scales (Cardinale *et al*., 2011). Such experiments are vital in providing a better understanding of the relationship between ecological functioning and diversity. However, they are extremely difficult to perform and in many instances observational studies are still required (Scherer-Lorenzen, 2005). However these are also problematic, due to the large number of study sites required and the fact that 'among-site abiotic variation has to be adequately accounted for by including relevant abiotic factors as covariates in statistical analyses' (Scherer-Lorenzen, 2005, pp. 8). Hooper *et al*. (2005, pp. 17) point out that 'few observational studies or experiments, in either microcosms or the field, have been able to completely avoid confounding the effects of species richness with effects of other variables on the measured responses'.

Another limitation associated with previous BEF research generally is that studies typically focus on species richness as the primary aspect of diversity (Cardinale *et al*., 2011; Hooper *et al*., 2005; Scherer-Lorenzen, 2005), whilst there is increasing evidence to suggest that other aspects of diversity (e.g. genetic, functional or landscape diversity) may have an equal, if not greater, effect on ecosystem function (Cardinale *et al*., 2011). For instance, it is differences in species' functional traits (i.e. species traits that 'influence ecosystem properties or species' responses to environmental conditions'; Hooper *et al*., 2005, pp. 6) that are the underlying cause of any biodiversity effects on ecosystem function, rather than species richness *per se*. As such, the traits of particular species and the diversity of traits between species are often more useful for interpretating potential effects on ecosystem function than simple number of species. It has been suggested that overall ecosystem functions exhibit a greater stability to environmental change and species' invasions in more species-rich communities (and therefore the services they are commonly associated with) because the greater diversity within and between functional groups means there is increased redundancy between species and less niche space available to potential invaders (Cardinale *et al*., 2011; Hooper *et al*., 2005; Scherer-Lorenzen, 2005). It has been argued, therefore, that ecological functions associated with species-poor communities are more susceptible to such pressures and change (Cardinale *et al*., 2011; Hooper *et al*., 2005; Begon, 1990). However, many ecosystems are naturally species-poor and/or contain species which have a disproportionate effect on ecosystem function (e.g. keystone species) (Hooper *et al*., 2005; Scherer-Lorenzen, 2005). The loss or disruption of these species in such contexts is likely to have a much greater impact on existing functions than the loss or disruption of other species present (see 'rivet hypothesis') (MA, 2005a; 2005b; Hooper *et al*., 2005; Scherer-Lorenzen, 2005). In such instances, high species diversity may not be a particularly appropriate conservation aim.

Understanding the links between species functional traits and ecosystem level effects remains a significant challenge (Cardinale *et al*., 2011; Hooper *et al*., 2005). However, there is evidence to suggest that genetic diversity within a species is also vitally important in terms of maintaining existing ecological functions and reducing susceptibility to environmental change and invasion (MA, 2005a; 2005b). For instance, there are a number of studies which suggest that genetic diversity within a species can influence ecological processes, such as productivity and recovery from environmental change, at magnitudes that are comparable to the effects of species richness (Hughes, 2008). Hooper *et al*. (2005, pp. 18) state that the genetic diversity of crops in agricultural ecosystems 'can reduce susceptibility of crops to climate variability, pests, pathogens, and invasion of weedy species'. These points suggest that, although a focus on species richness is likely to be inappropriate in some circumstances, managing other relevant aspects of diversity (e.g. genetic or functional diversity) is likely to be an equally valid approach in safeguarding existing ecological functions regardless of the specific ecological context (Cardinale *et al*., 2011; Hooper *et al*., 2005).

In summary there is strong theory, and some empirical evidence, to support the idea of a positive relationship between biodiversity and ecosystem function, particularly at the larger temporal and spatial scales characteristic of most natural systems. Biodiversity loss (both local and global) is likely to significantly compromise ecosystem properties, services and functioning with potential negative consequences for human wellbeing. Understanding this loss is therefore vital. Considering the inherent role that environmental conditions and species' traits play in influencing the relationship between biodiversity and ecosystem function, however, and the current limits in understanding of how they may interact to determine the strength and shape of the relationship in particular 'real-world' contexts, this remains a significant challenge (Hooper *et al*., 2005). Previous research has typically focused on species richness as the primary aspect of biodiversity whilst it is increasingly appreciated that other components (e.g. genetic or functional diversity) are equally, if not more, relevant for interpreting effects on ecosystem function (Cardinale *et al*., 2011; Hooper *et al*., 2005; Scherer-Lorenzen, 2005). Also, successful management of ecosystems often requires managing for multiple goals and a broad array of ecosystem services, which may place competing demands on ecological functions (Hooper *et al*., 2005, pp. 24). The majority of research, has typically focused on specific, single ecosystem functions or properties (e.g. primary production, nutrient retention) (Hooper *et al*., 2005) which 'may lead to misleading management recommendations if taken uncritically' (Scherer-Lorenzen, 2005, pp. 18). Despite the uncertainty, there is an imperative need for assessments of the potential for biodiversity loss and degradation from anthropogenic pressures (e.g. climate change, land use) in the natural world in order to gauge the potential impacts on ecosystem properties, goods and services and better contribute to adaptive management. Morecroft *et al*. (2012, pp. 548) writes: 'an incomplete evidence base is not a reason for inaction: we do not have time [on] our side: waiting for greater certainty will often make adaptation harder'. Hooper *et al*. (2005 pp. 24) and others (e.g. Morecroft *et al*., 2012; IPCC, 2007a) suggest a precautionary approach until this uncertainty is better resolved: 'adaptive management and maintaining a diversity of native species will help maintain future management options'. Concepts such as vulnerability, offer a broad perspective on the relationship between ecosystem structure, function and environmental variation. The concept is therefore highly relevant to understanding the potential risks to biodiversity from environmental pressures and change, particularly at larger spatial and temporal scales, and is increasingly applied within ecological research (Preston *et al*., 2011; De Lange *et al*., 2010).

2.3 Vulnerability

Although the concept of vulnerability has its roots in the social sciences, it is closely associated with the ecological concept of resilience and is increasingly used within the discipline of ecology in studying the impacts of stressors or environmental change on populations, communities and ecosystems (De Lange *et al*., 2010). De Lange *et al*. (2010, pp. 3873) suggest that vulnerability is a 'more complete descriptor' of long-term effects on ecosystems than resilience, and offers a more prospective approach to risk and impact assessment. Studies of resilience have traditionally been concerned with understanding ecological effects retrospectively (e.g. by asking questions, such as 'did the system return to its original state?' how long did this take? which factors were involved?)

(De Lange *et al*., 2010). Vulnerability is concerned with understanding the likelihood or potential for a system to be impacted by a particular change or stressor and the specific factors or traits that determine this and 'which ones may counteract' (De Lange *et al*., 2010, pp. 3874). Though the two concepts approach the question of ecological risk or impact from somewhat different perspectives, they are closely connected. For instance, understanding which factors or traits contributed to a system returning to its pre-disturbance state is obviously relevant in understanding potential current and future impacts and vulnerabilities. De Lange *et al*. (2010) suggest that resilience and vulnerability may be regarded as each other's antonym (e.g. a system which increases its resilience will be less vulnerable). The background of resilience studies is therefore highly relevant in any discussion of vulnerability, and is referred to here where appropriate. However, based on the information from De Lange *et al*. (2010) vulnerability is regarded as offering a more useful conceptual basis for predictive studies.

2.3.1 Definitions

The IPCC (2007a, pp. 21) offers this widely used definition of vulnerability in relation to climate change (e.g. Berry *et al*., 2008; Tremblay-Boyer & Anderson, 2007; Matsui *et al*., 2004):

> 'Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate change and the variation to which a system is exposed, its sensitivity and its adaptive capacity.'

Although the quote specifically relates to climate vulnerability, the same principles may be applied to other types of environmental change and potential risk. It therefore identifies three key elements that are required in understanding vulnerability (Berry, 2008).

Firstly, the *exposure* of a system to disturbance(s) or change(s) of particular magnitude is important. The IPCC (2001, pp. 987 & Brooks, 2003, pp. 5) regard exposure, in relation to climate change, as 'the nature and degree to which a system is exposed to significant climate variations'. The EEA (2012) defines exposure, more generally, as the contact of an organism or system to a physical agent or external stressor. Essentially, exposure relates to the character and magnitude of disturbance or environmental change (e.g. climate change) that a system experiences or is likely to experience.

Secondly, the *sensitivity* of the system is also important. The IPCC (2007a, pp. 881; 2001, pp. 993) defines sensitivity in relation to climate change as: 'the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. The effect may be direct (e.g. a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise)'. De Lange *et al*. (2010, pp. 3873) suggest sensitivity, more generally, to be the effect or 'potential impact' of a disturbance or environmental change on the system. Sensitivity is also referred to as the impact of environmental change on some effect parameter, e.g. the growth of a species (De Lange *et al*., 2010, pp. 3872: CBD, 2003, pp. 142). Brooks (2003, pp. 4 & 5) suggests that sensitivity relates to the inherent biological or social properties of a system affected by a particular hazard that 'act to amplify or reduce the damage resulting' from the 'first-order' physical impacts of the hazard. Sensitivity therefore concerns the relationship between the physical agent/stressor and the biological or social characteristics of the target system. For instance, Berry (2008, pp. 4) regards climate sensitive species as 'those that are near a climatic tolerance threshold' or 'have a small niche breadth'. In terms of climate then, sensitivity links the character and magnitude of the changes in climate to which a target system is exposed and its particular climatic tolerances or niche.

Adaptive capacity is the third component of vulnerability described above. The IPCC (2007a, pp. 869; 2001, pp. 982) defines adaptive capacity in relation to climate change, as 'the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences'. Similarly, Brooks (2003, pp. 8) suggests that adaptive capacity relates to the 'ability or capacity of a system to modify or change its characteristics or behaviour so as to better cope with existing or anticipated external stress'. 'Recovery potential' is a term often used instead of adaptive capacity (De Lange *et al*., 2010, pp. 3872). In relation to climate change, Berry (2008, pp. 5) distinguishes between 'two types of adaptation: autonomous (or spontaneous) adaptation and planned (or societal) adaptation', based on IPCC criteria. The former relates to the responses to climate change occurring at the species or habitat level (Berry, 2008). The latter 'includes human management and policy actions aimed at facilitating autonomous adaptation' (Berry, 2008, pp. 5). This highlights that the adaptive capacity of a system at any given time, is determined not only by the socio-economic context in which it exists but also its particular biological or ecological characteristics. These points suggest that essentially, adaptive capacity relates to the socio-economic and biological or ecological properties of a system, which give it the potential to reduce, moderate or recover from the effects of change.

Whilst the exposure component is relatively easily understood, ambiguities are apparent between the sensitivity and adaptive capacity components. For instance, the idea of sensitivity as the inherent/internal characteristics of a system that 'amplify or reduce damage…' (Brooks, 2003, pp. 4) appears equivalent to the perspective of a system's adaptive capacity being (at least) partially related to its ability to 'moderate potential damages' (IPCC, 2007a, pp. 869; 2001, pp. 982).

Adaptive capacity has close connections to the concept of resilience (De Lange *et al*., 2010; Haines-Young & Potschin, 2010; Luers *et al.*, 2003). For instance, based on the more traditional definition of resilience as a 'return time to a stable state following a perturbation' the concept is increasingly used to 'describe the abilities of systems…to recover from an adverse impact' (Morecroft *et al*., 2012, pp. 547). This emphasis on the ability to recover from disturbance closely mirrors the idea of 'recovery potential' from the adaptive capacity component of vulnerability. Resilience is often contrasted with resistance within ecological research. Whilst resilience is the ability of a system to return to its former (equilibrium) state following displacement from that state due to disturbance, resistance refers to the ability of the system to avoid displacement in the first place (Begon *et al*., 1990). Resilience (i.e. recovery time) is often used as an inverse measure of resistance (Scherer-Lorenzen, 2005). However, others regard resilience and resistance as more or less synonymous. For instance, Lawton *et al*. (2010: cited in Morecroft *et al*., 2012, pp. 547) regards a 'resilient ecological network as 'capable of absorbing, resisting or recovering from disturbance'. The IPCC (2007a, pp. 880) provides a similar definition of resilience as 'the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change'. Others (e.g. Morecroft *et al*., 2012; De Lange *et al*., 2010) provide much the same treatment of the relationship between resilience and resistance.

Clearly then, the concepts of resilience and vulnerability are closely related and there is a considerable degree of overlap between the various terms associated with each. Both concepts are essentially concerned with understanding the potential impacts on a system from disturbance or environmental change (Brooks, 2003). As such, whether one is concerned with resilience (in its broadest sense) or vulnerability, the relevant terms and concepts associated with each (i.e. resistance and recovery time or potential in the case of resilience, and sensitivity and adaptive capacity in the case of vulnerability) should be accounted for in order to gauge overall impacts effectively. Brooks (2003, pp. 10) writes: 'at any given time, we may view a system as exhibiting a certain degree of vulnerability to a specified hazard and as having a certain ability or potential to adapt so as to reduce its vulnerability to that hazard…'.

Due to the inherent ambiguities surrounding the resilience concept, and therefore by extension that of vulnerability, Morecroft *et al*. (2012, pp. 547) 'advocate a pragmatic approach' for practical purposes: 'accept that resilience is a broad term encompassing a series of related concepts and ensure that the intended meaning is clearly explained when applied to specific situations'. Based on the points raised in the previous paragraph, the sensitivity component of vulnerability, within this thesis, is regarded as referring to those properties of a system that determine the initial, 'first order', biophysical impacts of disturbance or environmental change. In this sense, sensitivity may be regarded as akin to the resistance concept from resilience studies in that it is related to those properties of the system which allow it to absorb or resist environmental change without experiencing significant change or adverse effects. Adaptive capacity is regarded as more closely akin to the more traditional meaning of resilience as: the ability of a system to 'recover from an adverse impact' (Morecroft *et al*., 2012, pp. 547). In this sense, therefore, adaptive capacity relates to those properties of a system which determine its potential to recover from disturbance after significant changes or adverse effects have been experienced.

2.3.2 Previous Vulnerability Research

Due to its characteristics, vulnerability has been increasingly employed in the study of the impacts of climate change, and other types of environmental change, particularly within the last decade (Preston *et al*., 2011). Despite (or maybe because of) the increasing focus on vulnerability and the subsequent developments within vulnerability studies, methods of conceptualising, constructing and assessing vulnerability are highly varied (Preston *et al*., 2011). This presents 'problems for the development of a consistent definition and its operationalization in assessment practice' as well as 'inter-study comparison' (Preston *et al*., 2011, pp. 179, 196).

Many studies have sought to assess vulnerability (either explicitly or implicitly) by modelling the impact of environmental change (particularly climate change) on species distributions or potential climate space under conditions of future change. Two related definitions of climate space exist within the literature. Firstly, climate space is regarded as synonymous with the concept of a species' fundamental climatic tolerance or niche (SNH, 2014; Kearney *et al*., 2010; Schmitz, 2007; Pearson & Dawson, 2003, Hutchinson, 1957). In this context, the climate space of a species, or habitat, is regarded as a multi-dimensional, conceptual construct describing the range of climatic conditions within which it can survive (SNH, 2014; Kearney *et al*., 2010; Schmidtz, 2007; Pearson & Dawson, 2003). The second definition of climate space relates to the specific area(s) where climatic conditions permit the survival of a species/habitat, either now or in the future (SNH, 2014; DEFRA, 2010; 2008; Piper *et al*., 2006; Harrison *et al.*, 2001). Vulnerability assessments focusing on the impacts of environmental change on species distributions or geographical climate space often equate loss of coverage or climate space with increased vulnerability (e.g. Berry *et al*., 2003). This assumption has some validity. However, Berry (2008), Botkin *et al*. (2007) and Thuiller *et al*. (2005) suggest that such assessments may misestimate vulnerability as they often do not address other details (e.g. land use change, population dynamics or species interactions) that are also relevant in determining overall impacts (e.g. Iverson *et al*., 1999).

Other studies have assessed vulnerability more comprehensively through a qualitative, or at least semi-quantitative, assessment of potential risk or harm (Preston *et al*. 2011). For instance, Mitchell *et al*. (2007) provide a qualitative assessment of the vulnerability of a number of sectors and broad habitat types in the UK to climate change. Whilst such assessments are valuable, they somewhat ignore the spatial characteristics of vulnerability, which is determined by a number of factors which may be highly heterogeneous in space and/or time (Preston *et al*. 2011). Understanding and conveying the spatial characteristics of vulnerability is essential for effective planning and risk management in the face of climate change and other pressures, as well as for communicating these risks effectively to relevant stakeholders (Preston *et al*. 2011).

Many studies have investigated social vulnerability and focus on understanding or 'characterising the internal socio-political determinants of vulnerability that influence how human and natural systems cope with or respond to stress' (Preston *et al*., 2011, pp. 185). Although these methods can be useful in providing a spatial context to vulnerability, they have been criticised due to the 'top-down' approach that is often applied and the specific vulnerability indicators (e.g. population, house prices, income, age) that are employed. Preston *et al*. (2011, pp. 185) state that because of these issues 'significant questions arise as to whether….such methods [are] relevant to vulnerability processes…' Wu *et al*. (2002) studied the social vulnerability of coastal communities in Cape May County, New Jersey to sea-level rise using a large number of social indicators. However, the selection of these indicators was based on a pre-existing framework and their validity/relevance, for the study area specifically, was not assessed. Relevant local factors and interactions may have been omitted, potentially leading to a misestimation of vulnerability within their study area specifically.

Brooks (2003) suggest that for non-human systems or where focusing on 'social' vulnerability is not as relevant, the term 'inherent vulnerability' may be more appropriate when referring to those internal characteristics of a system that determine its ability to adapt to or cope with change. This suggests a conceptual commonality underpinning the role that the inherent properties of systems play in influencing vulnerability in both natural and human systems. However, whilst the inherent vulnerability of social systems has received relatively strong focus, assessments of the inherent or 'endogenous' vulnerability of more natural ecological systems are often lacking (Preston *et al*., 2011). Of the 45 vulnerability studies Preston *et al*. (2011) analysed as part of their review into the spatial application of vulnerability, only 2% tackled ecosystem vulnerability specifically. Considering the apparent significance of the endogenous characteristics of systems in determining vulnerability and the intrinsic usefulness of vulnerability mapping for effective planning and risk management, such research is obviously vital.

Another limitation often associated with previous vulnerability studies is that they often assess the vulnerability of systems to potential future change in terms of their current characteristics (Preston *et al*., 2011). This is a useful starting point (Preston *et al*., 2011). However, these studies tend to neglect the fact that such characteristics are likely to be modified as a result of the future changes they encounter. For instance, Tremblay-Boyer & Anderson (2007) conducted a spatial assessment of vulnerability of ecosystem patches to future climate change and sea-level rise in Panama. This was based on a limited number of biophysical vulnerability indicators, including the spatial characteristics of individual ecosystem patches (e.g. patch 'irregularity'). Although the inclusion of such indicators has a sound conceptual underpinning, the potential impact of climate change and sea-level rise (as well as other factors, such as land use change) on the spatial characteristics of patches was not assessed. As such, the study is likely to misestimate future vulnerability. Preston *et al*. (2011) suggest that only about two-thirds of the studies they assessed used any sort of future biophysical scenario in their assessment. Considering the inherent role that future environmental change is likely to play in influencing vulnerability, this figure is relatively low.

2.4 Scale and Modelling Approaches

A number of additional general issues are relevant in providing predictions of the potential future impacts of environmental change (Botkin *et al*., 2007). The issue of scale is highly relevant, especially in relation to the particular factors that determine impacts (Botkin *et al*., 2007; Vogiatzakis, 2003; Pearson & Dawson 2003; Guisan & Zimmerman 2000; Woodward 1987). A significant proportion of previous research, on the potential ecological impacts of environmental change, has focused on investigating the potential ecological impacts of climate change (Preston *et al*, 2011; Berry, 2008). The subsequent discussion focuses on the issues apparent within these studies, particularly in modelling distributions. However, the same issues and considerations are also highly relevant to the study of the potential ecological impacts from other factors, and for other predictive modelling approaches.

2.4.1 Spatial Scale

Previous research into the ecological impacts of climate (and other environmental) change has tended to focus on providing assessments for a limited number of species at larger (regional or global) spatial scales or for more complex species assemblages for specific regions or ecosystems (Trivedi *et al*., 2008; Holman *et al*., 2005a; Pearson & Dawson, 2003; Guisan & Zimmerman 2000; Peng 2000; Zimmerman & Kienast*.,* 1999; Brzeziecki *et al.,* 1995; Brzeziecki *et al*., 1993). Recently, it has become increasingly appreciated that investigations of the potential ecological effects of climate change for entire landscapes at sub-regional scales should be a priority for future research (Morecroft *et al*., 2012; Berry, 2008; Trivedi *et al*., 2008; Holman *et al*., 2005a; CBD, 2003; Burnett *et al*., 1998). However, providing such assessments at this scale presents particular challenges; partly because of the relative importance of other non-climatic factors in influencing the occurrence, functioning and structure of ecological phenomena and the concomitant problems of reliably incorporating their influence into subsequent evaluations (Pearson & Dawson, 2003; Guisan & Zimmerman, 2000). Pearson & Dawson (2003) propose a general hierarchy of factors that they regard as playing a dominant role in determining species distribution across various spatial scales (Table 2.1).

Table 2.1: Hierarchy of the dominant distribution controls at different spatial scales (Source: Pearson & Dawson, 2003)

		Scale Domain						
		Global > 10000 km	**Continental** 2000-10000 km	**Regional** 200-2000 km	**Landscape** 10-200 km	**Local** 1-10 km	**Site** 10-1000m	**Micro** <10m
Factor	Climate	←	—	→				
	Topography			←	—	→		
	Land use				←	—	→	
	Soil Type					←	→	
	Biotic Interaction					←	—	→

The hierarchy clearly suggests that climate has influence over the occurrence of species at larger spatial extents, whilst at smaller scales non-climatic factors play a more important role. The table suggests that topographic and land use factors are the most important controls over the distribution of species at the 'landscape' scale. The results of some research support the scale dependencies outlined in the hierarchy. For instance, Pearson *et al.* (2002) found a good agreement between observed and simulated distributions for 32 plant species based on correlations between observed distributions and five climatic parameters at the European scale. Beerling *et al.* (1995) applied a static correlative model driven by three bioclimatic variables to simulate the distribution of Japanese knotweed (*Fallopia japonica*) for Europe and South-east Asia. They conclude that the 'European distribution is climatically determined' and report 'generally accurate' simulations for South-east Asia.

It should be noted, however, that the assumption that large spatial extents are associated with coarse data resolutions and small extents with fine data resolutions is inherent within the hierarchy. This distinction is important, as it does much to explain the proposed framework and acts to highlight the fact that one's scale of perception is a critical consideration when investigating the ecological effects of climate change. The implication then is not that climate plays no role in influencing species' distributions, and other ecological impacts, at sub-regional scales but rather that other (non-climatic) factors play a more dominant role *at the resolutions that are typically employed for investigation at these scales.* The role of climate in influencing ecological impacts at different spatial scales therefore may not be as clear cut as the hierarchy initially suggests.

Pearson & Dawson (2003, pp. 369) themselves state that their 'hierarchical framework may be imperfect and oversimplified'. Woodward (1987) argues that 'at all spatial scales the response of the plant to climate is a crucial feature in its presence'. Indeed, some sub-regional scale research suggests a significant relationship between climatic variables and the distribution of the ecological units under investigation (e.g. Trivedi *et al*., 2008). Zimmerman & Kienast (1999) used a static equilibrium model to study the influence of climatic factors on the spatial patterns of graminoid species and communities at the sub-regional scale within Switzerland using fine resolution (50m) data. They concluded that 'the climatic factors used to drive the model explained a major part of the observed patterns' (Zimmerman & Kienast, 1999, pp. 469).

It is reasonable to suppose therefore that climate does play some role in shaping distribution within a sub-regional context: particularly in relation to spatial extents which are defined as 'landscape' under Pearson & Dawson's (2003) nomenclature. As such, the use of climatic parameters as predictor variables to model potential changes in distribution may well provide a useful indication of the potential ecological impact of climate change within a sub-regional context. It should also be noted that Pearson & Dawson (2003, pp. 369) state that 'identifying appropriate scales of analysis for different environmental drivers, thus validating [or not] the scale dependencies outlined in Fig. 5 [their proposed hierarchical framework], should be the focus of further research'. Certainly, the extent to which climate directly influences the distribution of ecological phenomena at such scales is a valid area of further investigation from an academic and conservation management perspective, particularly when considering the threat that current and future climate change poses to the integrity of existing ecological systems (IPCC, 2007a; 2002; MA, 2005a; 2005b; CBD, 2003).

2.4.2 Ecological Scale

Scale is also important in influencing the appropriate level of ecological organisation that should be the focus of research investigating the potential ecological impacts of climate change (as well as other relevant factors). Although, some studies have focused at the level of community organisation (e.g. Zimmerman & Kienast, 1999; Brzeziecki *et al.,* 1995; Brzeziecki *et al*., 1993), previous research has tended to focus on species as the basic ecological units of investigation (Berry *et al*., 2006; 2002; Vogiatzakis 2003; Pearson *et al*., 2002; Guisan & Zimmerman, 2000; Wu

& Smeins, 2000; Franklin, 1998; Tremblay-Boyer & Anderson, 2007). From a theoretical perspective, the general focus on modelling at the species, rather than community, level within climate change related ecological research is conceptually sound. It is embedded in the discourse surrounding the community/continuum debate and is therefore intrinsically linked to the concept of the niche (Guisan & Zimmerman, 2000; Franklin, 1995). In relation to predictive change modelling, the community theory essentially implies that a community acts as a cohesive ecological unit and can therefore be treated in the same way as other more readily identifiable units (i.e. species). The continuum postulate regards the community as a far less cohesive entity, as it emphasises the individualistic response of species within the community to environmental gradients (continua). The theory suggests that extant communities are unlikely to move as a cohesive unit under conditions of future change (Guisan & Zimmerman, 2000; Zimmerman & Kienast, 1999; Franklin, 1995; Begon *et al*., 1990; Pears, 1985). Generally, the current perspective within ecology is closer to the individualistic, continuum concept. It is argued, therefore, that models simulating species rather than community distributions are more robust (Guisan & Zimmerman 2000; Zimmerman & Kienast, 1999; Begon *et al*., 1990).

From a general conservation policy perspective however, it is desirable to focus investigation at levels of ecological organisation higher than that of the species (Morecroft *et al*., 2012; Zimmerman & Kienast 1999; Burnett *et al*., 1998; Franklin, 1995; Tremblay-Boyer & Anderson, 2007). For instance, Morecroft *et al*. (2012, pp. 549) suggest that assessments of ecological vulnerability at the community level represent a more effective approach, because vulnerability at this scale of organisation encompasses and is enhanced by the vulnerability and 'capacity for change at genotype and species levels'. Similarly, assessments at the landscape scale are likely to be more useful than those at smaller spatial scales (e.g. local), as they will take account of a broader network of sites and so better represent vulnerability at higher levels of ecological organisation (Morecroft *et al*., 2012).

Furthermore, Zimmerman & Kienast (1999, pp 470) state that '...election of either the species or community approach depends heavily on the aim of the study. The focus on communities is related to the emphasis on concrete landscape patterns...'. This quote carries the implicit suggestion that communities should be the emphasis of investigations at the sub-regional, 'landscape' scale in order to provide a more holistic assessment. It is worth noting that their research found a higher degree of coincidence between simulated and observed patterns for communities than for species. Franklin (1995, pp. 483) asserts that, although 'fewer definitional uncertainties or abstractions' are associated with the predictive mapping of species distributions, communities are 'geographic entities and therefore can be predicatively mapped'.

There is also some suggestion by Zimmerman & Kienast (1999) and others (e.g. Vogiatzakis, 2003) that the use of species for investigating the potential ecological consequences of changes in climate is conceptually problematic within a static-empirical modelling context. This is because the observed presence of a species (on which the modelling is partially based) is by definition an expression of its realised niche (Pearson & Dawson, 2003; Guisan & Zimmerman 2000). It is therefore context sensitive and varies according to the influence of other species present (Pearson & Dawson, 2003). Climate change is likely to have an uncertain, chaotic and largely unpredictable influence on the interactions and interrelationship between these species (Pearson & Dawson, 2003). This implies that the reliability of results from assessments adopting a species-based focus, within particular modelling contexts (i.e. static empirical), is questionable. Additionally, as suggested in the discussion below, it is extremely difficult to provide robust, holistic community level simulations at intermediate to large spatial scales by using species as the basic units of investigation (Guisan & Zimmerman, 2000).

2.4.3 Modelling Approaches

The inherent interconnectedness and complexity of many ecological systems and the limitations in the extent of human knowledge and understanding of them is an important area of uncertainty, and presents a serious challenge in understanding the potential ecological effects of climate (and other environmental) change (Pearson & Dawson, 2003; Guisan & Zimmerman, 2000). Various methods have been used to investigate these effects. Such studies commonly attempt to explore climatically-induced ecological change by characterising the environmental requirements (niche) of species or communities and then using this to model potential changes in their distribution or geographical shifts in their suitable climate space under scenarios of future climate change (Guisan & Thuiller, 2005; Vogiatzakis 2003; Pearson & Dawson 2003; Guisan & Zimmerman 2000). Some general limitations, stemming from the different theoretical assumptions, practical considerations and related methodological practices associated with each of these various approaches, can be identified. The diversity of methodologies and techniques that have been used in an attempt to investigate the distribution of ecological phenomena makes concise classification difficult (Guisan & Zimmerman, 2000). However, a general distinction can be made between those approaches that are 'static' or 'dynamic' (Pearson *et al.*, 2002; Beerling *et al.*, 1995).

'Static' models tend to base their predictions on the statistical analysis of large-scale field data sets (Botkin *et al.*, 2007; Guisan & Zimmerman, 2000; Zimmerman & Kienast, 1999). Specifically, such models attempt to characterise the environmental requirements or tolerances (i.e. niche) of the ecological units under investigation (e.g. species, communities) by establishing a correlation between their current distributions and environmental factors deemed relevant to their survival (Pearson & Dawson, 2003; Guisan & Zimmerman, 2000). Environmental conditions outside of the current range of the target ecological units are regarded as outside of their environmental niche and therefore unsuitable for their presence or survival. This environmental niche is often referred to as the species' or communities' 'environmental envelope', or where the niche is established solely in terms of climatic factors; 'bioclimatic envelope' (Pearson & Dawson, 2003). The environmental or bioclimatic envelope information is then applied to spatial data depicting the future characteristics of relevant environmental conditions or resources in order to predict potential ecological impacts.

Such models are therefore correlative and empirical in nature. Their classification as static relates to the assumption that the observed relationships between the ecological units (e.g. species) and the various environmental (typically climatic) controls under investigation will continue to be maintained in the future (Pearson & Dawson 2003; Guisan & Zimmerman 2000). This assumption is often automatically incorporated due to the inherent characteristics of the relatively simple, statistical models that tend to be used (Guisan & Zimmerman 2000). A significant criticism of the static-empirical approach is that the derived results potentially misrepresent the potential future distribution or suitable climate space of the ecological units under investigation. This is because the sources of data and methods of analysis typically used often only facilitate characterisation of the species' currently realised niche and only allow for subsequent predictions to be based around the assumption that this niche will continue to hold under conditions of future change (Guisan & Thuiller 2005; Pearson & Dawson 2003; Vogiatzakis 2003; Guisan & Zimmerman 2000). It is argued that this assumption is problematic, as it is likely that the realised niche that a given species will occupy in the future will be different due to the dynamic and individualistic response of different species to climate change (Thuiller *et al*., 2005; Pearson & Dawson, 2003).

Although 'dynamic' models are also essentially concerned with identifying the environmental or bioclimatic envelopes of the ecological units under investigation (Pearson & Dawson, 2003) they aim to represent the dynamic physiological interactions and responses of ecological units to their environment more explicitly (Guisan & Zimmerman 2000). In many ways, the range of 'dynamic' models represents an attempt to address some of the problems generally associated with the static approach. It is argued that dynamic models are likely to produce more reliable predictions under climate change conditions for two interrelated reasons. First, it is suggested that the sources of data used for model parameterisation allow for better characterisation of the fundamental niche (Guisan & Zimmerman 2000). Second, their mechanistic qualities mean that such models are able to offer more realistic simulations by explicitly modelling the way in which this fundamental niche will be restricted in the future, due to the influence of dynamic and stochastic factors (e.g. biotic interactions) (Pearson & Dawson 2003; Guisan & Zimmerman 2000).

The recent development of dynamic simulation models undoubtedly represents significant progress towards a more realistic understanding of the potential ecological impact of future changes in climate. However, the complexity of many ecosystems and therefore that of the models required to realistically simulate them is significant (Pearson & Dawson 2003; Guisan & Zimmerman, 2000). Also, it is generally appreciated that 'only very few species have been studied in detail in terms of their dynamic responses to environmental change' (Guisan & Zimmerman, 2000, pp 148). These issues mean that, in many cases, the use of dynamic models to predict the ecosystem level effects of climate change at larger spatial scales and in a spatially explicit way remains a significant challenge (Botkin *et al*., 2007; Pearson & Dawson 2003; Guisan & Zimmerman 2000; Zimmerman & Kienast 1999). Furthermore, the accuracy of results obtained from such models has also been called into question, despite their apparent superiority. This is because they often fail to consider how important non-climatic factors will be influenced under conditions of future climate change. For example, Pearson & Dawson (2003) point out that most modelling effort fails to take any account of the possible role that evolutionary adaptation to climate change may play in influencing the future distribution of the species under investigation. Ibanez *et al.* (2006) suggest that elevated atmospheric CO_2 is likely to have a significant modifying effect on the interaction of coexisting species and therefore their potential future distribution. However, the consideration of these effects is often neglected (Pearson *et al.*, 2002). Such issues are apparent within both static and dynamic contexts. However, they demonstrate that the inherent uncertainties associated with the future role of climate change in influencing complex ecological systems means that dynamic approaches are also likely to produce unreliable results. It may be argued that the adoption of such an approach, at present, offers no better guarantee of predictive success.

The limitations associated with both static and dynamic approaches are part of the reason that Pearson & Dawson (2003, pp. 369) state that 'accurate predictions of biogeographical responses to future climate are not currently possible'. However, despite the apparent limitations of the static approach and its associated methods, Pearson & Dawson (2003, pp. 361) also suggest that it can provide a 'useful first approximation as to the potentially dramatic impact of climate change on biodiversity'. Indeed, because highly detailed knowledge of the physiology and behaviour of the ecological units under investigation is not required (Zimmerman & Kienast, 1999), the static approach potentially offers a more efficient, accessible and appropriate method for investigating the potential impact on ecosystems from climate change in some contexts. For instance, Zimmerman & Kienast (1999) state that their decision to utilise a static equilibrium approach was strongly necessitated by the large (high resolution, 50m) data sets required to account realistically for the high vegetation heterogeneity apparent within their study area. Such heterogeneity is a feature of many semi-natural landscapes at the sub-regional scale. This suggests that a static approach represents a potentially more useful methodology for assessing the possible ecological effects of climate change occurring at these scales.

2.5 Rationale and Aim

There is a clear need for spatially-explicit assessments of potential ecological impacts in order to assist in effective planning and risk management (Preston *et al*., 2011, pp. 178). The predictive modelling of species' (and community) distributions in relation to environmental change (particularly climate change) has gone far in this regard. However, a general criticism that may be made in relation to these studies is that their (explicit or implicit) representations of vulnerability (and therefore broader, overall impacts) is often limited because other properties, such as the potential to recover from or adapt to environmental disturbance, are not adequately considered. The literature highlights the importance of adopting a broader more holistic approach to the study of the ecological impacts of environmental change, and the relevance of the vulnerability concept within this context. This is particularly so when consideration is made of the interrelationship between ecological functioning, services and human wellbeing, the diversity of pressures ecosystems currently experience, as well as the fact that many pressures are likely to increase significantly in the future (CBD, 2010; MA, 2005a). A notable criticism that is often made of ecological impact assessments, generally, is that they often focus on a single or limited number of exogenous pressures (Preston *et al*., 2011). Studies employing scenarios of socio-economic and environmental change are likely to be more useful than those basing assessment solely on current characteristics and properties (Preston *et al*., 2011).

The literature also suggests that a focus at higher levels of ecological organisation (e.g. communities) is more desirable for practical modelling purposes as well as from a conservation perspective and for effective, sustainable management of ecosystem services. In turn, assessments conducted at the 'landscape' scale are likely to be more useful than those for smaller spatial scales because they are better able to capture a broader array of factors and processes that are relevant for ecological integrity, functioning and vulnerability (Morecroft *et al*., 2012; CBD, 2003, pp. 20). Focus at the landscape scale is also attractive because of the greater number of approximations that are required to produce assessments further up the scale hierarchy (Botkin *et al*., 2007, pp. 230). Verburg *et al*. (2006, pp. 54) defines landscapes as: 'spatial units whose character and functions are defined by the complex and region-specific interaction of natural processes with human activities that are driven by economic, social and environmental forces and values'. The landscape scale is likely to be more directly relevant to the scales with which stakeholders more commonly interact and at which relevant decisions can and should be made (Holman *et al*., 2005a). Despite these issues, there is a lack of current research examining vulnerability explicitly at the landscape scale within the UK (Berry, 2008; Trivedi et al., 2008). It has also been suggested that, despite the obvious role that the inherent properties of ecological systems play in ameliorating or modifying potential impacts, consideration of these characteristics are often lacking from vulnerability assessments (Preston *et al*., 2011).

Based on these points the primary aim of the research described in this thesis has been:

> **To provide a spatially-explicit assessment of the vulnerability of ecological communities at the landscape scale to two exogenous pressures (climate change and land use change).**

These pressures are deemed to be the most significant potential future stressors for terrestrial ecosystems, generally (CBD, 2010; Haines-Young, 2009; IPCC, 2007a; MA, 2005a; Sala *et al*., 2000). However, previous ecological research has tended to neglect the potential impacts of land use change on ecological phenomena (Berry, 2008; Botkin *et al*., 2007; CBD, 2003). Specifically, vulnerability was assessed for a number of conservationally significant broad vegetation communities within NNP under appropriate climate and socio-economic scenarios for the year 2050. Scenarios are used to account for the uncertainty that is associated with the future direction of these pressures.

Primarily the research was undertaken to investigate the relative impacts of climate and land use change on ecological communities at the sub-regional scale, as there is uncertainty regarding their relative significance in terms of future ecological effects (Berry, 2008; IPCC, 2007a; MA, 2005a; Sala *et al*., 2000). However, the methodology created to investigate this is in itself regarded as a relevant and useful output for assessing the ecological vulnerability of vegetation communities to these pressures (as well as others) in other contexts within the UK.

2.6 Study Area

The study area covers the extent of Northumberland National Park, ca. 1049km^2 (NNPA, no date[a]), within northern England (Figure 2.1). NNP was designated as a national park in 1956 (NNPA, 2009). The climate in general terms is temperate maritime. However, there is a reasonably strong altitudinal gradient within the Park, with upland areas such as the Cheviot Hills reaching an altitude of over 488m (NNPA, no date[b]). The highest point is the Cheviot itself at 815m (NNPA, no date[b]). The lowest elevations (ca. 50m) are associated with the river valleys on the park's north and north-eastern borders (NE, 2013b 2013c). In general, NNP experiences low mean temperatures and relatively high rainfall (>1100mm annual rainfall at the Cheviot) due to its altitudinal and latitudinal characteristics (NNPA, no date[b]). However its easterly position and the location of the higher ground mean a fairly significant rain-shadow effect influences the lower hills (<900mm annual rainfall) (NNPA, no date[b]). NNP has a history of extensive management. About 70% of the Park is moorland, much of which is used for low input livestock farming (NNPA, 2009; no date[c]). In addition, about 20% of the Park is managed as commercial forestry plantations. Notable semi-natural vegetation communities within the Park include blanket and raised bogs (5%), dwarf shrub heath (7%) and unimproved acid grassland (20%) (NNPA, no date[c]). The land covers within the Park are largely determined by the complex interaction of climate, topography, altitudinal gradient, soil type and human management (NNPA, 2009; no date[b]; no date[c]).

The park also partially covers five National Character Areas (NCAs) (Figure 2.2). Each NCA is a distinct natural area '…. defined by a unique combination of landscape, biodiversity, geodiversity and cultural and economic activity' (NE, 2013a). Such designations are useful in providing a deeper context to investigations, allowing more comprehensive, holistic conclusions and recommendations to be made (NE, 2013a). Some results and analysis in subsequent chapters are provided for these NCAs, specifically, their extents within the borders of NNP (areas of darker colour in Figure 2.2). The sections below provide a brief summary of the characteristics of each of the five NCAs.

Figure 2.1: Land use/landcover of Northumberland National Park, UK

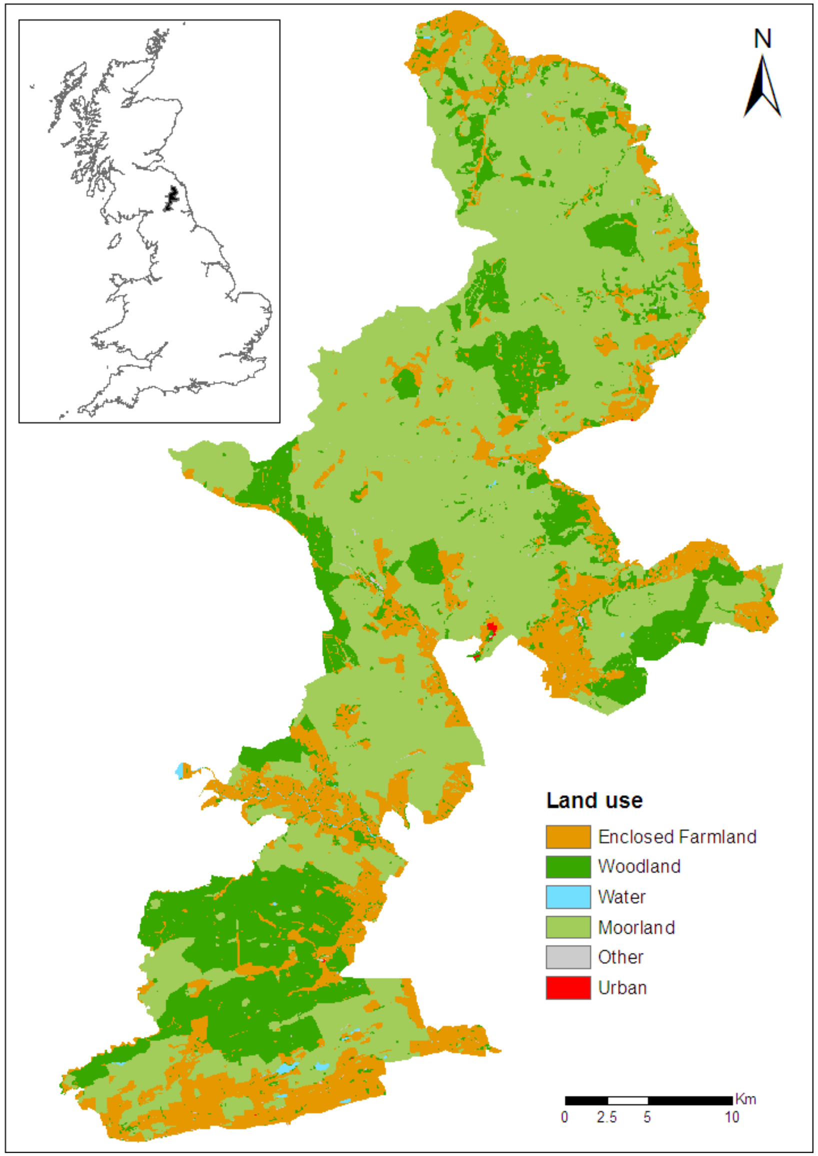
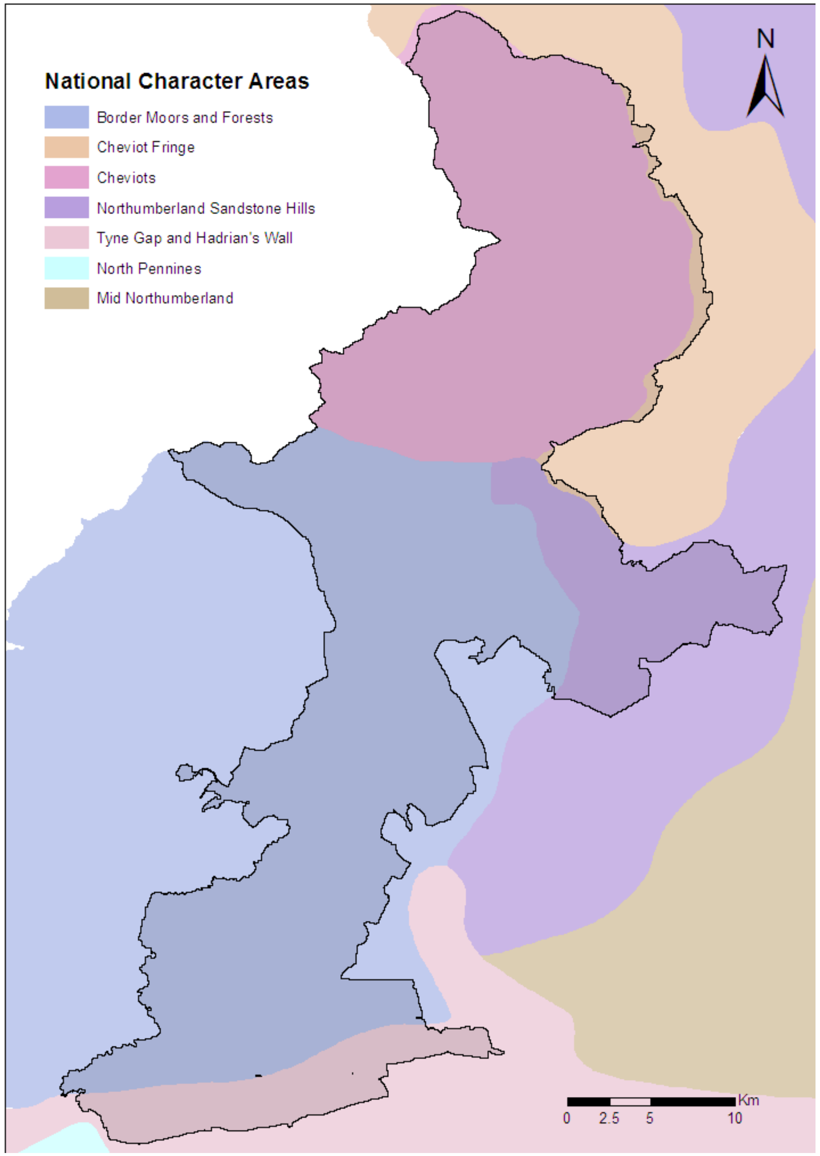


Figure 2.2: National Character Areas Associated with NNP.



Cheviots

NNP covers 99% (361km^2) of the NCA (NE, 2013b). The top of the Cheviot in the centre west of the NCA is the highest point (815m). Lower elevations are found in the deep narrow valleys that radiate from the central igneous cluster of the Cheviots (NE, 2013b). The minimum elevation is 50m in the College Valley to the north of the Cheviot Hills. The NCA is mainly upland. Mean elevation is 360m.

Because of its upland characteristics, the soils comprising the NCA are generally poor with a dominance of acidic peaty types (NE, 2013b). Better-draining acid soils occur on the steeper slopes of river valleys. Moorland (including heath and bog) dominates the area, much of which is grazed (NE, 2013b). The relatively small amount of enclosed farmland is mainly confined to the lower ground of the valley bottoms. The small amount of arable land that occurs within the NCA is confined to lower ground at its far northern tip. Large blocks of coniferous woodland occur on moorland to the south and east of the Cheviot Hills. However, smaller more scattered extents of more natural woodland types (e.g. oak, birch and alder) are found on the valley bottoms (NE, 2013b).

Cheviot Fringe

NNP covers only 3% (15km^2) of the NCA (NE, 2013c). The maximum elevation of the NCA within NNP is 320m in the lower reaches of the Cheviot foothills which border its far western edge (NE, 2013c). Lower elevations of 50m are observed within the NCA along the far north-eastern border of NNP, where elevation drops to form the 'undulating to flat lowland farmland landscape' that typically dominates the NCA to the east (NE, 2013c, pp. 5). Mean elevation is 189m. Although extents of semi-natural habitat types occur within the NCA, their distribution is limited. They include small, diffuse, patches of grazing marsh and semi-natural woodland types (NE, 2013c). Much of the NCA within NNP is dominated by enclosed, relatively intensive agriculture, including quite a high proportion of arable land (NE, 2013c).

Northumberland Sandstone Hills (NSH)

NNP covers 15% (105km^2) of the NCA (NE, no date[a]). The lowest elevations within NNP are 91m. The highest point (443m) is Simonside to the east. Simonside is surrounded by the Simonside Hills (ca. >250m). Mean elevation is 246m. Weathering of the underlying sandstone bedrock creates thin, acidic, nutrient-poor sandy soils, particularly above 250m. These soils are associated with the moorland (particularly dry heath), which covers about 50% of the NCA within NNP (NE, no date[a] & Figure 2.1). Grazing occurs on much of this moorland (NE, no date[a]). However, relatively productive soils supporting more intensive agriculture (including arable) in lowland areas also comprise quite a high proportion of the NCA within NNP (Figure 2.1). Fairly extensive conifer plantations occur within the area.

Border Moors and Forests (BMF)

NNP covers 39% (499km^2) of the NCA (NE, 2013d). BMF essentially encompasses an upland plateau dissected by wide shallow valleys (NE, 2013d). The elevation of the NCA within NNP ranges from 101m in the valleys up to 524m in north-western areas next to the border of the Cheviots NCA. Mean elevation is 264m.

The wet upland characteristics of the area mean that approximately 70% of soils are comprised of poorly draining wet very acid types with peaty top layers (NE, 2013d). These support the moorland (including bogs and heaths) that dominates much of the NCA (NE, 2013d). Extensive grazing occurs on much of this moorland. More productive soils are found at lower concentrations in the lower valleys, such as the North Tyne valley, which runs approximately west to east across the centre of the NCA. This is evidenced by the relatively high concentration of enclosed farm land that occurs in the area (Figure 2.1). The small extents of arable land that occur within the NCA are concentrated within this area (NE, 2013d). Extensive conifer plantations also lie within the NCA, particularly to the south (Figure 2.1). Smaller, more diffuse distributions of more natural woodland types also occur (NE, 2013d).

Tyne Gap and Hadrian's Wall (TG)

NNP covers 16% (70km^2) of the NCA (NE, no date[b]). The elevation of the NCA within NNP ranges from 139m to approximately 300-350m on the outcrops of the Whin Sill, which generally runs east to west across the north of the area. The NCA is generally lowland. Mean elevation is 223m and the NCA becomes increasing low and flat to the south, where more productive soils occur and more intensive farming dominates (including quite a high proportion of arable land) (NE, no date[b]). Moorland largely occurs in the more upland north, associated with the less fertile, more acidic soils that are present. Patches of conifer plantation and more natural woodland types are scattered throughout the NCA.

Chapter 3: The Role of Climate at the Landscape Scale

3.1 Introduction

The preliminary aim of the primary research covered in this section was to utilise an empirical, static equilibrium model to simulate the potential impact of past climate on the current distribution of BVC types within NNP. This was done partly in an attempt to investigate the role climate plays in influencing distributions within a sub-regional 'landscape' scale context. It is intended to offer some validation of the scale dependencies outlined in Pearson & Dawson's hierarchy (Table 2.1). This is considered important because, although the dominant role of climate in influencing occurrence at larger spatial scales (global to regional) is reasonably well documented, its influence at sub-regional 'landscape' scales has received relatively little attention. This is particularly true for semi-natural landscapes (such as NNP) which are influenced by human management.

The primary aim of the research is to provide an assessment of the potential vulnerability of the BVC types within the study area to climate and land use change. Comparison of the simulated current distribution of the BVC types (as determined by past climate) with their observed distribution allows the role of climate in influencing the distribution of the communities to be assessed. The role of climate in determining distributions is used here as a way of investigating the role of climate in influencing the vulnerability of the communities at the landscape scale.

This chapter describes the methodology employed to investigate the role of climate in influencing community distributions at the landscape scale within NNP. The findings from this stage of the research are presented at the end of the chapter, and are used to determine the most appropriate way of incorporating the influence of climate into the overall vulnerability assessment (also see: Chapter Five).

3.2 Climate Model for Simulating BVC Distributions

The basic ecological units used within the static equilibrium model used may be described as BVC types. The bioclimatic envelopes of these units were established in terms of average summer and winter temperature and precipitation for the period 1961-90.

This information was then applied to 50m resolution raster grids representing current climate in the study area, using a Bayesian classification. Current climate was based on average summer and winter temperature and precipitation values for the 1961-90 period. The application of the model provided a measure of the relative probability of occurrence of each BVC type (in terms of the selected climatic parameters) for each 50m cell for the current time slice.

The modelling process involved six basic stages: 1) definition of BVCs; 2) selection of climatic parameters; 3) establishment of the climatic envelopes of the BVCs; 4) creation of 50m raster grids representing the current climate of the north east of England; 5) calculating posterior probabilities for each BVC type for each cell of the current climate grids using a Bayesian classification; 6) model validation.

3.3 Ecological Data (BVCs)

The dependent variable used in the model is BVC type. The study utilised a classification of BVC types derived from the Joint Nature Conservation Committee (JNCC) and used within the Centre for Ecology and Hydrology's (CEH) Land Cover Map 2000 (LCM2000). The classification was adapted, so that the nominal categories considered in the statistical analysis corresponded more precisely to the nomenclature used within the Phase One Habitat Survey (P1HS) environmental audit scheme (JNCC, 2007). This was important, as the P1HS data are used as the basis for current mapped BVC distributions within NNP. Table 3.1 describes the correspondence between LCM2000 subclasses, P1HS subcategories and the nominal BVC categories used in this research. For all subsequent analysis of climatic parameters, the two datasets representing habitat distribution (LCM2000 and NNP's P1HS) were reclassified to represent the nominal BVC categories from Table 3.1.

Table 3.1: Correspondence between P1HS subcategories, LCM2000 subclasses and the nominal BVC categories used in the study (Adapted from: JNCC, 2007; CEH, 2002; Jackson, 2000; CEH, no date). It was not feasible to provide a separate treatment for neutral grasslands because of the different treatment of grasslands from JNCC (2007) and LCM 2000 nomenclature. Specifically, under LCM2000 nomenclature the soil pH associated with acid grasslands ('Acid grassland': 8.1), neutral grasslands ('Neutral rough grassland': 6.1 and 'Managed neutral grassland': 6.2) and calcareous grasslands ('Calcareous grassland': 7.1) respectively are: < 4.5; 4.5 - 5.5; > 5.5 (CEH, 2002). Under P1HS nomenclature the soil pH associated with acid grasslands, neutral grasslands and calcareous grasslands respectively are: < 5.5; 5.5 – 7.0; > 7.0 (JNCC, 2007). As such, the P1HS acid grassland subcategories (B11 & B12) include both acid grasslands and neutral grasslands from the LCM2000 nomenclature, whilst the LCM2000 'Calcareous grassland (7.1)' subclass includes neutral and calcareous sub-categories from P1HS nomenclature (i.e. B21, B22, B31 & B32). As such, and to maintain consistency with P1HS nomenclature the 'Acid Grassland' BVC output class corresponds exactly to the Acid grassland P1HS subcategories and includes LCM2000 subclasses 8.1, 6.1 and 6.2. The 'Neutral and Calcareous Grassland' BVC corresponds exactly to the LCM2000 subclass 7.1 and includes P1HS sub-categories B21, B22, B31 and B32.

LCM2000 subclass(es)	P1HS Sub categories (Code).	P1HS Broad Habitat (Code)	BVC (Code)
9.1 Bracken	Bracken: Continuous (C11)	Tall Herb & Fern (C)	Bracken (1)
10.1 Open dwarf shrub heath 10.2 Dense dwarf shrub heath	Dry dwarf shrub heath (D1)	Heathland (D)	Heath (2)
	Wet dwarf shrub heath (D2)		
	Dry heath/acid grassland mosaic (D5)		
	Wet heath/acid grassland mosaic (D6)		
5.1 Improved grassland 5.2 Set-aside grass	Improved grassland (B4)	Grassland and marsh (B)	Improved Grassland (3)
	Cultivated/disturbed land – amenity grassland (J12)	Miscellaneous (J)	
8.1 Acid grassland 6.1 Neutral rough grassland 6.2 Managed neutral grassland	Acid grassland: Unimproved (B11)	Grassland and marsh (B)	Acid Grassland (4)
	Acid grassland: Semi-improved (B12)		
7.1 Calcareous grassland	Neutral grassland: unimproved (B21)	Grassland and marsh (B)	Neutral and Calcareous Grassland (5)
	Neutral grassland: semi-improved (B22)		
	Calcareous grassland: unimproved (B31)		
	Calcareous grassland: semi-improved (B32)		
11.1 Fen, Marsh and Swamp (FMS)	Marsh/marshy grassland (B5)	Grassland and marsh (B)	FMS – Fen, Marsh, Swamp (6)
	Flush and Spring: Acid neutral flush (E21)	Mire (E)	
	Flush and Spring: Basic flush (E22)		
	Flush and Spring: Bryophyte dominated spring (E23)		
	Fen: Valley mire (E31)		
	Fen: Basin Mire (E32)		
	Fen: Flood plain mire (E33)		
	Swamp (F1)	Swamp, marginal and inundation	
12.1 Bogs (deep peat)	Bog: Blanket Bog (E161)	Mire (E)	Bog (7)
	Bog: Raised bog (E162)		
	Bog: Wet modified bog (E17)		

	Bog: Dry modified bog (E18)		
1.1 Broad-leaved/mixed Woodland	Woodland: Broadleaved: semi-natural (A111) Woodland: Broadleaved: plantation (A112) Woodland: Mixed: semi-natural (A131) Woodland: Mixed: plantation (A132) Woodland: Scrub: dense continuous (A21) Woodland: Recently felled woodland: broadleaved (A41) Woodland: Recently felled woodland: mixed (A43) Woodland: Introduced shrub (J14)	Woodland and scrub (A)	Broadleaved Woodland (8)
2.1 Coniferous woodland	Woodland: Coniferous: semi-natural (A121) Woodland: Coniferous: plantation (A122) Woodland: Recently felled woodland: coniferous (A42)	Woodland and scrub (A)	Coniferous Woodland (9)
4.1 Arable and horticulture: Cereals 4.2 Arable and horticulture: Horticulture/non-cereal or unknown 4.3 Arable and horticulture: not annual crop	Cultivated/disturbed land: arable (J11)	Miscellaneous (J)	Arable and Horticulture (10)

3.4 Climatic Parameters

The climate variables used within the model were mean monthly surface air temperature and total precipitation for December-February (Winter Temperature and Winter Precipitation) and June-August (Summer Temperature and Summer Precipitation) for the 1961-1990 long term average period. Climate data for the 1961-1990 period is commonly used as a baseline within research investigating the potential impacts of climate change on ecological phenomena, within the UK (e.g. Trivedi *et al.*, 2008; Berry *et al.*, 2007; Berry *et al.*, 2003; Pearson *et al.*, 2002). Table 3.2 provides details of the rationale for including the climatic parameters.

Table 3.2: Rationale behind the inclusion of the chosen (independent) climatic variables

	Description	Reference (if appropriate)
1	They are useful determinants of physiological processes limiting the distribution of plant species.	Meineri *et al*. (2012); Williams *et al.* (2007); Araujo *et al.* (2004); Woodward (1987)
2	They represent controls of seasonal temperature and moisture availability on plant distributions.	Meineri *et al*. (2012); Williams *et al.* (2007)
3a	They have a strong correlation with other proposed bioclimatic controls on species distributions (e.g. growing degree days, minimum and maximum annual temperature).	Williams *et al.* (2007)
3b	Pearson's correlation analysis revealed a strong correlation between the chosen temperature variables and a range of other climatic variables available as long term averages (for the 1961-90 period) from the United Kingdom Climate Impacts Programme (UKCIP). Many of these variables represent other proposed bioclimatic controls on species distributions.	See Table A1.1 for results of correlation analysis
4a	Spatially referenced datasets for these variables were readily available from the UKCIP.	
4b	Spatially referenced datasets relating probabilistic climate change projections for these variables were readily available from the UKCIP.	

3.5 Establishment of Climatic Envelopes

The bioclimatic envelopes of the BVC types were established using 5km resolution climate data for the UK from the UKCIP and the CEH's 25m resolution LCM2000 (used to represent the 'current' distribution of the selected BVCs in England and Wales). These data were used in order to establish an environmental envelope that was as close to the broad-scale realised climatic niche of the BVCs as possible (Pearson & Dawson, 2003). The data were converted into raster layers ('grids') for analysis within GIS software. The bioclimatic envelopes of the BVCs were then established using a correlative approach. Envelopes were based on the values of climate cells spatially coincident with the geographical distribution of the BVCs. The maximum and minimum climate values were assumed to represent the absolute limits of the BVCs' climatic envelope for a given parameter. In this way the suitable climate space for each of the BVCs was established separately for each climatic variable (Table A1.2).

3.6 Creation of Current Climate Grids

50m resolution raster grids representing 'current' climate within north-eastern England were created for each of the four climatic variables. The method applied to create these grids is similar to that described by Perry & Hollis (2005) in the creation of 5km x 5km grids representing average UK climate in terms of a range of variables for the 1961-1990 period. The method of grid creation was a two-stage process. The first involved multiple regression of the climate parameter with various geographic and topographic factors as independent variables. The second involved interpolation of the regression residuals. The regression surface and the interpolated residual surface were then added together to create the final climate grid.

3.6.1 Multiple Regressions

A subset of the 5km x 5km point data for the north east of England from the UKCIP09 5km Gridded Observation Data Sets was used as the climate data in the regression analysis. The geographic and topographical factors used to model Winter Temperature, Winter Precipitation, Summer Temperature and Summer Precipitation were Elevation, Latitude, Longitude and Euclidean Distance from coast, as stepwise regression revealed that they were all significant predictors (all P-values = 0.00). Table 3.3 gives the R^2 and adjusted R^2 values for all of the predictors against each of the climatic variables from single and multiple regression analysis. The multiple regressions with all independent variables were used to create the current climate grids for Summer Temperature, Winter Temperature and Summer Precipitation. Elevation, Longitude and Latitude were used to create the Winter Precipitation climate grid (Table 3.3).

Table 3.3: Results of the regression analysis (R^2 and adjusted R^2 values) that were used to determine which factors would be used in the creation of the current climate grids. R^2 provides a measure of the accuracy of the data model for single regressions. Adjusted R^2 is used to identify significant improvements of the accuracy of the model for multiple regressions through the inclusion or removal of additional explanatory factors. The results for the most significant factor(s) at each stage of the analysis are highlighted in bold

Regressions	**Independent Variables**	**Dependent Variables**			
		Temperature		**Precipitation**	
		Summer	**Winter**	**Summer**	**Winter**
Single Regressions	Elevation	**90.6**	**94.2**	**40.4**	**53.7**
	Longitude	7.5	13.6	24.7	18.6
	Latitude	0.0	2.7	5.7	11.3
	Coastal Distance	18.5	43.9	12.0	28.8
Multiple Regressions with 2 Independent Variables	Elevation & Longitude	90.6	94.8	**50.3**	**58.2**
	Elevation & Latitude	**94.1**	94.4	41.4	57.2
	Elevation & Coastal Distance	92.7	**95.8**	40.2	55.4
Multiple Regressions with 3 Independent Variables	Elevation & Longitude & Latitude	**94.9**	94.8	**55.9**	**66.4**
	Elevation & Longitude & Coastal Distance	92.7	96.2	50.4	59.7
	Elevation & Latitude & Coastal Distance	94.7	**96.7**	41.9	57.5
Multiple Regressions with all Independent Variables	Elevation & Longitude & Latitude & Coastal Distance	**95.2**	**96.7**	**59.1**	66.3*

* Stepwise regression revealed that Coastal Distance was not a significant predictor for Winter Precipitation (P-value = 0.65). Therefore it was not used to generate the final regression model for Winter Precipitation.

3.6.2 Inverse-distance weighting (IDW) of Regression Residuals

Inverse-distance weighting (IDW) was used to interpolate the residuals associated with the multiple regression models to create a regular 50m grid. This was done in an attempt to take some account of the error associated with the regression model, when creating the final 'current' climate grids (Field, 2005). IDW works by calculating the value of each grid cell as a weighted average of values from surrounding input points of known value. The weighting is based on the inverse distance of the sample point from the cell. The technique works on the principle that the known characteristic (in this case the residuals associated with the regression model) of areas in closer proximity have more in common with each other than they do with those that are further away (ESRI, 2001). Inverse squared distance weighting was chosen because of the relatively smooth environmental gradients that generally occur throughout the study area. To determine which input points would be used to calculate the values for each cell, a *variable* search radius was used and the number of sample points set to 12.

3.7 Calculation of Posterior Probabilities for Each BVC Type Using a Bayesian Classification

The dependent variable 'BVC' is a nominal variable. As such, more common regression approaches are not appropriate (Field, 2005; Brzeziecki *et al*., 1993). To overcome this problem a Bayesian classification was employed. This technique calculates the posterior probability of each cell belonging to each of the considered classes ('BVC'). The approach achieves this using the multivariate conditional probabilities, as provided by the BVC bioclimatic envelope data, and prior probabilities. The prior probability of the occurrence of each of the ten classes was assumed to be equal, i.e. 0.1 (Eastman, 2009; Brzeziecki *et al*., 1995; Brzeziecki *et al*., 1993; Clarke Labs, IDRISI Taiga, no date). The Bayesian method was considered to be particularly appropriate for investigating the role of climate in influencing the distribution of vegetation communities within a landscape context, because the classification assumes statistical normality in the distribution of the bioclimatic envelope data used to calculate the conditional probabilities (Kienast *et al*., 1996). It has been argued that the realised responses of communities to environmental gradients tend to exhibit greater statistical normality than those of individual component species, which are often non-normally distributed (e.g. skewed or bimodal) due to interactions with the other species present (e.g. competition or predation) (Heikkinen & Makipaa, 2010; Vogiatzakis, 2003; Austin, 2002; Zimmerman & Kienast, 1999; Begon *et al*., 1996; Austin & Smith, 1989). This suggests that the use of the Bayesian approach to model probabilities of community occurrence is appropriate from a theoretical context.

Figures A1.1a-A1.10d (Appendix 1: 'Normality Tests') show the frequency distributions for the BVCs in terms each of the climate variables. Visual analysis indicated that only fifteen of the forty datasets (ca. 38%) were normally distributed, fourteen (35%) were slightly skewed and 25 (ca. 28%) were highly skewed. However, it is feasible that (in the same way that species' realised responses within a community are non-normally distributed, due to the influence of biotic interactions) the realised responses of the BVCs within the UK for some of the climatic variables are skewed, due to the influence of other, non-climatic factors, such as land use history. This is particularly likely considering the scale of the data used to establish the bioclimatic envelopes and the significance of non-climatic factors (e.g. land use), in influencing biological distributions at scales comparable to that of the UK (FLUFP, 2010; Berry *et al*., 2006; Holman *et al*., 2005b; Pearson & Dawson, 2003; Berry *et al*., 2003; Berry *et al*., 2002; Pearson *et al*., 2002). Because of their assumptions, Bayesian methods are likely to somewhat compensate for the influence of such factors, when estimating probabilities of occurrence. From this context such methods are considered appropriate for investigating the *specific role of climate* in influencing community distributions, where data are not normally distributed, particularly where data are only slightly skewed (for further discussion see: Appendix 1; 'Normality Tests').

3.8 Model Validation

To evaluate the predictive performance of the model, a quantitative comparison was made between current mapped BVC distributions and simulated probabilities of occurrence within NNP. The degree of agreement (DA) for each BVC was ascertained as the percentage of pixels, with a posterior probability of over 0.5, spatially coincident with the BVC's current distribution. Probability values of ≥ 0.5 are commonly used as a threshold determining species or community occurrence in other research (Liu *et al.*, 2005) (e.g. Matsui *et al*., 2004; Bailey *et al*., 2002; Woolf *et al*., 2002). Table 3.4 shows the findings from this analysis.

Table 3.4: The degree of agreement between current observed distributions and probabilities of occurrence simulated using the four selected bioclimatic variables.

BVC (Code)	*Number of pixels comprising current extent*	DA (%)
Bracken (1)	13393	0.24
Heath (2)	82282	0.28
Improved Grassland (3)	18785	1.28
Acid Grassland (4)	104696	1.37
Neutral and Calcareous Grassland (5)	25940	40.47
Fen, Marsh & Swamp (6)	52627	0.00
Bog (7)	18102	29.98
Broadleaved Woodland (8)	6660	8.39
Coniferous Woodland (9)	80082	0.00
Arable & Horticulture (10)	2389	34.33
Total	**404956**	**4.75**

Table 3.4 shows notable variation in the prediction accuracies. BVCs such as Coniferous Woodland and FMS show the lowest DA (0.00). Very low DA is associated with other BVCs (i.e. Bracken, Heath, Improved Grassland, Acid Grassland and Broadleaved Woodland). The remaining BVCs

(Arable and Horticulture, Neutral and Calcareous Grassland and Bog) have poor to moderate simulation accuracies.

Despite this variation amongst BVCs, the overall DA is very low. These results suggest that climate has played a very limited role in determining the distribution of the BVCs within the study area. Considering the scale of the study area, the results therefore provide some validation of Pearson & Dawson's (2003) hierarchy concerning the role of climatic factors in influencing occurrence across various spatial scales.

Chapter 4: Land Use Modelling

4.1 Introduction

Land use has been identified as potentially having an important influence on ecological phenomena, particularly for semi-natural landscapes such as NNP (Berry, 2008; MA, 2005a; 2005b; Guisan & Zimmerman, 2000). For instance, Table 2.1 suggests that land use plays a dominant role over distributions at the landscape scale. IPCC (2007a), MA (2005a) and Sala *et al*. (2000) suggest that land use change is likely to have a greater impact than climate change on terrestrial ecosystems, globally. However, land use is often neglected from research investigating the future ecological impact of climate (and other environmental) change (Berry, 2008; Botkin *et al*., 2007; CBD, 2003).

Land use typically refers to the management and modification of the natural environment by humans to derive some benefit from the land (FLUFP, 2010; Clark, 1998). Within this context, the BVCs within NNP represent a mixture of recognised land uses (e.g. Arable and Horticulture, Improved Grassland) and semi-natural community types (e.g. Bog, Heath). However, the use of land to conserve, enhance or expand semi-natural communities is increasingly recognised as important in its own right, due to the role such communities play in helping to deliver vital goods and ecosystem services (FLUFP, 2010; Creedy *et al*., 2009). The extent to which land is valued and managed for conservation in the future will largely depend on prevailing economic, social and political trends and paradigms (FLUFP, 2010; Creedy *et al*., 2009; NE, 2009).

This chapter describes the formulation of appropriate land use change scenarios for the study area and, with reference to the information provided in Appendix 2, explains the modelling of future community distributions, as influenced by land use change. The results (maps depicting community distributions under the scenarios) are presented at the end of the chapter.

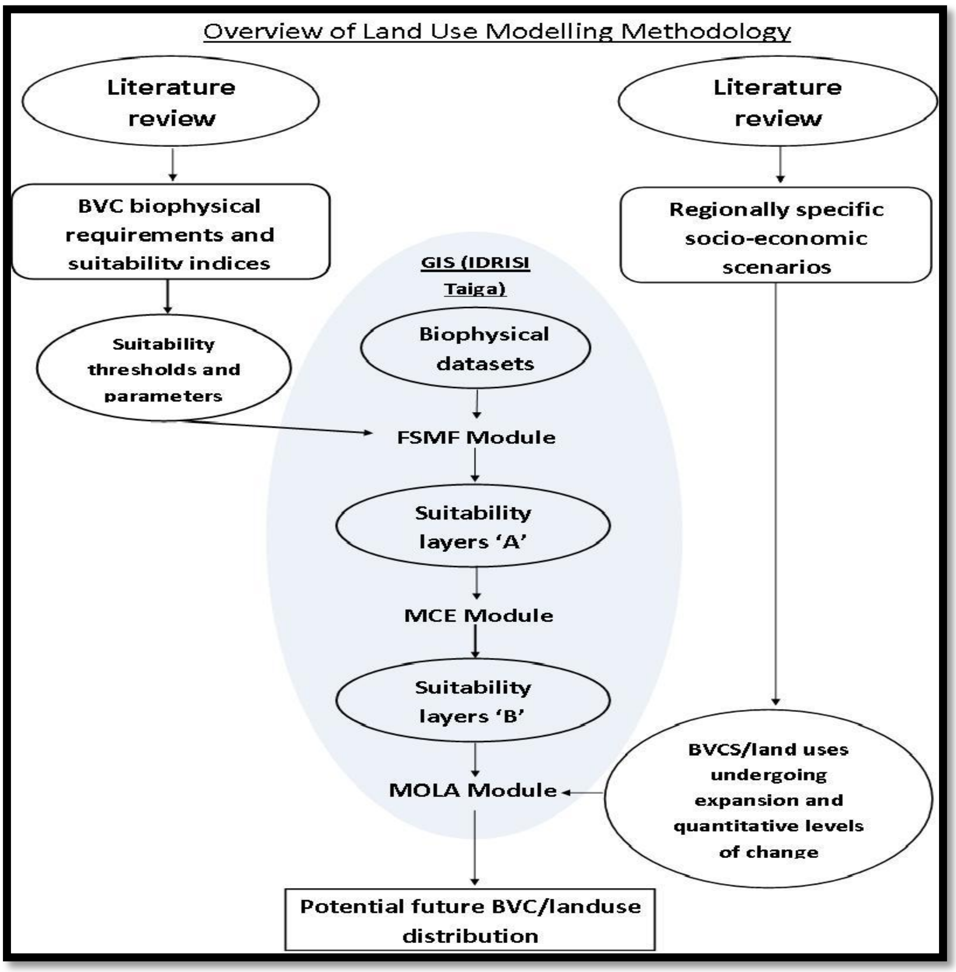
4.2 Overview of Method

For purposes of land use modelling, the classification of BVCs used to establish bioclimatic envelopes (Tables 3.1 and A2.1) was disaggregated (see: Section 4.3 for further details). This revised classification (see: Table 4.1 in Section 4.3) consists of a number of vegetation community types, which are of particular significance in terms of conservation, and others, which are regarded as less significant. Those communities identified as conservationally significant are defined as 'priority' BVCs (PBVCs) for the purposes of this research and are the particular focus of Chapters Five, Six and Seven. Those which are regarded as less significant in terms of conservation are defined as 'Non-Priority' BVCs (NPBVCs). To distinguish between the two classification schemes used within this research, all subsequent references to the vegetation units defined in Table 3.1 use the term BVC; references to the vegetation units defined in Table 4.1 use the term P/NPBVC.

Figure 4.1 provides an overview of the adopted land use modelling methodology. The model was applied using various *Idrisi* Taiga Change Analysis modules (Eastman, 2009; Clark Labs, IDRISI Taiga, no date). The methodology can be broadly separated into two distinct, yet interrelated, parts:

Part one (Figure 4.1: right side) involves the formulation of future socio-economic scenario storylines for the study area based on a review of literature and key driver analysis. This ensures that the storylines are reasonable, meaningful, and contextually relevant. The scenarios are used: 1) as a way to identify specific P/NPBVC types likely to expand under a particular set of future socio-economic circumstances and; 2) to derive quantitative estimates of likely levels of future expansion for those P/NPBVCs.

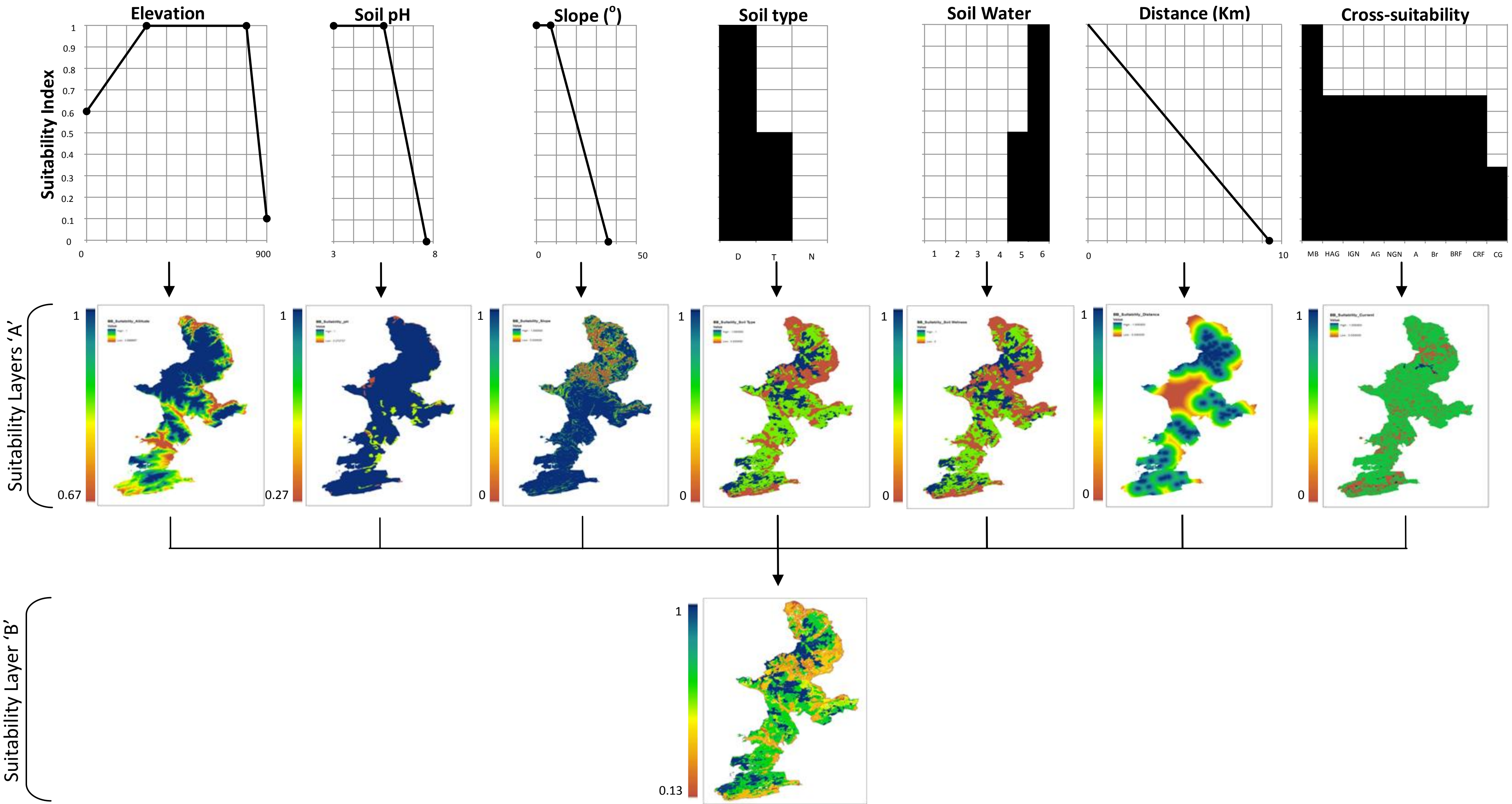
Figure 4.1



Part two (Figure 4.1: left side) involves the creation of spatially-explicit data for the study area expressing the suitability of land for specific P/NPBVC types in terms of certain significant biophysical and management related variables. This employed a 'knowledge-based' approach (Aspinall, 1998). Specifically, P/NPBVC requirements in terms of these variables are gauged through literature review. This information is then used to delineate suitability indices, for each P/NPBVC in relation to each of the variables. When applied to spatially-explicit biophysical data for the study area, within *IDRISI Taiga's* 'Fuzzy Set Membership Function' (FSMF) module, this information facilitates the creation of spatial data expressing the suitability of land for each P/NPBVC type in terms of each of the variables (Figure 4.1: 'Suitability Layers 'A''). Spatial data expressing the overall suitability of land within the study area for each P/NPBVC type ('Suitability Layers 'B'') are created by combining Suitability Layers 'A' for each P/NPBVC within *IDRISI Taiga's* 'Multi-Criteria Evaluation' (MCE) module. The overall suitability layers for the appropriate P/NPBVC types are then entered into *IDRISI Taiga's* 'Multiple Objective Land Allocation' (MOLA) module, along with the scenario specific information on levels of P/NPBVC expansion (see above), to produce the spatially explicit predictions of future P/NPBVC distributions.

Information from JNCC (2007), Lane (1999), Furniss & Lane (1999), Lane & Tait (1999), Fitter & Peat (1994), Grime *et al*. (1988), and Tansley (1949) was used to gauge the key characteristics of the P/NPBVCs. P/NPBVC suitability was ultimately modelled in terms of five biophysical variables (soil pH, soil water, soil type, elevation and slope) and two management related variables (distance and cross-suitability). The two management variables were used to incorporate significant human management considerations more directly into the scenarios (Verburg *et al*., 2006). For both economic and environmental reasons, areas in closer proximity to existing extents of a particular P/NPBVC are likely to be more suitable for its expansion than those further away (Griffiths *et al*., 2011; Swetnam *et al.*, 2010; Verburg *et al*., 2006; Busch, 2006; KanKaanpaa & Carter, 2004). Cross-suitability considers the potential for converting areas of land from one P/NPBVC to another, based on the management actions required to facilitate conversion (Griffiths *et al*., 2011). Figure 4.2 illustrates the creation of all suitability layers for Blanket Bog.

Figure 4.2: Creation of all suitability layers for Blanket Bog



An important assumption of this research is that the potential occurrence of P/NPBVC types is largely determined by their tolerances or suitability in terms of the selected biophysical and management variables. However, whilst the suitability indices are vital in determining the suitability of land for particular P/NPBVCs, it is important to note that the socio-economic trends inherent within the scenarios are the major drivers of future land use change (i.e. the socio-economic characteristics determine the specific P/NPBVC types undergoing expansion as well as appropriate quantitative information on associated levels of expansion).

The final results of the land use modelling are maps depicting the distribution of P/NPBVC patches in the future, as influenced by changes in land use (Figures 4.4 b & c). Landscape metrics (see: Chapter Six) and a Climate Stress measure (see: Chapter Five) are then applied to these results for the PBVCs (Table 4.1), so that their potential future vulnerability under the scenarios may be assessed.

This chapter primarily covers information relating to the first part of the methodology (Figure 4.1: right side). Detailed information relating to the basic P/NPBVC categories used for the land use modelling is provided in Section 4.3 to provide context to subsequent sections regarding the evaluation and validation of the land use model (stages of evaluation and validation of the land use model are not shown in Figure 4.1). Though providing a vital underpinning to the modelling of land use change, substantial information relating to the investigation of key biophysical and management variables, the associated P/NPBVC tolerances, delineation of suitability indices and the GIS software employed are provided in Appendix 2.

4.3 P/NPBVC Categories

Table 4.1 provides details of the P/NPBVC categories used for the land use modelling. The BVC categories used for the bioclimatic envelope model (see: Section 3.3) are based around a classification of broad habitat types developed by the JNCC and used within the Centre for Ecology and Hydrology’s Land Cover map 2000. This classification was necessary to capture large-scale, sufficiently broad, climatic envelopes for the BVCs. However, the thematic coarseness of the classification limits its usefulness as a basis for modelling community distributions (Botkin *et al*., 2007), particularly in terms of the selected biophysical and management variables deemed important in determining the spatial patterns of future land use change at the landscape scale. For instance, the FMS BVC (Table 3.1) comprises fens, marshes and swamps. Despite the similar, typically ‘wetland’, characteristics of these community types, there are ecologically significant differences between them, for instance in terms of their tolerances for different water regimes (JNCC, 2007; Furniss & Lane, 1999; Tansley, 1949). Modelling of distributions using the coarse thematic resolution of the original BVC classification would not account for these differences; potentially limiting the accuracy and usefulness of the predictions.

The classification was therefore somewhat disaggregated, so that the P/NPBVC categories used in the land use modelling corresponded more closely to the finer thematic resolution offered by the P1HS classification scheme. It was important to retain cohesion with this scheme, as P1HS data are used as a basis for current mapped distributions within the park. The disaggregation also allowed some of the amended categories to more closely correspond to particular 'priority' habitat types highlighted as being the most threatened within the UK by the UK Biodiversity Action Plan (UKBAP) (JNCC, 2013; 2011). Because of the conservation significance of these habitats, the amended categories that corresponded most closely with them were identified and selected for closer investigation in later stages of the research as PBVC types.

Table 4.1 also provides information on the relationship between the P/NPBVC categories and the original BVC and P1HS categories. The notes provide additional information on the rationale behind the disaggregation and the UKBAP 'priority' habitat types typically associated with particular PBVCs. The PBVCs are highlighted in green in Table 4.1.

Table 4.1: P/NPBVC categories used as a basis for the land use modelling and their relationship to the original BVC categories and relevant P1HS categories. NC = no change from original BVC. PBVCs are highlighted green. Sources: JNCC, 2011; JNCC, 2007, Jackson, 2000; NNPA, no date[c].

BVC	P/NPBVC	P1HS categories (code)	Notes
Bracken	Bracken (Br) (NC)	Bracken: Continuous (C11)	The P1HS category comprising this NPBVC is not covered by any UKBAPs (Jackson, 2000).
Heath	Heath	Dry dwarf shrub heath (D1)	Separate UKBAPs are included for 'Lowland Heathland' and 'Upland Heathland' (JNCC, 2011). Both plans include both 'wet' and 'dry' types. Heaths with less than 25% dwarf shrub coverage (i.e. Heath/Acid Grassland Mosaic) are excluded from both of the UKBAPs.
		Wet dwarf shrub heath (D2)	
	Heath/Acid Grassland Mosaic	Dry heath/acid grassland mosaic (D5)	
		Wet heath/acid grassland mosaic (D6)	
Improved Grassland	Improved Grassland: Priority (IGP)	Improved grassland (B4)	A UKBAP is included for 'Coastal and Floodplain Grazing Marsh' (JNCC, 2011). This plan includes the P1HS category 'Improved grassland' (B4) (Jackson, 2000).
	Improved Grassland: Non-Priority (IGNP)	Cultivated/disturbed land – amenity grassland (J12)	Although Jackson (2000) suggests that the P1HS category comprising this NPBVC is included under the UKBAP for 'Coastal and Floodplain Grazing Marsh', J12 is not regarded as a PBVC for purposes of this research based on JNCC (2007) descriptions.
Acid Grassland	Acid Grassland (NC)	Acid grassland: Unimproved (B11)	A UKBAP is included for 'Lowland Dry Acid Grassland' (JNCC, 2011). Acid Grassland is not considered as a PBVC due to the extensiveness of Acid Grassland within the study area and problems in determining conservationally significant types using the P1HS nomenclature.
		Acid grassland: Semi-improved (B12)	
Neutral & Calcareous Grasslands	Neutral Grassland: Priority (NGP)	Neutral grassland: Unimproved (B21)	UKBAPs are included for 'Upland Hay Meadows' and 'Lowland Meadows' (JNCC, 2011). These plans only refer to P1HS category B21 (JNCC, 2011; JNCC, 2007; Jackson, 2000).
	Neutral Grassland: Non-Priority (NGNP)	Neutral grassland: Semi-Improved (B22)	
	Calcareous Grassland (CG)	Calcareous grassland: Unimproved (B31)	The only instances of calcareous grassland occurring within NNP are very minor extents of P1HS category B32 in lowland areas. The UKBAP for 'Lowland Calcareous Grassland' (JNCC, 2011) suggests that these extents are unlikely to be covered by the plan. No mention of extents of B32 is made by NNPA (no date[c]).

Table continued....

BVC	P/NPBVC	P1HS categories (code)	Notes
FMS	Fen	Fen: Valley mire (E31)	Disaggregation of the FMS BVC was necessary to better highlight fundamental differences between constituent communities. Disaggregation was therefore partially made on this basis. For instance, an association with deep peat (>0.5m) is one of the main characteristics used by JNCC (2007) to distinguish between the P1HS category 'Fen' and the other P1HS categories associated with the FMS BVC. UKBAP's provided further justification for the disaggregation. JNCC (2011) and Jackson (2000) suggest that the UKBAP habitats relevant to the FMS BVC are: 'Purple Moor Grass and Rush Pastures', 'Lowland Fens' and 'Upland Flushes, Fens and Swamps'. The UKBAP for 'Upland Flushes, Fens and Swamps' suggests it includes P1HS categories E2 (Flush and Spring), E3 (Fen), F1 (Swamp) and B5 (Marsh). The description for Purple Moor Grass and Rush Pastures UKBAP (JNCC, 2011) strongly corresponds with that of 'Marsh/marshy grassland' (B5) from JNCC (2007). Marsh is therefore treated as a separate PBVC. 'Lowland Fens' strongly correspond with 'Fen' (E3) (JNCC, 2011; 2007). Fen is therefore also treated as a separate PBVC. Swamp is treated as a separate PBVC, due to its distinctive soil water characteristics (JNCC, 2007). For the purposes of this research, Flush & Spring is regarded as a NPBVC, due to its very limited coverage within NNP. Also, Flush & Spring is not mentioned by NNPA (no date[c]).
		Fen: Basin Mire (E32)	
		Fen: Flood plain mire (E33)	
	Flush & Spring (F&S)	Flush and Spring: Acid neutral flush (E21)	
		Flush and Spring: Basic flush (E22)	
		Flush and Spring: Bryophyte dominated spring (E23)	
	Marsh	Marsh/marshy grassland (B5)	
	Swamp	Swamp (F1)	
Bog	Blanket Bog (BB)	Bog: Blanket bog (E161)	There are separate UKBAPs for 'Blanket Bog' and 'Lowland Raised Bog' (JNCC, 2011). Descriptions from JNCC (2011) and JNCC (2007) suggest that 'Blanket bog' (E161) and 'Raised bog' (E162) correspond most closely to these UKBAPs. P1HS categories E17 and E18 are treated separately under the 'Modified Bog' NPBVC.
	Raised Bog (RB)	Bog: Raised bog (E162)	
	Modified Bog (MB)	Bog: Wet modified bog (E17)	
		Bog: Dry modified bog (E18)	
Broadleaved Woodland	Broadleaved Woodland: Priority (BLWP)	Woodland: Broadleaved: semi-natural (A111)	The main UKBAPs associated with the 'Broadleaved Woodland' BVC are: 'Upland Oakwood', 'Lowland Beech and Yew woodland', 'Upland Mixed Ashwoods' and 'Wet Woodland' (Jackson, 2000). Information from JNCC (2011; 2007) and NNPA (no date[c]) suggests that the UKBAP for 'Wet Woodland' is not relevant for NNP, For the remaining UKBAPs, descriptions from JNCC (2011; 2007) suggest that the P1HS category 'Woodland: Broadleaved: semi-natural' (A111) is the most relevant. The thematic resolution of P1HS nomenclature does not facilitate differentiation of the different UKBAP types. They are therefore matched by the Broadleaved Woodland: Priority PBVC.

Table continued…

BVC	P/NPBVC	P1HS categories (code)	Notes
Broadleaved Woodland (cont)	Broadleaved Woodland: Non-Priority (BLWNP)	Woodland: Broadleaved: plantation (A112)	The P1HS categories comprising this NPBVC are those which were previously included in the 'Broadleaved Woodland' BVC that are not covered by UKBAPs. The P1HS category 'Woodland: Mixed: semi-natural' (A131) may include a 10-90% coverage of either broadleaved or coniferous tree species. Woodland Mixed: semi-natural with a dominance of broadleaved species is therefore covered by UKBAPs. However, it is included under this NPBVC, due to the ambiguities in the P1HS nomenclature.
		Woodland: Scrub: dense continuous (A21)	
		Woodland: Introduced shrub (J14)	
		Woodland: Mixed: semi-natural (A131)	
		Woodland: Mixed: plantation (A132)	
	Broadleaved: Recently Felled Woodland	Woodland: Recently felled woodland: broadleaved (A41)	The recently felled broadleaved woodland types from P1HS nomenclature are matched by the 'Broadleaved: Recently Felled Woodland' NPBVC.
		Woodland: Recently felled woodland: mixed (A43)	
Coniferous Woodland	Coniferous Woodland (CW)	Woodland: Coniferous: semi-natural (A121)	'Native Pine Woodlands' is the only UKBAP habitat associated with the Coniferous Woodland BVC (JNCC, 2011; Jackson, 2000). 'Native Pine Woodlands' are relict indigenous pine woodlands dominated by Scots Pine (*Pinus sylvestris*) and are not likely to be associated with extents of coniferous woodland within NNP (JNCC, 2011). Also, Native Pine Woodlands are not referred to by NNPA (no date[c]). P1HS categories A121 and A122 are therefore listed under the Coniferous Woodland NPBVC.
		Woodland: Coniferous: plantation (A122)	
	Coniferous: Recently Felled Woodland	Woodland: Recently felled woodland: coniferous (A42)	The 'recently felled' coniferous woodland type from P1HS nomenclature is represented by the 'Coniferous: Recently Felled Woodland' NPBVC.
Arable	Arable (NC)	Cultivated/disturbed land: arable (J11)	A UKBAP is included for 'Arable field margins'. However, they are not identifiable from P1HS nomenclature.

4.4 Land Use Scenarios

4.4.1 Introduction

'[A scenario is] an internally consistent view of what the future might turn out to be...not a forecast, but one possible future structure'

(Porter, 1998, pp. 446-48)

The defining characteristic of many social-ecological systems is the variety, complexity and interconnectedness of the factors and processes that govern them. The ways in which these factors and processes will interact and manifest themselves in the future to create changes in the system is therefore often highly uncertain. The methods and approaches typically employed in scenario development require that the various factors, processes and interactions affecting a system be identified, defined and better understood. In this way, the key drivers and challenges likely to influence and affect the system in the future can be gauged. Scenarios allow for a limited selection of concise future narratives concerning the system to be constructed which are meaningful, reasonable and contextually relevant (Porter, 1998). Scenarios are therefore increasingly employed within conservation and natural resources management as a strategic tool to deal more effectively with the future uncertainty inherent within complex social-ecological systems (Preston *et al*., 2011; Rounsevell *et al*., 2006).

4.4.2 Scenario Storylines and Drivers of Land use Change

In developing and defining the land use scenario storylines used within the research, a number of sources were utilised. Summary information on these sources (e.g. time horizon, number of scenarios employed) is provided in Table 4.2.

A detailed discussion of each of these sources and the associated scenarios is beyond the scope of this thesis (for more comprehensive discussion and summary see Busch (2006) and the other relevant documents referred to below). Despite differences between the various sources (e.g. in the spatial and temporal scale of assessments as well as their particular remit and focus) a number of commonalities are apparent. This is perhaps unsurprising as all of the sources, with the exception of FLUFP (2010) and NE (2009); derive their scenario storylines directly from two global scenario exercises: Special Report on Emissions Scenarios (SRES) and Global Scenarios Group Futures (GSG) (Busch, 2006). Selection of these sources is therefore considered an advantage, as the scenario sets reflect the major uncertainties regarding land use change and depict a 'broad range of future pathways' whilst also retaining a good level of internal consistency (Busch, 2006, pp. 137; Holman *et al.*, 2005b). Another advantage of selecting scenarios from these sources is that consideration is often made of the potential influence of climate change on future socio-economic trends.

Table 4.2: Summary information on scenario analysis sources. Adapted from Busch (2006).

Base year	**Time Horizon**	**No. of Scenarios**	**Spatial scale**				**Focus**
			Global	World Regions/ Continents	National	Sub-national	
SRES (IPCC, 2000)							
1995	2100	4	✓	✓			Climate
GSG (Raskin *et al*., 2002; 1998)							
1995	2050	4	✓	✓			Environment, society
Global Environmental Outlook (GEO-3) (UNEP, 2002)							
2002	2032	4	✓	✓			Environment
Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM) (Schroter *et al*., 2004)							
2000	2080	4	✓	✓	✓	✓	Environment, climate
Busch (2006)							
1995-2002	2032-2050	4		✓	✓		Environment (agriculture)
Verburg *et al*. (2006)							
2000	2030	4		✓	✓		Environment
Kankaanpaa & Carter (2004)							
2000	2100	4		✓	✓		Environment (forestry)
Foresight Landuse Futures Project (FLUFP) (2010)							
2010	2060	3			✓	✓	Environment, climate
Creedy *et al*. (2009)							
2010	2060	4			✓	✓	Environment, climate
Holman *et al*. (2005a; 2005b)							
1990	2050	2				✓	Environment, climate

An important similarity between all of the sources is that they highlight the same key interrelated factors acting to drive land use change. Although the specific labelling of these factors differs between the sources, they may be generally defined as: population and demography; culture and society; economic development; technology; policy and regulation; and environment (Busch, 2006).

In basic terms, demographic trends within the various storylines are discussed in relation to projections of population growth. However, the way in which this growth is managed and allowed to develop influences specific levels of growth as well as its spatial distribution and impacts (FLUFP, 2010; Creedy *et al*., 2009). The culture and society driver is defined in a number of ways within the various sources; however, in general, it typically relates to the levels of cohesion or solidarity, within society, versus levels of self-interest. This is important, as levels of social cohesion tend to be related to the degree to which societies are able to adapt to, and cope with, current and future challenges (FLUFP, 2010; Busch, 2006). Economic development within the scenarios typically relates to levels of economic growth. Specific rates of growth differ, depending on the particular socio-economic context. Technology essentially refers to the degree of technological development and innovation. Policy and regulation is related to the strength and influence of policy and regulatory control from governance systems at various scales. Levels of policy and regulatory control may be high for purposes of environmental sustainability or as part of a move towards more economically focused regional or local protectionism (FLUFP, 2010; Busch, 2006). The environment driver, in simple terms, relates to the future quality or state of the environment. However, it may also be considered as indicative of the degree of environmental focus within the storylines, as this is often positively related to the extent to which environmental issues and pressures are effectively managed by society (FLUFP, 2010).

The major trends from each of the scenarios in terms of the six main drivers of land use change are visualised qualitatively in Table 4.3. Based on the analysis from the various sources the extent to which the scenarios depict a globally orientated world is also included.

Table 4.3: Qualitative summary of the relative direction of each of the key drivers under each scenario from the sources in Table 4.2. Sharply-tilted arrows indicate a relatively sharp increase or decrease. Moderately-tilted arrows represent more moderate change. Curved arrows indicate a change in the rate of growth or decline. Adapted from (Busch, 2006; Kankaanpaa & Carter, 2004). SRES and ATEAM results are presented together as the ATEAM scenarios are based directly on those of SRES (Schroter *et al*., 2004). As indicated by Busch (2006), the direction of the drivers from these two sources for their scenarios are exactly the same.

Scenario	Population and demography	Culture and society (solidarity)	Technology	Economy	Environment	Regulation	Globalisation
SRES, ATEAM							
A1	⤴	↘	⬈	⬈	↘	↘	↗
B1	⤴	↗	⬈	↗	⬈	⬈	↗
A2	⬈	⬊	↗	↗	↘	⬈	→
B2	↗	↗	↗	↗	↗	⬈	↘
GSG							
Market Forces	↗	↘	⬈	↗	↘	↘	↗
Policy Reform	↗	↗	⬈	↗	↗	↗	↗
Fortress World	↗	⬊	→	⤴	⤵	↗	↘
Great Transition	⤴	⬈	⬈	⤴	⤴	⬈	⬈
GEO-3							
Markets First	↗	↘	⬈	⬈	↘	↘	↗
Policy First	↗	↗	⬈	↗	⬈	⬈	↗
Security First	⬈	⬊	↗	↗	↘	⬈	↘

Table continued….

Scenario	Population and demography	Culture and society (solidarity)	Technology	Economy	Environment	Regulation	Globalisation
GEO-3 (cont)							
Sustainability First	↗	↗	↗	↗	↗	⬈	↗
Busch (2006)							
Global Markets	↗	↘	⬈	⬈	↘	↘	↗
Global Society	↗	↗	⬈	↗	⬈	⬈	↗
Continental Barriers	⬈	⬊	↗	↗	↘	⬈	↘
Regional Sustainability	↗	↗	↗	↗	↗	⬈	↗
Verburg *et al*. (2006)							
Global Economy	⤴	↘	⬈	⬈	↘	↘	↗
Continental Market	⤴	⬊	⬈	↗	↘	↘	→
Global Co-operation	⬈	↗	↗	↗	⬈	⬈	↗
Regional Communities	↗	↗	↗	↗	↗	⬈	↘
Kankaanpaa & Carter (2004)							
A1	⤴	↘	⬈	⬈	↘	↘	↗
B1	⤴	↗	⬈	⬈	↗	⬈	↗
A2	↗	⬊	↗	↗	⬊	⬈	→
B2	↗	↗	↗	↗	↗	⬈	↘
FLUFP (2010)							
Competition Rules	⬈	↘	⬈	⬈	↘	↘	↗
Valued Service	⬈	⤵	⬈	↗	⤵	⤵	→
Leading the Way	⬈	↗	⬈	↗	⬈	⬈	↗
Creedy *et al*. (2009)							
Go for Growth	↗	↘	⬈	⤴	↘	↘	↗
Succeed Through Science	↗	↗	⬈	⬈	↗	↗	↗
Connect for Life	↗	⬈	↗	↗	⬈	↗	↗
Keep it Local	→	⬊	↗	→	↘	⬈	↘
Holman *et al*. (2005a; 2005b)							
Regional Enterprise	↗	⬊	↗	↗	↘	⬈	→
Global Sustainability	⤴	↗	⬈	⬈	⬈	⬈	↗

Table 4.3 shows that, although some differences are exhibited between the trends for population technological and economic growth, all generally increase under the various scenario storylines (Busch, 2006). More dynamism is associated with interrelated future trends and characteristics relating to policy and regulation, culture and society and the environment. Typically, within the various sources, uncertainty within the factors is often related to two or three generic dimensions highlighted as particularly significant. These are: globalization versus regionalization; solidarity versus self-interest; economic versus environmental orientation (Busch, 2006; Kankaanpaa & Carter, 2004; Raskin *et al*., 2002; 1998; IPCC, 2000). Divergence in pathways between the scenarios is therefore often related to the dynamism of the factors within these dimensions.

Within storylines generally defined by a low level of self interest (i.e. high solidarity) there is typically a reduced focus on benefits in simple economic terms and a greater emphasis on sustainable development and the environment (FLUFP, 2010; Creedy *et al*., 2009; Busch, 2006; Verburg *et al*., 2006; Holman *et al*., 2005b; Kankaanpaa & Carter, 2004; UNEP, 2002; Raskin *et al*., 2002; 1998; IPCC, 2000). Such characteristics are often expressed through tighter more comprehensive environmental policy and regulatory control. This is facilitated by, and contributes to, the greater appreciation throughout society as a whole of the broader range of benefits that the environment provides. Demographic trends, as well as the extent and direction of economic and technological development, are therefore somewhat affected, so that they are more in line with these societal goals. For instance, despite the general increases in population, economic and technological growth under all investigated scenarios, under some storylines policy and regulatory controls act to manage or develop this change in a particular way so that longer-term social, economic and environmental sustainability is delivered more effectively.

Under other storylines, generally characterised by a higher level of self-interest, a greater emphasis is placed on achieving immediate fiscal and material benefits through more rapid economic growth (FLUFP, 2010; Creedy *et al*., 2009; Busch, 2006; Verburg *et al*., 2006; Holman *et al*., 2005b; Kankaanpaa & Carter, 2004; UNEP, 2002; Raskin *et al*., 2002; 1998; IPCC, 2000). As a result, the policy and regulatory environment is often relatively relaxed, allowing a free market approach to dominate. Management of social and environmental issues is therefore largely left to the 'self-correcting logic of competitive markets' (Raskin *et al*., 2002, pp 16). Relatedly, a lack of appreciation and concern within society of the wider benefits provided by the environment often predominates. Therefore, whilst some gains (e.g. greater economic equality) are achieved under some of the scenarios derived from such storylines, the economy, population growth and technological change are often managed or develop in step with the prevailing paradigm. Much less emphasis is therefore placed on the broader, long-term goals of economic, social and environmental sustainability.

Based on the above analysis it was possible to classify the scenarios along two major dimensions: (1) whether the 'world is either globally or regionally orientated' and (2) the extent to which the world exhibits a greater economic or environmental focus. This second dimension can be regarded as somewhat representative of the self-interest versus solidarity dimension referred to above, as the two axes are often positively related (Busch, 2006). Figure 4.3 shows the broad groupings of the scenarios on these two axes.

Figure 4.3: Classification of the scenarios from Table 4.3

Global

Economic

Environment

Global / Economic quadrant:

SRES	A1
GSG	Market Forces
GEO-3	Markets First
ATEAM	A1
Busch (2006)	Global Markets
Verburg *et al*. (2006)	Global Economy
Kankaapaa & Carter (2004)	A1
FLUFP (2010)	Competition Rules
Creedy et al. (2009)	Go for Growth

Global / Environment quadrant:

SRES	B1
GSG	Policy Reform
	Great Transition
GEO-3	Policy First
	Sustainability First
ATEAM	B1
Busch (2006)	Global Society
Verburg *et al*. (2006)	Global Co-operation
Kankaapaa & Carter (2004)	B1
FLUFP (2010)	Leading the Way
Creedy et al. (2009)	Connect for Life
	Succeed Through Science
Holman *et al*. (2005a; 2005b)	Global Sustainability

Regional / Economic quadrant:

SRES	A2
GSG	Fortress World
GEO-3	Security First
ATEAM	A2
Busch (2006)	Continental Barriers
Verburg *et al*. (2006)	Continental Market
Kankaapaa & Carter (2004)	A2
FLUFP (2010)	Valued Service
Creedy et al. (2009)	Keep it local
Holman *et al*. (2005a; 2005b)	Regional Enterprise

Regional / Environment quadrant:

SRES	B2
ATEAM	B2
Busch (2006)	Regional Sustainability
Verburg *et al*. (2006)	Regional Communities
Kankaapaa & Carter (2004)	B2

Regional

4.4.3 UK Context

Even those studies which have a finer spatial focus link the socio-economic changes at such scales to those further up the scale hierarchy. All of the sources were therefore useful in establishing a broad, overarching context to the development of socio-economic storylines for global and European scales. This was particularly true in terms of identifying the major drivers of land use change, the interconnections between the drivers and how they can interact to create different future realities However, because of their specific focus, FLUFP (2010) and Creedy *et al*. (2009) were particularly useful in providing a more UK specific context.

FLUFP (2010) assesses the future of UK land use over the next 50 years, ‘reviews trends across the major land use sectors’ and ‘does not judge one type of land use to be more or less important than another’ (FLUFP, 2010, pp. 10). These facets of the research stem from their remit to inform the strategic and long term land use planning agenda within the UK. Because of this, FLUFP (2010) provided a useful, objective, overarching context to the development of scenario storylines for the UK specifically. More detailed information from FLUFP (2010) on the major drivers of future land use change within the UK over the next fifty years and the key uncertainties associated with them are presented in Table 4.4. Where appropriate, information from the other sources detailed in Table 4.2 is also referred to.

Table 4.4: Six major drivers of future UK land use change from FLUFP (2010). The title of each driver is derived directly from FLUFP (2010).

Driver	Uncertainties
Demographic change	Projections suggest an increase in the population of the UK by 15 million by 2051 (FLUFP, 2010). Such an increase is generally congruent with the increases in population predicted for various scales from the majority of the scenarios from Tables 4.2 and 4.3. Other projected changes from FLUFP (2010) for the UK include an ageing population and an increase in the number of people living alone. Some uncertainty is associated with these predictions. For instance, projections of future population increase are partially based on a continuation of current trends of net inward migration; future trends depend on a number of factors, including the extremity of future climate change, as well as global political, environmental and economic conditions and are therefore somewhat uncertain. However, despite these uncertainties the report concludes future changes in demography coupled with increasing prosperity and aspirations will result in a significant increase in land use demands for housing, recreation, transport, water, food and energy. The ways in which these demands are managed are a major uncertainty. A key question in relation to demographic change within the UK is whether the spatial concentration of people will continue to agglomerate in urban centres or be more dispersed. The outcome largely depends on the future trends and characteristics of other key drivers. The distribution of people is partially linked to the economic geography of the country. Under some storylines, land-based industries account for a large proportion of the UK economy. Areas of production (and therefore the population generally) are more widely dispersed away from existing urban centres. These economic and demographic changes stem from changes in global economic and environmental conditions, as well as regional economic policy incentives. These incentives are implemented as part of a concerted policy framework which seeks to control the impact of land use demands in and around densely populated urban areas such as London and the South East. In other storylines, the population of such areas increases either through inaction or due to a political and societal willingness to accept the issues associated with the resultant increased demand for land. It can be seen therefore that the spatial distribution of people (whether widely dispersed or highly concentrated) is linked explicitly to other key drivers of land use change and has important implications for land use and the pressures on land throughout the UK.
Economic growth and changing global economic conditions	Economic growth, projected to the 2050s in the UK, is likely to be in the range of 1.5%-2.5% per annum (FLUFP, 2010). This generally represents a continuation of current trends within the UK and agrees well with projected trends in economic growth at a variety of scales from the scenarios in Table 4.3. Economic growth will intrinsically affect the demands on land within the UK. For instance, increased levels of affluence tend to create a greater demand for land for leisure and recreation as well as driving demand for larger houses that are more widely dispersed. The future economic and industrial geography of the UK will have vital implications for the location of jobs, homes and transport infrastructure. As suggested the economic geography of the UK is explicitly linked to future economic conditions. Changes in these drivers as well as others will have an important influence on land use. For example, rising global demand for food and changes in commodity prices will have an important influence on the amount of land brought into food production with obvious potential implications for other land use sectors. However, the specific character and scale of the land use impacts will be ameliorated by other drivers. For instance, because inherent 'market failings' are apparent within economies operating under conditions of pure competition the value and benefits of land within such systems is often underestimated (FLUFP, 2010, pp. 82). Appropriate policy and regulatory intervention by governance systems at a variety of scales can act to address this issue (FLUFP, 2010). Those scenarios with a greater economic focus (Figure 4.3) typically exhibit a lack of

	appropriate policy and regulation to help take account of the wider value and benefits that land provides. Levels of economic growth within these scenarios are relatively high and increase rapidly. However, relatively high environmental costs and impacts are often the upshot of the more exclusive economic focus. The scenarios with greater environmental focus typically have a higher level of environmental policy and regulatory intervention. Because of the greater restriction placed on markets, the trends for economic growth within these scenarios are therefore dampened, compared to those with a greater economic focus. However, environmental costs and impacts are generally less severe and managed more effectively. Economic growth within the UK, as well as at broader spatial scales, is likely to continue. However, these points demonstrate that the rate, magnitude and character of economic growth (and therefore the impacts on the UK land use system) are intrinsically linked to other drivers, such as the policy and regulatory environment, as well as prevailing societal values and attitudes.
Climate change	The 'environment' aspect within FLUFP (2010) is focused on the potential impacts and response to climate change. This is not to say that other sources of environmental pressure and change are not considered. However, climate change is identified by FLUFP (2010) as a particularly significant, future challenge for the UK and is used as a useful 'cross cutting', focal point for discussions on wider environmental, social and economic pressures on the land use system. Semi-natural habitats and land uses such as forestry and agriculture will be influenced directly by climate change related changes in temperature and precipitation patterns. However, the magnitude of change will largely determine the specific direct impacts. Under the majority of the scenarios in Table 4.3 climate change and other environmental pressures are generally expected to increase, particularly over the next 20 years. However, FLUFP (2010) as well as the other sources (Table 4.2) highlight the vital role land use can play in moderating climate change (and other environmental) impacts. A major difference between the analysed scenarios is the extent to which future worlds exhibit either an environmental or economic focus. As suggested in 'Economic growth and changing global economic conditions', the particular focus is often strongly related to the policy and regulatory environment, as well as prevailing values and attitudes within society. Under those scenarios with a greater environmental focus, there is a strong societal and governmental response to climate change and other environmental pressures, so that wider impacts are more effectively eliminated or reduced. For instance, increases in the coverage and enhancements in the quality of semi-natural habitat types, such as wetlands and woodlands, are a feature under many of these 'environmental' storylines (e.g. Creedy *et al*, 2009; Verburg *et al*., 2006; Kankaanpaa & Carter, 2004). Such characteristics, driven by prevailing societal, policy and regulatory trends, are typically geared towards sustained or enhanced provision of ecosystem services (e.g. CO_2 sequestration; flood prevention) in the face of climate change and other environmental pressures. As a result, the character of land use change within the UK is likely to be heavily influenced by the degree to which society as a whole values land in simple economic terms or whether a greater emphasis is placed on the broader value and more diverse benefits provided by the environment and land use system. FLUFP (2010) suggest that in practical terms, this will depend on the degree to which infrastructure and governance systems enable land to be maintained and managed as an integrated, multi-purpose resource. Moves towards a low carbon economy will also influence land use decisions, settlement patterns and may create greater competition for land and changes to landscape character. For instance, in order to meet European Union (EU) 2020 renewables targets significant increases in the UK's renewable energy capacity are required. Decisions over which sources of renewable energy are brought into the 'energy mix' to meet these targets will have important implications in terms of the

	pressures placed on land and the characteristics of land use within the UK.
Societal preferences, attitudes and motivations	FLUFP (2010) highlight that societies attitudes and preferences towards land use are a particularly significant driver of land use change and will interact with all of the other drivers in a number of ways. For instance, as suggested above, rising incomes will tend to influence societal preferences and so place particular demands on the land use system. The markets, through pricing, are one mechanism by which societal preferences are expressed and influenced. However, FLUFP (2010), as well as the other sources, also point out that institutional and governance arrangements (i.e. the policy and regulatory environment) are another particularly significant mechanism. For instance, fiscal incentives, market (and wider) regulation, education programmes as well as the extent to which systems are set up to facilitate a participatory approach to decision making are just some of the ways in which societal preferences and attitudes can be adapted and expressed (FLUFP, 2010). A more sustainable approach to land use within the UK is required if climate change and other environmental pressures are to be managed effectively (FLUFP, 2010). This in turn requires significant change towards more integrated institutional and governance systems which recognise the wider value and benefits of land and allow 'differences between the preferences of individuals and communities and societal needs' to be more effectively reconciled (FLUFP, 2010, pp. 14; MA, 2005a). The key general uncertainty for the UK is whether or not societal resistance to these changes in the land use system will be high or low (FLUFP, 2010). Resistance to the required reforms and changes is typically low under those scenarios depicting more environmentally focused worlds. In most instances, this is largely facilitated by stronger more concerted government policy and action at various levels. It is feasible that future attitudes, preferences and motivations within the UK will develop along such lines given sufficient incentive. Conversely, resistance to the changes required to facilitate a broader, more comprehensive approach to the environment is typically high under those scenarios with an economic focus. Such characteristics, typically, are largely attributed to a low level of response from government in terms of the environment and the broad range of benefits it provides. Under many of these scenarios, such characteristics often stem from a continuation of current trends (i.e. 'business as usual').
The policy and regulatory environment	As previously suggested there is a key relationship between societies' preferences, attitudes and motivations and the policy and regulatory environment: Institutional and governmental arrangements and actions can act not only to reflect these preferences but also to influence them (FLUFP, 2010). FLUFP (2010) highlight that a key challenge for UK policy makers is how to manage effectively the multiple demands placed on land by a diverse range of stakeholders (e.g. individuals, communities, institutions and society as a whole) at a variety of scales (e.g. local, national, regional and global). These demands may be in conflict (FLUFP, 2010; MA, 2005a). For instance, the demand for intensively managed agricultural land or land for urban development may conflict with the need for environmental protection (FLUFP, 2010; MA, 2005a). FLUFP (2010), specifically highlight that a more integrated approach to land use policy is required if competing demands are to be met. This requires a change in the land management system in order to allow greater responsiveness to the demands of these stakeholders, as well as enabling the wider benefits of land and the environment to be valued more effectively. As stated, under the environmentally-focused scenarios, through a strong, comprehensive response by governments, institutional and governance arrangements have largely been adapted so that land is more effectively managed within environmental limits in the face of competing demands and pressures. Therefore such changes may be regarded as feasible given sufficient impetus. FLUFP (2010) also highlights the important role that European policy has played in influencing UK land use, over the last 40 years or so, particularly within the agricultural sector. For instance, the character of the Common Agricultural Policy (CAP) has been adapted somewhat over recent years to enable a greater onus to be placed on stewardship of

	the environment when land use decisions are made by farmers and other relevant stakeholders (FLUFP, 2010). Continuation of such arrangements is likely to contribute to and support moves towards the more integrated, comprehensive UK land use management system recommended by the report. Indeed, such arrangements, in one form or another are often a feature under the environmentally focused scenarios. As stated, under the economic scenarios environmental policy and regulation at various levels is often weak and implemented largely on an *ad hoc* basis, so that only the most severe effects of environmental change are managed. Under many of these scenarios, potentially useful European level institutional arrangements (e.g. the CAP) have been severely weakened or scrapped entirely. In many instances, such developments are attributed to a continuation of current trends.
New Technologies	Under all of the analysed scenarios, new technologies and innovation generally increase regardless of the socio-economic context. Information from FLUFP (2010) further supports this trend for the UK specifically. However, the major uncertainty for the UK (as well as at other spatial scales) is the pace and specific character of change (FLUFP, 2010). Technology has a potentially important role to play in helping to achieve the shift towards the more holistic approach to land use management that FLUFP advocates for the UK. For instance, precision technologies that allow farmers to monitor soil condition and water quality will enable farming to reduce its environmental impact, whilst also maintaining high levels of productivity (FLUFP, 2010). A full discussion of the diverse range of technologies that may develop is not possible. In general, however, the degree to which new technologies develop to enable more sustainable, socially-desirable land use will depend heavily on incentives from the policy and regulatory environment and governance structures (FLUFP, 2010). For instance, under those scenarios in which land and the environment are afforded greater non-utilitarian value, the broader social, policy and regulatory environment drive innovation in a way that enables land to be managed more effectively within environmental limits and so better secures the provision of ecosystem goods and services in the long term (FLUFP, 2010, Creedy *et al.*, 2009; Busch, 2006). Under the more economically focused scenarios, there is often more rapid innovation. However this is often focused on meeting economic goals, largely at the expense of environmental security and the longer term provision of ecosystem good and services. Under such scenarios, precision soil monitoring technologies, for instance, may well develop. However, they are likely to be geared more towards meeting consumer demands. The utilisation of such technologies is therefore more likely to be focused towards maintaining or increase the productivity of land, rather than also ensuring that such increases are achieved within environmental limits (FLUFP, 2010; Creedy *et al.*, 2009).

4.4.4 NNP Scenarios

Based on the information in Table 4.4 and the classification of scenarios along the economy/environment axis (Figure 4.3), two land use scenario storylines were developed for the study area. The first ('Conservation First') is closely connected to the group of scenarios to the right of Figure 4.3. Under these storylines, there is typically less focus on economic growth, relatively strong environmental policy and regulation and generally high levels of social cohesion and solidarity. The second ('Going for Growth') is closely connected to the group of scenarios to the left of Figure 4.3. These scenarios are typified by a strong focus on rapid economic growth, relatively weak environmental policy and regulation and low levels of social cohesion and solidarity. The PBVCs within NNP (Table 4.1) are the specific focus of this research. The two storylines may therefore be regarded as plausible 'best' and 'worst' case scenarios in terms of the potential future impact from land use change on the PBVCs. They are used here as a way of tackling the overall uncertainty facing the PBVCs in terms of potential future land use change.

Details of the two scenarios are provided below. First a brief summary of each scenario is presented. This is followed by more detailed information on the characteristics of the two storylines and the particular sources used to establish the types and levels of land use change likely to take place at the landscape scale within NNP.

4.4.4.1 'Conservation First'

The scale and scope of the FLUFP (2010) analysis, as well as that from the other sources, presented problems in using their scenarios directly to simulate spatially explicit land use change at the landscape scale. The land use changes occurring within the park under Conservation First are primarily based around information relating to the desired changes in England's upland environment for 2060 from NE (2009). NE has a remit to manage, conserve and enhance the natural environment with the goal of protecting biodiversity and contributing to sustainable development (NE, 2011). The ambitions for the English uplands, as laid out by NE (2009), are underpinned by, and are partially a response to, the key future issues and challenges facing England's natural environment as identified by Creedy *et al*. (2009). Therefore, although NE (2009) does not provide detailed scenario analysis, the vision of the uplands, as laid out in the document, demonstrates a sufficient level of internal consistency with the trends described in Creedy *et al.'s* (2009) 'Connect for Life' as well as other, similarly classified scenarios (Figure 4.3). Conservation First is therefore deemed to represent a plausible 'best case' scenario storyline in terms of the potential changes affecting the PBVCs.

4.4.4.2 'Going for Growth'

Going for Growth is largely based around information relating to the potential changes in England's natural environment for 2060 from Creedy *et al*. (2009) under their 'Go for Growth' scenario. The scenario is based on a continuation of trends dominant during the first part of the 21st century and therefore can be regarded as a feasible 'business-as-usual' scenario and shares many attributes with scenarios similarly classified in Figure 4.3, particularly those to the top left. The implication from the various sources is that continuing with 'business as usual' is not a desirable option in terms of safeguarding biodiversity or making a significant contribution to sustainable development. 'Going for Growth' is deemed to represent a plausible 'worst case' scenario storyline in terms of the potential changes affecting the PBVCs.

4.4.5 Conservation First

Implicit within NE's (2009) vision for the uplands is the recognition of the diverse range of vital ecosystem services that land (and the uplands environment particularly) provides. These services include the provision of food, fresh water and fuel, climate and flood regulation, 'supporting' services such as soil formation and nutrient cycling and the provision of aesthetic, educational and recreational benefits (FLUFP, 2010). The major goal behind the proposed changes laid out in the vision is to 'help to deliver more of these services' through improvements in the environmental quality of the uplands.

In general, the vision is underpinned by a greater appreciation of the diverse range of benefits that the uplands environment provides throughout society as a whole. This potential future corresponds well with that generally described by scenarios with a greater environmental focus. It also fits well with FLUFP (2010) specifically regarding the desired changes for the UK's land use system stemming from the implementation of their general policy recommendations.

Climate change is specifically identified by NE (2009) as a major future challenge and many of the changes are focused towards adaptation and mitigation. For instance, increases in the extent and quality of semi-natural habitats (such as blanket bog, heath and semi-natural woodland) depicted in the vision are aimed at improving carbon sequestration as well as reducing the risk of wildfires, flooding and soil erosion (NE, 2009). Wetlands, although not explicitly mentioned by NE (2009), are referred to as important features, helping to prevent flooding, in a number of scenarios developed by Creedy *et al*. (2009). Under Creedys *et al*.'s (2009) 'Connect for Life' scenario, wetlands are predicted to increase throughout the UK to better facilitate the provision of ecosystem services. Increases in wetland habitats, such as fens and bogs, therefore should also be expected within NNP specifically, if the vision is implemented.

Due to the scope of the NE (2009) document, little detailed information on the characteristics of the other key drivers is provided. However, some general assumptions may be drawn, based on the information in the text and the discussion provided by FLUFP (2010) and Creedy *et al*. (2009), as well as the other sources. For instance, NE (2009) suggests that improvements in the semi-natural environment of the uplands will be made possible by, and will partially underpin, a 'secure' upland economy characterised by a diversification of rural livelihoods. Exactly how such change is facilitated in the future depends on the characteristics of the various key drivers. It is widely recognised that upland farmers make a highly significant contribution to the quality of the upland landscape and the rural economy. However, reductions in stocking levels are a particularly important feature of the vision. For instance, the occurrence of new woodland on slopes currently utilised for grazing purposes is related to the removal of grazing from such areas. This has obvious implications for the upland agricultural economy.

However, NE (2009) suggests that reductions in grazing will be offset partially by the expansion of hay meadows and 'rushy pastures' in other (lower altitude) areas. NE (2009) also argues that some of these extents may be managed intensively in order to support relatively high stocking rates. In other words, the vision implies a switch from the extensive low-input livestock farming that generally occurs across upland areas to a situation where more intense grazing occurs in particular localities in order to facilitate reduced or eliminated agricultural impacts elsewhere. Such changes fit well with FLUFP's (2010) recommendations regarding the 'multi-functional' use of land use at various scales. Also, recent reforms of the EU CAP have moved subsidy support for farmers away from production and some way towards rewarding environmental stewardship. Such policy reform may therefore help usher in NE's (2009) changes, whilst simultaneously supporting rural livelihoods (FLUFP 2010; NNPA 2009). However, the current CAP ended in 2013. This means that the NE's proposed changes are more likely to be facilitated by future policies which effectively subsidise farmers' contribution to the protection of the uplands environment and/or allow them to successfully diversify and compete more effectively in global markets (FLUFP, 2010).

NE (2009) suggests that changes in societies' preferences, attitudes and motivations are a major factor underpinning the vision. These changes include a better understanding throughout society as a whole of the various services that the uplands environment provides, as well as an increased appreciation of its inherent value. NE (2009) states that these changes are facilitated through ‘upland education programmes’ as well as increased visitor access. As the information in preceding sections suggests, appropriate policy and regulation will also play a significant role.

The characteristics of the vision suggest that the demography of the uplands will remain essentially unchanged. This fits well with a number of environmentally-focused scenarios from Table 4.3 and Figure 4.3 in which population growth and demographic change are managed in order to minimise environmental impacts. The technological changes underpinning the vision are largely related to the implementation of green energy and the achievement of low-carbon growth. These technologies include the installation of ground source heaters as well as solar and wind technologies. NE (2009, pp. 7) states that ‘power infrastructure is sited to minimise irreversible or unacceptable impacts on the environment and landscape’. It is likely that the new technologies implemented in upland areas as part of the vision will not have a significant impact on the distribution of the semi-natural habitats at the landscape scale. Such characteristics are generally congruent with the types of technological innovation apparent under a number of the environmentally-focused scenarios (Figure 4.3).

4.4.5.1 Conservation first: Types and Levels of Land Use Change

The above discussion provides some indication of the land cover changes occurring under Conservation First within NNP. Table 4.5 provides a summary of the main changes. Where appropriate, information on the key drivers, the areas affected and the associated changes in other land uses and land use practices is also included.

NE (2009) provides little information on the future levels of land use change. The increments of change for the P/NPBVCs under Conservation First were primarily based on NNP Local Biodiversity Action Plan (LBAP) and UKBAP restoration targets for associated priority habitats from DEFRA (2013). Table 4.6 provides details of the correspondence between the habitats and land uses from Conservation First; the UK/LBAP priority habitats and the relevant P/NPBVCs (refer to Table 4.1 for information on relevant P1HS categories). Details of the expansion figures that were used to simulate increases in extent that the P/NPBVCs undergo in the scenario are also included. Text box 4.1 demonstrates the methodology for deriving the expansion figures for the P/NPBVCs undergoing expansion under Conservation First from LBAPs and UKBAPs.

Table 4.5: Summary of main land use changes associated with Conservation First

Major changes/characteristics	Notes (drivers, associated changes and areas effected)
Increases in the extent of heath and blanket bog	The major drive behind these changes is the improvement and increased resilience of the uplands environment generally. Increases will assist in climate change mitigation and adaptation, as well as improving other environment services (e.g. improvements in water and soil quality). NE (2009) suggest that the increases in these semi-natural habitats will mainly occur in higher altitude areas and are most likely to involve expansion of existing extents. Notable reductions (or even cessation) of stocking rates, as well as rotational muir burning are associated with these changes (NE, 2009).
Increase in the extent of hay meadows	Increases in hay meadows are in part designed to assist with reductions in stocking rate in other areas of the uplands environment to facilitate increases in, for instance, bog and heath. They are also likely to assist in increasing the resilience of upland ecosystems generally. Increases are likely to be focused around existing extents in lowland areas.
Increases in woodland (plantation and semi-natural)	NE (2009) suggests that increases in both semi-natural woodland and plantations are a major component of their vision. Increases in semi-natural types are closely linked to increasing ecological resilience and improving environmental quality generally. Expansion of existing semi-natural extents is likely. Climate change mitigation (e.g. CO_2 sequestration) and adaptation (e.g. flood prevention and soil consolidation) are also major drivers. Moves towards a green energy infrastructure and low carbon growth are important aspects of the vision. Traditional woodland products (e.g. timber) also continue to make a contribution to the upland economy. Plantations are likely to remain an important feature in upland areas, in part as a local source of renewable energy (i.e. for wood fuel).
Increases in the extent of wetland habitats	Climate change adaptation (i.e. flood prevention), increased resilience of upland ecosystems generally and the facilitation of reductions in stocking rate in other areas of the park are the main drivers behind these changes.
Increase in tourism and visitor access	Increased access to upland areas by tourists and visitors is indicated as a vital component underpinning the diversification of rural livelihoods and the security of the upland economy. The vision assumes that the impact will be managed to minimise the impact at the landscape scale.
Increase in the extent of intensively-managed grazing land in some localities	The scenario suggests an increase in more intense grazing in particular localities in order to facilitate reduced or eliminated agricultural impacts elsewhere. Increases in the extent of Improved Grassland: Priority are used (along with Neutral Grassland: Priority) to represent increases in more intensively managed grasslands.

Table 4.6: Correspondence between the habitats and land uses from the Conservation First scenario, the UK/LBAP priority habitats and the relevant P/NPBVCs. The table also includes details of the expansion figures that were used to simulate increases in extent that the P/NPBVCs undergo in the scenario.

Scenario Land use/habitat	UKBAP/LBAP Priority Habitat(s)	P/NPBVCs	Overall increase in scenario (ha.) (cells)	Notes
Woodland: semi-natural	Semi-natural woodland	Broadleaved Woodland: Priority	3135 (12540)	NNP LBAP restoration targets (DEFRA, 2013a) relate to increases in the amount of 'new native woodland'. Broadleaved Woodland: Priority is the closest corresponding PBVC (DEFRA, 2013a; JNCC, 2011, 2007; NNPA, no date[c]).
Woodland: plantation	N/A	Broadleaved Woodland: Non-Priority *and* Coniferous Woodland	Unchanged	NE (2009) states that the coverage of woodland in upland areas is about 25% under the scenario. The current woodland coverage of NNP is approximately 20%. The increases in the extent of 'Semi-natural woodland' recommended by the NNP LBAP targets (see above) would, if achieved, see woodland accounting for approximately 34% of the area of the park. The LBAP targets exceed the desired increases suggested by NE (2009). It is assumed that the commercial plantations required under the scenario (Table 4.5) will predominantly occur within existing extents. As such, extents of Coniferous Woodland and Broadleaved Woodland: Non-Priority remain unchanged.
Heath	Upland heath	Heath	12549 (50196)	National UKBAPs include separate targets for 'upland' and 'lowland' heath. Large extents of the Heath PBVC occur below an elevation of 300m within NNP and therefore may be regarded as 'lowland heath', based on UKBAP criteria. However, LBAP targets for NNP only cover 'upland heath'. Also all extents of 'true' heath (i.e. P1HS categories D1 and D2: Table 4.1) within the park are regarded as upland heath by NNP's BAP (NNPA, no date[c]). The LBAP target for 'Upland heath' (DEFRA, 2013b) are applied to all extents of the Heath PBVC regardless of altitudinal context.
Bog	Blanket bog	Blanket Bog	2702 (10808)	NE (2009) indicates increases in the extent of bog generally. UKBAPs include separate targets for 'Lowland raised bog' and 'Blanket bog'. No LBAP numeric restoration targets are available for NNP in relation to either raised bog or blanket bog. UKBAP targets (T2 & T3) are used as the basis for increases in the extent of Blanket Bog within NNP (DEFRA, 2013c). UKBAP targets (T2 & T3: DEFRA, 2013d) for 'Lowland raised bog' are used as the basis for increases in the extent of Raised Bog within the park regardless of altitudinal context.
	Raised bog	Raised Bog	155 (620)	
Hay meadows	Upland hay meadows Lowland hay meadows	Neutral Grassland: Priority	626 (2504)	Increases in the extent of hay meadows are a particular feature of NEs vision. UKBAP's include separate targets for 'Upland hay meadows' and 'Lowland meadows'. No LBAP numeric targets are available for either of the habitats for NNP. The closest corresponding PBVC is Neutral Grassland: Priority (Table 4.1). The UKBAP target for 'Upland hay meadows' (T6: DEFRA, 2013e) are used as a basis for increases in the extent of Neutral Grassland: Priority (NGP) within NNP regardless of altitudinal context. T6 suggests a 157% increase on current coverage for NGP. However, due to researcher error the 626 ha increase used in this research represents a 257% increase on current NGP coverage within NNP.
Wetlands	Upland Flushes, Fens and Swamps Purple moor grass and rush pastures Lowland fens	Fen; Marsh; Flush & Spring; Swamp	Fen: 1060 (4240) Marsh: unchanged Flush & Spring: unchanged Swamp: unchanged	Increases in the extent of wetland habitats such as marsh and fen are suggested as an important component of Conservation First. A UKBAP is available for 'Upland flushes, fens and swamps'. The UKBAP description states that it is represented by the P1HS categories 'Fen' (E3); 'Flush and Spring' (E2); 'Marsh/marshy grassland' (B5) and 'Swamp' (F1). However, no LBAP or UKBAP targets have yet been set. Separate UKBAP's are available for 'Purple moor grass and rush pastures' and 'Lowland fens'. The closest corresponding P/NPBVC to 'Purple moor grass and rush pastures' is Marsh (Table 4.1). Marsh currently covers about 13% of the park. Percentage increases in Marsh based on UKBAP targets suggest an excessive level of coverage under Conservation First. The current Marsh coverage is therefore deemed to represent an adequate level in terms of contributing to climate change adaptation. Descriptions for 'Lowland fens' suggest the closest corresponding P/NPBVC is Fen (Table 4.1). UKBAP targets are only available for 'Fens'. The England UKBAP target (T3: DEFRA, 2013f) for 'Fens' is therefore used as a basis for increases in the extent of the Fen PBVC. Because of the lack of specific LBAP or UKBAP targets relevant for Swamp and Flush & Spring do not undergo expansion in this research. Also, the characteristics of Flush & Spring (i.e. small or extensive linear, soligeneous features often integrated with other wetland/ mire habitats) present challenges in modelling its distribution. Swamp is also not modelled separately, due to problems in representing accurately its soil water characteristics with the available data. Marsh, Flush & Spring and Swamp therefore do not undergo changes in extent in this scenario.
Intensively managed grazing land	Coastal and floodplain grazing marsh	Improved Grassland: Priority	518 (2072)	It is likely that increases in the extent of PBVCs such as Blanket Bog and Heath will require some increases in the extent of more intensively managed grasslands in some areas. The Improved Grassland: Priority (IGP) PBVC (i.e. P1HS category 'Improved Grassland' (B4)) corresponds closely to this description. IGP includes the UKBAP priority habitat 'Coastal and Floodplain Grazing Marsh' (CFGM). However aggregated UKBAP targets (T1 – T4: DEFRA, 2013g) for CFGM suggest an increase of over 350% above current levels. IGP currently has relatively high levels of coverage within NNP (See: Table 4.10). A 350% increase on this figure is regarded as representing an excessive level of coverage of intensively managed grazing land under Conservation First, considering the general ethos of the scenario and the fact that increases in NGP (see above) are also likely to contribute to meeting targets for more intensively managed-pastures. An increase of 11% above current levels is therefore regarded as generally appropriate for simulating increases in IGP under Conservation First. The 11% figure is assigned arbitrarily.

Box 4.1: Method for Calculating NNP Expansion Figures from LBAPs and UKBAPs under Conservation First

Table 4.6 shows that figures for the various P/NPBVCs undergoing expansion under Conservation First are based upon both UKBAPs and NNP LBAPs. Calculating expansion figures for PBVCs based on LBAPs was relatively straightforward. For instance, in the case of Heath and Broadleaved Woodland: Priority expansion figures are simply based on the amount of expansion required to meet future targets for NNP from DEFRA (2013a) and DEFRA (2013b), respectively.

Calculating expansion figures for PBVCs within NNP, based on UKBAPs, was somewhat more elaborate. Specifically, the expansion figures were based on the percentage increase in the UK (or England) coverage of a particular PBVC as indicated by relevant UKBAPs. For instance, relevant current UK Blanket Bog coverage from Target 2 (T2) DEFRA (2013c) is 271991 ha. Expansion targets (T2 and T3) for Blanket Bog from DEFRA (2013c) suggest an overall future coverage within the UK of 492991 ha:

Overall UK coverage (ha) for Blanket Bog from T2 = 430991
Overall UK coverage (ha) for Blanket Bog from T3 = 62000

$$430991 + 62000 = 492991$$

This represents an increase in coverage of 81%:

$$492991 – 271991 = 221000$$

$$(221000/271991) \times 100 = 81\%$$

The expansion figure for Blanket Bog for NNP under Conservation First (Table 4.6) therefore represents an 81% increase of the PBVCs current coverage (3343ha). NNP expansion figures based on UKBAPs for the other PBVCs (i.e. Raised Bog, Neutral Grassland: Priority and Fen) were calculated using the same method.

4.4.6 Going for Growth

A major characteristic of the Going for Growth scenario is the general decline in biodiversity and quality of the natural environment. The lack of policy incentivising adequate climate change mitigation and coordinated adaptation means that this situation partly stems from the direct, severe impacts of changes in the climate on the UK.

The context of a largely deregulated, market-driven economy competing under conditions of global free trade is another prominent characteristic of the scenario and plays a defining role in how land use decisions are made. For instance, these characteristics create a situation in the UK generally, where land used for conservation purposes has to compete directly with other land uses such as agriculture, forestry, energy production, raw materials and transport, as well as residential and commercial development. Such land uses are only sustained in the long term through market success. Ecosystem services which do not provide immediate financial gains are ascribed little or no value. Quality semi-natural landscapes remain only where they provide obvious fiscal success. However, even these are degraded and under pressure. National parks, specifically, are under corporate ownership by 2030; suggesting a weakening of the regulations and controls governing them (Creedy *et al*., 2009).

Under the scenario, the distribution of land uses is largely matched to those areas where they provide immediate economic gain. The reliance on the global economy and 'rapid turnover' of businesses within the scenario suggests considerable uncertainty and dynamism in the geographic distribution of land uses. However, information from Creedy *et al*. (2009) on the geography of particular land uses under the scenario, as well as the current economic land uses within NNP, provide some useful indications in terms of the potential future land uses affecting the study area. For instance, country sports currently make a significant economic contribution to the park and management of heather moor for grouse shooting is particularly important (NNPA, 2009). Deer stalking and pheasant shooting in the forests of the park are also carried out but are currently less important economically (NNPA, 2009). Creedy *et al*. (2009) specifically suggest that country sports are economically competitive in some areas which are under corporate management for such purposes. It is feasible that, under Going for Growth, grouse moor land, as well as forestry (associated with an increase in deer and pheasant hunting) will increase within some areas of NNP for economic reasons. Under such conditions it is quite possible that PBVCs such as Heath and BLWP as well as NPBVCs (e.g. Coniferous Woodland) will increase in extent to facilitate the increase in country sports.

The scenario also points towards a significant increase in the amount of land in the uplands used for energy production. These changes are not driven by environmental policy, but rather decreased availability of fossil fuels as resources become scarce. Renewable sources such as bio fuels (e.g. energy crops and wood fuel), wind and solar will make a notable contribution to the energy mix.

The implications for the study area in relation to food production under the scenario are complex. Creedy *et al*. (2009) state that the area of land used for food production, within the UK under their Go for Growth scenario, has declined because of biotechnological advances, cessation of the EU CAP and increased imports from abroad. However, in line with the general theme of the scenario, food production is retained where it proves economically viable. In relation to livestock farming specifically, this means catering to 'niche' markets (e.g. through the provision of 'ethical' foods). The systems required to produce such products often require additional land compared with conventional production systems (FLUFP, 2010; Creedy *et al*., 2009). However, the prevailing environmental values within society generally, under the scenario, suggest that domestic markets for 'niche' products are likely to be small. It is unlikely that demand will be sufficient to maintain current levels of livestock farming within the park.

Despite the overall national trend for declines in the area of land used for food production under the scenario, it is feasible that the area of land used for arable farming within NNP will increase. This is related to the direct effects of climate change and demographic trends. Currently, the major areas of arable production within England are in the South East (FLUFP, 2010; Creedy *et al*., 2009). The direct effects of climate change combined with a large future population and high rates of economic growth are likely to negatively impact on the economic viability of agriculture within the South East unless appropriately managed (FLUFP, 2010). Creedy *et al*. (2009) suggest that, under their Go for Growth scenario, this has largely failed to happen. Arable farming may become more viable in north-eastern England generally, due to the direct effects of climate change (e.g. through changes in the growing season) (NEA, 2004). Under Creedy *et al*.'s (2009) Go for Growth scenario, northern areas of England generally have low population densities compared to southern regions. This implies an increase in the economic viability of arable farming within north-eastern England, due to the relatively decreased pressures placed on the land use system. It is therefore feasible that some increases in the area of arable farmland within NNP will occur under the scenario in lowland areas. It is likely that these increases will occur to meet demand for food as well as bio-fuel production.

Throughout the UK generally, there is 'little change' in the overall area of wetland. This is because wetlands are managed in some areas of the UK for purposes such as flood prevention and water purification (FLUFP, 2010; Creedy *et al*, 2009; Busch, 2006).

4.4.6.1 Going For Growth: Types and Levels of Land Use Change

Table 4.7 provides a summary of the main land use changes under Going for Growth, where appropriate information on the key drivers, the areas affected and the associated changes in other land uses and land use practices is also included. Table 4.8 provides details of the correspondence between the habitats and land uses from Going for Growth and the relevant P/NPBVCs. Details of the expansion figures that were used to simulate increases in extent that the P/NPBVCs undergo in the scenario are also included. Relevant scenario results from a number of the additional sources in Table 4.2 were used in providing quantitative estimates of areal increases for the P/NPBVCs within NNP, due to the problems in obtaining such information directly from Creedy *et al*. (2009). Details of these sources are also provided in Table 4.8 where appropriate.

Table 4.7: Summary of main land use changes associated with Going for Growth

Major changes/characteristics	Notes (causes and areas effected)
Increases in the extent of heath	Expansion of heath within the scenario is linked to an increase in the use of the park for country sports (specifically grouse shooting). It is possible that the management for such purposes will be implemented less sensitively than it is currently, due to the change in management infrastructure, lack of environmental regulations and prevailing environmental attitudes generally. However the land use model is unable to account for such qualitative differences. Relatively dense heather moorland is the preferred habitat of the grouse populations currently present within the park (NNPA, 2009). Due to the characteristics of the scenario, current extents of Heath/Acid Grassland Mosaic are likely to be maintained, in order to contribute to the overall amount of habitat available to support increased use of the park for country sports.
Increases in the extent of woodland (plantation and semi-natural)	The use of land for energy provision in the uplands is stated as a major theme within the scenario. Due to a decreased availability of fossil fuels, renewable sources make a significant contribution to the energy mix. It is likely therefore that some expansion of commercial forestry will occur under the scenario in order to provide wood fuel. The increase in the use of the park for country sports (specifically deer hunting) is also likely to contribute to increases in the extent of commercial forestry as well as semi-natural woodland. Increase in the use of some areas of the park for amenity purposes is also likely to result in an increase in semi-natural woodland.
Use of land for bio-fuels	Increased use of the uplands for energy provision. Future demographic trends and climate changes are also likely to increase the economic viability of the use of land within the park for bio-fuel production.
Increases in the extent of arable farming	Increased economic viability due to the effects of climate changes (e.g. changes in the thermal growing season), the negative impacts of climate change compounded by high levels of population growth and resource demands in areas currently used for arable farming (i.e. South East England) are key drivers influencing the expansion of arable land.
Retaining of ‘wetlands’	Existing areas of wetland within the park are likely to be retained for purposes such as climate change adaptation (e.g. flood prevention) and other vital environmental services (e.g. water purification) (Creedy *et al*., 2009; Verburg *et al*., 2006).
Use of land for wind farms	Increased use of the uplands for energy provision. The altitudinal characteristics of the uplands mean that under the scenario wind farms are common features. The suitability of land for energy generation from wind was not considered as part of the modelling for the scenario. It is assumed that wind farms can be established without significant large scale disturbance of the original land cover.
Water collection	Upland areas are also used for water collection under the Creedy *et al*. (2009) scenario. However, the suitability of land for water collection was not considered as part of the modelling.

Table 4.8: Correspondence between the habitats and land uses from Going for Growth and relevant P/NPBVCs. Details of the expansion figures that were used to simulate increases in extent that the P/NPBVCs undergo in the scenario are also included.

Scenario Land use/habitat	P/NPBVC	Overall increase in scenario (ha.) (cells)	Notes
Woodland semi-natural	Broadleaved Woodland: Priority	865 (3461)	Expansion figures represent a 100% increase on current levels and are largely arbitrarily assigned. The expansion is mainly related to the increase in the use of the park for country sports (especially deer hunting) and is therefore regarded as feasible under the socio-economic conditions affecting the study area under Going for Growth.
Heather Moor	Heath	12549 (50196)	No adequate secondary sources were available on which to base levels of Heath expansion under Going for Growth. Expansion figures are based on those for Heath occurring under Conservation First. However, whereas the expansion of Heath under Conservation First occurs largely for purposes of conservation and increased environmental resilience, the increase occurring under Going for Growth is mainly linked to the increased use of the park for country sports (especially grouse shooting) for largely economic reasons. Such activities rely on good quality heathland habitat (NNPA, 2009).
Woodland Plantation	Coniferous Woodland	1864 (7455)	Expansion figures represent a 10% increase on current levels. This is based on Kankaanpaa & Carter (2004), who predict a 10% increase in forestry in the UK by 2020, based on the characteristics apparent under their A1 scenario storyline; the 10% increase for 2020 is largely due to an increase in commercial forestry. There are very close similarities between the general characteristics of the Going for Growth and A1 scenarios. Kankaanpaa & Carter (2004) predict a 5% reduction in forestry for the UK for 2050. However, it was felt appropriate to use the predicted increase in forestry for 2020 from the A1 scenario as a basis for the increase in commercial forestry (here represented by the Coniferous Woodland NPBVC) under Going for Growth within NNP for a number of reasons: **1)** A major assumption inherent in the A1 scenario is that fossil fuels are in abundant supply. This is not the case under Going for Growth. As suggested in Table 4.7 the use of the UK uplands for energy provision is one of the defining characteristics of the scenario. It is likely that commercial forestry within NNP will play an important role in this regard. It is reasonable to assume that an increase in commercial forestry within NNP will occur to meet some of the demand for energy from renewable sources. **2)** The trends for forestry that are predicted to occur within the UK for 2050 by Kankaanpaa & Carter (2004) under the A1 scenario are partially related to afforestation on abandoned agricultural land. However, this trend is likely to be less pronounced within north-eastern England specifically, due to a combination of demographic factors, the direct effects of climate change and an increased demand for crops for bio-fuels. Because of these issues, it is likely that much of the afforestation on abandoned agricultural land that occurs under A1 will not occur under Going for Growth within NNP specifically. **3)** Some of the expansion of commercial forestry under Going for Growth is partially due to an increase in the use of forests for recreational purposes (e.g. deer hunting). At the national scale under A1 this is insufficient to generate an increase in forestry. However, according to the defined characteristics of Going for Growth there is a marked increase in the use of NNP for recreational purposes (especially country sports) due to the increased economic viability of such activities within the area. The 10% increase in commercial forestry within NNP specifically can also be partially justified within this context.
Arable farm land Energy crops (bio-fuels)	Arable	355 (1418)	Expansion figures represent a 60% increase on current levels. This is based on Busch (2006, pp. 134), who predict an approximately 60% increase in cropland across 'Western Europe' (15 EU countries including the UK), based on the characteristics of the SRES A1 and GEO-3/SEI 'Markets First' scenarios. These scenarios have very good general correspondence with Going for Growth. The increases in cropland under the SRES A1 scenario, specifically, are partially attributable to an increase in bio-fuel demand. The rest of the expansion is due to an increase in crop production for food export. Although this specific characteristic is not particularly apparent within the Going for Growth storyline an increase in cropland for food production within NNP under the scenario is feasible, due to the combination of demographic factors and the direct effects of climate change that act to make arable farming within the north east much more economically viable than it is currently and compared to south-eastern England in the future. Some support for this is provided by the findings of Holman *et al*. (2005a, pp. 31) which predict approximately a 100% increase in arable farm land within the north west of England for the year 2050. These predictions are made for their regional enterprise scenarios, the general characteristics of which are similar to those of Going For Growth. Within this context the 60% increase in Arable adopted within this study may be regarded as a somewhat conservative estimate of the changes likely to occur within NNP under Going for Growth.
Wetlands	Marsh, Fen, Flush & Spring, Swamp, Blanket Bog, Raised Bog	Unchanged	Creedy *et al*. (2009, pp. 27, 68) strongly suggest that under Going for Growth conditions the area of wetlands remains approximately stable. This is largely related to their use for mitigation against the direct effects of climate change. This characteristic is supported by the scenario conditions used by Verburg *et al*. (2006, pp. 44) to simulate fine-scale land use change within Europe under their A1 and A2 scenarios.

4.5 Model Evaluation

Two evaluative approaches were applied in order to assess the accuracy of the Habitat Suitability Indices (HSIs) (Appendix 2) and their usefulness as a basis for simulating P/NPBVC distributions. First, as an initial assessment of the accuracy of the HSIs, the degree of agreement (DA) between a P/NPBVC's overall suitability layer, created using only the five biophysical variables (soil water, soil type, soil pH, elevation and slope), and its observed current distribution was considered. Second, the MOLA module was used to simulate current P/NPBVC distributions for the study area, as influenced by the five biophysical variables. These results were then compared to observed current distributions. The accuracy of initial simulations was quite low. However, technical issues associated with MOLA contributed to these results. Techniques were applied to address these issues, in order to provide a more accurate assessment of the reliability of future simulations. Details of the model evaluation are provided below.

4.5.1 Degree of Agreement (DA) Between P/NPBVC Suitability Layers and Current Observed Distributions

As a preliminary method of evaluating the accuracy of the HSIs for each P/NPBVC, the DA between a P/NPBVC's overall suitability layer and its observed current distribution was calculated. The DA was ascertained as the percentage of pixels from the P/NPBVC's overall suitability layer, with a suitability score equal to or greater than 0.5, spatially coincident with the P/NPBVC's current distribution (Table 4.9).

Table 4.9: DA between overall suitability layers and extant distributions. Organised in descending order.

P/NPBVC	DA (%)
Heath	100.00
Acid Grassland	100.00
Heath/Acid Grassland Mosaic	100.00
Blanket Bog	100.00
Broadleaved Woodland	100.00
Calcareous Grassland	100.00
Modified Bog	100.00
Bracken	100.00
Improved Grassland: Priority	99.97
Marsh	99.88
Fen	99.64
Raised Bog	99.36
Neutral Grassland: Non-Priority	99.16
Neutral Grassland: Priority	99.08
Flush & Spring	98.78
Swamp	97.65
Coniferous Woodland	96.84
Improved Grassland: Non-Priority	96.11
Arable	92.05

If the accuracy of the HSIs were poor, or the choice of variables spurious, low DA values would be expected. The results above suggest that this was not the case. This preliminary exercise suggested that the HSIs accurately characterise the requirements of the P/NPBVCs in terms of the selected biophysical variables and had potential for modelling P/NPBVC distributions.

4.5.2 Simulation of Current Distributions

Comparisons of simulated and observed distributions are commonly used in model evaluation (Guisan & Zimmerman, 2000). The HSIs and the MOLA module were employed to simulate current P/NPBVC distributions within the study area (see: Table 4.11, 'Column A' for results). The areal requirements used in the simulation were based on current NNP P/NPBVC coverage calculated from the P1HS data. Table 4.10 provides details of the order in which P/NPBVCs were input to the MOLA module for Simulation 1 and their areal requirements (areal requirements are entered into the MOLA module as the number of 50m cells).

Table 4.10: Order of input of P/NPBVCs and their areal requirements used in Simulation 1

Code	P/NPBVC	Areal Requirements (ha) based on P1HS
1	Bracken	3334
2	Heath	7405
3	Neutral Grassland: Priority	244
4	Acid Grassland	26062
5	Improved Grassland: Priority	4628
6	Fen	485
7	Blanket Bog	3343
8	Broadleaved Woodland	1652
9	Coniferous Woodland	19807
10	Arable	591
11	Calcareous Grassland	8
12	Modified Bog	899
13	Heath/Acid Grassland Mosaic	13092
14	Improved Grassland: Non-Priority	45
15	Neutral Grassland: Non-Priority	6163
16	Flush & Spring	82
17	Marsh	11571
18	Swamp	43
19	Raised Bog	78

The accuracy of Simulation 1 was then assessed by comparing it with the observed current P/NPBVC distributions from the P1HS data. A cross-tabulation matrix was produced to show the frequency of correctly and incorrectly simulated pixels for each P/NPBVC (Eastman, 2009). Correctly simulated pixels are those that are simulated as a particular P/NPBVC in Simulation 1 that coincide spatially with the observed current distribution of that P/NPBVC. High frequencies of correctly simulated pixels would be expected if the model were robust.

For the purposes of accuracy assessment, the results for Neutral Grassland: Priority and Neutral Grassland: Non-Priority are treated concomitantly as 'Neutral Grassland'. Pixels of Neutral Grassland: Priority in Simulation 1 coinciding with observed current extents of Neutral Grassland: Non-Priority are regarded as correctly simulated, and vice versa. This is because the suitability indices for these P/NPBVCs demonstrate that their tolerances, in terms of each of the key biophysical variables, are identical (See: Appendix 2b). For the same reason, the results for Heath, Acid Grassland and Heath/Acid Grassland Mosaic are also treated as 'Moorland'. Differences in the current distribution patterns of these P/NPBVCs are likely to be strongly influenced by factors relating to historic land use and management decisions. Due to issues concerning the adequacy and availability of data and information, these factors are not explicitly represented when simulating current distributions. Errors in simulating the current distributions of these P/NPBVCs are therefore to be expected. However, in future simulations, this issue is addressed through the land use characteristics inherent within the scenarios and the inclusion of additional variables (distance and cross-suitability) allowing more explicit representation of future management.

Table 4.11, column A, presents the results of Simulation 1 as the proportion of correctly simulated pixels for each P/NPBVC, as well as the overall proportion of correctly simulated pixels. 'Proportion correct' is commonly used to assess the correspondence between observed and simulated distributions (Pontius Jr & Millones, 2010; Guisan & Zimmerman, 2000, Brzeziecki *et al.*, 1995). However a number of issues were identified as affecting the results of this initial simulation and are discussed below.

Table 4.11: The results ('percentage correctly simulated') for: Simulation 1 (column A), the 'reordering of P/NPBVC inputs' simulations (column B) and the 'rotation of suitability layers' simulations (column C). The P/NPBVC are organised by the results of column 'C' (highest 1st).

P/NPBVC	Column		
	A (%)	B (%)	C (%)
Moorland	52.81	72.61	80.16
Blanket Bog	43.40	43.40	56.11
Marsh	16.24	16.24	29.26
Arable	9.77	9.77	23.82
Fen	1.70	1.70	23.31
Improved Grassland: Priority	20.56	21.38	22.10
Neutral Grassland	8.23	10.11	21.55
Bracken	12.19	12.22	16.40
Coniferous Woodland	9.99	9.99	14.77
Flush & Spring	5.79	6.40	14.02
Broadleaved Woodland	1.70	1.76	7.61
Swamp	2.94	2.94	5.29
Modified Bog	0.00	0.00	1.11
Calcareous Grassland	0.00	0.00	0.00
Improved Grassland: Non-Priority	0.00	0.00	0.00
Raised Bog	0.00	0.00	0.00
Overall correctly simulated	**32.03**	**44.37**	**49.10**

4.5.2.1 Issues with the MOLA Procedure

Reordering of P/NPBVC Inputs

Aspects of the MOLA procedure were identified as affecting the results of Simulation 1. The order in which the P/NPBVCs were input to MOLA was an issue. In allocating pixels to particular P/NPBVCs, MOLA affords precedence to those input to the procedure first. To address this issue, simulations were run in which the order of P/NPBVC input was systematically varied. The number of P/NPBVCs made it impractical to run simulations with every possible permutation of inputs. Instead five broad groups were devised based on the order in which P/NPBVCs were input to

Simulation 1 (Table 4.12a). The input of these groups to MOLA was then systematically re-ordered, allowing four different simulations to be run (i.e. Simulations: 2a - 2d). Table 4.12b provides details of the reordering of the P/NPBVC groups in each of the simulations. The areal requirements of the P/NPBVCs in the simulations were the same as Simulation 1 (Table 4.10).

The results of Simulation 1 and Simulations 2 a - d were then processed individually to produce Boolean images, each representing the distribution of an individual P/NPBVC in each of the simulations (presence = 1; absence = 0). Boolean layers showing the composite distribution of each P/NPBVC across these simulations were then created by combining the relevant Boolean images. Boolean layers of current observed P/NPBVC distributions were also produced from the P1HS data.

MOLA seeks to allocate those pixels regarded as most suitable for a particular objective (Clark Labs, IDRISI Taiga, no date). However, as discussed, the allocation of pixels is determined somewhat arbitrarily according to the order in which P/NPBVCs are input to the procedure. The systematic reordering of P/NPBVCs described above attempts to counteract this. Pixels assigned to a P/NPBVC in any one of the simulations are likely to represent areas to which it is most suited. Disparities in P/NPBVC distributions between the simulations are probably due to the technical issues apparent with the MOLA procedure. The composite P/NPBVC distributions were compared to the current observed distributions to gauge the proportion of correctly simulated pixels. The results are presented in Table 4.11: Column B and demonstrate a notable increase in the overall percentage of correctly simulated pixels compared to Column A.

Table 4.12a: Grouping of P/NPBVCs based ordering of inputs.

Order	P/NPBVC	Group
1	Bracken	A
2	Heath	
3	Neutral Grassland: Priority	
4	Acid Grassland	
5	Improved Grassland: Non-Priority	B
6	Fen	
7	Blanket Bog	
8	Broadleaved Woodland	
9	Coniferous Woodland	C
10	Arable	
11	Calcareous Grassland	
12	Modified Bog	
13	Heath/Acid Grassland Mosaic	D
14	Improved Grassland: Non-Priority	
15	Neutral Grassland: Non-Priority	
16	Flush & Spring	
17	Marsh	E
18	Swamp	
19	Raised Bog	

Table 4.12b: Systematic ordering of P/NPBVC based on original group categories (A-E) in simulations 1 and 2a-d.

Simulation				
1 (original order)	2a	2b	2c	2d
A	B	C	D	E
B	C	D	E	A
C	D	E	A	B
D	E	A	B	C
E	A	B	C	D

Rotation of Suitability Layers

Another issue affecting the results was the requirement for suitability layers to be ranked prior to being input to MOLA. Pixels are assigned an individual rank value which enables MOLA to make decisions about which are the most suitable areas for a particular P/NPBVC in cases where the suitability values of pixels are tied. As part of the ranking process, the original range of real suitability values (i.e. 0.0-1.0) is rescaled to an integer byte range (i.e. 0-255) (Clarke Labs, IDRISI Taiga, no date). Effectively, this is a reclassification of the original suitability values into 256 ordinal categories, but preserves the basic distribution of the original suitability data (i.e. high suitability values are assigned to the highest values in the byte range and low suitability values are assigned to the lowest byte values). Pixels are then assigned individual rank values based on class membership *and* their relative position within the raster layer. Within each 0-255 ordinal category, individual ranks are assigned systematically in normal raster order (left to right, top to bottom) (Clarke Labs, IDRISI Taiga, no date). This means that of two pixels, with the same suitability value in a P/NPBVCs overall suitability layer, the one closer in proximity to the top left of the image will be assigned a higher ranked suitability value. This pixel will therefore take precedence when pixels are being allocated to that P/NPBVC. The upshot of this is that the accuracy of simulations is significantly influenced by the semi-arbitrary way in which rank values are assigned.

To address this issue, the overall suitability layers for each P/NPBVC were systematically rotated clockwise by 90^o, 180^o and 270^o prior to being ranked. This rotation ensured that in resolving ties between the values of pixels in the original suitability layers the MOLA procedure was effectively forced to depart from normal raster order in assigning individual ranks. Three new current simulations (3a, 3b and 3c) were run each utilising a different set of rotated images. Table 4.12c summarises the rotation of suitability layers used in each of the simulations and the effective order in which tied pixels are individually ranked because of the rotation. The rationale and methods for determining the proportion of correctly simulated pixels across these simulations was the same as that for simulations 1 and 2a-d. The results are presented in Table 4.11: Column C.

Table 4.12c: The rotation applied to the suitability layers used in simulations 1 and 3a-c. The effective order in which tied pixels are individually ranked as a result of the rotation is also included.

Simulation	Clockwise rotation (^{o})	Order of ranks
1	0^0	Left to right, top to bottom (Normal raster order)
3a	90^o	Bottom to top, left to right
3b	180^o	Right to left, bottom to top
3c	270^o	Top to bottom, right to left

Table 4.11: Columns B and C show that the effects of the technical issues discussed above have a combined effect on the results of some P/NPBVCs in Simulation 1. Explicit assessment of these combined effects was not possible, due to the time constraints associated with the research. The table also shows that the order in which P/NPBVCs are input to the procedure has a lesser effect on simulation accuracy (column B) compared to the way in which individual pixels are ranked (column C).

The results presented in Table 4.11 column C are regarded as a generally robust initial measure of the accuracy of the HSIs in defining the biophysical requirements of the P/NPBVCs and their usefulness for providing meaningful predictions of P/NPBVC distributions. Brzeziecki *et al*. (1995) reported an average 'intraclass correlation coefficient' of 50% in their study simulating zonal forest communities in Switzerland. Zimmerman & Kienast (1999) report levels of coincidence of 58% between observed and simulated distributions of Swiss grassland communities. The initial overall results of this research (49%) are therefore regarded as reasonable.

Comparison of the results for individual P/NPBVCs demonstrates considerable variation. For instance, Moorland and Blanket Bog were simulated with high to moderate levels of accuracy (80.16% and 56.11% respectively). The proportion of correctly simulated pixels for several other P/NPBVCs was 0.00% (i.e. Calcareous Grassland; Improved Grassland: Non-Priority and Raised Bog). Other P/NPBVCs that were simulated with very low levels of accuracy were: Modified Bog (1.11%); Swamp (5.29%); Broadleaved Woodland (7.61%), Flush & Spring (14.02%), Coniferous Woodland (14.77%) and Bracken (16.40%). The simulation accuracy of the remaining P/NPBVCs ranges from low to moderately low. It is likely that the relatively high levels of accuracy for Moorland and Blanket Bog (which between them account for approximately half of the study area) compensate for the generally poor levels of accuracy observed for the majority of the P/NPBVCs.

A number of issues can be identified to explain the results of Table 4.11 column C. They can be summarised as follows: 1) omission of relevant (non-biophysical) factors; 2) accuracy of underlying data; 3) characteristics of the modelling units and accuracy of the HSIs.

4.5.2.2 Omission of Relevant Factors

The omission of factors relating to land use and biotic interactions, combined with aspects of the modelling methodology, play a significant role in influencing the accuracy of the simulated distributions.

Empirical information was used to delineate the HSIs. They may therefore be regarded as representing the realised niche of the ecological units in terms of the selected biophysical variables. As such, the HSIs for some variables are likely to indirectly incorporate the influence of non-biophysical factors such as land use and biotic interactions (e.g. herbivory). Furthermore, in delineating the slope and elevation indices, an attempt was made to represent suitability in terms of human management. However, the extent to which these approaches can account accurately for the complexity of 'real-world' relationships within the modelling context is limited.

The characteristics of the FSMF module mean that suitability in terms of the biophysical variables is represented linearly, by interpolation through the relevant thresholds. In simulating distributions, MOLA then uses this information to assign the most suitable pixels. In most cases, pixels with the highest suitability are likely to be those that are defined by optimum, or near optimum, biophysical conditions. However, in reality, species are often restricted from some or all of their optimum biophysical range because of the influence of biotic interactions and past land use characteristics, particularly within semi-natural landscapes (Pearson & Dawson, 2003). Similar issues are likely to apply to communities, particularly in terms of historic land use. The characteristics of the FSMF module and the lack of relevant empirical information made it impossible to represent this adequately when delineating the HSIs. These issues, combined with the characteristics of the MOLA procedure and the omission of factors relating explicitly to biotic interactions and land use, are likely to explain some of the disparities between simulated and observed distributions; particularly for some P/NPBVC types.

For instance, the HSIs demonstrate the close similarities between the biophysical requirements of Heath, Acid Grassland and Heath/Acid Grassland Mosaic (Appendix 2). Rodwell *et al*. (1991a; 1992) and Tansley (1949) suggest that in areas characterised by suitable biophysical conditions, factors related to the use of land for recreation and agriculture largely determine difference between the observed distributional patterns of these community types. Specifically, the presence and relative intensity of grazing and/or muir burning is particularly important. The treatment of these P/NPBVCs as 'Moorland' in simulating current distributions somewhat compensates for the lack of explicit representation of these factors. This approach is valid for analysis purposes in order to evaluate the reliability of future simulations. The results for these P/NPBVCs in Simulation 1 when treated separately were: 5.90% (Heath), 31.69% (Acid Grassland) and 17.87% (Heath/Acid Grassland Mosaic). The disparities between these individual results and those for 'Moorland' can be largely attributed to the lack of explicit representation of the historic characteristics of factors such as grazing and muir burning within the model. The accuracy of simulated current distributions for other P/NPBVCs is also likely to be affected. For instance, the establishment of woodlands is dependent upon the absence of grazing and muir burning (Tansley, 1949). Declines and losses of blanket and raised bog communities have been associated with intensive grazing and/or muir burning both nationally and within the study area (Rodwell *et al*., 1991a & NNPA, no date[d]). Observed distributions of other 'wetland' P/NPBVCs (e.g. Marsh and Fen) are also likely to have been somewhat affected.

In the future simulations, land use is addressed in two ways. Firstly, the inherent characteristics of the scenarios themselves are used to determine the prevailing land use trends within the park and therefore resultant changes in P/NPBVC distributions. For instance, under Conservation First the prevailing economic, social and cultural characteristics enable a reduction of stocking rates and muir burning, largely to facilitate expansion of semi-natural PBVCs such as Heath. It is assumed that these reductions will occur where the natural regeneration of these PBVCs is easiest (i.e. areas characterised by suitable biophysical conditions). Simulated future distributions inherently incorporate the influence of future changes in land use factors. For this reason, the results for Moorland in Table 4.11 column C are regarded as a useful assessment of the accuracy of Heath, Acid Grassland and Heath/Acid Grassland Mosaic for future simulations.

Secondly, two additional factors, cross-suitability and distance, are incorporated into the model for producing future simulations. These measures enable the influence of future management actions and decisions on future distributions to be included more directly. For instance, cross-suitability uses information on the physical and vegetation characteristics of existing P/NPBVC patches to gauge suitability in terms of the potential for conversion from one P/NPBVC type to another, based on required management actions and policy considerations. 'Distance' measures the suitability of pixels for a particular P/NPBVC in terms of their proximity to existing extents of that P/NPBVC. Pixels closer in proximity receive a higher suitability score than those further away. The logic of this is that future area increases in a particular P/NPBVC are most likely to occur in close proximity to areas where it currently occurs because of practical, economic, and policy considerations. It was not possible to gauge the value of these factors in simulating current distributions, as data on the distribution of the P/NPBVCs prior to the P1HS do not exist. However, other work (e.g. Griffith *et al*., 2011; Swetnam *et al.*, 2010; Eastman, 2009; Verburg *et al*., 2006; Busch, 2006) demonstrates the importance of these factors in terms of their potential influence on future distributions. The robustness of future simulations is likely to be notably increased through their inclusion.

Physical modifications of the environment related to anthropogenic land use are also likely to have played a significant role in determining observed distribution patterns. For instance, drainage and peat cutting have further contributed to losses and declines of bog communities. Other 'wetland' P/NPBVCs are also likely to have been affected. In many cases, drainage has been undertaken in order to facilitate plantations of large commercial conifer forests (NNPA, 2009; no date[c]). Revealingly, simulation accuracies of the Coniferous Woodland and Broadleaved Woodland P/NPBVCs are amongst the lowest. The soil water indices associated with Broadleaved Woodland and Coniferous Woodland are regarded as generally robust. It is possible that their poor simulation accuracy (as well as that of other P/NPBVCs) is partly due to issues concerning the accuracy of some of the underlying data.

4.5.2.3 Underlying data

Soil pH and Soil Water

There are issues over the reliability of the data relating to soil pH and soil water for the study area because of practical and methodological considerations associated with the research. For sound methodological reasons, the soil water characteristics of the P/NPBVCs were established according to the scheme used by Jarvis *et al*. (1984), which categorises soils according to 'wetness class'. Data relating directly to the wetness class of soils within NNP was not readily available. Data on the water characteristics of soils within NNP in terms of other measures do exist. However, adequately relating these measures to the established soil water characteristics of the P/NPBVCs proved problematic. Furthermore, the data are costly to obtain.

An ArcGIS shapefile of the soil series within NNP was obtained from Northumberland National Park Authority (NNPA). Jarvis *et al*. (1984) describe the typical wetness class and soil pH of various soil types (i.e. 'soil series') within Northern England. The soil pH and soil water maps for NNP were created by entering the information from Jarvis *et al*. (1984) to the appropriate soil series records in the attribute table of the shapefile.

The natural water characteristics of some soils can be significantly altered by drainage related to the use of land for agriculture, recreation or forestry (Jarvis *et al*. 1984). Some soils within NNP are likely to have been affected by such measures. However, there was no adequate method to determine which soils in particular had been affected and to what extent. To maintain consistency when determining the water characteristics of the soil types within NNP, the wetness class representing the soil's 'natural' conditions was used. A similar approach was applied for soil pH. It is possible however, that this method misrepresents the true pH and water characteristics of some soils within NNP specifically, with resultant impacts on simulation accuracies.

For instance, large extents of Coniferous Woodland in southern and eastern areas of the park are the result of afforestation taking place in the 1950s and 1960s. This was often facilitated through drainage of the original waterlogged soils (NNPA, No date[c]). The soils data are unlikely to account for this. Due to the extents of broadleaved plantations within the park, the simulation of Broadleaved Woodland is also likely to have been somewhat affected. The simulation accuracies of communities such as Neutral Grassland and Improved Grassland (Priority and Non-Priority) and Arable are likely to have been influenced by potential errors in the soil pH data. These P/NPBVCs generally occur on 'better quality' soils which, in terms of pH and other characteristics, are naturally more suited for agricultural use. However, in some cases, their occurrence is also dependent upon measures to artificially raise soil pH (JNCC, 2007; Tansley, 1949). It is likely that at least some occurrences within the study have been facilitated by such measures. Again, the data do not account for these human modifications of the natural characteristics of soils within NNP.

Generally, soils at lower elevations within the park are most likely to be impacted by anthropogenic modifications. The relatively high levels of simulation accuracy for Blanket Bog and Moorland are likely to be partially due to their typical association with upland areas where the soils are more likely to have retained their natural characteristics.

The probable errors in the underlying soils data will affect the reliability of both current and future simulations.

P1HS Data

The P1HS method is designed to facilitate rapid mapping of semi-natural vegetation over large areas for conservation purposes (JNCC, 2007; Cherrill & McClean, 1999). The method seeks to identify 'homogeneous' areas of vegetation primarily on the basis of dominant plant species as well as topographic and hydrological characteristics (JNCC, 2007; Stevens *et al.*, 2004; Cherrill & McClean, 1999). However, because of the characteristics of the method, potential issues have been identified with the reliability of the data produced.

In assessing P1HS maps, Cherrill & McClean (1999) report an average degree of agreement in pair-wise comparisons of only 26.6%. Misclassification of ecologically-related vegetation types is the most common issue affecting the reliability of maps, due to surveyor bias, insufficient data and inherent ambiguities in the P1HS habitat descriptions. Classification errors between certain mire habitats (e.g. bogs and fens) and other closely-related habitats such as grasslands and heaths were a particular issue because of their floristic similarities and lack of adequate soils data. Identification of different grassland types is also problematic. For instance, semi-improved neutral grassland and semi-improved acid grasslands, in particular, were often confused because the 'definitions based on the relative abundance of species indicative of a particular soil pH were also not applied consistently' (Cherrill & McClean, 1999, pp. 140). Similar classification errors may be associated with the P1HS data for NNP. The floristic and biophysical definitions of the different vegetation types modelled in this research were largely based on those provided by JNCC (2007). Some of the poor results in Table 4.11 will be related to the classification errors inherent within the P1HS data rather than the model *per se*.

4.5.2.4 Characteristics of the Ecological Units and Accuracy of the HSIs

Definitional uncertainties concerning the ecological units used in the research and the extent to which the HSIs adequately represent their biophysical requirements also need consideration. The discussion in previous sections and information in Appendix 2 highlights that determining definitional boundaries between vegetation types that are often closely related is conceptually problematic and often relies on somewhat arbitrary criteria. In defining ecological units used in this research (and therefore the biophysical conditions that are associated with them) an effort was made to maintain consistency with the vegetation types defined in JNCC (2007). However, the inherent ambiguities in defining broad vegetation types, and the methodology applied in determining their biophysical characteristics, means that intrinsic uncertainties are associated with simulated distributions.

This is likely to be compounded by the capacity of the HSIs themselves to adequately represent community tolerances in terms of some biophysical variables. For instance, the categories relating to soil water and soil type each encompass a broad range of soils. Furthermore, the suitability values used to represent community requirements in terms of these variables were assigned according to a subjective scale. Every effort was made to determine ecologically-relevant differences between the communities using this approach. However, the extent to which it is capable of capturing the subtleties of real-world responses associated with continuous environmental gradients is limited.

In contrast, the HSIs for soil pH, elevation and slope may be regarded as more meaningfully defined. However, the accuracy of the indices for some P/NPBVCs in terms of the study area specifically, requires some discussion. For instance, slope and (particularly) elevation are used here as surrogates for other factors (such as temperature, precipitation, soil depth as well as land use and management) that have more direct physiological significance on community occurrence. However, the interrelationship between these variables is likely to differ at similar topographic positions within different regions of the UK (Guisan & Zimmerman, 2000). Guisan & Zimmerman (2000, pp. 151-152) describe this phenomenon as 'the law of relative site constancy', which refers to 'the fact that species tend to compensate regional differences in climatic conditions by selecting comparable microsites by changing their topographic positions'. Due to the sources and rationale used to define the indices for slope and elevation (particularly in terms of optimum thresholds; see Appendix 2), they may be regarded broadly valid for the north east of the UK. This was done partially to facilitate application of the model elsewhere. Because of this, their applicability to the study area specifically may be somewhat diminished. However, in many instances, information specific to NNP provided verification of the information from the secondary sources. Furthermore, in the case of many P/NPBVCs, the descriptive statistics (Table A2.12) were used directly to determine slope and elevation thresholds; particularly those relating to absolute maximum tolerances. It is unlikely that the characteristics of the slope and elevation indices (as well as those for soil pH) could diminish the accuracy of the model significantly when applied to the study area specifically.

Despite the issues discussed above the model is considered a useful tool for modelling distributions under future scenarios. For instance, overall levels of accuracy are comparable to those of other research simulating community distributions (e.g. Zimmerman & Kienast, 1999; Brzeziecki *et al*., 1995). In some instances, these studies have employed relatively sophisticated statistical techniques (e.g. logistic regression). The overall results provide some evidence of the potential for employing relatively simple methods and techniques in simulating community distributions within semi-natural landscapes. Also, high to moderate levels of accuracy are associated with the Moorland P/NPBVCs (Heath, Acid Grassland and Heath/Acid Grassland Mosaic) and Blanket Bog in the current simulations, despite the issues relating to the reliability of data and lack of explicit representation of some variables. Certainly, the simulation accuracy of many of the P/NPBVCs is relatively low, at least partially because of these issues. However, as the discussion suggests, a number of features associated with the future simulations (e.g. the intrinsic characteristics of the scenarios used and the inclusion of additional variables) go some way to addressing these issues. The accuracy of future simulations is likely to be notably improved.

In addition to these points it is felt that the proposed methodology represents a useful tool for gauging the concomitant impact of future changes in climate and land use on the resilience of conservationally significant community types within the study area and elsewhere. The defined HSIs are based on sound reasoning and empirical evidence and are therefore regarded as robust. This is largely confirmed by the DA between observed P/NPBVC distributions and their overall suitability layers (Table: 4.9).

4.6 Model Calibration

To further improve the accuracy and predictive power of the model, a stage of model calibration was undertaken (Guisan & Zimmerman, 2000). This involved running a series of simulations of current P/NPBVC distributions in which the five selected biophysical predictor variables were systematically omitted. This is akin to the step-wise procedures commonly used within statistical modelling approaches (e.g. Least Squares or Logistic Regression) (Guisan & Zimmerman, 2000). Specifically, a manual backwards elimination procedure was applied due to the approach of using physiological principles when selecting the five biophysical variables (Section A2.3). Table 4.13 provides details of the variables included in each of the calibration simulations.

The accuracy of each of the simulations was assessed by comparing them to current observed P/NPBVC distributions from P1HS data. As before, a cross-tabulation matrix identified correctly simulated pixels. To assess any changes in the accuracy of the model through the exclusion of particular variables, the overall accuracy, as well as the accuracy for individual P/NPBVCs from each simulation was compared to those of Simulation 1 (Table 4.11: Column A).

Table 4.14 provides the overall results of the accuracy assessment for each of the simulations: C1-C15. The results of Simulation 1 are also included. A 4% change in accuracy between each of the calibration simulations and Simulation 1 was subjectively defined as a significant difference. Significant differences are highlighted in Table 4.14.

Table 4.13: Summary of the calibration simulations. Ticks indicate the variables used in each of the calibration simulations

No. of Variables Omitted	Simulation	Variables				
		Elevation	Slope	Soil pH	Soil Water	Soil Type
1	C1		✓	✓	✓	✓
	C2	✓		✓	✓	✓
	C3	✓	✓		✓	✓
	C4	✓	✓	✓		✓
	C5	✓	✓	✓	✓	
2	C6			✓	✓	✓
	C7		✓		✓	✓
	C8		✓	✓		✓
	C9		✓	✓	✓	
	C10	✓			✓	✓
	C11	✓		✓		✓
	C12	✓		✓	✓	
	C13	✓	✓			✓
	C14	✓	✓		✓	
	C15	✓	✓	✓		
3	C16	✓	✓			
	C17	✓		✓		
	C18	✓			✓	
	C19	✓				✓
	C20		✓	✓		
	C21		✓		✓	
	C22		✓			✓
	C23			✓	✓	
	C24			✓		✓
	C25				✓	✓

Table 4.14: The overall and individual P/NPBVC results from the calibration simulations C1-15 and simulation 1 (green column). Results highlighted in red show significant decreases in accuracy between the calibration simulation and Simulation 1. Significant increases in accuracy are highlighted in green. Figures that are italicised and in bold highlight the highest simulation accuracies for each P/NPBVC in simulations 1 and C1-C15: P/NPBVC abbreviations: Moor = Moorland; BB = Blanket Bog; IGP = Improved Grassland: Priority; NG = Neutral Grassland; Br = Bracken; CW = Coniferous Woodland; F&S = Flush & Spring; BLW = Broadleaved Woodland; MB = Modified Bog; CG = Calcareous Grassland; IGNP = Improved Grassland: Non-Priority; RB = Raised Bog.

P/NPBVC	1	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	CY
Moor	52.81	44.92	46.61	47.07	48.44	52.20	40.05	39.9	***57.45***	46.68	46.44	49.38	51.61	47.88	50.25	45.24	55.37
BB	43.40	30.61	50.15	40.02	42.99	42.99	***52.76***	30.25	33.46	24.16	50.15	50.15	49.95	42.67	42.67	25.39	51.82
Marsh	16.24	13.12	15.34	19.39	17.02	12.74	9.41	13.11	14.01	12.43	15.34	***20.34***	13.07	15.05	12.73	17.21	10.66
Arable	9.77	10.28	6.60	8.80	5.58	9.94	6.51	7.45	5.41	4.91	***16.33***	8.84	6.60	11.04	8.16	5.41	12.52
Fen	1.70	0.31	1.81	1.73	1.70	1.70	0.00	0.31	0.26	0.26	1.75	1.75	***3.76***	1.70	1.71	0.00	2.11
IGP	20.56	19.30	19.81	13.33	19.97	***20.61***	18.38	7.22	20.04	19.92	3.50	19.26	19.75	9.58	12.51	20.03	21.73
NG	8.23	8.86	10.39	10.40	8.81	9.31	13.17	8.26	9.19	9.33	10.95	10.97	11.01	***14.91***	5.68	8.78	7.12
Br	12.19	11.41	12.42	12.32	12.35	8.39	11.41	***14.36***	13.35	9.21	12.32	12.32	12.32	11.98	8.57	7.99	17.25
CW	9.99	15.78	9.97	12.99	13.35	9.85	15.80	15.63	***23.62***	15.68	10.15	11.55	11.55	20.98	9.95	11.54	33.47
F&S	5.79	***16.77***	6.76	3.35	0.00	**0.61**	14.02	16.77	0.00	0.00	7.01	0.00	0.00	0.00	0.61	0.00	4.57
BLW	1.70	0.97	0.85	3.06	4.30	1.77	0.05	1.80	1.86	1.92	1.04	3.54	3.54	***4.92***	3.07	1.20	6.34
Swamp	***2.94***	0.00	0.00	0.00	2.94	0.00	0.00	0.00	2.94	0.00	0.00	0.00	0.00	2.94	0.00	2.94	0.00
MB	0.00	0.00	0.00	0.00	***4.54***	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00	3.45	0.00	0.00	0.47
CG	***0.00***	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IGNP	***0.00***	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RB	***0.00***	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Overall % Correctly Simulated	32.03	28.64	29.32	30.12	30.80	31.23	26.88	25.75	36.36	29.11	28.62	31.60	31.18	31.75	29.74	28.13	37.79

4.6.1 Calibration Results

4.6.1.1 Omission of One and Two Variables

The results showed that the overall accuracy of the model was only improved in one of the calibration simulations: C8 (excluded variables: elevation and soil pH). This overall significant increase in accuracy is due to the significant increase in accuracy for two of the most extensive P/NPBVCs; Moorland and Coniferous Woodland. The results also showed significant increases in accuracy for individual P/NPBVCs across the various calibration simulations. Most notably, the accuracy of Blanket Bog was shown to be significantly improved through the omission of slope as a predictor variable (e.g. simulations C2, C6, C10-12). Other notable increases in accuracy were demonstrated for Marsh (C11), Arable (C10), Neutral Grassland (C13) and Flush & Spring (C1). Other, non-significant increases in accuracy were also observed for many of the P/NPBVCs across simulations C1-15.

Based on these results, an additional simulation (CY) was conducted using the specific combination of variables from simulations C1-15 which produced the greatest improvement in accuracy for individual P/NPBVCs. The results highlighted in bold italics in Table 4.14 relate to the specific combination of variables used for each P/NPBVCs in simulation CY. The results of simulation CY are also included in Table 4.14.

Simulation CY showed an overall increase in accuracy compared to Simulations 1 and C8. It should be noted, however, that the improvement in accuracy for some P/NPBVCs observed in simulations C1-15 were not replicated directly in CY. For instance, although the accuracy of Moorland and Blanket Bog was improved compared to Simulation 1, the increase was not as great as that observed in their most accurate calibration simulations: C8 and C6 respectively. Furthermore, the accuracy of four P/NPBVCs (Marsh, Neutral Grassland, Flush & Spring and Swamp) in simulation CY was observed to decrease compared to Simulation 1. Most notably, Marsh demonstrated a significant decrease in accuracy. In general, however, the individual accuracy of most of the P/NPBVCs was shown to improve in simulation CY compared to Simulation 1, as well as the calibration simulations. For instance, Bracken, Coniferous Woodland and Broadleaved Woodland all demonstrated a significant increase compared to Simulation 1. Coniferous Woodland also showed a significant improvement in accuracy compared to its most accurate calibration simulation (C8).

The calibration procedures undertaken up to this point were regarded as beneficial in improving the overall accuracy of the model, as well as the simulation accuracy for the majority of the P/NPBVCs.

4.6.1.2 Omission of Three Variables

Simulations C16-25 were undertaken to ascertain if any further improvements in model accuracy could be gained from the omission of additional variables. To assess any changes in the accuracy of the model through the exclusion of additional variables, the results from each simulation (C16-25) for individual P/NPBVCs were compared to those for the best combination of variables from simulations C1-15 (i.e. results highlighted in bold italics from Table 4.14). Overall accuracies were compared to that from simulation CY. Table 4.15 provides details of the results.

The results suggested that further improvements in the simulation accuracy of *some* P/NPBVCs could potentially be made by excluding 3 variables. For instance, significant improvements in the accuracy of Blanket Bog, Improved Grassland: Non-Priority and Coniferous Woodland were observed in simulations C25, C23 and C22, respectively, compared to their best results from simulations C1-15.

A further simulation (CX) was conducted using the specific combination of variables from simulations C1-25 which produced the greatest improvement in accuracy for individual P/NPBVCs. The results highlighted in bold italics in Table 4.15 relate to the specific combination of variables used for Blanket Bog, Coniferous Woodland and Improved Grassland: Non-Priority in simulation CX. The combination of variables used for the other P/NPBVCs in simulation CX follows that used in simulation CY. The results of simulation CX and CY are also provided in Table 4.15.

The results showed a significant decrease in overall accuracy in simulation CX compared to simulation CY (i.e. 32.71 and 37.79 respectively). Three P/NPBVCs (Moorland, Arable and Coniferous Woodland) also showed a significant decrease in accuracy in CX compared to CY. The accuracy of three P/NPBVCs (Marsh, Neutral Grassland and Bracken) showed only a slight increase in CX compared to CY. The accuracy of the remaining P/NPBVCs either showed a non-significant decrease or remained the same in CX compared to CY. On balance, simulation CX performed poorly compared to simulation CY. Based on these results, it was deemed unlikely that additional improvements in accuracy could be gained by further calibration analysis (i.e. by conducting simulations including only one predictor variable).

Table 4.15: The overall and individual P/NPBVC results from the calibration simulations C16-25 and those for the best combination of variables from simulations C1-15 (1st green column). Results highlighted in red show significant decreases in accuracy. Significant increases in accuracy are highlighted in green. P/NPBVC abbreviations: Moor = Moorland; BB = Blanket Bog; IGP = Improved Grassland: Priority; NG = Neutral Grassland; Br = Bracken; CW = Coniferous Woodland; F&S = Flush & Spring; BLW = Broadleaved Woodland; MB = Modified Bog; CG = Calcareous Grassland; IGNP = Improved Grassland: Non-Priority; RB = Raised Bog.

P/NPBVC	Best combo from Sims C1-14	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	CY	CX
Moor	57.45	46.45	48.72	45.75	49.12	49.55	41.52	53.15	41.89	53.98	48.50	55.37	47.39
BB	52.76	26.40	2.99	50.07	50.15	12.59	23.73	33.03	52.55	52.76	***66.49***	51.82	50.18
Marsh	20.34	14.72	17.46	13.10	20.32	12.68	12.34	13.57	6.51	12.87	10.79	10.66	11.59
Arable	16.33	9.18	9.56	16.54	16.71	2.07	2.20	3.93	0.00	6.18	8.89	12.52	4.78
Fen	3.76	0.00	0.00	3.76	3.76	0.00	0.00	0.26	0.00	0.00	0.00	2.11	2.11
IGP	20.61	9.16	19.29	2.10	7.53	19.68	4.86	5.85	19.88	17.59	0.00	21.73	21.72
NG	14.91	8.92	10.91	7.79	8.40	8.76	6.94	5.45	12.64	13.24	0.00	7.12	7.19
Br	14.36	7.93	3.63	5.17	11.95	11.53	11.20	14.36	9.28	11.41	11.41	17.25	17.39
CW	23.62	24.94	11.28	9.94	12.48	32.19	16.25	***33.04***	15.27	28.22	28.22	33.47	26.99
F&S	16.77	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00	0.91	0.91	4.57	4.57
BLW	4.92	4.57	4.68	3.10	4.78	4.65	0.27	2.67	0.79	0.05	0.05	6.34	2.45
Swamp	2.94	2.94	0.00	0.00	0.00	2.94	0.00	2.94	0.00	0.00	0.00	0.00	0.00
MB	5.54	0.00	1.67	0.00	0.00	0.00	0.00	0.14	0.17	0.00	0.00	0.47	0.00
CG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IGNP	0.00	8.48	0.00	0.00	7.78	0.00	0.00	5.85	***19.88***	0.00	0.00	0.00	0.00
RB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Overall % Correctly Simulated	37.79*	30.69	29.04	27.52	31.00	33.44	26.00	35.30	27.22	36.23	30.72	37.79	32.71

* Overall % correctly simulated is from simulation CY

4.7 Final Simulations

The specific combination of variables for each P/NPBVC used in simulation CY is used as the basis for future simulations.

Due to time and resource constraints, no attempt was made to tackle the effects of the technical issues associated with the MOLA module on the simulation results when assessing the accuracy of simulations C1-25, and CX. This approach is regarded as adequate in capturing relevant changes in the accuracy of the model results through the calibration procedure. It is likely that had reordering or rotation procedures been applied to the results of simulations C1-25 and CX the observed accuracy improvements would have been proportional to those observed for Simulation 1 when the same procedures were applied (Table 4.11). Rotation procedures were applied to the results of simulation CY. This was done to provide a more thorough assessment of the improvements in model accuracy gained through the calibration procedure and the reliability of simulations of future P/NPBVC distributions. Table 4.16 provides the results of the rotation procedure applied to simulation CY and (for comparative purposes) Simulation 1.

The results in Table 4.16 show a significant improvement in overall accuracy of 16.28% between Simulations 1 and CY. Significant increases in accuracy are also observed for seven P/NPBVCs: Moorland (5.22%); Blanket Bog (9.78%); Marsh (5.82%); Fen (21.88%); Bracken (7.06%); Coniferous Woodland (59.50%); Modified Bog (4.07%). Non-significant increases in accuracy are observed for three P/NPBVCs: Improved Grassland: Priority (1.40%); Neutral Grassland (2.52%); Broadleaved Woodland (2.85%). The accuracy of four P/NPBVCs remained the same at 0.00%: Calcareous Grassland; Improved Grassland: Non-Priority and Raised Bog. Two NPBVCs showed non-significant decreases in accuracy: Arable (-0.39%) and Flush & Spring (-3.04%). One PBVC (Swamp) showed a significant decrease in accuracy (-5.29%).

Table 4.16: The results of the rotation procedures applied to simulations 'CY' and '1'. Results highlighted in green show significant increases in accuracy. Significant decreases in accuracy are highlighted in red.

P/NPBVC	Simulation	
	1 (Rotated)	CY (Rotated)
Moorland	80.16	85.38
Blanket Bog	56.11	65.89
Marsh	29.26	35.08
Arable	23.82	23.43
Fen	23.31	45.69
Improved Grassland: Priority	22.10	23.50
Neutral Grassland	21.55	24.07
Bracken	16.40	23.46
Coniferous Woodland	14.77	74.27
Flush & Spring	14.02	10.98
Broadleaved Woodland	7.61	10.46
Swamp	5.29	0.00
Modified Bog	1.11	5.18
Calcareous Grassland	0.00	0.00
Improved Grassland: Non-Priority	0.00	0.00
Raised Bog	0.00	0.00
Overall % Correctly Simulated	**49.10**	**65.38**

On balance, the final CY rotation simulation shows significant improvement in overall accuracy and for specific P/NPBVCs compared to the final Simulation 1 rotation. The overall accuracy of the model (65%) is regarded as 'good' and exceeds that of other models, employing relatively sophisticated statistical techniques, to simulate community distributions (e.g. Zimmerman & Kienast; 1999; Brzeziecki *et al.*, 1995). The results provide additional evidence of the potential for employing relatively simple methods and techniques in simulating community distributions within semi-natural landscapes.

To test the degree to which simulations of future distributions are influenced by the technical issues associated with the MOLA module, rotation procedures (see above: 'Rotation of Suitability Layers') were applied to the results of the land use modelling under the scenarios (see Section 4.8). Table 4.17 shows the overall proportion of correctly simulated pixels between each of the non-rotated scenario results layers and the associated rotated layers.

Table 4.17: Overall proportion of correctly simulated pixels between each of the non-rotated scenario results layers and the associated rotated layers

Scenario	Rotated Layer	Proportion Correctly Simulated (%)
Conservation First	90^o	97.89
	180^o	98.09
	270^o	98.92
Going for Growth	90^o	98.48
	180^o	98.55
	270^o	99.13

The proportion of pixels correctly simulated ranges between approximately 98 and 99% (Table 4.17). This suggests that the effects of the technical issues associated with the MOLA procedure are far less pronounced in the simulations of future distributions. The accuracies associated with the CY simulation (Table 4.16) should therefore be regarded as indicative of those P/NPBVCs undergoing expansion within the future scenarios. Thus, the results for a number of P/NPBVCs (i.e. Moorland: Heath, Blanket Bog, Fen & Coniferous Woodland) undergoing expansion under the scenarios should be regarded with a relatively high degree of certainty.

The results (Table 4.16) show that the simulation accuracies for a number of P/NPBVCs remain quite low (e.g. <40%). In relation to the scenarios employed within this research specifically, this issue is not regarded as particularly problematic as many of these P/NPBVCs (i.e. Marsh, Bracken, Flush & Spring, Swamp, Modified Bog and Calcareous Grassland) do not undergo expansion. The errors associated with those P/NPBVCs may be of interest to other end-users who wish to explicitly model changes in their distribution under other circumstances (i.e. under different scenarios and/or in different locations). Other P/NPBVCs which show low accuracies relevant to this and other research are: Arable; Improved Grassland: Priority; Neutral Grassland (Priority and Non-Priority); Broadleaved Woodland (Broadleaved Woodland: Priority) and Raised Bog. However, due to the inclusion of additional variables when modelling future distributions (i.e. cross-suitability and distance), future simulations (for all P/NPBVCs) should be regarded as more robust. It is not possible to verify the improvements in accuracy achieved through the inclusion of these additional variables, as data on the distribution of the P/NPBVCs within the study area prior to the P1HS do not exist.

4.8 Results

The results of the land use modelling are maps showing the distributions of each P/NPBVC under each time slice within NNP. The PBVCs are the specific focus of Chapters Five, Six and Seven. Figures 4.4a-c show the distributions of the PBVCs under each time slice within NNP.

Tables 4.18 & 4.19 show the dominance of each PBVC within each time slice at the NNP and NCA levels in terms of their proportional number of patches (Table 4.18), as well as their proportional areal coverage (Table 4.19). Proportional number of patches helps in interpreting the results of subsequent chapters relating to Climate Stress, Geometric and Overall Vulnerability, as landscape and class level summary statistics for these measures are based on averages of patch characteristics. Proportional areal coverage is also used in interpreting the results of the section on Matrix Vulnerability, as they are influenced by the presence and areal dominance of particular types of 'modified' and 'semi-natural' P/NPBVCs.

Figure 4.4a: Current PBVC distributions within NNP

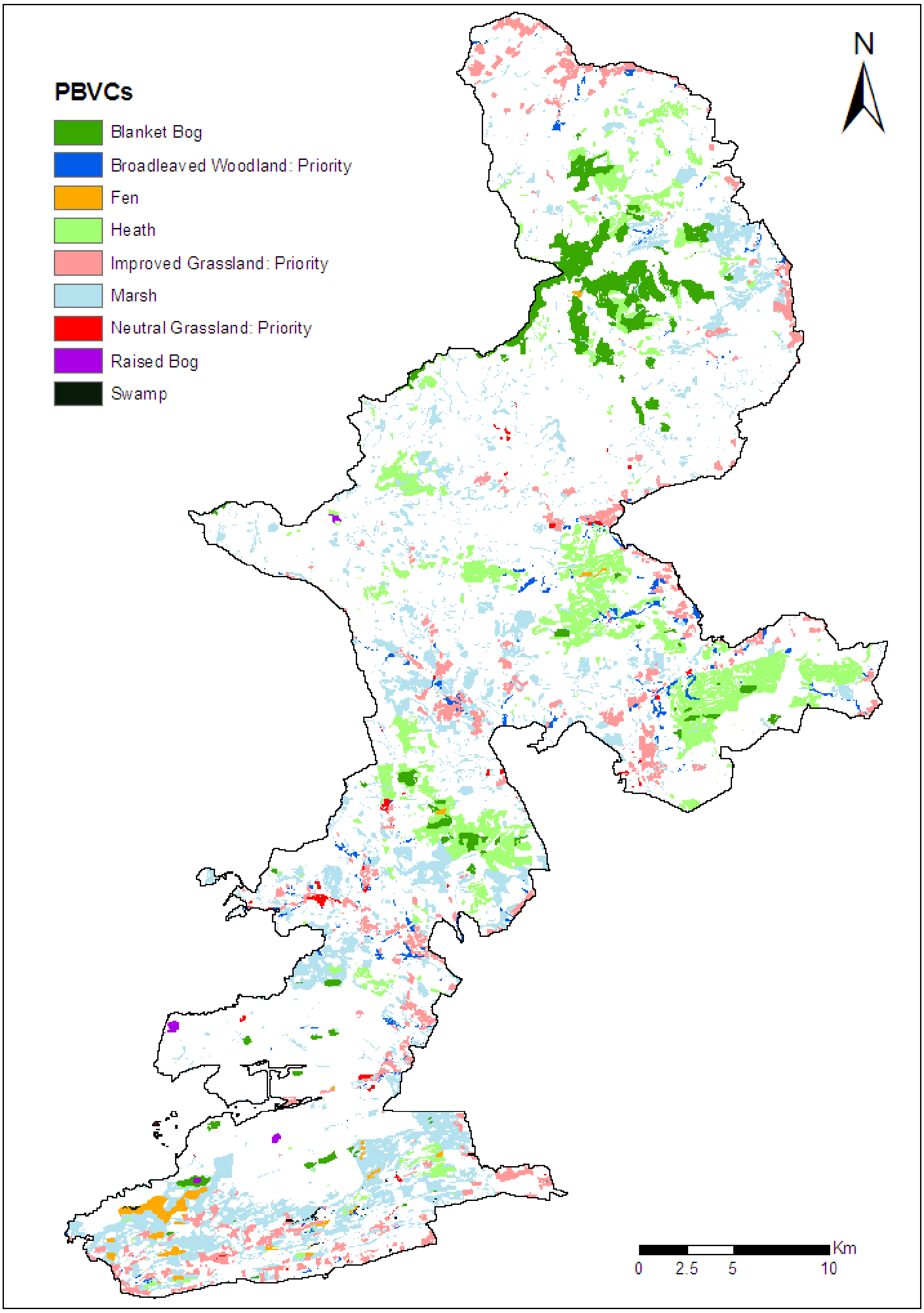


Figure 4.4b: PBVC distributions within NNP under Conservation First

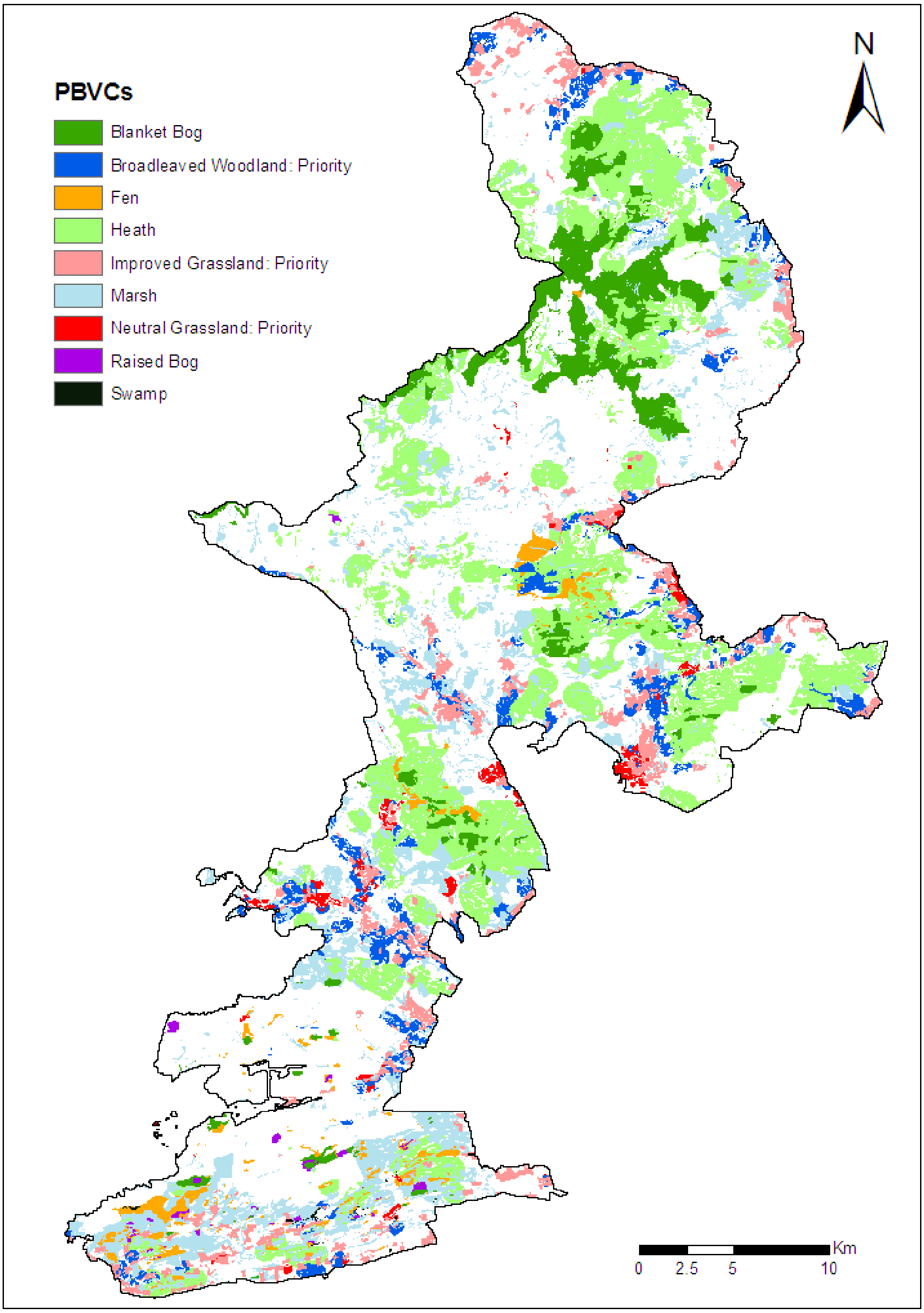


Figure 4.4c: PBVC distributions within NNP under Going for Growth.

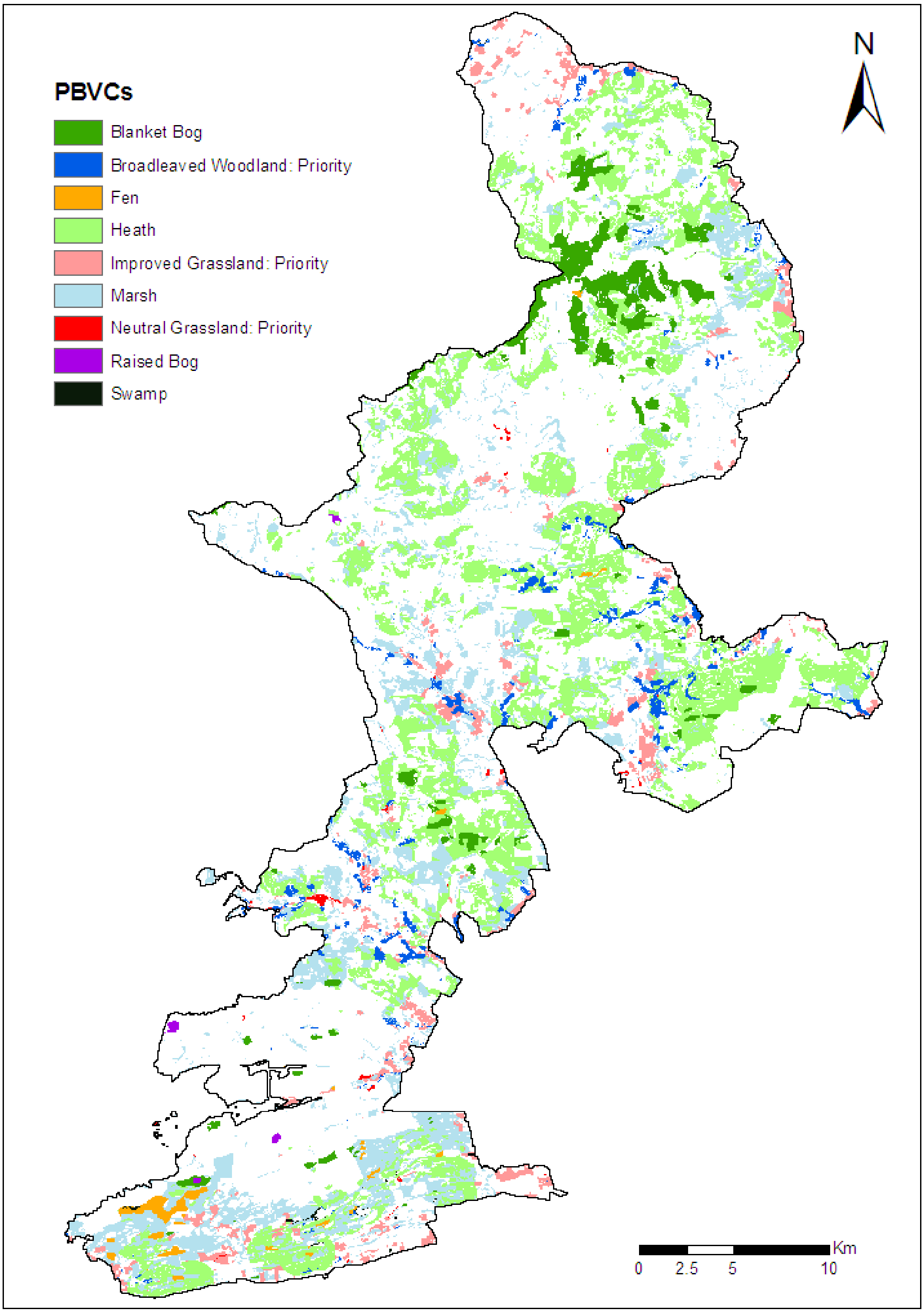


Table 4.18: Proportional number of patches for each PBVC at the National Park (last column) and NCA level. Numbers of patches are proportional to the overall number of PBVC patches within the study area or individual NCAs. The colour coding of cells is used to highlight the relative dominance of PBVCs in terms of proportional number of patches under each time slice: Deep green = most dominant PBVC; light green = second most dominant PBVC; blue = third; yellow = fourth; orange = fifth; red = sixth; purple = 7th, 8th and 9th most dominant PBVCs. Abbreviations: 'Cur' = current time slice; 'CF' = Conservation First; 'GFG' = Going for Growth; 'BLWP' = Broadleaved Woodland: Priority; 'IGP' = Improved Grassland: Priority; 'NGP' = Neutral Grassland: Priority.

PBVC	Cheviot			Cheviot Fringe			Northumberland Sandstone Hills			Border Moors and Forests			Tyne Gap and Hadrian's Wall			Northumberland National Park		
	Cur	CF	GFG	Cur	CF	GFG	Cur	CF	GFG	Cur	CF	GFG	Cur	CF	GFG	Cur	CF	GFG
Blanket Bog	2.85	5.08	2.59	0.00	0.00	0.00	3.41	5.14	3.23	2.01	3.26	1.85	1.09	1.58	1.01	2.28	3.71	2.10
BLWP	5.51	7.30	4.29	14.46	21.78	13.83	20.45	21.26	15.59	9.94	9.00	7.58	7.61	7.92	7.09	9.43	9.77	7.32
Fen	0.30	0.28	0.27	0.00	0.00	0.00	0.57	3.74	0.54	1.07	9.99	0.98	3.53	20.00	3.29	0.93	7.62	0.86
Heath	14.96	15.53	25.65	0.00	8.91	17.02	16.76	20.09	28.49	7.69	9.30	17.18	7.34	11.49	18.99	10.66	12.32	20.82
IGP	7.28	6.75	4.92	31.33	22.77	22.34	14.20	10.51	11.02	9.29	7.47	8.40	22.55	16.44	16.20	10.60	8.64	8.55
Marsh	67.32	63.22	61.13	43.37	35.64	38.30	42.33	34.81	40.05	66.92	55.93	61.70	47.55	34.65	44.30	62.57	53.03	57.64
NGP	1.48	1.57	0.89	10.84	10.89	8.51	2.27	4.44	1.08	2.49	3.17	1.75	2.99	2.57	2.28	2.39	2.92	1.67
Raised Bog	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24	1.58	0.22	0.00	0.00	0.00	0.12	1.11	0.11
Swamp	0.30	0.28	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.30	0.33	7.34	5.35	6.84	1.02	0.87	0.94

Table 4.19: Proportional areal coverage for each PBVC at the National Park (last column) and NCA level. Coverage is proportional to the overall coverage of PBVCs within the study area or individual NCAs. The colour coding of cells and abbreviations follows the same format as Table 4.18.

PBVC	Cheviot			Cheviot Fringe			Northumberland Sandstone Hills			Border Moors and Forests			Tyne Gap and Hadrian's Wall			Northumberland National Park		
	Cur	CF	GFG	Cur	CF	Cur	Cur	Cur	GFG	Cur	CF	GFG	Cur	CF	GFG	Cur	CF	GFG
Blanket Bog	32.43	28.75	20.24	0.00	0.00	0.00	3.29	2.52	2.67	4.53	4.77	3.36	0.48	0.95	0.34	11.67	12.23	8.28
BLWP	1.42	4.52	1.70	6.15	17.62	8.11	7.10	13.32	10.20	3.07	9.43	5.18	1.11	7.16	0.80	3.02	8.17	4.29
Fen	0.00	0.07	0.10	0.00	0.00	0.00	0.17	0.50	0.14	2.59	5.58	1.92	4.18	7.02	3.00	1.69	3.13	1.20
Heath	22.33	45.35	53.99	0.00	14.18	50.40	63.13	61.64	71.05	21.89	35.55	42.10	5.20	17.36	40.10	25.84	40.33	49.42
IGP	12.77	6.36	4.66	74.58	51.13	29.77	14.90	12.53	7.12	13.19	9.31	7.19	31.67	23.11	14.66	16.15	10.41	7.49
Marsh	30.62	14.66	19.11	16.18	10.42	10.94	10.67	7.09	8.69	52.90	31.89	39.19	55.82	40.72	40.11	40.37	23.42	28.66
NGP	0.40	0.26	0.19	3.08	6.65	0.79	0.74	2.41	0.12	1.14	2.60	0.55	0.66	1.67	0.35	0.85	1.76	0.37
Raised Bog	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.81	0.44	0.00	1.37	0.00	0.27	0.47	0.19
Swamp	0.02	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.06	0.08	0.89	0.65	0.64	0.15	0.09	0.11

Chapter 5: Climate Stress: Vulnerability Measure 1 (VM1)

5.1 Introduction

The results in Section 3.8 clearly highlight the minimal role that climate has played in influencing the distribution of BVC communities within the study area specifically, and may apply to semi-natural environments at the landscape scale more generally. It may therefore be inferred that climate change is not the main component influencing the vulnerability of BVC types within the park and at the sub-regional scale more generally. However, the widely-used IPCC (2007a) definition of vulnerability (Section 2.3) inherently recognises that the magnitude of climate change to which a system is exposed and its particular climatic tolerances or niche are crucial factors determining its vulnerability. As stated, Section 3.8 suggests that climate has not had a significant direct influence on the current distribution of the BVCs within NNP. However, this is no guarantee that climate will not play an important role influencing the vulnerability of the BVCs in the future; particularly as temperature and precipitation levels may move towards the limits of the climatic tolerances of the BVC types (Berry, 2008).

Considering Berry's (2008, pp. 4) definition of climate sensitive species as 'those that are near a climatic tolerance threshold' or that 'have a small niche breadth' and the significance of sensitivity in influencing vulnerability (i.e. a more sensitive system is one that is likely to be more vulnerable), the implication is that the vulnerability of a system will increase with a greater magnitude of change relative to its particular climate tolerances (Berry, 2008). The scale characteristics of the data used in Chapter Three to establish the bioclimatic envelopes of the BVCs (Tables 3.1 & A1.2) provide a useful representation of their climatic tolerances. Because of these points, it is felt that the bioclimatic envelope data, when applied to scenarios of future climate change, provide a potentially useful tool for gauging the future climatic stress of the BVCs and therefore levels of vulnerability.

This chapter explains the creation of future climate grids for the study area and describes the methodology of a bioclimatic envelope approach to quantifying the Climate Stress of the PBVCs. The second part of the chapter presents the results of applying this approach to the PBVCs within NNP under current and future time slices. Relevant trends and issues at the NNP and NCA levels and for individual PBVCs are then discussed.

5.2 Methodology

The BVC bioclimatic envelope data (Table A1.2) are used to measure the current and future Climate Stress of PBVC patches. Table 4.1 shows the correspondence between the BVCs and P/NPBVCs and therefore indicates the BVC bioclimatic envelope data used to estimate the Climate Stress of the relevant PBVCs. For instance, the data for the Bog BVC (Table A1.2) are used as a basis to gauge the Climate Stress of the Blanket Bog *and* Raised Bog PBVCs (Table 4.1). As indicated (Section 4.3) there are disparities between the thematic resolution of the BVC (Table 3.1) and PBVC categories (Table 4.1). This introduces potential errors in the results. However these were the best available data on which to base estimations of current and future PBVC stress.

5.2.1 Future Climate

The future climate of the park was estimated, based on UKCIP climate change projections related to the chosen climatic variables (Section 3.4) for the medium emissions (ME) scenario for 2050 (UKCIP, 2010). Due to the scope of the research, it was desirable to estimate future changes in climate based on a single emissions scenario (Beaumont *et al*., 2008). Due to time lags within the climate system, future climate up to 2050 has already been determined by historic greenhouse gas emissions (Dunn & Brown, 2010; Mitchell *et al*., 2007). Projected changes in climate up to 2050 based on different emissions scenarios, exhibit only minor differences, as each scenario is similar (Dunn & Brown, 2010; Beaumont *et al*., 2008; Mitchell *et al*., 2007; IPCC, 2007b). Beyond this time frame, climate projections exhibit much more variation due to greater divergence in emission trends between different scenarios (Dunn & Brown, 2010; Beaumont *et al*., 2008). From this perspective, the use of the medium emissions scenario is regarded as appropriate for providing a reasonable single estimate of climate change up to 2050, indicative of the overall range in climate projected from different emissions scenarios.

It is also worth noting that recent studies have demonstrated that CO_2 emissions from fossil fuels since 2000 have increased at a rate greater than previous decades (Canadell *et al*., 2007; Raupach *et al*., 2007). Beaumont *et al*. (2008) suggest that because of this, all of the SRES emissions scenarios have underestimated emissions growth since 2000. Therefore, the authors advocate the use of the more ‘extreme’ scenarios (i.e. A1 and A2) for impact assessments, instead of the ‘conservative’ B1 and B2 scenarios, because A1 and A2 are based on more intensive use of fossil fuels. The UKCP09 medium emissions projections used here are derived from the SRES A1B scenario (UKCIP, no date) and therefore also fit well with these recommendations.

5.2.1.1 Creation of Future 50m Climate Grids

50m raster grids depicting future climate within NNP under the ME scenario were created for 2050 for each of the climate variables. These were based on climate change predictions from the UKCP09's probabilistic climate projections available from the UKCP09 User Interface at 25km resolution. These projections provide values of climate change for specific climate variables relative to the 1961-90 baseline average. One of the main strengths of UKCP09 (compared to UKCIP02) is that the more robust methodology allows measures of probability to be assigned to specific values of future climate change (Dunn & Brown, 2010; UKCIP, 2009a; 2009b). For the purposes of this investigation, values of future climate change from the UKCP09's 50% probability level were used as the basis for creating the future climate grids.

To create each future climate grid, a spatial sub-set of the UKCP09 projection data for the particular variable in question was extracted and converted into a point layer. Splining was used to interpolate the sub-setted climate projections point data onto a 50m grid. This method was chosen because it allows estimated values to exceed the minimum and maximum values within the dataset (ESRI, 2012). It was considered appropriate, as it would represent the future climate changes occurring at spatial scales finer than the 25km resolution provided by the projections more successfully. To determine which input points would be used to calculate the values for each cell, a *fixed* search radius was used and the number of sample points set to 4. A weighting of 0.1 was specified as the weighting for the known points contributing to each cell's value. These parameters were chosen because of the relatively small variation between the values of the 25km cells within each of the projection layers. The interpolated gridded projection data were then used to adjust the values of the relevant current climate grid to create a future 50m climate grid.

The range of values for NNP from each of the future climate grids are as follows: Summer Temperature (11.23 – 16.74^{o}C); Winter Temperature (0.95 – 5.33^{o}C); Summer Precipitation (48.95 – 93.43mm); Winter Precipitation (56.76 – 144.89mm).

5.2.2 Climate Stress

5.2.2.1 Issues with Bayesian Classification for Estimating Climate Stress

The Bayesian classification used in Chapter Three was not considered appropriate for the accurate calculation of the climatic stress of the PBVCs. Specifically, the probability of class membership across all available classes, calculated by the Bayesian approach, must always equal 1. The posterior probability that a pixel belongs to a particular class is determined not only by the evidence available for that class but also on the available evidence for all of the other classes under consideration.

In this research, the calculated posterior probability of a pixel is regarded as representing the probability of occurrence for a particular BVC or PBVC, given the available bioclimatic envelope data. In the context of the calibration and testing of the bioclimatic envelope model, the application of the Bayesian approach, because of its characteristics, was appropriate in terms of measuring the role that past climate has played in determining BVC distributions. In other words, in terms of climate, the likelihood that a particular BVC will occur at a particular location is determined not only by its own climatic requirements but also those of other BVCs.

The climatic stress (as defined within this research) experienced by a PBVC (see below) is determined by its particular bioclimatic requirements and is not dependent on those of other PBVCs. Straightforward utilisation of the probability values from the Bayesian technique applied in previous stages was deemed inappropriate for estimating the current and future climatic stress of the PBVCs.

5.2.2.2 Estimating Climate Stress

Figure 5.1 illustrates the concept of Climate Stress applied within this research, which underpins subsequent methods for estimating the Climate Stress of PBVC patches in later stages. The figure shows the potential change in Climate Stress of a hypothetical pixel ('A') under current ('T1') and future ('T2') climatic conditions for a target PBVC in terms of an individual climate variable (in this case summer temperature). The bell curve represents the hypothetical bioclimatic envelope of the PBVC in terms of the climate variable, as determined by the bioclimatic envelope data (Table A1.2). The area of the curve can be regarded as the PBVC's suitable climate space. The centre of the curve represents optimum conditions for the PBVC in terms of the climate variable and is associated with the highest probabilities of occurrence and least climatic stress. Increasing distance from the centre of the curve indicates a change within climate space towards lower probabilities of occurrence and increasing stress for the PBVC. Under current conditions, the pixel exhibits near optimum conditions for the PBVC (i.e. 10.5^{o}C). The PBVC is therefore likely to be relatively unstressed if occupying the area represented by the pixel. Under future conditions (T2), due to climate change, the pixel has shifted *within climate space* and exhibits less optimum conditions for the target PBVC (i.e. 15^{o}C). The PBVC is therefore likely to be more stressed if occupying the area represented by the pixel.

Comparison of the bioclimatic envelope data (Table A1.2) with the ranges in climate predicted to influence NNP in the future under the ME scenario (Section 5.2.1.1) demonstrates that, in a minority of cases, the future climate of some areas of the park, in terms of some of the selected climate variables, is slightly outside of the bioclimatic tolerances of the BVCs, and therefore the specific PBVCs they are associated with. Specifically, the maximum summer temperature affecting some areas of NNP in the future (i.e. 16.74°C), is higher than Bog's maximum tolerance in terms of summer temperature. Also, the minimum future winter temperature (i.e. 0.95°C) is lower than the minimum winter temperature tolerance of the FMS BVC. By 2050, vegetation communities are unlikely to occur in areas characterised by climate outside of their particular bioclimatic tolerances. Before estimating Climate Stress, the future distributions of each of the PBVCs associated with Bog (i.e. Blanket Bog and Raised Bog) and FMS (i.e. Fen, Marsh and Swamp) under the land use scenarios were compared to the future climate grids. This analysis confirmed that no future PBVC occurrences were associated with areas characterised by climate outside of bioclimatic tolerances (i.e. areas of NNP in which they are unlikely to occur in the future because of prevailing climate conditions).

Figure 5.2 provides an overview of the methodology used within this research to estimate the Climate Stress of PBVC patches under current and future conditions.

Figure 5.1: Applied concept of Climate Stress.

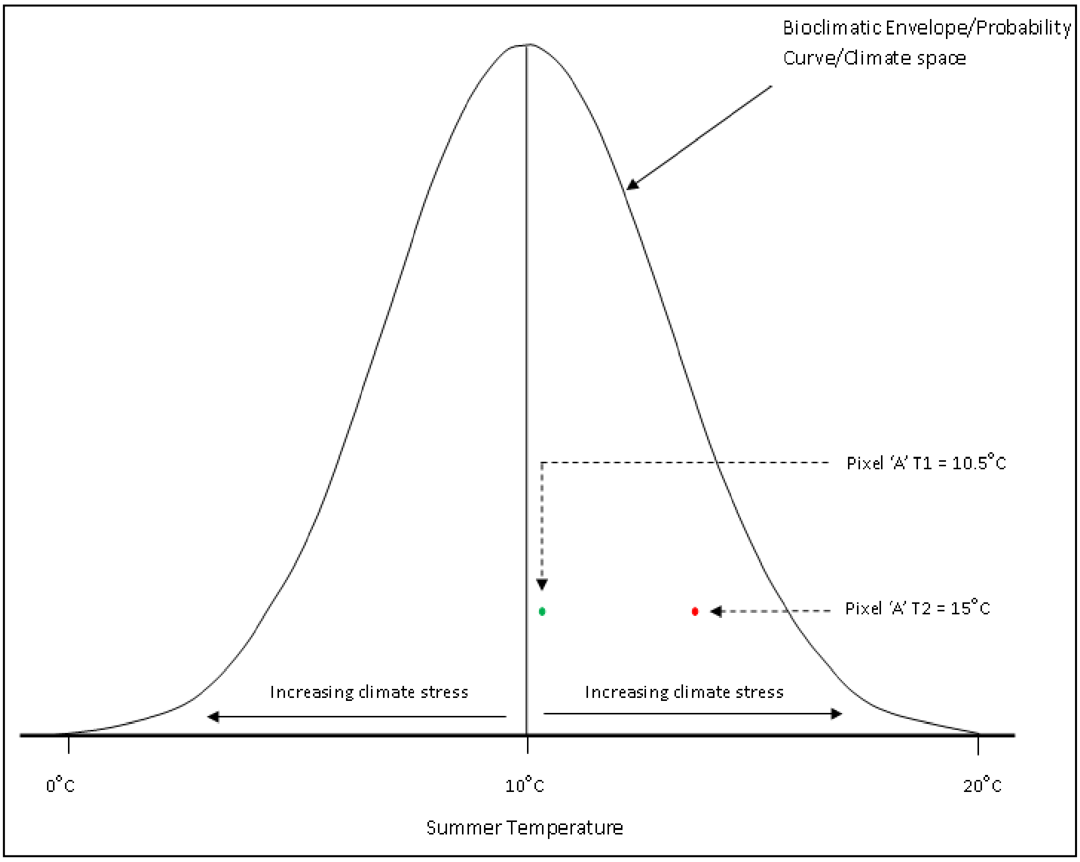
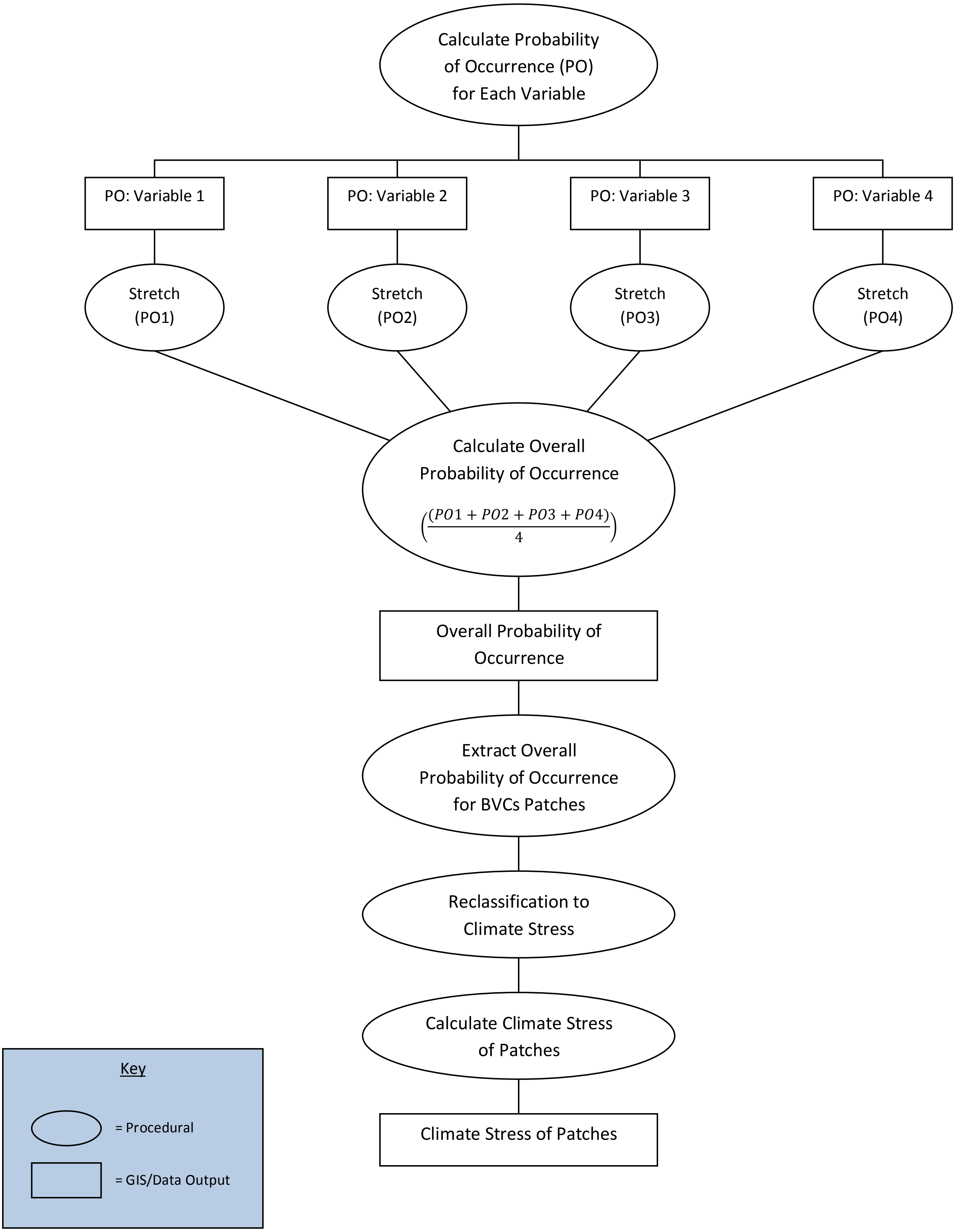


Figure 5.2: Overview of methodology used to estimate Climate Stress of PBVC patches



Probability of Occurrence for Individual Variables

To calculate the current and future probability of occurrence for each PBVC, in terms of each individual climatic variable, the bioclimatic envelope data were utilised as follows:

$$P = \frac{1}{\sigma\sqrt{2\pi}} e^{-0.5\left(\frac{x-\mu}{\sigma}\right)^2}$$

Equation 1

where P equals the probability of a pixel belonging to a particular PBVC given μ and σ, where μ is the mean value for a given PBVC in terms of a particular climatic variable from the bioclimatic envelope data; σ is the relevant standard deviation and x is the value of the relevant climatic variable for the pixel under consideration. Equation 1 is the standard probability density function for estimating the probability associated with a specific value (x) from a normally distributed continuous variable (from: Harris & Jarvis, 2011). The above technique allows the probability of occurrence of an individual PBVC to be estimated for a pixel for a given climatic variable solely in terms of its established bioclimatic response data for that variable.

The issues previously discussed regarding the appropriateness of Gaussian models for estimating the bioclimatic responses of the BVCs (Section 3.7 and Appendix 1; 'Normality Tests') are also relevant in applying Equation 1 to measure the responses of the PBVCs. Table 5.1 summarises the frequency distributions of the relevant bioclimatic envelope data for estimating the probability of occurrence of specific PBVCs. The table demonstrates that two thirds of these responses were either normally distributed or only slightly skewed. Equation 1 was therefore regarded as generally suitable for estimating the probability of occurrence of the PBVCs. However, the issues concerning the appropriateness of applying a Gaussian approach to estimate probabilities of occurrence in cases where bioclimatic envelope data are skewed (Section 3.7 & Appendix 1; 'Normaility Tests') should be noted.

Table 5.1: Summary of the different types of climatic response for the BVCs relevant to modelling the Climate Stress of specific PBVCs. '1' = normally distributed, 2 = slightly skewed, 3 = highly skewed. PBVC abbreviations: 'BLWP' = Broadleaved Woodland: Priority; 'IGP' = Improved Grassland: Priority; 'NGP' = Neutral Grassland: Priority.

BVC	**PBVC(s)**	**Temperature**		**Precipitation**	
		Summer	**Winter**	**Summer**	**Winter**
Bog	Blanket Bog, Raised Bog	1	1	1	1
Broadleaved Woodland	BLWP	2	1	3	3
Fen, Marsh & Swamp (FMS)	Fen, Marsh, Swamp	2	2	3	3
Heath	Heath	1	1	2	2
Improved Grassland	IGP	2	1	3	3
Neutral & Calcareous Grassland	NGP	2	1	3	3

Linear Stretching of Probability Values

Table A1.2 demonstrates the different range of values of the bioclimatic envelopes for temperature compared to those for precipitation. Because of this, notable differences were apparent between the ranges of probability values calculated for temperature and precipitation using the above method. A linear stretching procedure was applied to tackle this issue. Specifically, the probability data for each PBVC for each variable was stretched within the 0 – 1 range using the maximum potential probability achievable for the PBVC in terms of the variable (i.e. the value returned for *P* in Equation 1, when *x* is equal to the mean value from the bioclimatic envelope data) as the upper limit/bound and '0' as the lower limit/bound. This ensured that the range of probability values obtained was less biased when determining the overall probability of occurrence for each PBVC. The linear stretch also ensured that the original frequency distribution of the unstretched data was retained.

Overall Probability of Occurrence

Using the above methods, a number of raster datasets were produced depicting the probability of occurrence of each PBVC in terms of each of the four climate variables for each 50m pixel of the current and future climate grids for the extent of NNP. Raster grids depicting the overall probability of occurrence of each PBVC for each pixel within the study area for current and future climate were produced as follows:

$$PO = \frac{(y1+y2+y3+y4)}{4} \qquad \text{Equation 2}$$

where *PO* is the overall probability of occurrence of a PBVC, *y*1*, y*2*, y*3 *and y*4 are the relevant raster grids describing the probability of occurrence of the PBVC in terms of each of the individual climate variables; dividing the result of the top line of the equation, by the number of variables considered, ensured that the *PO* values returned were all within the 0 -1 range.

The overall probability of occurrence values for pixels within individual PBVC patches from each of the three time slices were then extracted. Probability values extracted for current PBVC patches were those calculated from the current climate grids. Values extracted for PBVC patches under Conservation First and Going for Growth were those calculated from the future climate grids.

Reclassification to Climate Stress

The ranges of *PO* values were then reclassified (Table 5.2). This resulted in more meaningful values of Climate Stress. For example, pixels with a value between 0.0 and 0.20 (stressed) scored 1 and pixels with a value between >0.80 and 1.0 (unstressed) scored 0.

Table 5.2: Reclassification of *PO* values to values of Climate Stress.

***PO* values**	**Climate Stress Category**	**Climate Stress Value**
0.0 – 0.20	Stressed	1
>0.20 – 0.40	Moderately Stressed	0.75
>0.40 – 0.60	Intermediate	0.5
>0.60 – 0.80	Moderately Unstressed	0.25
>0.80 – 1.0	Unstressed	0

Climate Stress of Patches

The Climate Stress of individual PBVC patches were then determined as follows:

$$Pstress = \frac{Ssum}{Ppixel}$$

Equation 3

where *Pstress* is the Climate Stress of an individual PBVC patch, *Ssum* is the sum of Climate Stress values from all pixels within the patch and *Ppixel* is the total number of pixels within the patch. This allowed patches to be assigned a single Climate Stress value (between 0 – 1), based on the proportion of Climate Stress values for pixels within their extent. For example, patches comprised exclusively of stressed pixels scored 1; patches comprised exclusively of unstressed pixels scored 0; patches with half stressed pixels and half intermediate pixels scored 0.75; patches with half unstressed and half intermediate pixels scored 0.25.

5.3 Results

Results are first presented at the landscape and class (PBVC) level for the National Park (Tables 5.3; 5.4 and Figures 5.3a-c). This allows general trends for the park, as well as for each PBVC, to be identified and causes investigated. Summary results are then presented at the landscape level for each NCA, allowing for comparison with trends for the National Park (Tables 5.5 & 5.6). Finally, PBVC results for each NCA are provided (Table 5.7). This allows the specific causes of levels of Climate Stress within each NCA, and therefore relevant differences between them, to be identified. The PBVC results for each NCA also highlight the areas of the park where particular PBVCs experience their highest and lowest levels of Climate Stress, currently, and under the future scenarios. They are useful in identifying potential 'climate-refugia' (Gavin *et al*., 2014; Keppel & Wardell-Johnson, 2012; Morecroft *et al*., 2012) for individual PBVCs.

5.3.1 Northumberland National Park (NNP)

5.3.1.1 Landscape and Class Level Results

Table 5.3 (bottom row) shows that the highest levels of average Climate Stress, for the PBVCs overall and across the whole study area, are observed for the current time slice. The lowest levels of Climate Stress are observed under Conservation First. Average levels of Climate Stress, for the PBVCs overall, decrease notably under Conservation First and Going for Growth (by 0.283 and 0.274 respectively) compared to those estimated for current conditions. Levels of Climate Stress in both future scenarios are generally similar. Figures 5.3a-c further highlight the general trend of decreasing levels of Climate Stress associated with the PBVCs under the future scenarios.

Table 5.3: Average levels of Climate Stress for all PBVCs (bottom row) and for each individual PBVC across NNP under each time slice. Values in brackets show the difference in Climate Stress between the current and future time slices. Values highlighted red or green show (respectively) the highest and lowest Climate Stress (or change in Climate Stress) under each time slice. Values highlighted red or green in bold italics show the highest/lowest levels of Climate Stress (or change in Climate Stress) across all of the time slices.

PBVC	**Current**	**Conservation First**	**Going for Growth**
Blanket Bog	0.266	0.619 (0.353)	0.593 (0.327)
Broadleaved Woodland: Priority (BLWP)	0.436	0.080 (-0.356)	0.109 (-0.327)
Fen	0.714	0.267 ***(-0.448)***	0.293 (-0.422)
Heath	0.493	0.422 (-0.071)	0.449 (-0.044)
Improved Grassland: Priority (IGP)	0.397	0.101 (-0.297)	***0.005*** (-0.392)
Marsh	0.624	0.269 (-0.356)	0.269 (-0.356)
Neutral Grassland: Priority (NGP)	0.386	0.101 (-0.284)	0.117 (-0.285)
Raised Bog	0.125	***0.735 (0.612)***	0.568 (0.443)
Swamp	0.264	0.264 (0.000)	0.264 (0.000)
Average Climate Stress	**0.551**	**0.268 *(-0.283)***	0.277 (-0.274)

Figure 5.3a: Climate Stress of all PBVC patches within NNP under the current time slice. Maps depicting the Climate Stress of patches for specific PBVCs are available upon request.

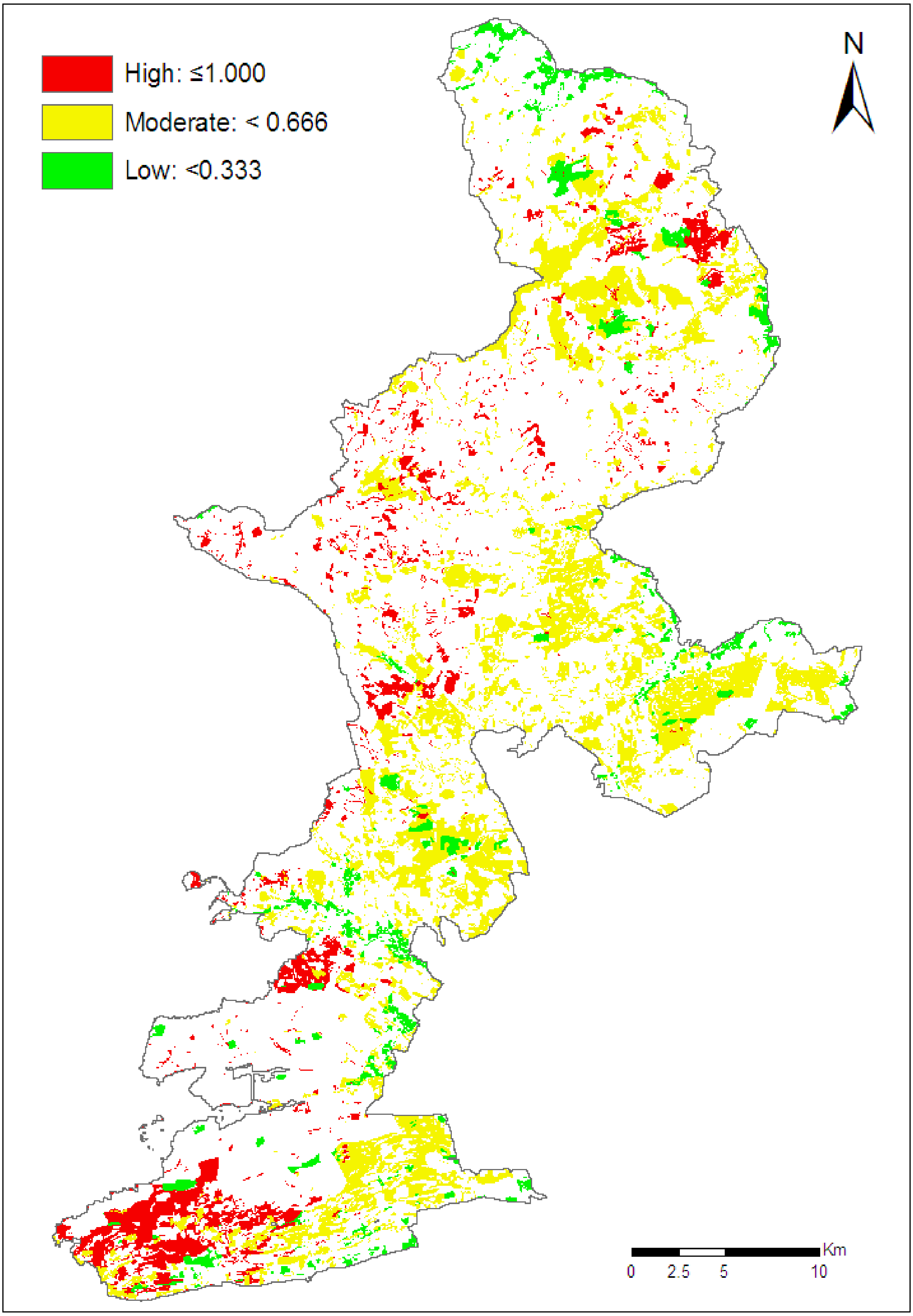


Figure 5.3b: Climate Stress of all PBVC patches within NNP under Conservation First. Maps depicting the Climate Stress of patches for specific PBVCs are available upon request.

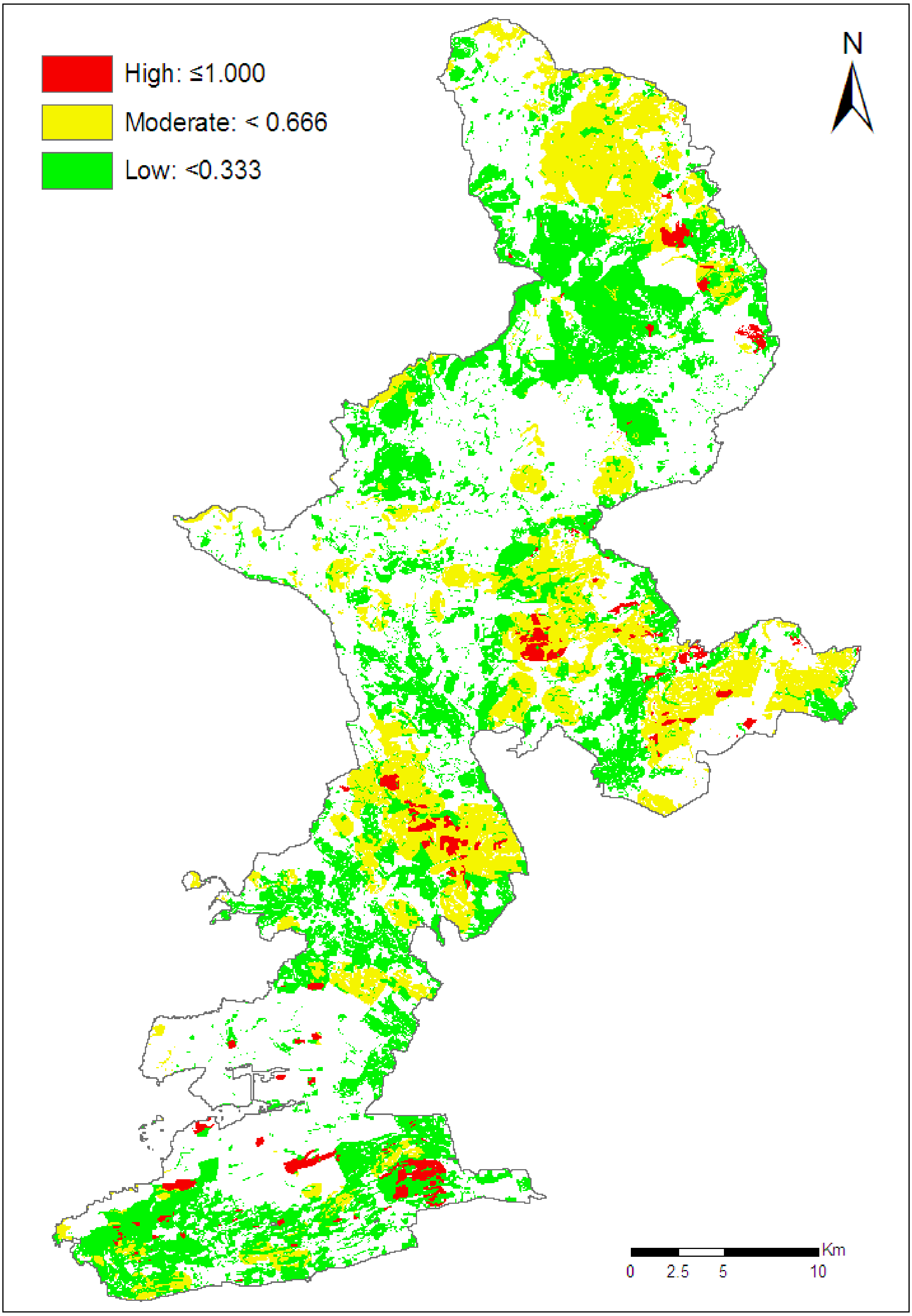


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Figure 5.3c: Climate Stress of all PBVC patches within NNP under Going for Growth. Maps depicting the Climate Stress of patches for specific PBVCs are available upon request.

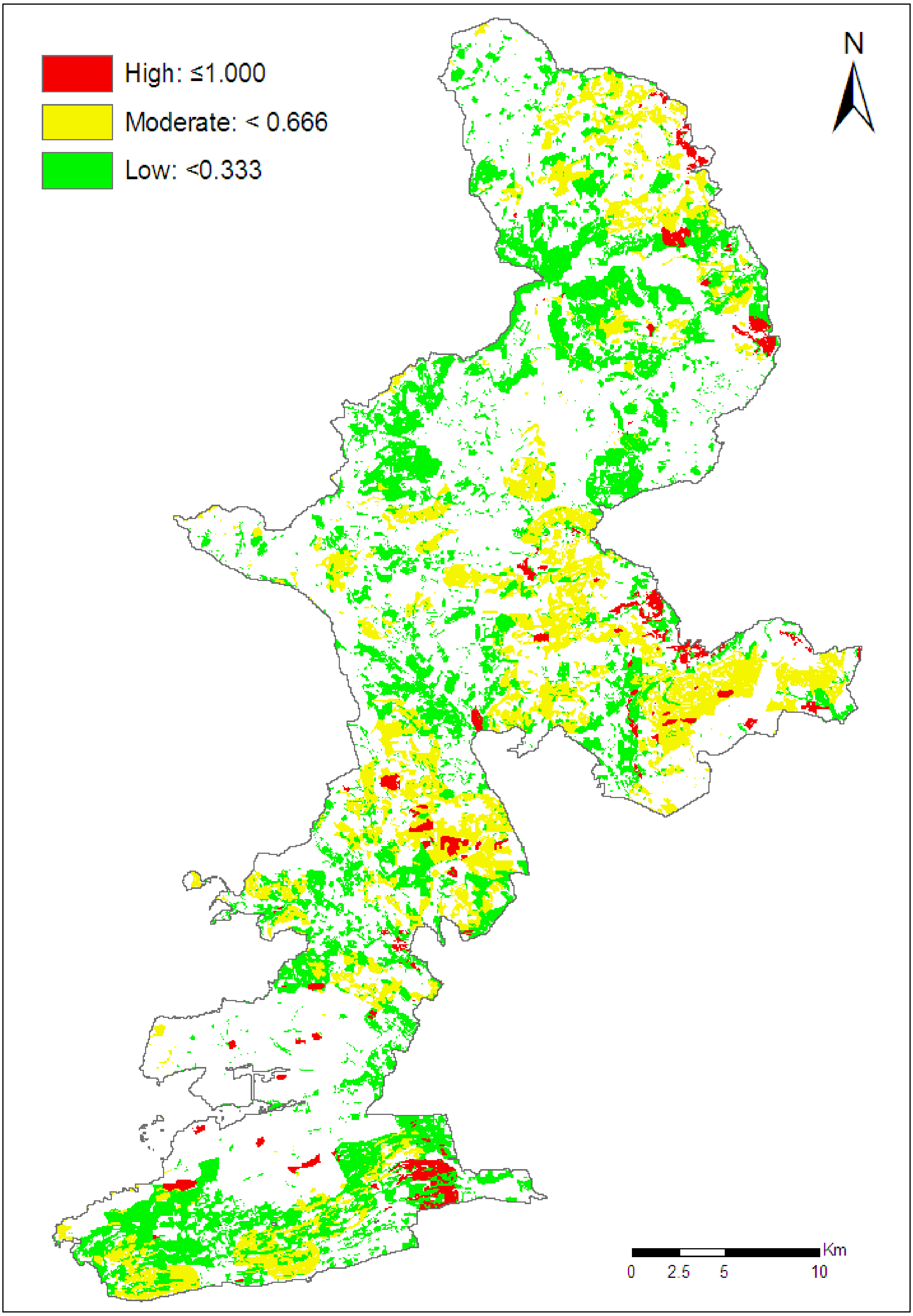


Table 5.3 also shows that the highest and lowest levels of Climate Stress for the current time slice are for Fen and Raised Bog respectively. Under Conservation First, Raised Bog and BLWP exhibit the highest and lowest levels of Climate Stress respectively. Under Going for Growth, the highest and lowest levels of Climate Stress are observed for Blanket Bog and IGP respectively. Across all time slices, the PBVC which exhibits the most Climate Stress is Raised Bog under Conservation First; the PBVC with the lowest Climate Stress overall is IGP under Going for Growth.

The Climate Stress results for many of the PBVCs between the current and future time slices show notable variation: For the majority of the PBVCs (BLWP, Fen, IGP, Marsh and NGP), Climate Stress decreases notably under Conservation First and Going for Growth when compared to the current time slice. Climate Stress for Heath decreases slightly. However, Climate Stress increases notably for both Blanket Bog and Raised Bog under both future scenarios. Climate Stress for Swamp remains constant under both future scenarios from current levels.

These trends do much to explain the differences between the average levels of Climate Stress under current and future scenarios (Table 5.3), as well as differences in the ranking of the PBVCs between current and future time slices (Table 5.4). For instance, Blanket Bog and Raised Bog are amongst the lowest ranked PBVCs in terms of Climate Stress under the current time slice. The large increase in the Climate Stress of these PBVCs under climate change conditions means that they are consistently the two most climatically stressed PBVCs in the future scenarios. The biggest decrease in the ranking of the PBVCs between current and future time slices is observed for BLWP, IGP and Fen: BLWP and IGP currently exhibit the fourth and fifth highest levels of Climate Stress respectively. However, they are ranked as the two least stressed PBVCs under the future scenarios. Due to the large decreases in the Climate Stress of Fen under the future time slices (Table 5.3), it shifts from being ranked currently as the most climatically stressed PBVC (second overall) to the fifth and fourth most stressed under Conservation First and Going for Growth respectively (15^{th} and 13^{th} overall respectively). Only minor changes are observed in the ranking of NGP and Swamp (Table 5.4). This is probably related to the relatively small (or, in the case of Swamp, the non-existent) changes observed between current and future time slices. Some of the smallest changes in the Climate Stress between current and future time slices are observed for Heath, which is consistently the third least climatically-stressed PBVC across all time slices.

Table 5.4: The ranking of each PBVC (high to low), in terms of average Climate Stress, for the study area across all time slices. Numeric prescripts denote rank of NCA within each time slice.

Rank	Current	Conservation First	Going for Growth
1		1. Raised Bog (0.735)	
2	1. Fen (0.714)		
3	2. Marsh (0.624)		
4		2. Blanket Bog (0.619)	
5			1. Blanket Bog (0.593)
6			2. Raised Bog (0.568)
7	3. Heath (0.493)		
8			3. Heath (0.449)
9	4. BLWP (0.436)		
10		3. Heath (0.422)	
11	5. IGP (0.397)		
12	6. NGP (0.386)		
13			4. Fen (0.293)
14		4. Marsh (0.269)	5. Marsh (0.269)
15		5. Fen (0.267)	
16	7. Blanket Bog (0.266)		
17	8. Swamp (0.264)	6. Swamp (0.264)	6. Swamp (0.264)
18	9. Raised Bog (0.125)		
19			7. NGP (0.117)
20			8. BLWP (0.109)
21		7. NGP (0.101)	
22		8. IGP (0.101)	
23		9. BLWP (0.080)	
24			9. IGP (0.005)

5.3.2 National Character Areas (NCAs)

5.3.2.1 Landscape Level Results

Table 5.5 shows that the highest level of average Climate Stress in the current time slice is for the Cheviots; the lowest levels are observed for the Cheviot Fringe. Under Conservation First, the highest levels are observed for the NSH NCA; the Cheviot Fringe exhibits the lowest levels of climate stress for this scenario. Under Going for Growth, NSH exhibits the highest levels of climate stress; again the lowest is observed for the Cheviot Fringe. The highest level of climate stress across all time slices is for the Cheviots NCA under current conditions. The lowest level of Climate Stress across all time slices is for the Cheviot Fringe under Conservation First.

Table 5.6 ranks the NCAs according to their levels of Climate Stress. The table clearly shows that the top five overall ranks are consistently occupied by those NCAs under the Current time slice. This further supports the point that, generally, levels of Climate Stress within NNP are likely to decrease notably in the future. The Cheviot Fringe is consistently shown as the least climatically stressed NCA in each of the three time slices. Also in terms of its overall rank, the Cheviot Fringe is shown as the least and second least climatically stressed NCA under Conservation First and Going for Growth respectively. This is despite the fact that only a relatively moderate decrease in Climate Stress is exhibited for this NCA under the future scenarios (Table 5.5). Although the largest decrease in Climate Stress in both of the future scenarios is observed for the Cheviots NCA (Table 5.5), it still ranks consistently high in each of the three time slices. Possibly the most notable change in the ranking of NCAs between scenarios is for NSH; it is ranked as the second least climatically stressed NCA in the current time slice and the most stressed under both future scenarios. Table 5.5 suggests that this is at least partially due to the fact that the NSH exhibits the smallest decrease in Climate Stress of all the NCAs under both future scenarios.

Table 5.5: Average levels of Climate Stress for all PBVCs across each NCA under each time slice. Values in brackets show the difference in Climate Stress between the current and future time slices. The highlighting of specific values follows the same format as that for Table 5.3.

	Current	Conservation First	Going for Growth
Cheviots	***0.589***	0.263 ***(-0.326)***	0.277 (-0.312)
Cheviot Fringe	0.421	***0.245*** (-0.176)	0.250 (-0.171)
Northumberland Sandstone Hills (NSH)	0.441	0.311 (-0.130)	0.321 ***(-0.120)***
Border Moors and Forests (BMF)	0.563	0.261 (-0.302)	0.272 (-0.291)
Tyne Gap and Hadrian's Wall (TG)	0.513	0.262 (-0.251)	0.264 (-0.249)

Table 5.6: The ranking of each NCA (high to low), in terms of average Climate Stress under each time slice. Numeric prescripts denote rank of NCA within each time slice.

Overall Rank	Current	Conservation First	Going for Growth
1	1. Cheviots (0.589)		
2	2. BMF (0.563)		
3	3. TG (0.513)		
4	4. NSH (0.441)		
5	5. Cheviot Fringe (0.421)		
6			1. NSH (0.321)
7		1. NSH (0.311)	
8			2. Cheviots (0.277)
9			3. BMF (0.272)
10			4. TG (0.264)
11		2. Cheviots (0.263)	
12		3. TG (0.262)	
13		4. BMF (0.261)	
14			5. Cheviot Fringe (0.250)
15		5. Cheviot Fringe (0.245)	

5.3.2.2 Class Level Results

Table 5.7 shows that across all time slices, over all NCAs, Fen in the current time slice within the Cheviot NCA exhibits the highest levels of Climate Stress. IGP in the Going for Growth scenario within the TG NCA is the least climatically stressed overall.

Cheviots

Fen exhibits the highest levels of Climate Stress under each of the three time slices. The lowest levels of Climate Stress are observed for Swamp under current conditions and NGP in both of the future scenarios. The highest overall level of Climate Stress is observed for Fen in the current time slice. The lowest is for NGP under Going for Growth.

Cheviot Fringe

Marsh and NGP respectively exhibit the highest and lowest levels of Climate Stress under current conditions. Under both future scenarios, Heath is indicated as the most climatically stressed. The least climatically stressed PBVCs under Conservation First and Going for Growth are BLWP and IGP respectively. The highest overall level of Climate Stress is for Heath under Conservation First. The lowest is for IGP under Going for Growth.

Northumberland Sandstone Hills

The highest and lowest levels of Climate Stress for the current time slice are for Heath and NGP respectively. Under Conservation First, Blanket Bog and BLWP exhibit the highest and lowest levels of Climate Stress respectively. Blanket Bog and IGP exhibit the highest and lowest respective levels of Climate Stress under Going for Growth. The highest and lowest levels of Climate Stress overall are associated with Blanket Bog and IGP respectively under Going for Growth.

Border Moors and Forests

Fen and Raised Bog are the most and least climatically stressed PBVCs respectively under current conditions. Under Conservation First Raised Bog and BLWP exhibit the highest and lowest levels of Climate Stress respectively. The PBVCs which are the most and least climatically stressed under

Going for Growth are Blanket Bog and IGP respectively. Across all scenarios, Raised Bog under Conservation First exhibits the highest levels of Climate Stress; IGP under Going for Growth exhibits the lowest levels of stress.

Tyne Gap and Hadrian's Wall

Currently Fen exhibits the highest levels of Climate Stress; Blanket Bog exhibits the lowest levels. The most and least climatically stressed PBVCs under Conservation First are Raised Bog and NGP respectively. Under Going for Growth Blanket Bog and IGP are the most and least climatically stressed PBVCs respectively. Raised Bog under Conservation First exhibits the highest level of Climate Stress across the time slices. IGP under Going for Growth is the least climatically stressed across the time slices.

Table 5.7: Average levels of Climate Stress for each PBVC within each NCA under each time slice. The highlighting of specific values follows the same general format as that for Tables 5.3 and 5.5. Values followed by '*' denote the PBVCs with the highest/lowest levels of Climate Stress across all NCAs and all time slices.

NCA	PBVC	Current	Conservation First	Going for Growth
Cheviot	Blanket Bog	0.424	0.277 (-0.147)	0.256 (-0.168)
	BLWP	0.400	0.178 (-0.222)	0.204 (-0.196)
	Fen	***0.790****	0.540 (-0.250)	0.540 (-0.250)
	Heath	0.501	0.317 (-0.184)	0.341 (-0.160)
	IGP	0.367	0.257 (-0.110)	0.038 (-0.329)
	Marsh	0.687	0.268 (-0.419)	0.268 (-0.419)
	NGP	0.463	0.067 (-0.396)	***0.008 (-0.455)***
	Raised Bog	N/A	N/A	N/A
	Swamp	0.250	0.250 (0.000)	0.250 (0.000)
Cheviot Fringe	Blanket Bog	N/A	N/A	N/A
	BLWP	0.413	0.130 (-0.238)	0.198 (-0.215)
	Fen	N/A	N/A	N/A
	Heath	N/A	***0.688*** (0.688)	0.665 ***(0.665)***
	IGP	0.353	0.187 (-0.166)	***0.005*** (-0.348)
	Marsh	0.508	0.250 (-0.258)	0.250 (-0.258)
	NGP	0.263	0.168 (-0.095)	0.145 (-0.118)
	Raised Bog	N/A	N/A	N/A
	Swamp	N/A	N/A	N/A
Northumberland Sandstone Hills	Blanket Bog	0.252	0.755 (0.503)	***0.756*** (0.504)
	BLWP	0.424	0.114 (-0.310)	0.130 (-0.294)
	Fen	0.500	0.250 (-0.250)	0.250 (-0.250)
	Heath	0.500	0.528 (0.028)	0.556 (0.056)
	IGP	0.382	0.200 (-0.182)	***0.002*** (-0.380)
	Marsh	0.468	0.250 (-0.218)	0.250 (-0.218)
	NGP	0.251	0.193 (-0.058)	0.020 (-0.231)
	Raised Bog	N/A	N/A	N/A
	Swamp	N/A	N/A	N/A
Border Moors and Forests	Blanket Bog	0.266	0.619 (0.353)	0.593 (0.327)
	BLWP	0.436	0.080 (-0.356)	0.109 (-0.327)
	Fen	0.714	0.267 (-0.447)	0.293 (-0.421)
	Heath	0.493	0.422 (-0.071)	0.449 (-0.044)
	IGP	0.397	0.101 (-0.296)	***0.005*** (-0.392)
	Marsh	0.624	0.269 (-0.355)	0.269 (-0.355)
	NGP	0.386	0.101 (-0.285)	0.117 (-0.269)
	Raised Bog	0.125	***0.735*** (0.610)	0.568 (0.433)
	Swamp	0.264	0.264 (0.000)	0.264 (0.000)
Tyne Gap and Hadrian's Wall	Blanket Bog	0.250	0.753 (0.503)	0.750 (0.500)
	BLWP	0.467	0.063 (-0.404)	0.067 (-0.400)
	Fen	0.718	0.270 ***(-0.448)***	0.283 (-0.435)
	Heath	0.443	0.571 (0.128)	0.561 (0.118)
	IGP	0.398	0.077 (-0.321)	***0.000**** (-0.398)
	Marsh	0.664	0.256 (-0.408)	0.256 (-0.408)
	NGP	0.347	0.022 (-0.325)	0.055 (-0.292)
	Raised Bog	N/A	***0.775 (0.775)***	N/A
	Swamp	0.250	0.250 (0.250)	0.250 (0.000)

5.4 Discussion

5.4.1 NNP

The results indicate a notable reduction in aggregate levels of Climate Stress exhibited for the PBVCs at the NNP level under both of the future scenarios compared to those of the Current time slice (Table 5.3: Bottom Row). Table 5.3 also suggests that this result is largely due to notable reductions in the Climate Stress of many of the PBVCs under both of the future scenarios compared to the Current time slice. Blanket Bog and Raised Bog are exceptions to this trend; the Climate Stress associated with both of these PBVCs for NNP increases significantly under both of the future scenarios compared to current levels.

The specific characteristics of individual PBVCs go some way to explaining these trends. For instance, most of the PBVCs which demonstrate a notable decrease in Climate Stress between current and future time slices are those broadly defined as 'lowland' in this research (see: Appendix 2a). In terms of climate such community types are more typically associated with relatively warm and/or dry conditions (Tansley, 1949). Although much of the area of NNP may be defined as lowland under the criteria used in this research, the park's geographical characteristics mean that it experiences relatively low temperatures and, in places, relatively high rainfall. At present, the climate of much of the park, in terms of precipitation and particularly temperature, is likely to represent sub-optimum conditions for many of these lowland PBVCs. The predicted changes in climate affecting the park in the future include an increase in summer and winter temperature; an increase in winter precipitation and a decrease in summer precipitation. It is likely that, overall, these changes will represent more optimum climatic conditions for many of the lowland PBVCs. It is reasonable to expect therefore that they will experience less climatic stress in the future.

Conversely, the PBVCs experiencing notable increases in Climate Stress under the future scenarios (i.e. Blanket Bog, Raised Bog) are those more typically associated with cooler wetter conditions. The current climate of many areas of the park is likely to represent more optimum conditions for these PBVCs. However, the climate changes affecting the park in the future will mean that many areas come to represent sub-optimum or even marginal conditions. Heath is categorised as an 'upland' PBVC type in this research suggesting that it also has a general requirement for cooler, wetter conditions. However, it experiences a small decrease in overall Climate Stress under the future scenarios. Although Heath is undoubtedly a typical upland PBVC type, it can occur more abundantly at lower elevations than other upland PBVCs such as Blanket Bog (Tansley, 1949). It is therefore likely to have a greater tolerance of the warmer, drier conditions predicted to occur in the future.

5.4.2 NCAs

Table 5.6 shows that when the Climate Stress values of the five NCAs across all time slices are ranked the top five ranks are consistently occupied by those from the current time slice: providing further evidence of the notable overall reduction in Climate Stress likely to occur in the future. However, these overall trends mask some important characteristics in terms of the ranking of particular NCAs within the time slices.

For instance, the relatively small decrease in the Climate Stress of the NSH NCA under both future scenarios at least partially accounts for its change from being the fourth most climatically stressed NCA under current conditions (4^{th} overall) to the most stressed NCA in both future time slices (7^{th} and 6^{th} respectively overall). Tables 5.7 and 4.18 suggest that this is partially due to trends across the time slices for the three most dominant PBVCs within the NCA (i.e. Marsh, BLWP and Heath). For instance, Marsh is consistently the most dominant PBVC within the NCA (as well as all of the others) under each of the time slices (Table 4.18). Table 5.7 shows that the decrease in Climate Stress that Marsh experiences under both of the future scenarios within NSH is less than the decrease it experiences in the other NCAs. BLWP and Heath (the second and third most dominant PBVCs within the NCAs under the scenarios) also generally experience only moderate decreases in Climate Stress within NSH compared to the PBVCs with similar levels of dominance in other NCAs. This, combined with the fact that less dominant PBVCs (e.g. Blanket Bog) experience a relatively high increase in Climate Stress within NSH compared to the other NCAs, does much to account for the high ranking of the NCA within each of the future time slices.

The consistently low ranking of the Cheviot Fringe NCA is largely attributable to the Climate Stress characteristics of Marsh and IGP. For instance, Marsh's current level of Climate Stress is generally less within the Cheviot Fringe than other NCAs. Marsh experiences relatively small decreases under both of the scenarios within the NCA Table 5.7. However, when combined with Marsh's low current level of Climate Stress, Marsh's level of Climate Stress remains comparatively low under both future scenarios. IGP is consistently indicated as the second most dominant PBVC within the Cheviot Fringe. The average level of Climate Stress currently associated with the IGP patches within Cheviot Fringe is often notably less than that of other PBVCs with similar levels of dominance in other NCAs under the current time slice (Tables 5.7 & 4.18). Although the proportion of IGP patches under both future scenarios reduces somewhat, it is still the second most dominant PBVC within the NCA (Table 4.18). The decrease in Climate Stress that IGP experiences within the Cheviot Fringe under Going for Growth is often notably greater than that associated with the other dominant PBVCs from the other NCAs. The low ranking of the Cheviot Fringe under Conservation First however is not related to the trends for IGP, as the PBVC exhibits a relatively small decrease compared to the other PBVCs within similar levels of dominance from the other NCAs. However, BLWP, which has similar levels of dominance to IGP within the NCA under the scenario (Table 4.18), experiences a relatively large decrease in climate stress. In general, it appears that the low ranking of the Cheviot Fringe across the various time slices is largely due to its relatively warm and dry conditions associated with its lowland position within the park. Such conditions are well-suited to the typically lowland PBVCs which dominate its area across all three time slices.

The relatively high ranking of the Cheviots NCA in each of the time slices is largely related to the characteristics of Marsh and Heath within the area. More than 70% of the PBVC patches within the NCA belong to these two PBVCs (Table 4.18). The Climate Stress associated with these PBVCs is somewhat higher than that for the other dominant PBVCs in the other NCAs under the current time slice. The Climate Stress of all of the PBVCs within the Cheviots reduces under both future scenarios, in many instances notably so. However, the Climate Stress of the dominant PBVCs (Marsh and Heath) within the Cheviots reduces by a relatively small amount under the scenarios. Thus, their levels of Climate Stress, under the scenarios, in many cases remain higher than that of the dominant PBVCs (particularly Marsh) from the other NCAs.

The results for NCAs in terms of the most and least climatically stressed PBVCs under each of the time slices agree quite well with those for individual PBVCs at the NNP level. For instance, in many instances in the current time slice, the ‘upland’ PBVCs (e.g. Heath, Blanket and Raised Bogs) are identified as the least climatically stressed whilst the ‘lowland’ PBVCs are indicated as the most stressed (Table 5.7). In many instances under the future scenarios this situation is reversed. A particularly notable trend is related to Blanket Bog within the Cheviot NCA. Its climatic stress within the NCA decreases under the scenarios compared to current levels. This represents a significant divergence from the trends observed for this PBVC both at the NNP level and for the other NCAs and is likely related to the upland characteristics of the Cheviots NCA.

In summary, the results indicate a notable reduction in aggregate levels of Climate Stress in both of the future scenarios compared to current levels at the national park scale. However, this overall result somewhat obscures the divergence in the trends for particular PBVC types between current and future time slices, with the more ‘upland’ PBVCs experiencing considerable increases in their Climate Stress. Although the NCA level results provide further support for those at the NNP level, they also show that the geographical (and therefore climatic) characteristics of individual NCAs, combined with the characteristics of the particular PBVCs of which they are comprised, does much to influence relative levels of Climate Stress for the NCAs both now and in the future.

Chapter 6: Land Use Vulnerability (VM2a & b)

6.1 Introduction

It is widely recognised within the discipline of landscape ecology, and ecology more generally, that environmental patterns strongly influence ecological processes and therefore ecosystem functioning, structure and integrity (Morecroft *et al*., 2012; McGarigal, 2006; Gurevitch *et al.*, 2002; Araujo & Williams, 2000; Farina, 1998; Begon *et al*., 1990; Turner, 1989). For instance, the spatial characteristics of habitat, at various scales, within a landscape interact with organism perception to control vital higher-level processes such as metapopulation interactions and community structure (McGarigal, 2006; Murphy & Lovett-Doust, 2004; Gurevitch *et al*., 2002; Begon *et al*., 1990; Turner, 1989). Disruption of the spatial patterns of habitat within a landscape could therefore compromise the functional integrity of ecosystem structure by 'interfering with critical processes necessary for population persistence and the maintenance of biodiversity and ecosystem health' (McGarigal, 2006, pp. 1; Turner, 1989).

In order to adequately gauge ecological vulnerability, it is therefore essential to understand how spatial patterns affect ecological processes and functioning and provide appropriate methods to quantify, measure and assess the relevant spatial characteristics of a landscape (Preston *et al*., 2011; McGarigal, 2006; Forman, 2001). This is particularly true considering that human activities, particularly land use and land use change, have the potential to strongly influence the spatial patterning of ecological phenomena (Haines-Young, 2009; McGarigal, 2006; MA, 2005a; 2005b).

This chapter reviews the landscape ecology literature with reference to the relationship between ecological patterns, processes, functioning and vulnerability. Appropriate landscape metrics are identified based on this information and the methods for applying these measures to assess the vulnerability of the PBVCs are then explained. The results from applying these metrics to the PBVCs within NNP under current and future time slices are then presented. This is followed by a discussion of relevant trends and issues at the NNP and NCA levels and for individual PBVCs.

6.2 Literature Review

Landscape ecology makes the distinction between 'patch' and 'matrix' as the basic spatial elements within a landscape (McGarigal, 2006; Murphy & Lovett-Doust, 2004; Forman, 2001). Patches may be defined as 'discrete areas of relatively homogeneous conditions at a particular scale' (McGarigal, 2006, pp. 1). Often the emphasis is placed on a particular patch type (e.g. forest, pasture) (McGarigal, 2006). The mosaic of other patches or elements within the landscape is the matrix (McGarigal, 2006; Forman, 2001; Farina, 1998). MacArthur and Wilson's Theory of Island Biogeography (TIB) (1967) and Levins' Metapopulation Theory (1969) underpins much of the treatment and perceived ecological role of these different elements within landscape ecology (Morecroft *et al*., 2012; McGarigal, 2006; Gurevitch *et al*., 2002; Forman, 2001; Begon et al., 1990; 1996). Typically, patches are regarded as analogous to oceanic islands surrounded by a neutral or inhospitable homogenous marine matrix (McGarigal, 2006; Gurevitch *et al*., 2002). Although some of these assumptions have been brought into question recently with the introduction of recent field data and more realistic concepts (McGarigal, 2006; Forman, 2001), the above theories do provide a useful starting point from which to understand the relationship between spatial pattern and ecological functioning within landscapes.

6.2.1 Area, Population Size and Species Richness

Islands, and by extension habitat patches, of greater area tend to support larger populations and higher species richness (Dufour *et al*., 2006; Gurevitch *et al*., 2002; Heino, 2000; Laurance *et al*., 2002; Begon, 1990; Macarthur & Wilson, 1969). These characteristics are thought to contribute positively to the stability and persistence of the constituent populations and communities (Begon *et al*., 1990, pp. 772-773). For instance, one of the predictions of the TIB is for area to be negatively correlated with extinction rates (Gurevitch *et al*., 2002; Begon, 1990). The results of a 22 year study of rainforest fragments provide some support for this (Laurance *et al*., 2002). This correspondence occurs because the larger populations associated with larger islands are less likely to become extinct, for a number of reasons. Firstly, larger populations are likely to exhibit increased genetic diversity (Gurevitch *et al*., 2002; Begon et al., 1996; 1990). Hence, the chance of extinction for such populations is likely to be decreased because they will be better 'able to evolve in response to changes in their environment' (Hopper *et al*. 2005; Hughes *et al*., 2008; Gurevitch *et al.*, 2002, pp. 347; Begon *et al*., 1990). For instance, in relation to deterministic climate changes (e.g. increases in average temperatures), smaller populations will be less likely to contain a sufficient number of individuals capable of sustaining the population under these changed conditions (Hooper *et al.*, 2005; Gurevitch *et al.*, 2002; Begon *et al.*, 1990). Secondly, smaller populations are inherently more susceptible to 'chance' extinction due to random demographic variations around the populations' average intrinsic rate of increase (Gurevitch *et al.*, 2002; Begon *et al*., 1990). Smaller populations are, therefore, more prone to extinction regardless of any environmental change that may affect them. Such populations, and the functions and services they are typically associated with, are likely to be less stable over time (Cardinale *et al*., 2011; Hughes, 2008; Hooper *et al.*, 2005, MA, 2005a; 2005b; Gurevitch *et al.*, 2002; Begon *et al*., 1990).

The more conventional view within ecology is that more complex communities (e.g. those with a greater number of species) are inherently more stable than less complex ones (Hooper *et al.*, 2005; Scherer- Lorenzen, 2005; Begon *et al*., 1996; 1990). Some research, however, has provided evidence contradicting the 'diversity-stability' hypothesis (Scherer- Lorenzen, 2005; Begon *et al*., 1990). For instance, Begon *et al*. (1990) point to a number of instances from real world and mathematically-modelled communities, where greater complexity/diversity appears to result in less stability (i.e. less resistance and resilience). From this perspective, the use of area to gauge the potential vulnerability of a habitat patch in terms of its species richness seems questionable. However, other work suggests that the stability (resistance) of the community was positively influenced by increased complexity at lower trophic levels (e.g. Pimm, 1979, 1982 and Hairston, 1968, cited in: Begon *et al*. 1990). This may be because the increased diversity of resources available higher up the food chain enabled species to compete less intensively, reducing the chances of competitive exclusion of one or more of the species (Begon *et al*., 1990). Furthermore, as highlighted in Chapter Two, the increased diversity of more species-rich communities should enhance the stability of ecological functions and service provision because they are likely to have an increased capacity to maintain existing ecological roles in the event of perturbations and environmental change (Cardinale *et al*., 2011; Scherer-Lorenzen, 2005; Thebault & Loreau, 2005; Hooper *et al*., 2005; Lawton, 1994). This can be regarded as analogous to the situation described above for more genetically-diverse populations. Isabell *et al*. (2009) recently demonstrated the significance of plant species richness in maintaining the stability of ecosystem functioning in long-term experimental grassland communities through complementary effects and redundancy.

6.2.2 Habitat Heterogeneity

Habitat heterogeneity (e.g. variations in elevation, slope, and soil type) can also play a vital role in facilitating the persistence of populations and communities over time (Botkin *et al*., 2007; Dufour et al., 2006; Tews *et al*., 2004; Gurevitch *et al.*, 2002; Araujo & Williams, 2000; Heino, 2000; Burnett *et al*., 1998; Nichols *et al*., 1998; Lack, 1969). This is particularly relevant in the case of the extreme weather events associated with climate change (e.g. an increase in the frequency and magnitude of heat waves and flooding) (IPCC, 2007a; 2007b). Increased habitat heterogeneity within an area affected by such events is likely to offer increased opportunities for survival and subsequent recovery for constituent populations and species (Botkin *et al*., 2007; Hooper *et al*., 2005). Although some studies have failed to demonstrate a positive relationship between area and habitat heterogeneity, e.g. Abbott (1978, cited in Begon *et al*., 1990, pp. 775-6), it is likely that, on balance, larger areas will contain greater variation in habitat and conditions (Lack, 1969; Laurance *et al*., 2002, pp. 607). For instance, Tonn & Magnuson (1982, cited in Begon *et al*., 1990, pp. 775) found that the habitat heterogeneity within northern Wisconsin lakes was closely correlated with lake area. Such research suggests that using the area of relevant landscape elements to infer vulnerability to climate change is valid.

6.2.3 Edge Effects

Edge effects relate to systematic differences between conditions close to the edges of patches compared to those of the interior (McGarigal, 2006; Gurevitch *et al.*, 2002; Forman, 2001). For instance, edges of heavily vegetated patches tend to experience greater wind speeds, increases in available light, greater differences in the magnitude of diurnal temperature variations and decreases in humidity compared to more sheltered interior areas (Gurevitch *et al*., 2002; Forman, 2001; Farina, 1998). Because of these differences, edges can be more sensitive to external factors (Tremblay-Boyer & Anderson, 2007). For instance, the decreases in humidity associated with the edges of patches of woodland and heath can lead to an increase in the severity and frequency of fires (Gurevitch *et al*., 2002). Other edge effects include an increased susceptibility to colonisation by invasive species and an increase in vegetation (e.g. trees) affected by wind damage (Gurevitch *et al*., 2002). Although edge effects are not always detrimental, overall they tend to have negative impacts on the composition and structure of existing communities (MA, 2005a; 2005b; CBD, 2003; Gurevitch *et al*., 2002; Mesquita *et al*., 1999).

6.2.4 Isolation, Connectivity and the Metapopulation

The degree of isolation of a patch of habitat is relevant in determining the persistence of constituent species or local populations in terms of metapopulation dynamics (Forman, 2001; Begon *et al.*, 1990; Levins, 1969). The population of a particular species inhabiting, or the composition of the community comprising, an individual patch can be affected by immigration from neighbouring or nearby areas (Begon *et al.*, 1990; Levins, 1969; MacArthur and Wilson, 1967). Local populations, comprising or occupying a patch that would otherwise be headed towards extinction, may be maintained due to the influence of inward dispersal of individuals from other patches (Murphy & Lovett-Doust, 2004; Gurevitch *et al.*, 2002; Farina, 1998). The proximity of the patch to other patches or populations of similar type within the landscape is obviously an important determinant of metapopulation dynamics (McGarigal, 2006; Begon *et al*., 1990). Patch size is also likely to be relevant in this, since larger islands represent a larger 'target' for dispersing species (Begon *et al*., 1990).

Arguments relating to the potential for local populations or communities (and therefore the ecological functions they are associated with) to be sustained through the process of metapopulation dynamics are undoubtedly valid. However, it is also possible that the increased connectivity of less isolated patches of habitat will also play a role in facilitating the spread of influences or factors which may negatively impact the biota comprising the patch (Morecroft *et al*., 2012). For instance, Murphy & Lovett-Doust (2004, pp. 6) point out that landscape corridors, as well as enabling re-establishment of locally extinct populations, can also facilitate 'the spread of diseases.....or species of concern'. Considering climate and land use change are predicted to, amongst other things, promote the spread, and exacerbate the impacts, of diseases and invasive species on existing communities (MA, 2005a; 2005b; RHS, 2005; CBD, 2003; Forseth, 1997; Williamson, 1996), gauging the remoteness of a patch to infer its future vulnerability is problematic (Morecroft *et al*., 2012). Connectivity could just as easily be associated with increases in vulnerability as decreases.

Providing meaningful estimates of population persistence or stability (in terms of connectivity and metapopulation dynamics) is inherently linked to the dispersal ability of target species (Gurevitch *et al*., 2002; McGarigal, 2006). Murphy & Lovett-Doust (2004) suggest notable differences in the dispersal abilities of even closely related taxa. The situation is complicated further by the likelihood that the often complex characteristics of the surrounding matrix (see below) also influence movement between patches (Murphy & Lovett-Doust, 2004; Gurevitch *et al*., 2002; Forman, 2001). The interaction of these factors is likely to result in somewhat unexpected and disparate dispersal patterns of different species. This is probably even more pertinent to plant species 'which rely on a variety of other organisms and agents (water, wind) to disperse' (Murphy & Lovett-Doust, 2004).

These points, combined with the characteristics of the methodology applied within this research (e.g. no specific focal species), as well as the lack of adequate information on species-specific dispersal abilities, suggest that incorporating measures of patch isolation or connectivity to infer vulnerability is a potentially spurious approach.

6.2.5 The Matrix

Contrary to the island biogeographical model of landscapes, the landscape mosaic approach (McGarigal, 2006, pp. 2) explicitly recognises that the matrix, in which a specific focal type of patch is embedded, is made up of a mosaic of different elements characterised by varying degrees of hospitableness. For instance, Fagan *et al*. (1999) demonstrate how the characteristics of land adjacent to habitat patches can act to influence immigration rates. Immigration is likely to be seriously impeded for a patch surrounded by relatively 'hard' impermeable land cover types, such as a patch of forest adjacent to an industrial or developed area (Murphy & Lovett-Doust, 2004, pp. 10). It is likely to be far less restricted for a patch bounded by relatively 'soft' permeable types, such as a mature forest patch surrounded by regrowth forest (Murphy & Lovett-Doust, 2004, pp. 7). The landscape mosaic model is therefore likely to represent a more ecologically meaningful and relevant approach than that of the biogeography model; particularly within a mainland, semi-natural context.

As previously suggested above, adequately incorporating the influence of matrix attributes on species specific dispersal capacities is conceptually problematic generally, and within the particular context of this research. However, the above points do demonstrate the important influence characteristics of the matrix have on patch processes and function and therefore the usefulness of considering these attributes in determining the potential vulnerability of target patch types.

Biernacki *et al.* (unpubl, cited in Murphy & Lovett-Doust, 2004, pp. 11) investigated the effects of land use in the matrix surrounding designated natural areas in Ontario, Canada. They report that 'the types of land use and their proportions....had highly significant effects on species richness'. Laurance *et al*. (2002, pp. 610) report that Amazonian forest fragments enclosed by 5-10m tall regrowth forest 'experienced less intensive changes in microclimate and had lower edge related tree mortality' than similar patches surrounded by cattle pastures. Mesquita *et al*. (1999) also found that forest bordered by cattle pasture had significantly higher tree mortality rates compared to patches adjacent to other, more vegetatively similar types. These examples suggest that matrix type has the potential to notably alter the magnitude and penetration (into the patch) of edge effects. They also suggest that the particular vegetation structure of the surrounding matrix is important in providing a buffer against negative edge effects (Mesquita *et al*., 1999). Laurance *et al*. (2002, pp. 611) states:

> 'In general, the more closely the matrix approximated the structure and microclimate of the primary forests, the more likely that fragmentation-sensitive species could use it.'

These points, as well as providing additional support for the general idea that the character of the matrix has an important influence on particular focal patches, also offer a number of further implications. First, the specific type of land cover(s) surrounding a patch and their relative proportions play a role in influencing patch characteristics. Second, greater similarity between the surrounding matrix and a target patch type means the matrix is more likely to provide an effective buffer against edge effects. Third, more human-modified patch types are likely to have a greater detrimental impact on the health and functioning of less modified 'semi-natural' types. Also, the land covers immediately adjacent to target patches are likely to have a greater influence than those further away (Laurance *et al.*, 2002; Mesquita *et al.*, 1999).

6.3 Methods

6.3.1 Introduction

The above discussion provides a number of important implications in terms of the specific measures of landscape spatial patterns and structure that can be used to provide a meaningful assessment of the future vulnerability of PBVC patches. A measure of patch area is likely to be useful, particularly in the context of environmental change, due to the apparent relationship between area, species richness, population size, habitat heterogeneity and ecological stability.

Total area is also related to the amount of interior habitat a patch contains (i.e. all other things being equal, a larger patch will tend to contain more interior area). However, the complexity of the shape of the patch, specifically the perimeter-to-area ratio is also relevant in gauging its edge affected area (Gurevitch *et al*., 2002). Other studies have often employed a core-area metric to integrate patch size, shape complexity and edge effect distance into a single measure (e.g. Tremblay-Boyer & Anderson, 2007). The edge buffer representing the edge effect distance defined by the user can be defined arbitrarily (e.g. Tremblay-Boyer & Anderson, 2007) but ideally should be relevant to the phenomena of interest (McGarigal, 2006). Previous research suggests that the edge affected-distance can vary quite considerably between individual patches of even closely-related type. For instance, Laurance *et al*. (2002) report that edge effects can penetrate up to 300-400m into the interior of Amazonian rainforest fragments. However, Mesquita *et al*. (1999) suggest that the edge-affected distance for fragments of rainforest within the Amazon can be up to about 100m and depends on the specific type of vegetation surrounding the fragments (there appeared to be a greater depth of penetration into pasture bordered edges than those surrounded by regrowth forest). This apparent variation between the edge-affected areas of fragments of similar type is likely to be even more pronounced where differences in type are evident.

These points combined with the general approach adopted within this study (i.e. no specific PBVC is the particular focus of the research) suggest that a user-defined buffer applied uniformly to all PBVC patches may produce spurious results. However, even if secondary information was available on the likely edge-affected area of different patches and patch types within the specific context of NNP, it would be impractical to adjust the edge buffer for individual patches or PBVC types.

Section 6.2 discussed the theoretical and methodological problems associated with adequately gauging the influence of connectivity on the vulnerability of habitat patches. Integration of measures of patch isolation, connectivity or dispersion (McGarigal, 2006, pp. 4) into the vulnerability assessment is regarded as inappropriate.

Finally, the necessity of incorporating the characteristics of the matrix surrounding target patches into the vulnerability assessment is apparent. It is likely that areas immediately adjacent to focal patches will have the greatest impacts (e.g. Laurance *et al.*, 2002; Mesquita *et al.*, 1999). The reviewed literature suggests a basic distinction between land-cover types that have experienced greater anthropogenic modification and more natural types. Negative impacts on more natural land-cover types tend to be greatest when they are adjacent to more modified land-covers (Murphy & Lovett-Doust, 2004; Laurance *et al*., 2002). The proportion of modified land adjacent to target patches can determine the magnitude of impacts (e.g. Biernacki *et al.* (unpubl. In Murphy & Lovett-Doust, 2004, pp. 11).

Based on these points, two broad measures were used to assess the vulnerability of PBVCs in terms of their spatial and contextual characteristics. The first is a measure of patch Geometry ('Geometric Vulnerability' (VM2a)) that combines patch area and shape complexity. The second is a measure of boundary characteristics ('Matrix Vulnerability' (VM2b)). Together these measures represent the vulnerability of patches to changes in land use, in terms of the potential impact on patch size, complexity and boundary characteristics.

6.3.2 Patch Geometry (VM2a)

6.3.2.1 Patch Shape Complexity (SC)

Patch shape complexity was gauged by measuring the area and perimeter of a PBVC patch and comparing its perimeter to that of a perfect circle with the same area. The theory underpinning this approach is that 'a circle has the least perimeter per area of any shape, which means there are fewer edges that are susceptible to change' (Tremblay-Boyer & Anderson, 2007, pp. 12). The perimeter of a patch's perfect circle was calculated:

$$P_{circle} = 2(\pi A)^{0.5} \qquad \text{(Equation 4)}$$

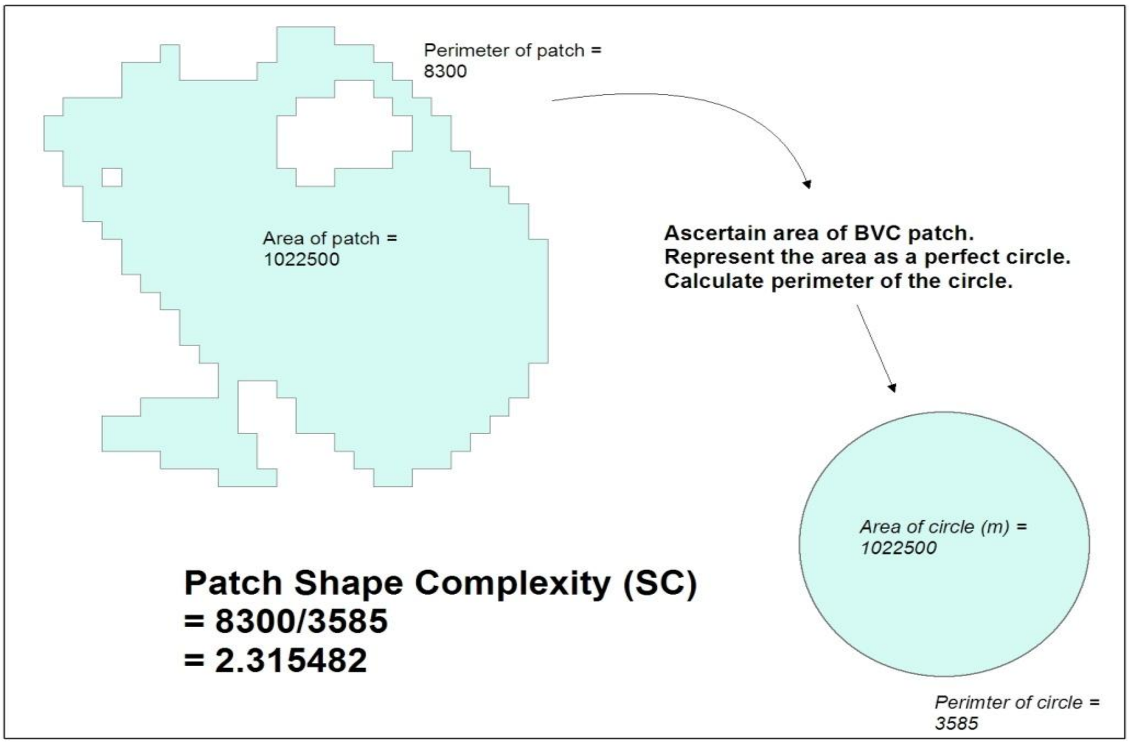
Where P_{circle} is the perimeter of a perfect circle with the same area as the PBVC patch and *A* is the area of the PBVC patch.

Once the area and perimeter of the patch and its perfect circle are determined, the shape complexity of the patch was calculated:

$$SC = \frac{P_{patch}}{P_{circle}} \qquad \text{(Equation 5)}$$

Where *SC* is the shape complexity of the PBVC patch, P_{patch} is the perimeter of the PBVC patch and P_{circle} is the perimeter of its perfect circle (Figure 6.1). Higher *SC* values equal greater complexity.

Figure 6.1: (not to scale) Conceptual method for ascertaining the shape complexity (*SC*) of PBVC patches. In this instance, the patch's perimeter is over two times as long as a perfect circle with the same area (Adapted from: Tremblay-Boyer & Anderson, 2007). Gaps in patches are included as perimeter.



6.3.2.2 Area (A)

Despite the usefulness of measures of patch shape complexity they do not incorporate vital information on area (i.e. patches of different size but the same shape complexity have the same *SC* values). The area of each PBVC patch within each scenario was therefore calculated. An edge effect buffer was not applied due to the issues discussed in Section 6.3.1.

6.3.2.3 Combining the 'SC' and 'A' Measures: Patch Geometry (VM2a)

There were significant disparities between the range of values for patch area and *SC* within the park. This meant that more common methods of normalisation (e.g. as a simple ratio of the maximum value: as in Wu *et al.*, 2002, pp. 264) were not appropriate because of the bias it afforded to the *SC* component when values were combined.

The values of patches for *SC* and area were ranked separately in terms of their position within an ordered list of values for the respective variable for all PBVC patches across all time slices within the park. This normalised values for each measure within a more equable numerical range.

The ranked value of each patch for each of the two measures was then combined:

$$CR_{patch} = SC_{rank} + A_{rank} \qquad \text{Equation 6}$$

Where CR_{patch} is the combined rank of a PBVC patch, SC_{rank} is the ranked *SC* value of the patch and A_{rank} is the ranked *A* value of the patch. This resulted in a range of values between 13500 and 43914.

These values were then rescaled within the 0-1 range (13500 = 0; 43914 = 1) using a linear stretching procedure to provide the Geometric Vulnerability (VM2a) of each patch:

$$VM2a = \frac{CR_{patch} - 13500}{43914 - 13500} \qquad \text{Equation 7}$$

This allowed for better comparison with the value range of the other vulnerability measures (i.e. 1 = most vulnerable, 0 = least vulnerable).

6.3.3 Matrix Characteristics (VM2b)

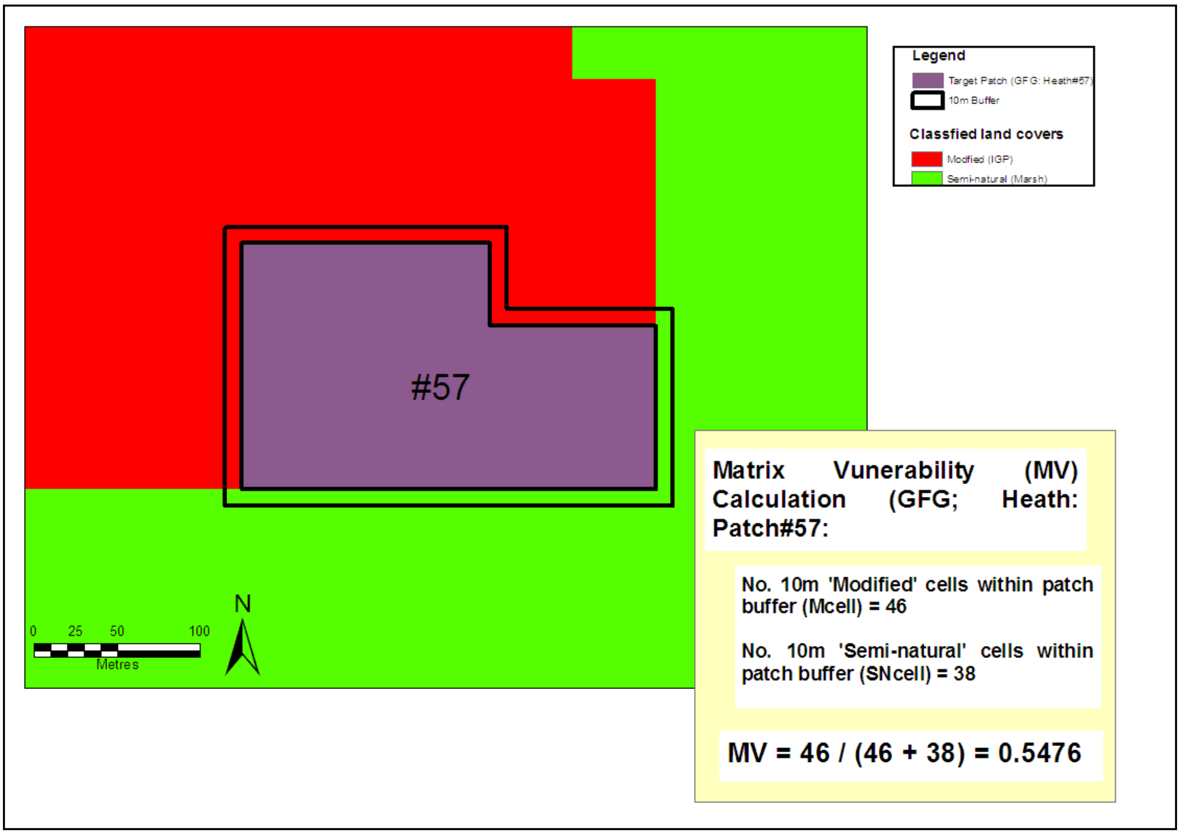
To gauge patch vulnerability in terms of matrix characteristics, all P/NPBVCs within the park were categorised as either 'Modified' or 'Semi-natural' (see: Table A3 for details of this classification). 10m buffer zones were then created around the edge of each target BVC patch under each of the time slices. Matrix vulnerability was estimated as the proportion of *Modified* P/NPBVCs within this buffer as follows:

$$MV = \frac{M_{cell}}{M_{cell} + SN_{cell}} \qquad \text{(Equation 8)}$$

Where MV is the Matrix Vulnerability of the PBVC patch; M_{cell} is the number of 10m 'Modified' cells within the 10m patch buffer and SN_{cell} is the number of 10m 'Semi natural' cells within the buffer (Figure 6.2).

The characteristics of this method mean that only those land covers which are likely to have the greatest impact on the target patch (i.e. those immediately adjacent to it) are considered when gauging its vulnerability. Adequate land cover data for areas immediately adjacent to NNP's external border was not readily available. For target BVC patches sharing a boundary with the border of NNP, Matrix Vulnerability was calculated based on the proportion of 'Modified' P/NPBVCs adjacent to the patch's boundary within NNP. For example, a hypothetical target P/NPBVC patch is bounded by five 'Modified' cells, and six 'Semi natural' cells within NNP. Twelve cells adjoin the border of NNP. In the Matrix Vulnerability calculation for this patch M_{cell} = 5 and SN_{cell} = 6.

Figure 6.2: MV calculation for Heath patch #57 under the GFG scenario. MV = 0.5476 as there is a slightly greater proportion of 'Modified' cells than 'Semi-natural' cells within the 10m buffer.



6.4 Geometric Vulnerability (VM2a): Results and Discussion

Results and Discussion sections for Geometric Vulnerability are provided separately to those for Matrix Vulnerability. The results sections for both of these measures are presented following the same general structure as the results for Climate Stress (Chapter Five).

6.4.1 Results

6.4.1.1 Northumberland National Park (NNP)

Landscape and Class level results

Table 6.1a shows that essentially there are no differences between average levels of vulnerability in terms of geometry for the PBVCs overall across NNP under the time slices: all exhibit moderate levels of vulnerability. Figures 6.3a-c show that this occurs despite the overall increase in PBVC coverage under the future scenarios. There is a very slight decrease (0.001) in vulnerability under Going for Growth compared to current and Conservation First levels (Table 6.1a).

Table 6.1a: Average Geometric Vulnerability for all of the PBVCs (bottom row) and for each individual PBVC under each time slice. Values in brackets show the difference in vulnerability between the current and future time slices. Values highlighted red or green show (respectively) the highest and lowest vulnerability (or change in vulnerability) under each time slice. Values highlighted red or green in bold italics show the highest/lowest levels of vulnerability (or change in vulnerability) across all of the time slices.

PBVC	**Current**	**Conservation First**	**Going for Growth**
Blanket Bog	0.460	0.545 (0.085)	0.460 (0.000)
Broadleaved Woodland: Priority (BLWP)	0.649	0.615 ***(-0.034)***	0.626 (-0.023)
Fen	0.466	0.611 (0.145)	0.466 (0.000)
Heath	0.566	0.595 (0.029)	0.581 (0.015)
Improved Grassland: Priority (IGP)	0.518	0.533 (0.015)	0.544 (0.026)
Marsh	0.651	0.651 (0.000)	0.651 (0.000)
Neutral Grassland: Priority (NGP)	0.580	0.583 (0.003)	0.600 (0.020)
Raised Bog	***0.270***	0.531 (0.261)	***0.270*** (0.000)
Swamp	***0.679***	***0.679*** (0.000)	***0.679*** (0.000)
Average Geometric Vulnerability	0.620	0.620 (0.000)	0.619 (-0.001)

Figure 6.3a: Geometric Vulnerability of all PBVC patches within NNP under the current time slice. Maps depicting the Geometric Vulnerability of patches for specific PBVCs are available upon request.

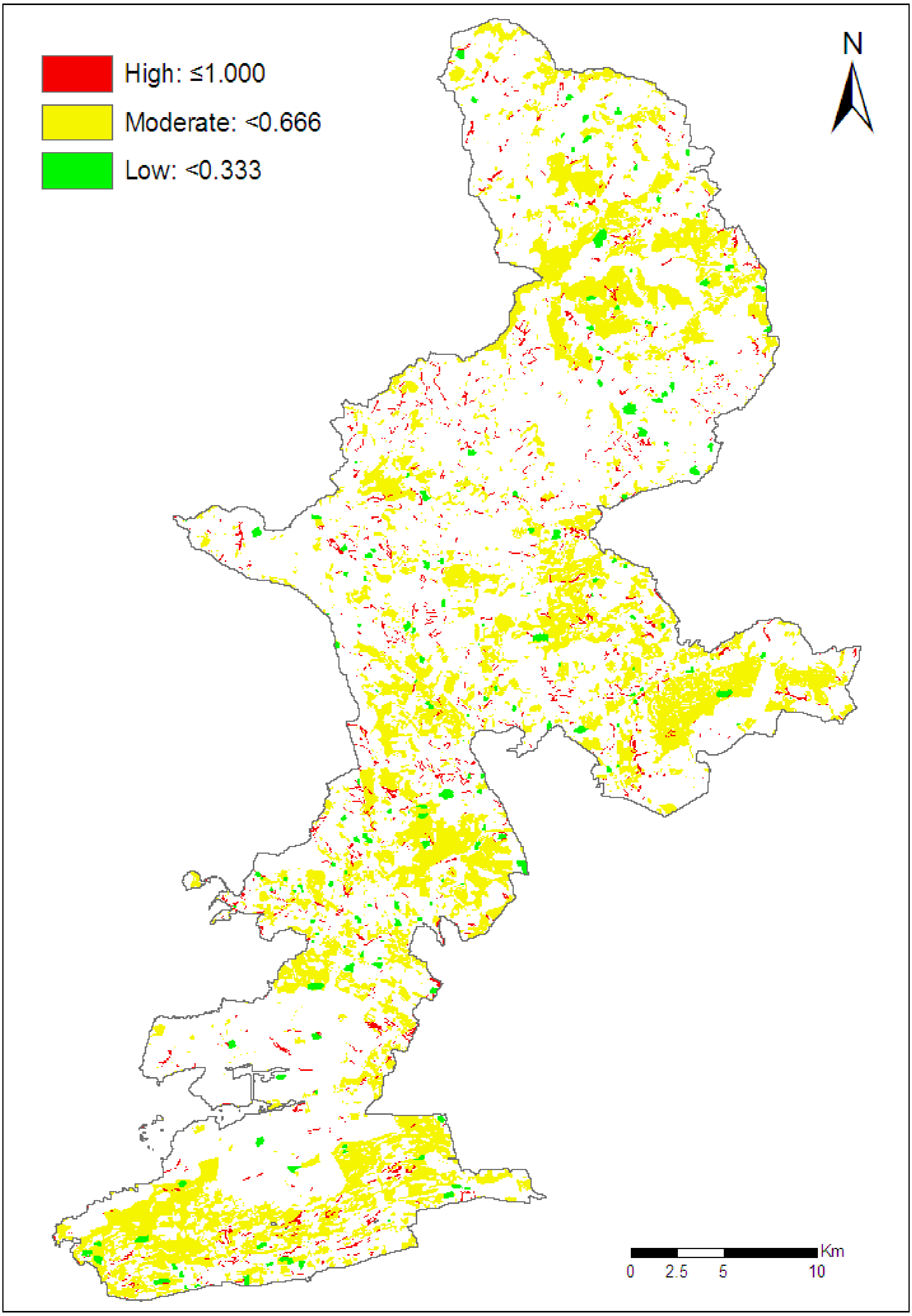


Figure 6.3b: Geometric Vulnerability of all PBVC patches within NNP under Conservation First. Maps depicting the Geometric Vulnerability of patches for specific PBVCs are available upon request.

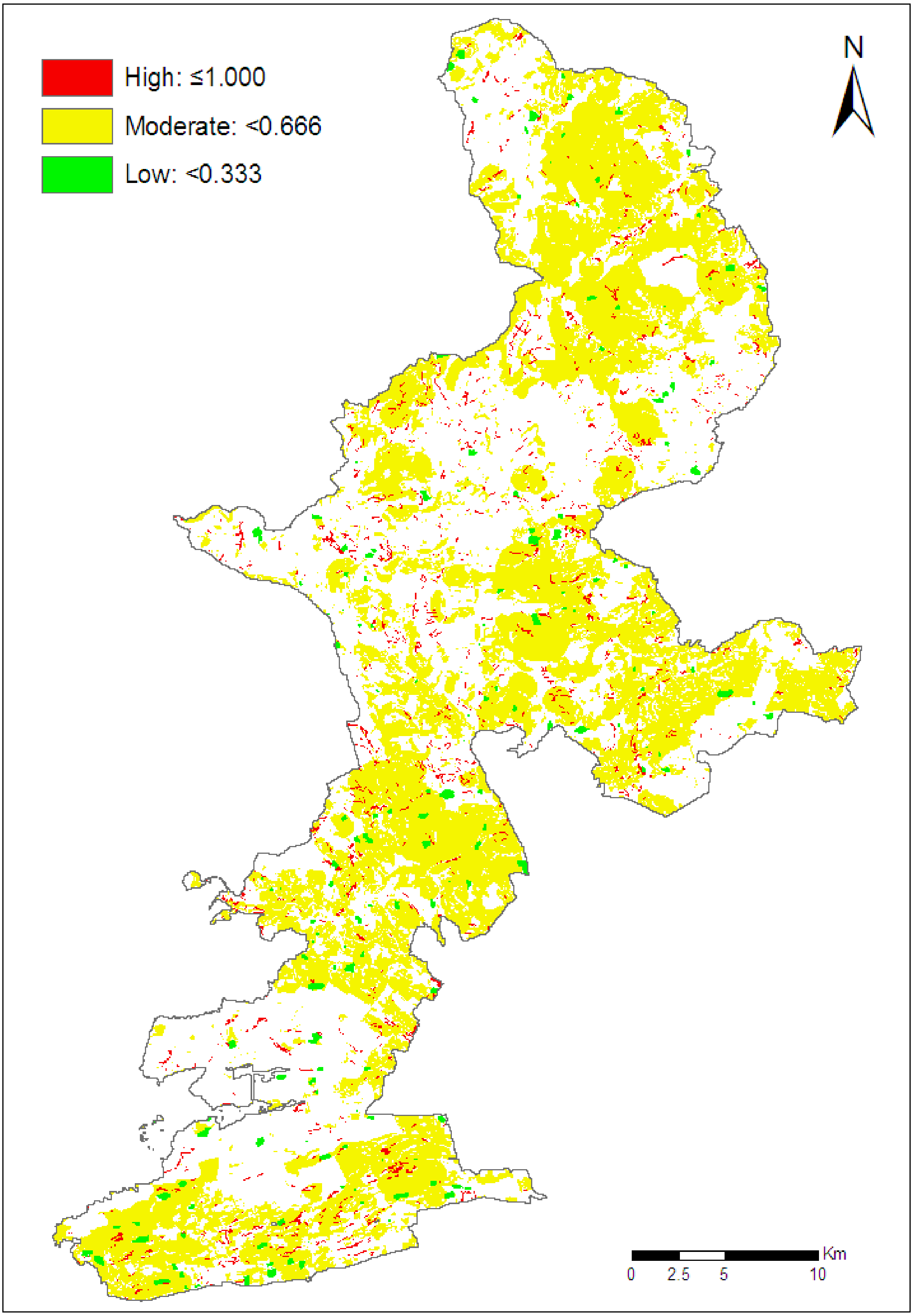
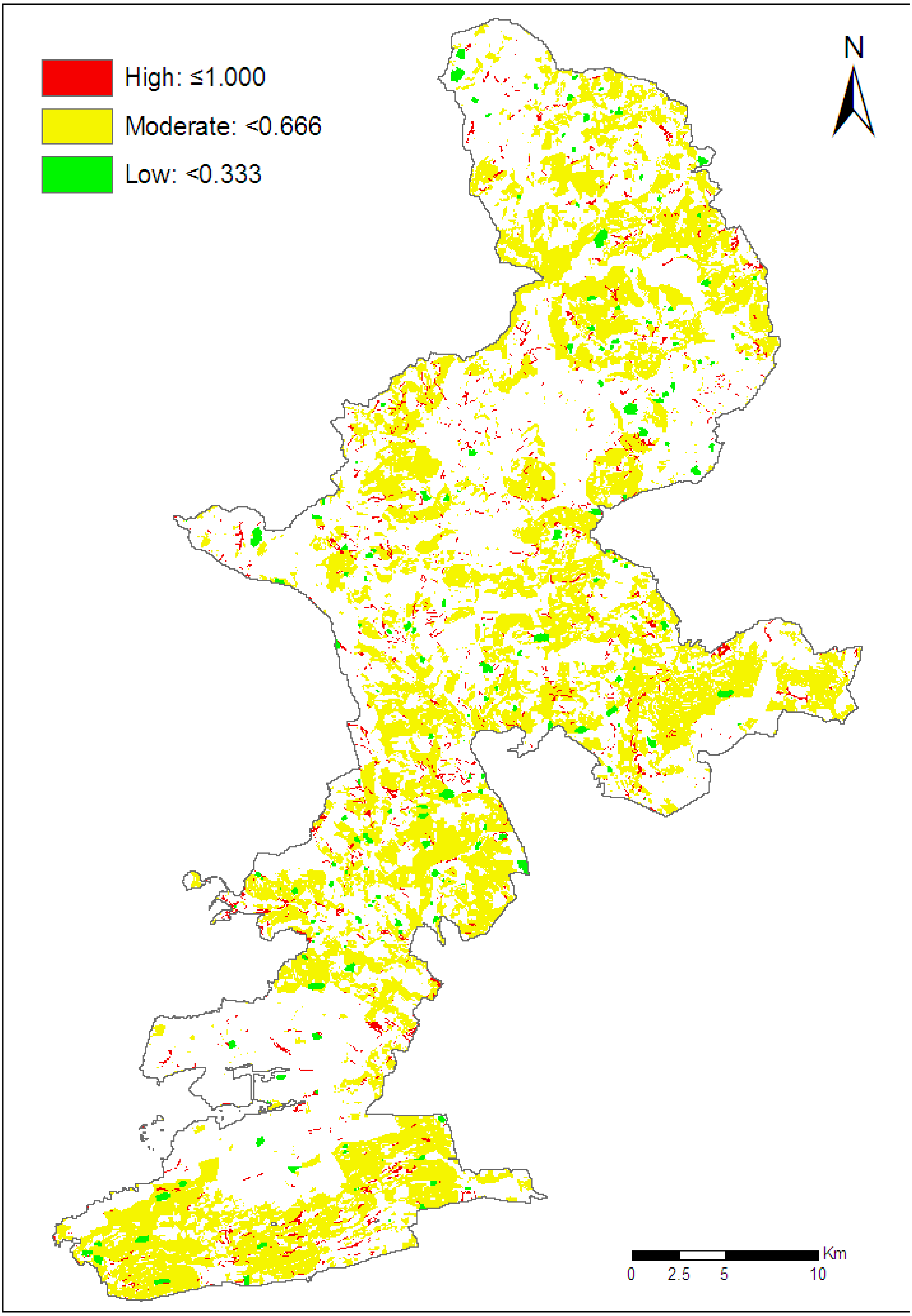


Figure 6.3c: Geometric Vulnerability of all PBVC patches within NNP under Going for Growth. Maps depicting the Geometric Vulnerability of patches for specific PBVCs are available upon request.



In terms of individual PBVCs, the highest and lowest levels of vulnerability in each of the time slices are associated with Swamp and Raised Bog respectively. The vulnerability associated with Swamp (0.679) does not change across all three time slices. The lowest vulnerability across all three time slices is associated with Raised Bog currently and under Going for Growth.

The results for many of the PBVCs are broadly similar (Table 6.1a). The majority of PBVCs generally exhibit moderate levels of vulnerability. The range of average vulnerability values for all PBVCs (excluding Raised Bog) over all three time slices is only 0.213. The vulnerability of Raised Bog is notably lower than most of the other PBVCs under the current time slice and Going for Growth. Although the vulnerability of Raised Bog increases under Conservation First, it is still lower than that associated with the other PBVCs. Raised Bog is therefore consistently ranked as the least vulnerable PBVC under each of the time slices. Overall, Raised Bog currently and under Going for Growth is ranked as the second least and least vulnerable PBVC respectively (Table 6.2).

Most of the PBVCs exhibit only slight changes in vulnerability between the current and future time slices. For instance, with the exception of Fen and Raised Bog under Conservation First, the biggest single change in vulnerability under both of the future scenarios is an increase of 0.085 associated with Blanket Bog under Conservation First.

In general, the largest changes in vulnerability compared to current conditions are observed for Conservation First (Table 6.1a). For instance, the largest and second largest increases in vulnerability occur between these time slices for Raised Bog and Fen, respectively. Because of the more notable changes in vulnerability occurring under Conservation First, some changes are observed in terms of the ranking of particular PBVCs under the scenario, compared to the current time slice (Table 6.2). For instance, due to the relatively large increase in the vulnerability of Fen (0.145) under Conservation First, its rank increases from seventh most vulnerable currently (18th overall), to the fourth most vulnerable under the future scenario (6th overall). The relatively moderate increase in the vulnerability of Blanket Bog under Conservation First (0.085) means that its rank increases from the eighth most vulnerable PBVC currently (19th overall) to the seventh most vulnerable under Conservation First (13th overall). These relatively large increases, combined with the relatively small increases associated with IGP and NGP under the scenario (0.015 and 0.003 respectively), largely explains the change in ranking of both these PBVCs under Conservation First. The ranking of IGP decreases from the sixth most to eighth most vulnerable PBVC, between the current time slice and Conservation First. The ranking of NGP decreases from the fourth most vulnerable PBVC currently to the sixth most vulnerable PBVC under Conservation First. Although the largest single increase in vulnerability is associated with Raised Bog under Conservation First (0.261), it is still ranked as the least vulnerable PBVC under the scenario.

However, because of the increase, levels of vulnerability associated with Raised Bog under Conservation First are much closer to that of the other PBVCs.

Because only very minor changes are associated with the PBVCs currently, compared to Going for Growth, there are no changes in the ranking of the PBVCs under the scenario. Indeed in terms of overall ranking the PBVCs currently and under Going for Growth also exhibit very little difference.

For purposes of analysis in subsequent sections, statistics relating to average patch area, SC and Geometric Vulnerability and for each individual PBVC under each time slice for NNP are presented in Table 6.1b.

Table 6.1b: Number of patches, average area, SC and Geometric Vulnerability (GV) and for each individual PBVC under each time slice for NNP.

PBVC	Current				Conservation First				Going for Growth			
	No. patches	**Av. Area (m^2)**	**Av. SC**	**GV**	**No. patches**	**Av. Area (m^2)**	**Av. SC**	**GV**	**No. patches**	**Av. Area (m^2)**	**Av. SC**	**GV**
Blanket Bog	78	428622	1.847	0.460	150	403000	1.700	0.545	78	428622	1.847	0.460
BLWP	323	26788	1.630	0.649	395	102152	1.827	0.615	272	63621	1.816	0.626
Fen	32	151484	1.608	0.466	308	50154	1.514	0.611	32	151484	1.608	0.466
Heath	365	202870	1.759	0.566	498	400186	1.841	0.595	774	257813	1.873	0.581
IGP	363	127479	1.791	0.518	349	147436	1.838	0.533	318	95142	1.721	0.544
Marsh	2143	53994	1.630	0.651	2143	53994	1.630	0.651	2143	53994	1.630	0.651
NGP	82	29695	1.504	0.580	118	73686	1.676	0.583	62	23831	1.484	0.600
Raised Bog	4	194375	1.530	0.270	45	51722	1.485	0.531	4	194375	1.530	0.270
Swamp	35	12143	1.441	0.679	35	12143	1.441	0.679	35	12143	1.441	0.679
Average	381	83680	1.660	0.620	449	122285	1.685	0.620	413	108601	1.702	0.619

Table 6.2: The ranking of each PBVC (high to low), in terms of average Geometric Vulnerability, for the study area across all time slices. Numeric prescripts denote rank of NCA within each time slice.

Rank	Current	Conservation First	Going for Growth
1	1. Swamp (0.679)	1. Swamp (0.679)	1. Swamp (0.679)
2	2. Marsh (0.651)	2. Marsh (0.651)	2. Marsh (0.651)
3	3. BLWP (0.649)		
4			3. BLWP (0.626)
5		3. BLWP (0.615)	
6		4. Fen (0.611)	
7			4. NGP (0.600)
8		5. Heath (0.595)	
9		6. NGP (0.583)	
10			5. Heath (0.581)
11	4. NGP (0.580)		
12	5. Heath (0.566)		
13		7. Blanket Bog (0.545)	
14			6. IGP (0.544)
15		8. IGP (0.533)	
16		9. Raised Bog (0.531)	
17	6. IGP (0.518)		
18	7. Fen (0.466)		7. Fen (0.466)
19	8. Blanket Bog (0.460)		8. Blanket Bog (0.460)
20	9. Raised Bog (0.270)		
21			9. Raised Bog (0.270)

6.4.1.2 National Character Areas

Landscape Level Results

Table 6.3 shows that the highest and lowest levels of vulnerability in terms of geometry in each of the three time slices are associated with the Cheviots and Cheviot Fringe respectively. Overall the Cheviot NCA under Conservation First exhibits the highest vulnerability. The lowest vulnerability overall is associated with the Cheviot Fringe under Going for Growth. NSH is consistently ranked as the third most vulnerable NCA in each of the time slices. There is very little difference between the vulnerability of the NCAs within and between the three time slices. For instance, the overall range of vulnerability values across all NCAs across all time slices is 0.036.

Table 6.4 does reveal some interesting trends. For instance, the Cheviot NCA is most, second most and third most vulnerable NCA in terms of overall ranking. The Cheviot Fringe, in terms of overall ranking, is the least, second least and third least vulnerable NCA. The ranking of the other NCAs demonstrates some variation between each of the time slices. For instance, TG is ranked fourth currently and under Conservation First (11^{th} and 10^{th} respectively overall). However, its ranking increases to second under Going for Growth (fourth overall), reflecting the relatively large increase in vulnerability (0.016) that the NCA experiences under the scenario.

BMF ranks as the second most vulnerable NCA currently and under Conservation First (7th and 6th overall). Its rank decreases to the fourth most vulnerable NCA under Going for Growth (8th overall). This is due to the decrease in vulnerability of 0.002 that the NCA experiences under the scenario (Table 6.3) and the relatively large increases associated with NSH and TG.

Table 6.3: Average Geometric Vulnerability for all PBVCs across each NCA under each time slice. Values in brackets show the difference in vulnerability between the current and future time slices. The highlighting of specific values follows the same format as that for Table 6.1a.

NCA	**Current**	**Conservation First**	**Going for Growth**
Cheviots	0.633	***0.635*** (0.002)	0.626 ***(-0.007)***
Cheviot Fringe	0.604	0.606 (0.002)	***0.599*** (-0.005)
Northumberland Sandstone Hills (NSH)	0.611	0.615 (0.004)	0.617 (0.006)
Border Moors and Forests (BMF)	0.615	0.616 (0.001)	0.613 (-0.002)
Tyne Gap and Hadrian's Wall (TG)	0.608	0.609 (0.001)	0.624 ***(0.016)***

Table 6.4: The ranking of each NCA (high to low), in terms of average Geometric Vulnerability under each time slice. Numeric prescripts denote rank of NCA within each time slice.

Overall Rank	**Current**	**Conservation First**	**Going for Growth**
1		1. Cheviot (0.635)	
2	1. Cheviot (0.633)		
3			1. Cheviot (0.626)
4			2. TG (0.624)
5			3. NSH (0.617)
6		2. BMF (0.616)	
7	2. BMF (0.615)	3. NSH (0.615)	
8			4. BMF (0.613)
9	3. NSH (0.611)		
10		4. TG (0.609)	
11	4. TG (0.608)		
12		5. Cheviot Fringe (0.606)	
13	5. Cheviot Fringe (0.604)		
14			5. Cheviot Fringe (0.599)

Class Level Results

Table 6.5 shows that, across all time slices over all NCAs, Swamp in the Cheviots exhibits the highest levels of vulnerability in terms of geometry (0.853). Fen, under Going for Growth, within the NSH NCA, exhibits the lowest levels of vulnerability overall (0.250).

Cheviots

Swamp exhibits the highest levels of vulnerability under each of the three time slices. The lowest levels of vulnerability currently and under Going for Growth are observed for Blanket Bog. The lowest vulnerability under Conservation First is associated with NGP. Overall, the highest vulnerability is for Swamp under each of the three time slices. The lowest level of vulnerability overall is for Blanket Bog currently and under Going for Growth.

Cheviot Fringe

The highest levels of vulnerability are associated with Marsh under each of the three time slices. These are also the highest levels of vulnerability overall for the NCA. The lowest levels of vulnerability are associated with IGP under each of the three time slices. The lowest levels of vulnerability overall for the NCA are associated with IGP currently and under Going for Growth.

Northumberland Sandstone Hills

Marsh under each of the three time slices also exhibits the highest levels of vulnerability within the NSH NCA. These are also the highest levels of vulnerability overall for the NCA. Currently the least vulnerable PBVC within the NCA is NGP. This is the lowest vulnerability overall. Blanket Bog is the least vulnerable PBVC under both future scenarios.

Border Moors and Forests

Swamp under each of the three time slices exhibits the highest levels of vulnerability. These are also the highest levels of vulnerability overall for the NCA. The lowest levels of vulnerability under each of the three time slices are observed for Raised Bog. Its vulnerability currently and under Going for Growth are the lowest for the NCA overall.

Tyne Gap and Hadrian's Wall

The highest levels of vulnerability currently and under Going for Growth are associated with BLWP. These are also the highest levels of vulnerability overall. The most vulnerable PBVC under Conservation First is Swamp. Blanket Bog under each of the three time slices exhibits the lowest levels of vulnerability: Its levels of vulnerability currently and under Conservation First are the lowest overall.

Table 6.5: Average Geometric Vulnerability for each PBVC within each NCA under each time slice. The highlighting of specific values follows the same general format as that for Tables 6.1a and 6.3: Values followed by an '*' denote the PBVCs with the highest/lowest Overall Vulnerability across all NCAs across all time slices.

NCA	PBVC	Current	Conservation First	Going for Growth
Cheviot	Blanket Bog	***0.479***	0.578 ***(0.099)***	***0.479*** (0.000)
	BLWP	0.636	0.605 (-0.031)	0.673 (0.037)
	Fen	0.564	0.564 (0.000)	0.564 (0.000)
	Heath	0.573	0.602 (0.029)	0.562 (-0.011)
	IGP	0.496	0.529 (0.033)	0.521 (0.025)
	Marsh	0.664	0.664 (0.000)	0.664 (0.000)
	NGP	0.590	0.528 ***(-0.062)***	0.606 (0.016)
	Raised Bog	N/A	N/A	N/A
	Swamp	***0.853****	***0.853**** (0.000)	***0.853**** (0.000)
Cheviot Fringe	Blanket Bog	N/A	N/A	N/A
	BLWP	0.633	0.632 (-0.001)	0.592 (-0.041)
	Fen	N/A	N/A	N/A
	Heath	N/A	0.562 (0.562)	0.571 ***(0.571)***
	IGP	***0.462***	0.489 (0.027)	***0.462*** (0.000)
	Marsh	***0.680***	***0.680*** (0.000)	***0.680*** (0.000)
	NGP	0.668	0.594 ***(-0.074)***	0.665 (-0.003)
	Raised Bog	N/A	N/A	N/A
	Swamp	N/A	N/A	N/A
Northumberland Sandstone Hills	Blanket Bog	0.437	0.485 (0.048)	0.437 (0.000)
	BLWP	0.621	0.620 (-0.001)	0.600 (-0.021)
	Fen	0.576	0.644 (0.068)	0.576 (0.000)
	Heath	0.602	0.597 (-0.005)	0.611 (0.009)
	IGP	0.530	0.556 (0.026)	0.555 (0.025)
	Marsh	***0.663***	***0.663*** (0.000)	***0.663*** (0.000)
	NGP	***0.398***	0.569 ***(0.171)***	0.517 (0.119)
	Raised Bog	N/A	N/A	N/A
	Swamp	N/A	N/A	N/A
Border Moors and Forests	Blanket Bog	0.452	0.547 (0.095)	0.452 (0.000)
	BLWP	0.647	0.614 ***(-0.033)***	0.625 (-0.022)
	Fen	0.432	0.600 (0.168)	0.432 (0.000)
	Heath	0.544	0.577 (0.026)	0.571 (0.027)
	IGP	0.525	0.548 (0.023)	0.554 (0.029)
	Marsh	0.641	0.641 (0.000)	0.641 (0.000)
	NGP	0.568	0.587 (0.019)	0.592 (0.024)
	Raised Bog	***0.270****	0.541 ***(0.271)***	***0.270**** (0.000)
	Swamp	***0.669***	***0.669*** (0.000)	***0.669*** (0.000)
Tyne Gap and Hadrian's Wall	Blanket Bog	***0.429***	0.445 (0.016)	***0.429*** (0.000)
	BLWP	***0.692***	0.618 ***(-0.074)***	***0.692*** (0.000)
	Fen	0.452	0.634 (0.182)	0.452 (0.000)
	Heath	0.623	0.621 (-0.002)	0.613 (-0.010)
	IGP	0.507	0.507 (0.000)	0.564 (0.057)
	Marsh	0.650	0.650 (0.000)	0.650 (0.000)
	NGP	0.574	0.559 (-0.015)	0.638 (0.064)
	Raised Bog	N/A	0.483 ***(0.483)***	N/A
	Swamp	0.661	0.661 (0.000)	0.661.000)

6.4.2 Discussion

6.4.2.1 NNP

The results in Tables 6.1a and 6.2 clearly show that there is essentially no difference in aggregate levels of Geometric Vulnerability between current and future time slices. All time slices generally demonstrate moderate levels of vulnerability. These results may be partially attributable to the number of PBVCs that retain their current distribution under the future scenarios, particularly Going for Growth. For instance, due to the land use trends developed for Going for Growth (Tables 4.7 & 4.8) the current distributions of all of the 'wetland' PBVCs were maintained when simulating land use change under the future scenario. For similar reasons the current distributions of Marsh and Swamp are also unchanged under Conservation First. The geometry of the patches associated with these PBVCs does not change between current and future time slices (see Table 6.1b).

Despite these characteristics, the overall results are somewhat surprising; particularly in the case of Conservation First, as a number of PBVCs do undergo changes in their distribution (Tables 4.5 and 4.6). For instance, a number of PBVCs under Conservation First (Blanket Bog, Fen, Heath, IGP, NGP and Raised Bog) and Going for Growth (Heath, IGP and NGP) experience a related increase in vulnerability in terms of geometry (Table 6.1a): Although the increases in vulnerability are very small (with the exception of Raised Bog and Fen under Conservation First), some differences between overall levels of Geometric Vulnerability between current and future time slices may be expected.

However, the vulnerability of BLWP decreases under both of the future scenarios. It is likely that the lack of change in aggregate levels of vulnerability between current and future time slices is due to the combination of the relatively high proportion of patches that retain their characteristics from current and future scenarios, the large number of PBVCs which demonstrate only a very small degree of change in levels of vulnerability under the future time slices and the trends for BLWP. For instance, Table 4.18 shows that the proportion of patches belonging to those PBVCs under Conservation First whose geometry remains the same, changes very little or whose vulnerability generally reduces (i.e. those associated with BLWP), is 91%. The overall results are likely to be biased in favour of the characteristics of the patches of these PBVCs, even in the case of Conservation First, where more distinct variations in levels of Geometric Vulnerability are observed.

A notable exception to these general trends is Raised Bog. Its vulnerability is low currently (and under Going for Growth). Its vulnerability increases notably under Conservation First and is associated with moderate vulnerability under the scenario. Although Fen generally exhibits moderate levels of vulnerability in each of the three time slices, it is worthy of note, as it experiences a relatively large increase in vulnerability under Conservation First.

The results of this research (Table 6.1b), as well as the findings of others (e.g. Didham & Ewers, 2012) suggest that there is positive relationship between patch area and complexity (i.e. larger habitat fragments tend to have greater shape complexity than smaller remnants). Decreases in patch vulnerability associated with increased area are likely to be somewhat offset by increases in vulnerability associated with increases in patch shape complexity. The results for individual PBVCs, to some degree, may be interpreted within this context. For instance, Table 6.1b shows that a number of PBVCs undergoing expansion under Conservation First (Heath, IGP, NGP) and Going for Growth (Heath) experience an increase in average patch size, an associated increase in patch shape complexity and an increase in Geometric Vulnerability under the scenarios. This suggests that in these particular instances increasing coverage has been facilitated through the expansion or creation of larger more complex patches. The decreases in vulnerability associated with increasing patch area are more than offset by the increases in vulnerability associated with the increases in shape complexity.

Other PBVCs under Conservation First (Blanket Bog, Fen and Raised Bog) and Going for Growth (IGP and NGP) demonstrate a general decrease in patch area, a decrease in patch shape complexity and an increase in Geometric Vulnerability. As well as providing further evidence for the relationship between patch area and complexity, these results also suggest that for these PBVCs specifically, the land use changes under the scenarios act to create smaller, less complex patches. However the decreases in shape complexity are not enough to compensate for decreases in area.

In relation to IGP and NGP under Going for Growth, these decreases are due to the encroachment of other P/NPBVCs as indicated by the decreases in the proportional number of patches and areal coverage associated with these PBVCs under the scenario (Tables: 4.18 & 4.19). For the other PBVCs, change is associated with increased areal coverage and an increase in the number of patches. These results suggest that increased coverage within the park is facilitated by the creation of a greater number of smaller, less complex patches. This could mean that the specific distribution of areas of available suitable habitat within the study area is more diffuse than for other PBVCs, which therefore leads to the creation of smaller more diffuse patches. This is particularly pertinent to Raised Bog and Fen. Table 4.18 shows that the proportion of patches required to facilitate their expansion under Conservation First, relative to their proportion of patches currently, is far greater than that of other PBVCs undergoing expansion. The relatively large increases in Geometric Vulnerability that they experience are due to the comparatively high number of small patches that have to be created to facilitate their increased coverage.

BLWP experiences an increase in patch area and complexity under both future scenarios, providing further evidence of the positive relationship between patch area and complexity (Table 6.1b). However, BLWP is quite unusual in that it is the only PBVC to experience a decrease in Geometric Vulnerability under the scenarios. Increases in shape complexity appear insufficient to counteract decreases in vulnerability associated with increased area. This may suggest that areas of available suitable habitat, for this PBVC specifically, are quite spatially concentrated.

6.4.2.2 NCAs

The variations in aggregate Geometric Vulnerability for individual NCAs (Tables 6.3 and 6.4) have a good general concurrence with the overall results observed for NNP as, on the whole, the vulnerability of individual NCAs differs little between current and future time slices. For instance, the highest level of change observed for all of the NCAs across both future time slices is only 0.016 (Table 6.3). Also, the ranking of the NCAs does not differ between the current time slice and Conservation First (Table 6.4). Only small changes in the ranking of the NCAs occur under Going for Growth.

Tables 6.3 and 6.4 clearly show that the Cheviots is the most vulnerable NCA in terms of patch geometry within and between each of the three time slices. The results are quite strongly influenced by those for Marsh within each NCA. For instance, Table 4.18 shows that Marsh is consistently the most dominant PBVC in all of the NCAs across the time slices (often by quite a significant margin). Table 6.5 shows that the average Geometric Vulnerability of Marsh within the Cheviots NCA is higher than it is in all of the other NCAs under each time slice except for the Cheviot Fringe. However, the proportion of Marsh patches comprising the Cheviot Fringe is notably less than that comprising the Cheviot (Table 4.18). Therefore the impact of Marsh on the results from the Cheviot Fringe will be less than that for the Cheviot (as well as other NCAs). It is also worth noting that the high ranking of the Cheviots is partially due to the very high vulnerability associated with Swamp under the time slices, although, the proportion of patches of Swamp within the NCA is low (Table 4.18).

Tables 6.3 and 6.4 also show that Cheviot Fringe is the least vulnerable NCA in terms of patch geometry within and between each of the three time slices. As stated, although the vulnerability of Marsh within the Cheviot Fringe is higher than in the other NCAs, its proportional dominance in terms of number of patches is notably less. The proportion of the NCA comprised of other PBVCs (i.e. BLWP and IGP), when their patches are combined, is often greater or similar to that of Marsh (Table 4.18). Table 6.5 shows that the vulnerability of BLWP and particularly IGP within Cheviot

Fringe under each of the time slices is notably less than that associated with the dominant PBVCs (i.e. Marsh and various others) from the other NCAs across the various time slices.

The switch in ranking that takes place between TG and BMF under Going for Growth (Table 6.4) is not related to the characteristics of Marsh within the NCAs because its vulnerability does not change between the two time slices (Table 6.5). Instead, the change is driven by the vulnerability characteristics of a number of different PBVCs within their extents. For instance, Table 4.18 shows that IGP is the third most dominant PBVC within TG under Going for Growth. IGP's vulnerability increases by 0.057 under Going for Growth from the Current time slice (Table 6.5). This increase is comparable to the combined increase experienced by the second and third most dominant PBVCs (i.e. Heath and IGP) within BMF under Going for Growth. Also, BLWP is the fourth most dominant PBVC within both the BMF and TG NCAs under Going for Growth: BLWP experiences a relatively large decrease in vulnerability within BMF compared to TG under the scenario.

In summary, vulnerability in terms of geometry differs little between current and future time slices. NNP as a whole, individual NCAs and individual PBVCs all generally demonstrate moderate levels of vulnerability. In general, this is probably due to the large numbers of PBVCs which retain their extents between current and future time slices, because of the characteristics of the scenarios, as well as the minimal changes in vulnerability that are associated with many of the PBVCs that do undergo distributional change. Raised Bog is a notable exception to these trends.

There is some evidence for a positive relationship between increased coverage and increased Geometric Vulnerability. This is potentially related to an increase in the area of patches (to facilitate the increase in coverage) and an associated increase in the edge complexity of the patches. However, the vulnerability results for a number of PBVCs (i.e. BLWP, IGP and NGP) contradict this trend. These results suggest that changes in vulnerability for individual PBVCs are not only affected by changes in patch size (and therefore complexity) but also the distribution of suitable areas of land on which patch expansion or creation can occur and the resultant impacts on patch geometry as a whole.

6.5 Matrix Vulnerability (VM2b): Results and Discussion

6.5.1 Results

6.5.1.1 Northumberland National Park

Landscape and Class Level Results

Table 6.6 and Figures 6.4a-c show that average levels of Matrix Vulnerability are generally low across the time slices. However Figures 6.4a-c also show higher levels of Matrix Vulnerability associated with certain patches, particularly those in more lowland areas towards the borders of the park. The highest Matrix Vulnerability, for the PBVCs, overall across the whole study area, is observed for the current time slice (Table 6.6). The lowest Matrix Vulnerability occurs under the Going for Growth scenario. Average Matrix Vulnerability decreases slightly under Conservation First (by 0.034) compared to that under current conditions. The decrease under Going for Growth is slightly greater than for Conservation First.

Table 6.6: Average Matrix Vulnerability for all of the PBVCs (bottom row) and for each individual PBVC for NNP under each time slice. Values in brackets show the difference in Matrix Vulnerability between the current and future time slices. Values highlighted red or green show (respectively) the highest and lowest Matrix Vulnerability (or change in Matrix Vulnerability) under each time slice. Values highlighted red or green in bold italics show the highest/lowest levels of Matrix Vulnerability (or change in Matrix Vulnerability) across all of the time slices. IGP and NGP are excluded from analysis as Matrix Vulnerability for these PBVCs was not calculated due to issues in establishing suitable criteria on which to base analysis of their Matrix Vulnerability.

PBVC	**Current**	**Conservation First**	**Going for Growth**
Blanket Bog	0.071	0.051 (-0.020)	0.052 (-0.019)
Broadleaved Woodland: Priority (BLWP)	***0.360***	0.356 (-0.004)	0.262 (-0.098)
Fen	0.060	0.089 (0.029)	0.031 (-0.029)
Heath	0.113	0.153 ***(0.040)***	0.125 (0.012)
Marsh	0.206	0.165 (-0.041)	0.141 ***(-0.065)***
Raised Bog	***0.000***	0.021 (0.021)	***0.000*** (0.000)
Swamp	0.057	0.053 (-0.004)	0.046 (-0.009)
Average Matrix Vulnerability	**0.204**	0.170 (-0.034)	**0.143 *(-0.061)***

Figure 6.4a: Matrix Vulnerability of all PBVC patches within NNP under the current time slice. Maps depicting the Matrix Vulnerability of patches for specific PBVCs are available upon request.

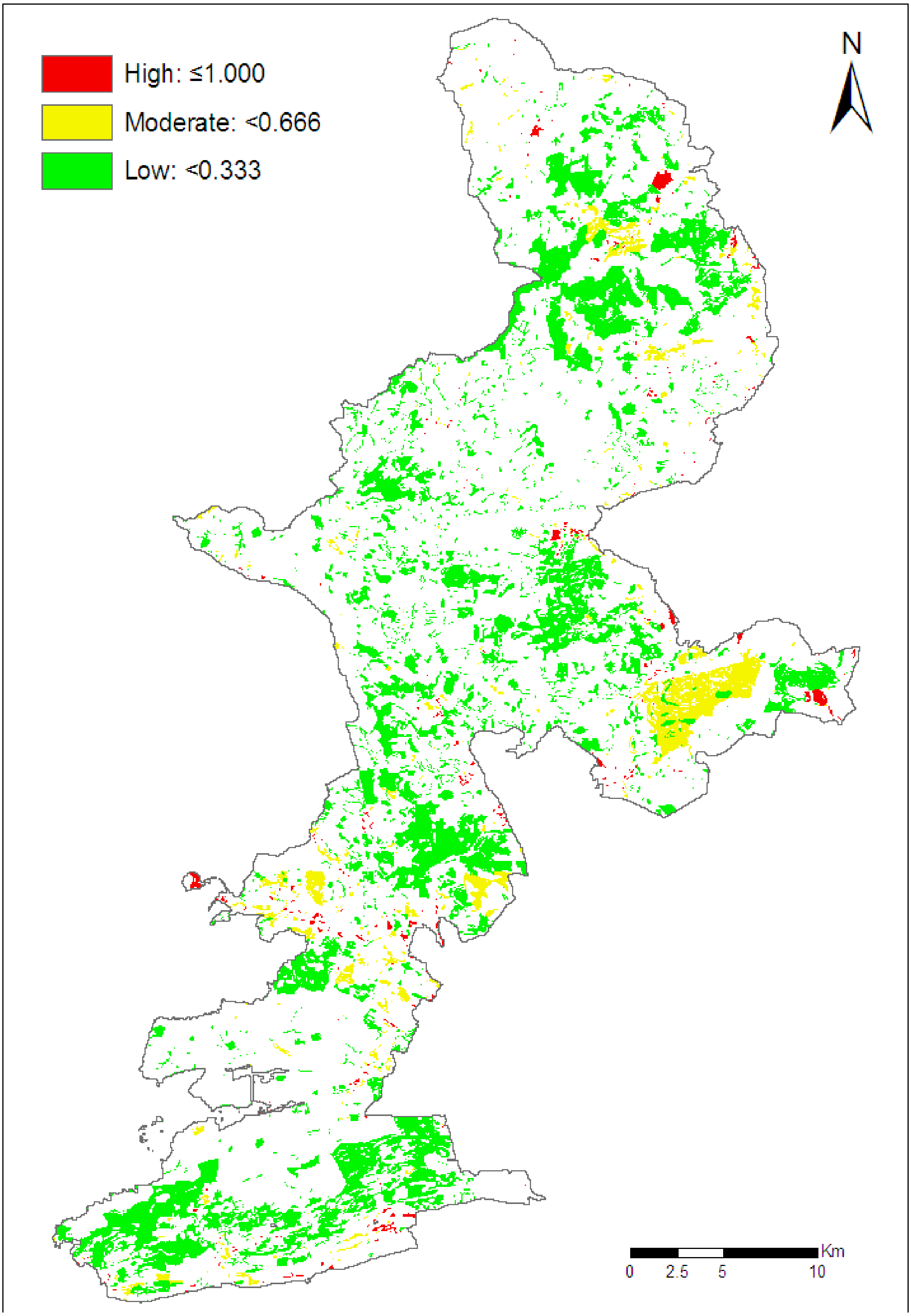


Figure 6.4b: Matrix Vulnerability of all PBVC patches within NNP under Conservation First. Maps depicting the Matrix Vulnerability of patches for specific PBVCs are available upon request.

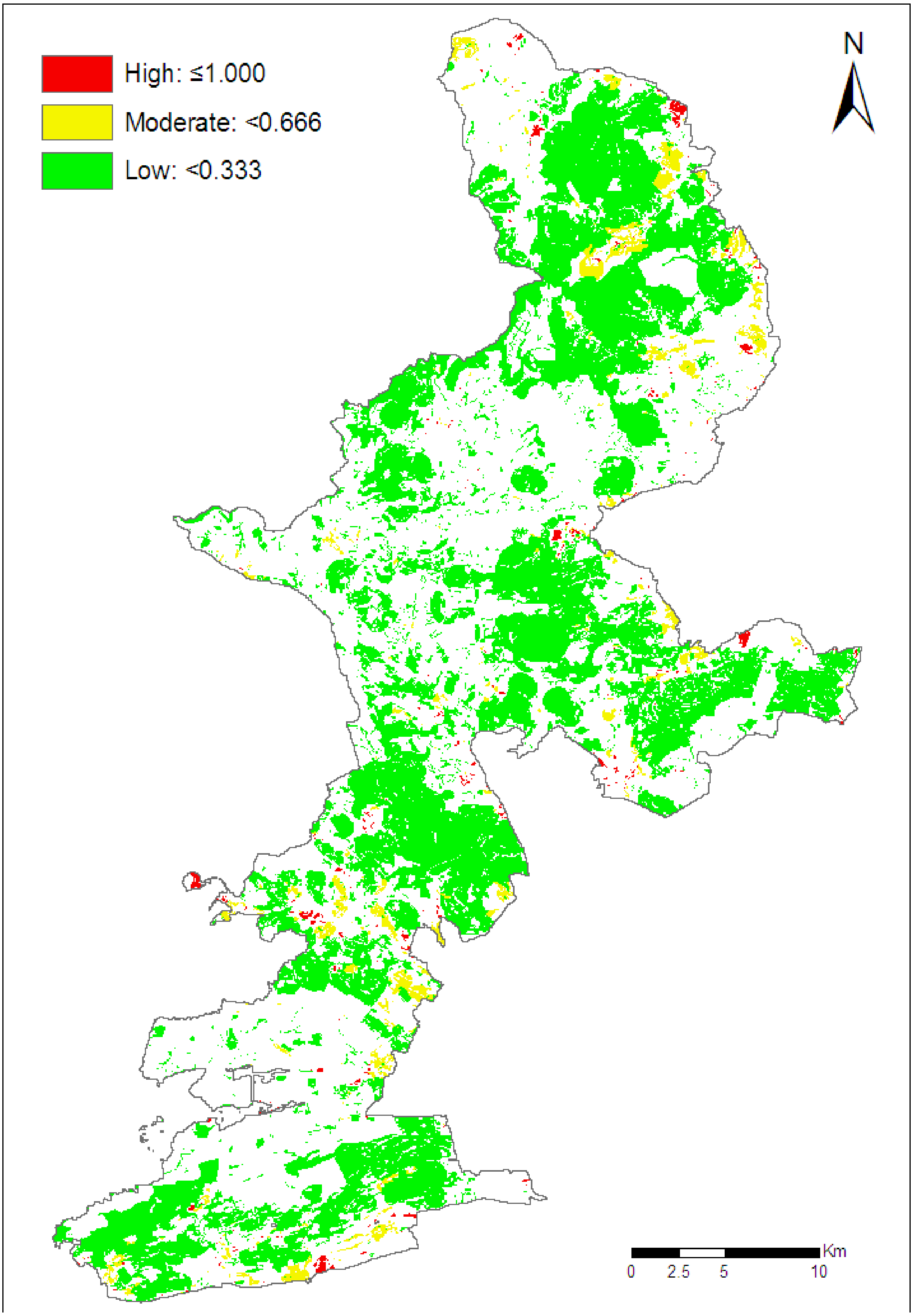


Figure 6.4c: Matrix Vulnerability of all PBVC patches within NNP under Going for Growth. Maps depicting the Matrix Vulnerability of patches for specific PBVCs are available upon request.

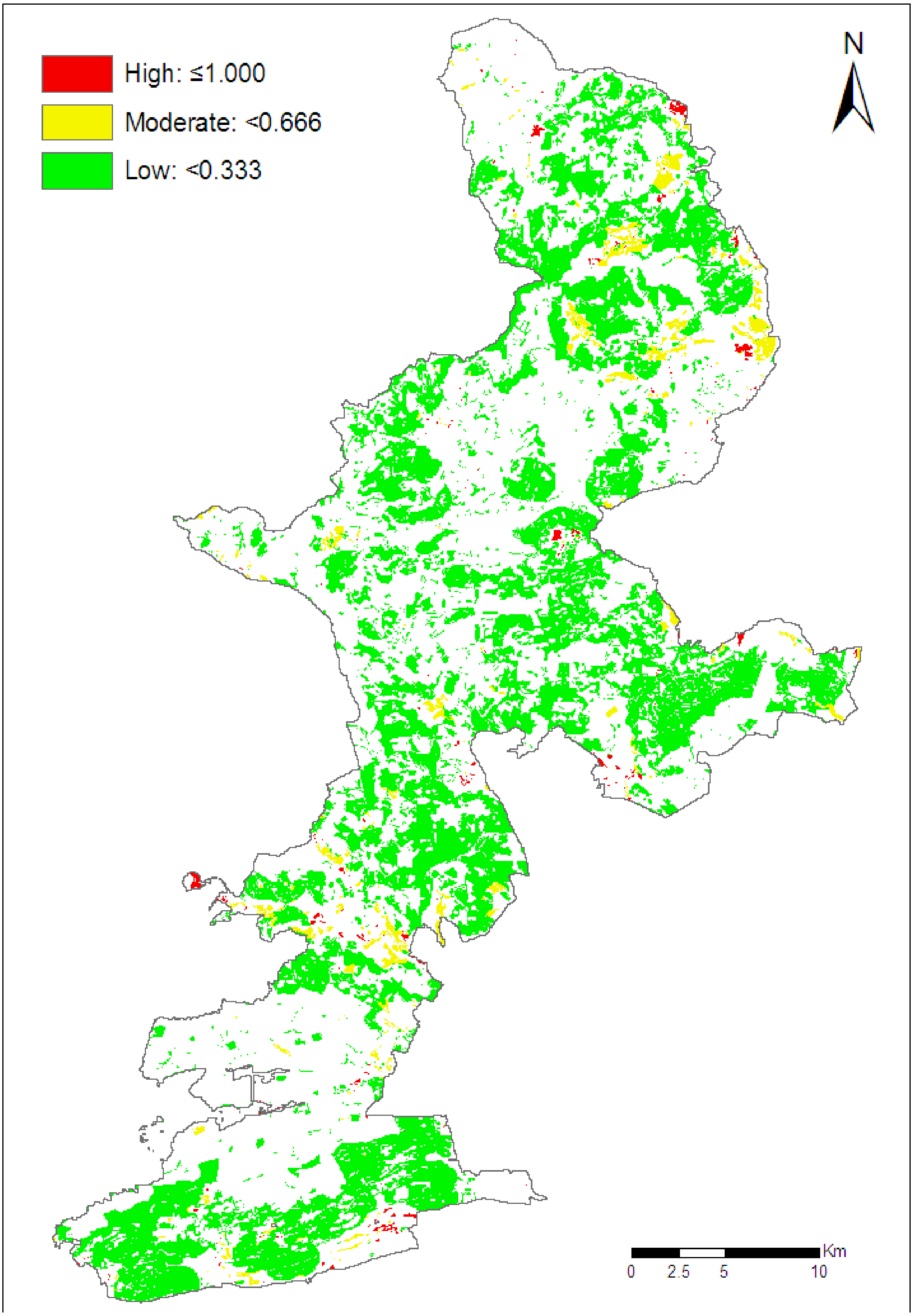


Table 6.6 also shows that the highest and lowest levels of Matrix Vulnerability across all time slices are for BLWP and Raised Bog, respectively. BLWP under the current time slice exhibits the highest Matrix Vulnerability overall. Raised Bog currently, and under the Going for Growth scenario, exhibits the least Matrix Vulnerability overall (0.000).

The results show notable variation between the PBVCs within each of the time slices. For instance, many of the PBVCs, i.e. Blanket Bog, Fen, Swamp and particularly Raised Bog, exhibit low Matrix Vulnerability under all time slices. Relatively speaking, the other PBVCs (Heath, Marsh and BLWP) exhibit moderate to high levels of Matrix Vulnerability across the three time slices. Most of the PBVCs, however, exhibit only slight changes in their Matrix Vulnerability between current and future time slices. Table 6.7 shows very close similarities in the ranking of PBVCs between current and future time slices. For instance, BLWP, Marsh, Heath and Raised Bog are consistently ranked, respectively, as the most, second most, third most and least vulnerable PBVCs within each of the time slices. This is despite the fact that, in some instances, BLWP, Marsh and Heath exhibit some of the largest changes in Matrix Vulnerability between current and future time slices (Table 6.6).

Quite small changes in Matrix Vulnerability are associated with Blanket Bog, Fen and Swamp. However, due to their typically low vulnerability scores, these changes are sufficient to cause some small differences in the ranking of the PBVCs between current and future time slices. For instance, currently Blanket Bog, Fen and Swamp are ranked fourth, fifth and sixth respectively. Under Conservation First, due to the relatively large increase in vulnerability associated with Fen, the small decrease associated with Swamp and a relatively large decrease associated with Blanket Bog, they are ranked as fourth, fifth and sixth respectively. Under Going for Growth, Fen experiences a relatively large decrease in vulnerability, compared to the other two PBVCs, and is ranked sixth. Blanket Bog and Swamp are ranked fourth and fifth respectively. Although Blanket Bog experiences a larger decrease in vulnerability under the scenario compared to Swamp, it is insufficient to reduce its ranking because of its relatively high levels of vulnerability compared to Swamp.

Table 6.7 also shows that the overall ranking of individual PBVCs tends to decrease under the future scenarios. These results therefore generally concur well with those at the NNP landscape level (Table 6.6).

Table 6.7: The ranking of each PBVC (high to low), in terms of Matrix Vulnerability, for the study area across all time slices. Numeric prescripts denote rank of PBVC within each time slice.

Rank	Current	Conservation First	Going for Growth
1	1. BLWP (0.360)		
2		1. BLWP (0.356)	
3			1. BLWP (0.262)
4	2. Marsh (0.206)		
5		2. Marsh (0.165)	
6		3. Heath (0.153)	
7			2. Marsh (0.141)
8			3. Heath (0.125)
9	3. Heath (0.113)		
10		4. Fen (0.089)	
11	4. Blanket Bog (0.071)		
12	5. Fen (0.060)		
13	6. Swamp (0.057)		
14		5. Swamp (0.053)	
15			4. Blanket Bog (0.052)
16		6. Blanket Bog (0.051)	
17			5. Swamp (0.046)
18			6. Fen (0.031)
19		7. Raised Bog (0.021)	
20	7. Raised Bog (0.000)		7. Raised Bog (0.000)

6.5.1.2 National Character Areas (NCAs)

Landscape Level Results

Table 6.8 shows that the highest levels of average Matrix Vulnerability across all three time slices are consistently observed for the Cheviot Fringe. Currently, the lowest level observed is for the Cheviots. The BMF NCA is shown as the least vulnerable in terms of matrix characteristics under both future scenarios. Overall, the highest level of Matrix Vulnerability is observed currently for the Cheviot Fringe. The least vulnerable NCA overall is BMF under Going for Growth.

Table 6.9 reveals some important trends. For instance, Cheviot Fringe, NSH and TG occupy the top three ranks in each of the three time slices. The Cheviot Fringe is consistently ranked as the most vulnerable NCA in every time slice. NSH and TG are ranked respectively as the second most and third most vulnerable NCAs both currently and under Conservation First. Under Going for Growth their ranks are reversed. This is probably due to the notable decrease in the Matrix Vulnerability of NSH under the scenario (Table 6.8). Indeed, the overall ranking of NSH under Going for Growth is less than the overall current ranking of the BMF and Cheviots NCAs, as well as the Cheviots under Conservation First.

BMF and Cheviots are generally the lowest ranking NCAs overall and in terms of each time slice. BMF and Cheviots are ranked respectively as the fourth and fifth most vulnerable NCAs currently. This situation is reversed under both future scenarios.

Finally, it is also worth noting that the pattern of ranks across the time slices further supports the results in Table 6.8 showing decreasing Matrix Vulnerability under both of the future scenario compared to the current time slice and a greater decrease under Going for Growth than Conservation First.

Table 6.8: Average Matrix Vulnerability for all PBVCs across each NCA under each time slice. Values in brackets show the difference in Matrix Vulnerability between the current and future time slices. The highlighting of specific values follows the same format as Table 6.6.

	Current	**Conservation First**	**Going for Growth**
Cheviots	0.174	0.161 ***(-0.013)***	0.141 (-0.033)
Cheviot Fringe	***0.505***	0.484 (-0.021)	0.375 (-0.130)
Northumberland Sandstone Hills (NSH)	0.298	0.240 (-0.058)	0.158 ***(-0.140)***
Border Moors and Forests (BMF)	0.183	0.141 (-0.042)	***0.127*** (-0.056)
Tyne Gap and Hadrian's Wall (TG)	0.290	0.218 (-0.072)	0.187 (-0.103)

Table 6.9: The ranking of each NCA (high to low), in terms of average Matrix Vulnerability under each time slice. Numeric prescripts denote rank of NCA within each time slice.

Overall Rank	**Current**	**Conservation First**	**Going for Growth**
1	1. Cheviot Fringe (0.505)		
2		1. Cheviot Fringe (0.484)	
3			1. Cheviot Fringe (0.375)
4	2. NSH (0.298)		
5	3. TG (0.290)		
6		2. NSH (0.240)	
7		3. TG (0.218)	
8			2. TG (0.187)
9	4. BMF (0.183)		
10	5. Cheviots (0.174)		
11		4. Cheviots (0.161)	
12			3. NSH (0.158)
13		5. BMF (0.141)	4. Cheviots (0.141)
14			5. BMF (0.127)

Class Level Results

Table 6.10 shows that, across all time slices over all NCAs, BLWP under the current time slice in the Cheviot Fringe exhibits the highest levels of Matrix Vulnerability. A number of the PBVCs (i.e. Fen and Raised Bog currently and under Going for Growth, as well as Swamp under Going for Growth) exhibit no vulnerability (0.000) in terms of matrix characteristics in the BMF and NSH NCAs. These are the lowest levels of Matrix Vulnerability overall.

Cheviots

BLWP exhibits the highest levels of Matrix Vulnerability under each of the three time slices. The lowest levels of vulnerability under all time slices are observed for Fen. The highest overall level of Matrix Vulnerability is observed for BLWP under Conservation First. The lowest is for Fen in all time slices (0.008).

Cheviot Fringe

BLWP again exhibits the highest levels of Matrix Vulnerability under each of the three time slices. BLWP's highest vulnerability overall is under the current time slice. Marsh is shown as the least vulnerable PBVC under the current time slice. Heath is the least vulnerable under both future scenarios. Heath's vulnerability under Going for Growth is the lowest overall.

Northumberland Sandstone Hills

BLWP is shown as the most vulnerable PBVC under all three time slices. Its highest vulnerability overall is for the current time slice. Fen is shown as the least vulnerable PBVC currently and under Going for Growth. Blanket Bog is the least vulnerable PBVC under Conservation First. Overall, the least vulnerable PBVC is Fen currently and under Going for Growth.

Border Moors and Forests

The PBVC with the highest vulnerability within each of the time slices is again BLWP. BLWP's vulnerability, currently, is the highest overall. Raised Bog is the least vulnerable PBVC currently. Swamp is the least vulnerable PBVC under Conservation First. Raised Bog and Swamp are both indicated as the least vulnerable PBVCs under Going for Growth. Overall, the lowest Matrix Vulnerability (0.000) is observed for Raised Bog currently and under Going for Growth and Swamp under Going for Growth.

Tyne Gap and Hadrian's Wall

BLWP is shown as the most vulnerable PBVC currently and under Conservation First. Blanket Bog is the most vulnerable PBVC under Going for Growth. BLWP under current conditions exhibits the most vulnerability overall. Swamp is the least vulnerable PBVC under current conditions; Raised Bog is the least vulnerable under Conservation First. This is the lowest level of vulnerability overall. Fen is the least vulnerable under Going for Growth.

Table 6.10: Average Matrix Vulnerability for each PBVC within each NCA under each time slice. The highlighting of specific values follows the same general format as that for Tables 6.6 and 6.8. Values followed by an '*' denote the PBVCs with the highest/lowest Matrix Vulnerability across all NCAs across all time slices.

NCA	PBVC	Current	Conservation First	Going for Growth
Cheviot	Blanket Bog	0.056	0.043	0.026
	BLWP	0.377	***0.436***	0.369
	Fen	***0.008***	***0.008***	***0.008***
	Heath	0.089	0.148	0.072
	Marsh	0.182	0.143	0.131
	Raised Bog	N/A	N/A	N/A
	Swamp	0.059	0.055	0.055
Cheviot Fringe	Blanket Bog	N/A	N/A	N/A
	BLWP	***0.560****	0.535	0.372
	Fen	N/A	N/A	N/A
	Heath	N/A	0.427	***0.308***
	Marsh	0.487	0.468	0.405
	Raised Bog	N/A	N/A	N/A
	Swamp	N/A	N/A	N/A
Northumberland Sandstone Hills	Blanket Bog	0.064	0.048	0.031
	BLWP	***0.352***	0.351	0.180
	Fen	***0.000****	0.092	***0.000****
	Heath	0.231	0.218	0.176
	Marsh	0.321	0.228	0.149
	Raised Bog	N/A	N/A	N/A
	Swamp	N/A	N/A	N/A
Border Moors and Forests	Blanket Bog	0.056	0.053	0.052
	BLWP	***0.331***	0.307	0.264
	Fen	0.053	0.061	0.043
	Heath	0.093	0.103	0.096
	Marsh	0.178	0.144	0.123
	Raised Bog	***0.000****	0.026	***0.000****
	Swamp	0.012	0.009	***0.000****
Tyne Gap and Hadrian's Wall	Blanket Bog	0.325	0.099	0.301
	BLWP	***0.498***	0.386	0.246
	Fen	0.088	0.139	0.015
	Heath	0.094	0.191	0.100
	Marsh	0.335	0.281	0.240
	Raised Bog	N/A	***0.008***	N/A
	Swamp	0.067	0.062	0.053

6.5.2 Discussion

6.5.2.1 NNP

Possibly the most notable result is that aggregate levels of Matrix Vulnerability for the PBVCs are generally low across all time slices (Table 6.6). Considering the designated status of NNP (NNPA, 2009) this result is largely expected in the case of the current time slice. However, the results also suggest the PBVCs overall will experience a slight decrease in aggregate levels of Matrix Vulnerability under both of the future scenarios, compared to current levels. The decrease under Going for Growth is greater than that occurring under Conservation First. Intuitively, this may seem somewhat surprising, considering the underlying characteristics of the scenario. However, investigation of the types and levels of land use change occurring under the scenarios does much to explain the results. For instance, Table 4.19 and Figures 4.4 b & c show that most of the increases in areal coverage occurring under the scenarios tend to be associated with PBVCs classified as 'semi-natural' types under the criteria used within this research (e.g. Blanket Bog, BLWP, Fen, Heath, and Raised Bog). Furthermore, the overall increase in areal coverage of 'modified' PBVC types under Going for Growth is notably less than that under Conservation First (Tables 4.6, 4.8 & 4.19). The decreases in Matrix Vulnerability under the future scenarios are generally due to the greater overall levels of expansion of semi-natural PBVC types occurring on extant areas of 'modified' land covers than vice-versa: This phenomenon is likely to be less pronounced under Conservation First than under Going for Growth.

The results for individual PBVCs at the scale of the National Park are also relevant. For instance, there are very low values of Matrix Vulnerability associated with many of the PBVCs (Blanket Bog, Fen, Swamp and Raised Bog), whilst fewer PBVCs (BLWP, Marsh and Heath) are associated with levels of vulnerability that are relatively high across all three time slices. Such attributes largely account for the low aggregate levels of Matrix Vulnerability across the time slices.

The apparently divergent characteristics in Matrix Vulnerability between Blanket Bog, Fen, Swamp and Raised Bog on one hand, and BLWP, Marsh, and (to some degree) Heath on the other, may be partially due to differences in their respective ecological characteristics and geographic contexts they are typically associated. For instance, BLWP, tends to have a greater tolerance for particular physical conditions (e.g. relatively deep soils with neutral pH) than many of the other PBVCs. Marsh also tends to have an increased tolerance for neutral soils and is most closely associated with more or less level areas (JNCC, 2007). Such conditions tend to occur most frequently in lowland locales and also favour the occurrence or creation of the modified P/NPBVC types (e.g. Arable and the various types of Neutral and Improved Grasslands). It is to be expected that extents of BLWP and Marsh will tend to occur adjacent to, or in mosaic with, these modified

P/NPBVCs in lowland areas within the park. On the other hand, PBVCs such as Blanket Bog and Raised Bog tend to be associated with low soil pH and, in the case of Blanket Bog, can occur readily on relatively steep slopes in more remote upland areas. Such conditions tend not to favour the occurrence of modified P/NPBVC types. They are therefore less likely to occur adjacent to each other, either naturally or through management.

Although Heath also tends to be most closely associated with upland locations, it may be less restricted to such areas due to its greater tolerance of drier soil types compared to Blanket Bog and Raised Bog (See: Tables A2.3, A2.13c & A2.13g). In this context, it is perhaps unsurprising that Heath exhibits levels of Matrix Vulnerability that are more comparable to those of BLWP and Marsh.

Swamp is associated with generally low levels of Matrix Vulnerability. It is unlikely to occur with the modified P/NPBVC types because of the high water levels that are associated with it, making the management typically required to facilitate the occurrence of the modified types in such areas undesirable or inappropriate.

6.5.2.2 NCAs

The results for individual NCAs have a very good general agreement with those discussed previously in relation to the characteristics of the Matrix Vulnerability observed at the national park level. Tables 6.8 and 6.9 show that the Matrix Vulnerability of all of the NCAs decreases under both future scenarios compared to current conditions. Also, the decrease occurring for all of the NCAs under Going for Growth is greater than that for Conservation First. Furthermore, Table 6.9 also shows that the bottom three ranks overall are occupied by NCAs under the Going for Growth scenario.

Possibly, the most notable single result highlighted in Tables 6.8 and Table 6.9 is that the Cheviot Fringe NCA is consistently the most vulnerable within each of the three time slices. Tables 4.19 & 6.10 show that the only PBVCs for which Matrix analysis was conducted, that occur within this NCA across the various time slices are BLWP, Marsh and Heath. All of these PBVCs exhibit their highest levels of vulnerability within this particular NCA under each of the time slices (Table 6.10). This is perhaps to be expected, due to the strong lowland characteristic of the NCA and the resultant high proportion of modified types under each of the time slices. For instance, Table 4.19 shows that the proportional coverage of NGP and IGP accounts for approximately 78%, 58% and 32% of the PBVCs within the Cheviot Fringe under each of the time slices, respectively. However, comparison with the results in Table 6.10 also shows that Matrix Vulnerability within the NCA under each of the future scenarios decreases along with the proportion of these PBVCs.

Table 6.8 suggests that the difference in ranking of the NSH and TG NCAs under current conditions and Conservation First (Table 6.9), compared to that observed under Going for Growth, is largely due to the notable decrease in Matrix Vulnerability associated with NSH under Going for Growth compared to that of TG. This in turn is again related to the vulnerability characteristics of the dominant PBVC (Marsh) within each of the NCAs under Going for Growth. For instance, Table 6.10 indicates that Marsh's vulnerability within the TG NCA is 0.240, whilst its vulnerability within NSH is only 0.149.

Although there is little difference between the Matrix Vulnerability of BMF and Cheviots currently, Tables 6.10 and 4.18 indicate that the higher rank of the BMF NCA is at least partially due to the relatively high proportion of IGP and NGP patches in BMF, as matrix vulnerability for these PBVCs was not assessed and most of the other PBVCs experience higher levels of vulnerability within the Cheviots.

The switch in ranking of the BMF and Cheviot NCAs observed under Conservation First may be due to the trends for Heath and BLWP. For instance, BLWP is the third and fourth most dominant PBVC within the Cheviots and BMF respectively, and has comparable proportions of patches between the NCAs (Table 4.18). Table 6.10 shows that the vulnerability of BLWP within BMF is notably lower than within the Cheviots. Heath is the second and third most dominant PBVC within the Cheviots and BMF respectively (Table 6.18) and exhibits somewhat lower vulnerability within BMF (Table 6.10). The other PBVCs tend to exhibit lower vulnerability within Cheviots compared to BMF under Conservation First. The ranking of the BMF and Cheviots under Going for Growth is largely due to the trends for BLWP and Marsh, although those for Raised Bog and Swamp play some role. Marsh is the most dominant PBVC within both NCAs under the scenario and has comparable levels of dominance between the two areas (Table 4.18). The vulnerability of Marsh within BMF is somewhat lower (Table 6.10). BLWP, the fourth most dominant PBVC in both NCAs, also exhibits lower vulnerability within BMF. Although Raised Bog and Swamp account for a small proportion of patches within both NCAs (no extents of Raised Bog occur within the Cheviots), there is a greater proportion of these PBVCs within BMF. Both PBVCs exhibit no vulnerability associated with their matrix characteristics within the NCA (Table 6.10).

Chapter 7: Overall Vulnerability (VM3)

7.1 Introduction

Each of the separate measures presented in previous chapters (VM1, VM2a, VM2b) were used to construct an index of the Overall Vulnerability for the PBVC types. When combined, these measures allow the combined effect of climate and land use on the current and future vulnerability of PBVC patches to be assessed. This chapter briefly describes the methods used to construct the Overall Vulnerability index. The Overall Vulnerability results for the PBVCs within NNP are then presented, followed by a more extensive discussion of relevant issues and trends, with particular reference to the relative influence of the individual vulnerability components in determining Overall Vulnerability. Targeted management recommendations for NNP are then provided, based on these findings, followed by a summary of the major findings of the research and a critique of the adopted approach.

7.2 Methods

Overall Vulnerability (VM3) was calculated as the sum of VM1, VM2a and VM2b:

$$VM3 = VM1 + VM2a + VM2b \qquad \text{(Equation 9)}$$

The potential range for Overall Vulnerability is between 0-3. Weighting was not applied to the individual components comprising Overall Vulnerability. The vulnerability construct applied within this research therefore regards patch vulnerability as a simple function of Climate Stress, its spatial attributes (i.e. area, shape) and the characteristics of the surrounding matrix. In basic terms, a smaller, more complex patch, surrounded by a greater proportion of modified land covers that experiences greater climatic stress, is one that is more vulnerable.

VM2a and VM2b are primarily used within this research to gauge vulnerability due to land use change or characteristics. Thus formulated, VM3 is effectively biased in favour of these measures. However, in the initial application of VM3, equal weighting of the individual vulnerability components was regarded as more appropriate in order to investigate relevant sources of vulnerability more thoroughly and so provide more targeted management recommendations. Furthermore, the results and discussion below clearly highlight the relative roles of climate and land use in influencing community vulnerability within NNP, and are therefore useful in addressing the main aim of the research.

7.3 Results

The overall results are presented as follows: First, landscape and class level results for the National Park are provided (Tables 7.1 – 7.3). This allows general trends for the park as well as for each PBVC to be identified and general causes investigated. Second, summary results are presented at the landscape level for each NCA (Tables 7.4 - 7.6). Similarities and differences between the trends for individual NCAs and those for the National Park are identified and general causes investigated. Third, PBVC results for each NCA are provided (Tables 7.7, 7.8 & A4a-e). This allows for: a) the specific causes of levels of vulnerability (i.e. PBVCs and specific vulnerability factors) within each NCA to be identified (Tables 7.7 & A4a-e); b) identification of the specific NCAs in which PBVCs are most and least vulnerable (Table 7.8). The NCA results are valuable in identifying potential 'refugia' (Gavin *et al*., 2014; Keppel & Wardell-Johnson, 2012; Morecroft *et al*., 2012) within NNP for individual PBVCs. They are thus useful in informing potential future management policies and actions (Keppel & Wardell-Johnson, 2012; Morecroft *et al*., 2012; Klausmeyer *et al*., 2011).

7.3.1 Northumberland National Park (NNP)

7.3.1.1 Landscape and Class level results

Table 7.1 suggests that aggregate levels of Overall Vulnerability, for the PBVCs, at the scale of the national park, under current conditions are moderate and are the highest across the three time slices. Levels of vulnerability decrease to low-moderate under both future scenarios. The decrease occurring under Going for Growth is slightly greater than that for Conservation First (by 0.015). Across the three time slices, NNP exhibits the least vulnerability under Going for Growth. Figures 7.1a-c further highlight the general trend of decreasing levels of Overall Vulnerability associated with the PBVCs under the future scenarios.

Table 7.1: Average Overall Vulnerability for all of the PBVCs (bottom row) and for each individual PBVC under each time slice. Values in brackets show the change in vulnerability between the current and future time slices. Values highlighted red or green show (respectively) the highest and lowest vulnerability (or change in vulnerability) under each time slice. Values highlighted red or green in bold italics show the highest/lowest levels of vulnerability (or change in vulnerability) across all of the time slices.

PBVC	**Current**	**Conservation First**	**Going for Growth**
Blanket Bog	0.798	1.216 (0.418)	1.105 (0.307)
Broadleaved Woodland: Priority (BLWP)	1.445	1.052 (-0.393)	0.998 (-0.447)
Fen	1.241	0.966 (-0.275)	0.789 ***(-0.452)***
Heath	1.173	1.170 (-0.003)	1.154 (-0.019)
Improved Grassland: Priority (IGP)	0.915	0.634 (-0.281)	0.550 (-0.365)
Marsh	***1.482***	1.084 (-0.398)	1.061 (-0.421)
Neutral Grassland: Priority (NGP)	0.967	0.684 (-0.283)	0.717 (-0.250)
Raised Bog	***0.395***	1.287 ***(0.892)***	0.837 (0.442)
Swamp	1.001	0.996 (-0.005)	0.989 (-0.012)
Average Overall Vulnerability	1.349	1.039 (-0.310)	1.024 (-0.325)

Figure 7.1a: Overall Vulnerability of all PBVC patches within NNP under the current time slice. Maps depicting the Overall Vulnerability of patches for specific PBVCs are available upon request.

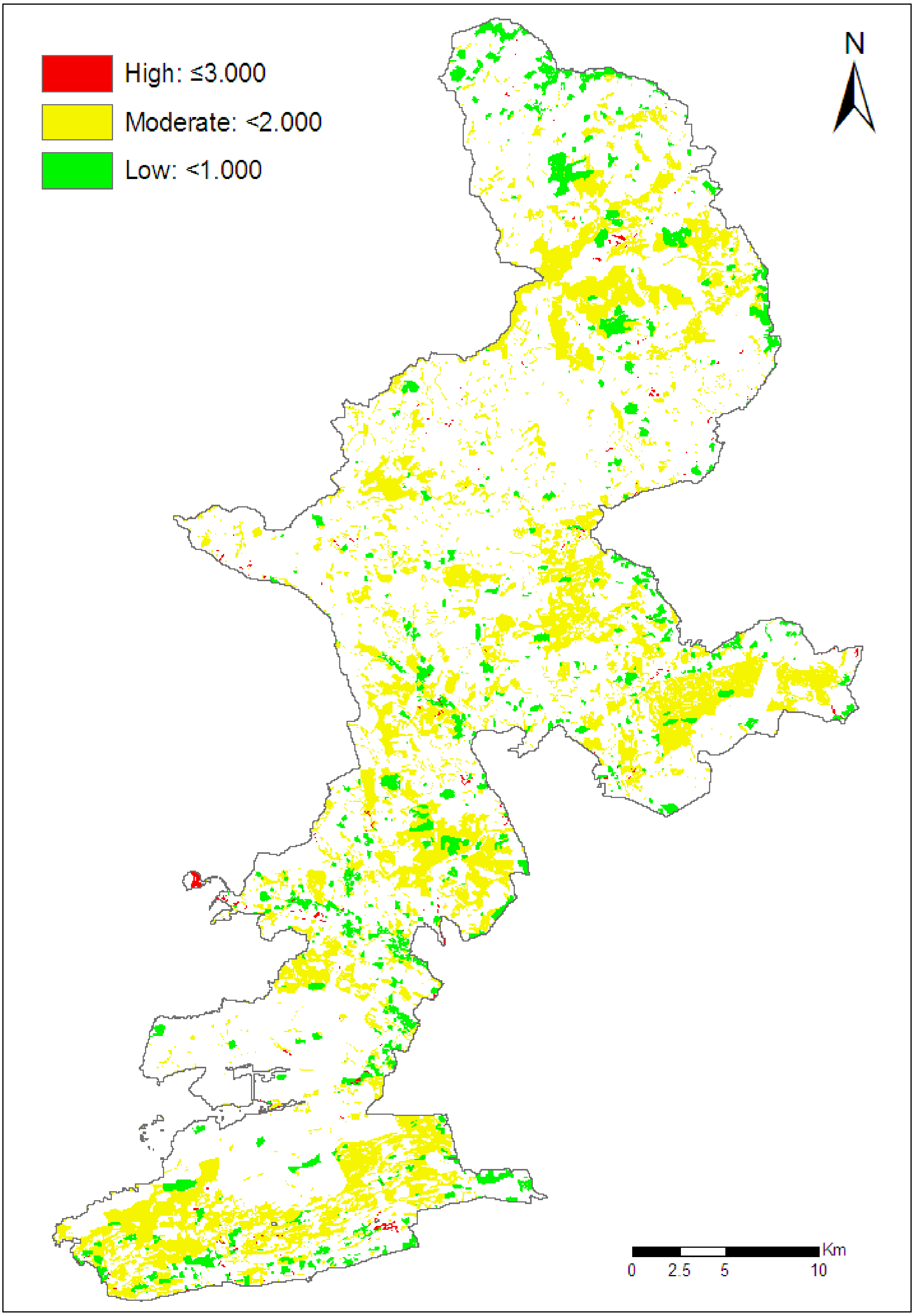


Figure 7.1b: Overall Vulnerability of all PBVC patches within NNP under Conservation First. Maps depicting the Overall Vulnerability of patches for specific PBVCs are available upon request.

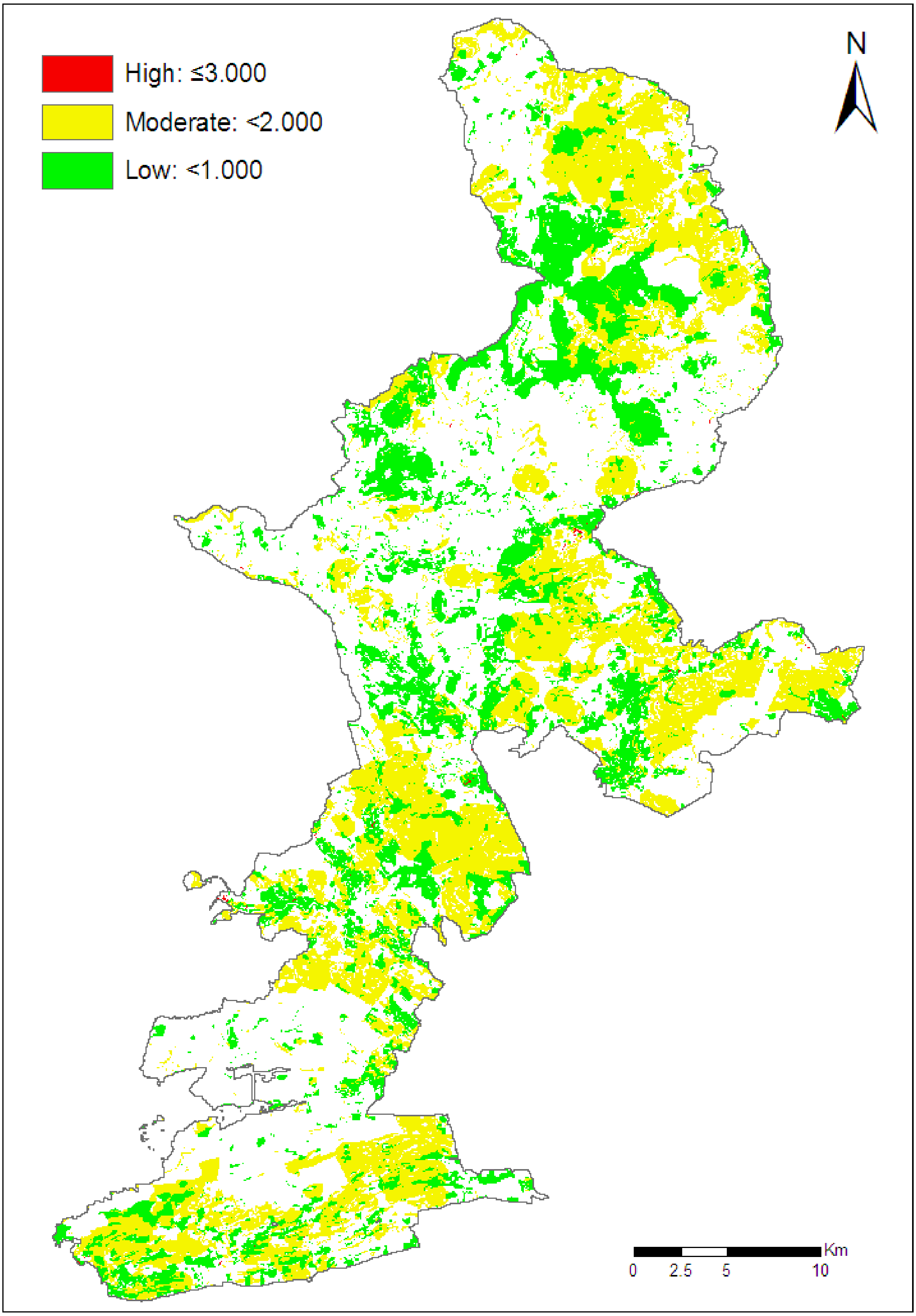
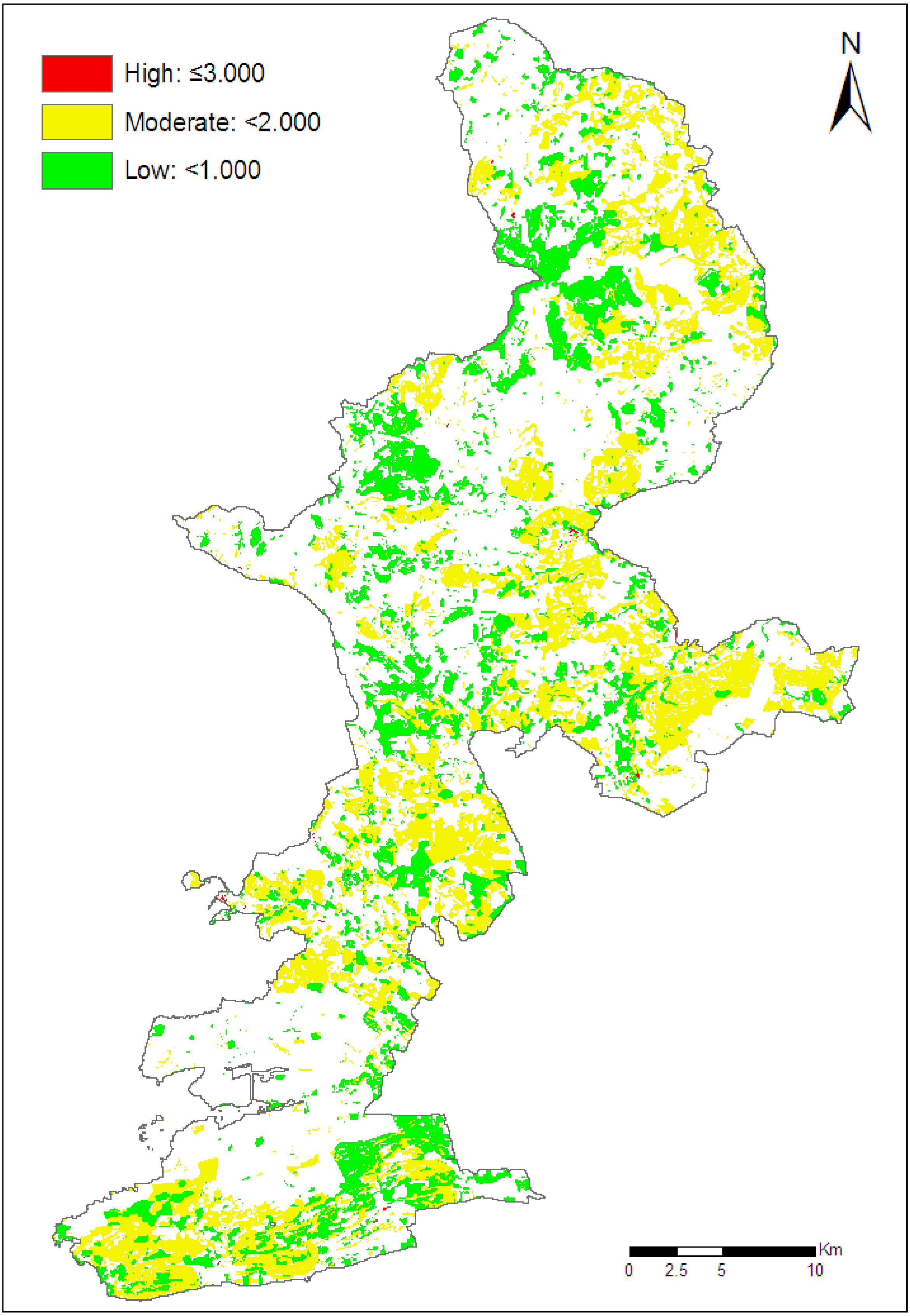


Figure 7.1c: Overall Vulnerability of all PBVC patches within NNP under Going for Growth. Maps depicting the Overall Vulnerability of patches for specific PBVCs are available upon request.



In terms of individual PBVCs, Marsh and Raised Bog are indicated as the most and least vulnerable, currently (Table 7.1). These are the highest and lowest levels of vulnerability, respectively, across all time slices. Raised Bog and Heath are the most vulnerable PBVCs under Conservation First and Going for Growth respectively. IGP and NGP are indicated as the least and second least vulnerable PBVCs, respectively under both future scenarios. However, the low levels of Overall Vulnerability for IGP and NGP are partially related to the omission of Matrix Vulnerability from their overall results. Excluding IGP and NGP reveals Fen to be the least vulnerable PBVC under both future scenarios.

The results for the individual PBVCs demonstrate interesting trends within and between the time slices. For instance, the vulnerability of the majority of PBVCs (BLWP, Fen, Heath, IGP, Marsh, NGP and Swamp) decreases (in many cases quite notably) under both of the future scenarios compared to the current time slice. In most instances, the decrease is greater under Going for Growth. Conversely, Overall Vulnerability for Raised Bog and Blanket Bog increases notably under the future scenarios compared to current levels. Because of these trends, Blanket Bog and Raised Bog change from being the two least vulnerable PBVCs currently, to the most vulnerable PBVCs under Conservation First (Table 7.2). Although the ranking of Raised Bog is quite low under Going for Growth, the ranking of Blanket Bog under the scenario is high.

Due to the decreases in vulnerability predicted for the majority of the PBVCs in the future, many of them also experience a concomitant decrease in ranking under the future scenarios compared to the current time slice. Most notably, Fen decreases from the third most vulnerable PBVC under the current time slice (fourth overall) to the sixth and seventh most vulnerable PBVC under Conservation First and Going for Growth (15th and 22nd overall respectively). Fen exhibits the largest decrease in vulnerability of all of the PBVCs across all time slices under Going for Growth. Marsh and BLWP are currently ranked as the most and second most vulnerable PBVCs, respectively. The ranking of Marsh and BLWP decreases to the fourth and fifth most vulnerable PBVCs, respectively, under Conservation First (10th and 12th overall). They are ranked as third and fourth most vulnerable PBVCs, respectively, under Going for Growth (11th and 14th overall).

Less notable changes in ranking are associated with NGP and IGP. They are ranked, respectively, as the sixth and seventh most vulnerable PBVCs currently (17th and 19th overall) and the eighth and ninth most vulnerable under Conservation First (24th and 25th overall) and Going for Growth (23rd and 26th overall). Swamp and Heath are somewhat unusual, in that their vulnerability decreases, but their ranking under the scenarios increases or remains generally the same compared to current conditions (Table 7.2). These trends are due to the relatively minor decreases in vulnerability that these PBVCs experience under both of the scenarios.

Table 7.2: The ranking of each PBVC (high to low), in terms of average Overall Vulnerability, for the study area across all time slices. Numeric prescripts denote rank of the NCA within each time slice.

Rank	Current	Conservation First	Going for Growth
1	1. Marsh (1.482)		
2	2. BLWP (1.445)		
3		1. Raised Bog (1.287)	
4	3. Fen (1.241)		
5		2. Blanket Bog (1.216)	
6	4. Heath (1.173)		
7		3. Heath (1.170)	
8			1. Heath (1.154)
9			2. Blanket Bog (1.105)
10		4. Marsh (1.084)	
11			3. Marsh (1.061)
12		5. BLWP (1.052)	
13	5. Swamp (1.101)		
14			4. BLWP (0.998)
15		6. Swamp (0.996) 6. Fen (0.966)	
16			5. Swamp (0.989)
17	6. NGP (0.967)		
18			
19	7. IGP (0.915)		
20			6. Raised Bog (0.837)
21	8. Blanket Bog (0.798)		
22			7. Fen (0.789)
23			8. NGP (0.717)
24		7. NGP (0.684)	
25		8. IGP (0.634)	
26			9. IGP (0.550)
27	9. Raised Bog (0.395)		

For analysis purposes, the results and trends for each of the individual vulnerability measures (including Overall Vulnerability) are provided in Table 7.3.

The table suggests that, in the case of most PBVCs, levels of Climate Stress have the greatest impact on changes in Overall Vulnerability. For instance, for most PBVCs, Climate Stress shows notably more variation than Matrix or Geometric vulnerability between the current time slice and future scenarios. Also Table 7.3 clearly shows that in all cases trends for Overall Vulnerability closely match those for Climate Stress. However, Matrix and Geometric vulnerability are significant in terms of the role they play in either ameliorating or exacerbating the trends for Climate Stress. For instance, the trends for BLWP in terms of Matrix and Geometric vulnerability under each of the scenarios are generally the same as those for Climate Stress (Table 7.3). The reduction in Overall Vulnerability is exacerbated as a result. On the other hand, the trends for Heath in terms of Matrix and Geometric vulnerability are opposite to those for Climate Stress: The reduction in Climate Stress is therefore somewhat ameliorated.

The trends for the other PBVCs exhibit a more mixed response. Matrix Vulnerability for Blanket Bog slightly decreases under both future scenarios and therefore acts to somewhat dampen the Climate Stress trends. However, Blanket Bog's Geometric vulnerability increases under Conservation First and therefore acts to exacerbate the increases in Climate Stress. Geometric vulnerability remains static under Going for Growth and has no effect on the established trends for Climate Stress and Matrix Vulnerability.

Trends for Swamp and Marsh are similar, in that they both experience a decrease in Matrix Vulnerability under both future scenarios, whist their Geometric Vulnerability remains unchanged. The Climate Stress trends for Marsh are therefore slightly exacerbated by those for Matrix Vulnerability. Swamp is unusual, in that it experiences no future change in Climate Stress. The slight decreases in Overall Vulnerability that it experiences in the future are solely influenced by the changes that it experiences in terms of its boundary characteristics.

Trends for IGP and NGP for each vulnerability measure under each scenario mirror each other exactly. Both experience moderate decreases in Climate Stress and slight increases in Geometric Vulnerability. The trends for patch geometry therefore act to slightly ameliorate those for Climate Stress. However, both PBVCs are unusual in that their Matrix Vulnerability is not assessed within this study. This is probably the primary reason for their consistently low ranking in each of the time slices. Through inclusion of Matrix Vulnerability, it is possible that their levels of Overall Vulnerability would be higher and exhibit more distinct variation. However, strong criteria on which to base analysis of Matrix Vulnerability for these PBVCs could not be established.

Fen exhibits large decreases in Climate Stress under both scenarios, slight and moderate increases in Matrix and Geometric Vulnerability, respectively, under Conservation First, and slight decreases in Matrix Vulnerability and unchanged Geometric Vulnerability under Going for Growth. The trends under Conservation First therefore tend to counteract those for Climate Stress, whilst the trends under Going for Growth either slightly exacerbate or have no effect on those for Climate Stress. Despite these points, the relatively large decreases in Climate Stress which Fen exhibits means it is indicated as the least vulnerable PBVC after IGP and NGP in terms of Overall Vulnerability under both scenarios (Table 7.1).

Under Conservation First, the large increase in Climate Stress experienced by Raised Bog is exacerbated by the slight and moderate increases in Matrix and Geometric Vulnerability, respectively. It is largely because of these characteristics that Raised Bog exhibits the highest Overall Vulnerability under the scenario. Matrix and Geometric Vulnerability remain unchanged between the current time slice and Going for Growth. Although the increase in Climate Stress that it experiences under Going for Growth is high, its Overall Vulnerability is quite low compared to some other PBVCs.

Table: 7.3: Summarising results and trends for Climate Stress, Matrix, Geometric and Overall Vulnerability for all PBVCs (bottom row) and each individual PBVC under each time slice for NNP. For Climate Stress, Matrix and Geometric Vulnerability: Cells highlighted green indicate 'low' levels of stress/vulnerability (i.e. <0.333); cells highlighted orange indicate 'moderate' levels of stress/vulnerability (i.e. 0.333 to < 0.666); red indicates 'high' stress/vulnerability (i.e. ≥0.666). For Overall Vulnerability: Cells highlighted green indicate 'low' levels of vulnerability (i.e. <1.000); cells highlighted orange indicate 'moderate' levels of vulnerability (i.e. 1.000 to <2.000); red indicates 'high' vulnerability (i.e. ≤3.000).

Arrows in the '*T*' column describe the general stress/vulnerability trend between the current time slice and the future scenarios. For Climate Stress, Matrix and Geometric Vulnerability: Arrows pointing straight up/down indicate a large change (i.e. ≥0.400). Arrows angled up/down indicate slight to moderate levels of change (i.e. >0.000 - <0.4000). Horizontal arrows indicate no change between the current time slice and future scenarios. For Overall Vulnerability: large change; ≥0.800; slight to moderate change; >0.000 - <0.800; Horizontal arrows indicate no change between the current time slice and future scenarios. Green arrows indicate that the trend for Matrix or Geometric Vulnerability is generally the same as that for Climate Stress. Red arrows indicate that the trend for Matrix or Geometric Vulnerability generally differs from that of Climate Stress. Black arrows indicate that the Matrix or Geometry trends neither counteract nor reinforce the established trends for Climate Stress.

Abbreviations: 'C' = current time slice; 'CF' = Conservation First; 'GFG' = Going for Growth; '*T*' = Trend.PBVC codes: 'BB' = Blanket Bog; 'BLWP' = Broadleaved Woodland: Priority; 'IGP' = Improved Grassland: Priority; 'NGP' = Neutral Grassland: Priority; 'RB' Raised Bog'.

PBVC	Climate Stress					Matrix					Geometry					Overall				
	C	CF	*T*	GFG	*T*	C	CF	*T*	GFG	*T*	C	CF	*T*	GFG	*T*	C	CF	*T*	GFG	*T*
BB	0.266	0.619	↗	0.593	↗	0.071	0.051	↘	0.052	↘	0.460	0.545	↗	0.460	→	0.798	1.216	↗	1.105	↗
BLWP	0.436	0.080	↘	0.109	↘	0.360	0.356	↘	0.262	↘	0.649	0.615	↘	0.626	↘	1.445	1.052	↘	0.998	↘
Fen	0.714	0.267	↓	0.293	↓	0.060	0.089	↗	0.031	↘	0.466	0.611	↗	0.466	→	1.241	0.966	↘	0.789	↘
Heath	0.493	0.422	↘	0.449	↘	0.113	0.153	↗	0.125	↗	0.566	0.595	↗	0.581	↗	1.173	1.170	↘	1.154	↘
IGP	0.397	0.101	↘	0.005	↘	N/A					0.518	0.533	↗	0.544	↗	0.915	0.634	↘	0.550	↘
Marsh	0.624	0.269	↘	0.269	↘	0.206	0.165	↘	0.141	↘	0.651	0.651	→	0.651	→	1.482	1.084	↘	1.061	↘
NGP	0.386	0.101	↘	0.117	↘	N/A					0.580	0.583	↗	0.600	↗	0.967	0.684	↘	0.717	↘
RB	0.125	0.735	↑	0.568	↑	0.000	0.021	↗	0.000	→	0.270	0.531	↗	0.270	→	0.395	1.287	↑	0.837	↗
Swamp	0.264	0.264	→	0.264	→	0.057	0.053	↘	0.046	↘	0.679	0.679	→	0.679	→	1.001	0.996	↘	0.989	↘
Overall	0.551	0.268	↘	0.277	↘	0.204	0.170	↘	0.143	↘	0.620	0.620	→	0.619	↘	1.349	1.039	↘	1.024	↘

7.3.2 National Character Areas

7.3.2.1 Landscape Level Results

Table 7.4 indicates that, in general, levels of Overall Vulnerability for the NCAs are currently moderate. All of the NCAs experience a decrease in vulnerability under Conservation First and Going for Growth. Vulnerability for the NCAs under both scenarios may be classified generally, as low to low-moderate. In this sense, the trends for the NCAs at the landscape level across the time slices largely mirror those for NNP (Table 7.1).

In terms of individual NCAs, Cheviot Fringe, currently exhibits the lowest levels of vulnerability. However, the NCA is predicted as the most vulnerable under Conservation First and Going for Growth. This is related to the relatively small decreases in vulnerability that the NCA experiences under the scenarios compared to the other NCAs. Cheviot Fringe's overall rank, however, changes only slightly under the scenarios compared to current conditions. It is ranked 5th currently and 6th and 8th under Conservation First and Going for Growth, respectively (Table 7.5).

The most vulnerable NCA currently is NSH (Table 7.4). This is also the highest level of vulnerability of any NCA across all three time slices. NSH experiences the largest decreases in vulnerability of all the NCAs under both future scenarios. However, despite this, its overall rank within each scenario remains high: it is the second most vulnerable NCA under Conservation First and Going for Growth (7th and 9th respectively overall).

The least vulnerable NCA under both future scenarios is BMF. Its vulnerability under Going for Growth is the lowest of all NCAs across all time slices. This is due to BMF experiencing relatively large decreases in vulnerability in both future scenarios. Its rank decreases from the third most vulnerable NCA currently (3rd overall) to the fifth most vulnerable under Conservation First and Going for Growth, respectively (14th and 15th overall respectively) (Table 7.5).

TG and Cheviots experience relatively moderate decreases in Overall Vulnerability under the scenarios compared to current conditions. The changes in ranking associated with these NCAs (particularly TG) within each time slice are less pronounced than for other NCAs (e.g. BMF and Cheviot Fringe). The ranking of TG increases slightly from fourth most vulnerable NCA currently to the third most vulnerable under Conservation First and Going for Growth (10th and 12th overall respectively). The Cheviots decrease in ranking from second most vulnerable NCA currently (2nd overall) to fourth most vulnerable under both future scenarios (11th and 13th respectively overall). These changes represent quite a notable decrease in the overall ranking of the Cheviot NCA.

Table 7.4: Average Overall Vulnerability for all PBVCs across each NCA under each time slice. Values in brackets show the difference in vulnerability between the current and future time slices. The highlighting of specific values follows the same format as that for Table 7.1.

	Current	Conservation First	Going for Growth
Cheviots	1.355	1.046 (-0.309)	1.035 (-0.320)
Cheviot Fringe	1.316	1.172 ***(-0.144)***	1.108 (-0.208)
Northumberland Sandstone Hills (NSH)	***1.557***	1.130 (-0.427)	1.077 ***(-0.480)***
Border Moors and Forests (BMF)	1.339	1.003 (-0.336)	***0.999*** (-0.340)
Tyne Gap and Hadrian's Wall (TG)	1.336	1.048 (-0.288)	1.038 (-0.298)

Table 7.5: The ranking of each NCA (high to low), in terms of average Overall Vulnerability under each time slice. Numeric prescripts denote rank of NCA within each time slice.

Overall Rank	Current	Conservation First	Going for Growth
1	1. NSH (1.557)		
2	2. Cheviots (1.355)		
3	3. BMF (1.339)		
4	4. TG (1.336)		
5	5. Cheviot Fringe (1.316)		
6		1. Cheviot Fringe (1.172)	
7		2. NSH (1.130)	
8			1. Cheviot Fringe (1.108)
9			2. NSH (1.077)
10		3. TG (1.048)	
11		4. Cheviots (1.046)	
12			3. TG (1.038)
13			4. Cheviots (1.035)
14		5. BMF (1.003)	
15			5. BMF (0.999)

The trends in Table 7.6 are generally similar to those at the NNP level (Table 7.1: Bottom row). For instance, trends for Overall Vulnerability for each NCA closely follow those for Climate Stress. Trends for Matrix Vulnerability at the NCA level also tend to exacerbate those for Climate Stress, whilst those for Geometric Vulnerability under Conservation First tend to ameliorate the Climate Stress trends. However, Geometric Vulnerability under Going for Growth within the NCAs exhibits a more mixed response. For instance, within the Cheviots, Cheviot Fringe and BMF Geometric Vulnerability decreases and therefore acts to exacerbate the Climate Stress trends. Geometric Vulnerability increases under Going for Growth within the NSH and TG and therefore acts to dampen the associated Climate Stress trends. It should be noted, however, that the differences in Geometric Vulnerability between the current time slice and both future scenarios are small and therefore appear to have relatively little impact on overall levels of vulnerability within the NCAs.

Table 7.6: Summarising results and trends for Climate Stress, Matrix, Geometric and Overall Vulnerability for all PBVCs taken together within each NCA. The formatting of cells and arrows is the same as that for Table 7.3.

PBVC	Climate Stress					Matrix					Geometry					Overall				
	C	CF	*T*	GFG	*T*	C	CF	*T*	GFG	*T*	C	CF	*T*	GFG	*T*	C	CF	*T*	GFG	*T*
Cheviots	0.589	0.263	↘	0.277	↘	0.174	0.161	↘	0.141	↘	0.633	0.635	↗	0.626	↘	1.355	1.046	↘	1.035	↘
CF	0.421	0.245	↘	0.250	↘	0.505	0.484	↘	0.375	↘	0.604	0.606	↗	0.599	↘	1.316	1.172	↘	1.108	↘
NSH	0.441	0.311	↘	0.321	↘	0.298	0.240	↘	0.158	↘	0.611	0.615	↗	0.617	↗	1.557	1.130	↘	1.077	↘
BMF	0.563	0.261	↘	0.272	↘	0.183	0.141	↘	0.127	↘	0.615	0.616	↗	0.613	↘	1.339	1.003	↘	0.999	↘
TG	0.513	0.262	↘	0.264	↘	0.290	0.218	↘	0.187	↘	0.608	0.609	↗	0.624	↗	1.336	1.048	↘	1.038	↘

7.3.2.2 Class Level Results (by NCA)

Table 7.7 indicates that Heath within the Cheviot Fringe NCA under Conservation First is the most vulnerable PBVC overall. Raised Bog currently within BMF is the least vulnerable PBVC overall. In many instances, the results indicate that IGP and NGP are the least and/or second least vulnerable PBVCs in individual NCAs under each time slice. However the results for these PBVCs are probably due to the lack of Matrix analysis conducted for them. The descriptions below, therefore, also highlight those PBVCs which are the least vulnerable when the results for IGP and NGP are omitted.

Cheviots

Marsh, BLWP and Swamp are indicated as the most vulnerable PBVCs under each of the time slices, respectively. The vulnerability of Marsh currently is the highest across all three time slices. Blanket Bog is the least vulnerable PBVC currently. NGP and IGP are indicated as the least vulnerable PBVCs under Conservation First and Going for Growth, respectively. The vulnerability of IGP under Going for Growth is the lowest overall. Exclusion of both these PBVCs from the results suggests Heath and Blanket Bog are the least vulnerable PBVCs under Conservation First and Going for Growth, respectively. Blanket Bog's vulnerability under Going for Growth is the lowest overall.

Cheviot Fringe

Marsh is the most vulnerable PBVC currently. Heath is the most vulnerable under both future scenarios. Heath under Conservation First is the most vulnerable across all time slices. IGP and NGP are the least vulnerable PBVCs under Conservation First. IGP is the least vulnerable PBVC under Going for Growth. This is also the lowest level of vulnerability across the time slices. Omission of NGP and IGP from the results suggests that BLWP is the least vulnerable PBVC under both future scenarios. Its vulnerability under Going for Growth is the lowest overall.

Northumberland Sandstone Hills

Marsh is currently the most vulnerable PBVC. It also has the highest vulnerability exhibited across all three time slices. Heath is the most vulnerable PBVC under both future scenarios. NGP is the least vulnerable PBVC currently and under Conservation First. The least vulnerable PBVC under

Going for Growth is IGP. This is also the lowest level of vulnerability overall. Excluding IGP and NGP suggests that Blanket Bog is currently the least vulnerable PBVC. This is also the lowest level of vulnerability across the time slices. Fen is the least vulnerable PBVC under both future scenarios.

Border Moors and Forests

Marsh is currently the most vulnerable PBVC. It also has the highest level of vulnerability across the three time slices. Raised Bog and Blanket Bog are the most vulnerable PBVCs under Conservation First and Going for Growth, respectively. Raised Bog is currently the least vulnerable PBVC. This is also the lowest level of vulnerability across the time slices. IGP is the least vulnerable PBVC under both future scenarios. Excluding IGP and NGP reveals Fen to be the least vulnerable PBVC under both future time slices.

Tyne Gap and Hadrian's Wall

BLWP is currently the most vulnerable PBVC. It also has the highest level of vulnerability overall. Blanket Bog is the most vulnerable PBVC under both future scenarios. IGP is the least vulnerable PBVC under both future time slices. Its vulnerability under Going for Growth is the lowest overall. Omission of IGP and NGP suggests that Swamp and Fen are the least vulnerable PBVCs under Conservation First and Going for Growth respectively. Of these, Fen under Going for Growth is the least vulnerable overall.

Summary results and trends for Climate Stress, Matrix and Geometric and Overall Vulnerability for each PBVC within each NCA are provided in Tables A4 (a-e).

Table 7.7: Average Overall Vulnerability for each PBVC within each NCA under each time slice. The highlighting of specific values follows the same general format as Tables 7.1 and 7.4. Values followed by an '*' denote the PBVCs with the highest/lowest Overall Vulnerability across all NCAs across all time slices.

NCA	PBVC	Current	Conservation First	Going for Growth
Cheviots	Blanket Bog	0.928	1.075 ***(0.147)***	0.856 (-0.072)
	BLWP	1.484	1.158 (-0.326)	1.145 (-0.339)
	Fen	1.417	1.088 (-0.329)	1.088 (-0.329)
	Heath	1.151	1.045 (-0.106)	1.059 (-0.092)
	IGP	0.954	0.653 (-0.301)	***0.523*** (-0.431)
	Marsh	***1.496***	1.085 (-0.411)	1.072 (-0.424)
	NGP	1.028	0.564 ***(-0.464)***	0.601 (-0.427)
	Raised Bog	N/A	N/A	N/A
	Swamp	1.162	1.157 (-0.005)	1.157 (-0.005)
Cheviot Fringe	Blanket Bog	N/A	N/A	N/A
	BLWP	1.610	1.331 (-0.279)	1.142 ***(-0.468)***
	Fen	N/A	N/A	N/A
	Heath	N/A	***1.701* (1.701)***	1.570 (1.570)
	IGP	0.832	0.690 (-0.142)	***0.469*** (-0.363)
	Marsh	***1.653***	1.398 (-0.255)	1.335 (-0.318)
	NGP	0.978	0.690 (-0.288)	0.790 (-0.188)
	Raised Bog	N/A	N/A	N/A
	Swamp	N/A	N/A	N/A
Northumberland Sandstone Hills	Blanket Bog	0.760	1.297 ***(0.537)***	1.241 (0.481)
	BLWP	1.413	1.090 (-0.323)	0.894 ***(-0.519)***
	Fen	1.076	0.986 (-0.090)	0.826 (-0.250)
	Heath	1.333	1.412 (0.079)	1.403 (-0.070)
	IGP	0.886	0.776 (-0.110)	***0.558*** (-0.328)
	Marsh	***1.454***	1.141 (-0.313)	1.062 (-0.392)
	NGP	0.651	0.728 (0.077)	0.580 (-0.071)
	Raised Bog	N/A	N/A	N/A
	Swamp	N/A	N/A	N/A
Border Moors and Forests	Blanket Bog	0.671	1.291 (0.620)	1.227 (0.556)
	BLWP	1.418	0.968 ***(-0.450)***	0.977 (-0.441)
	Fen	1.182	0.926 (-0.256)	0.743 (-0.439)
	Heath	1.129	1.097 (-0.032)	1.132 (0.003)
	IGP	0.934	0.608 (-0.326)	0.554 (-0.380)
	Marsh	***1.448***	1.052 (-0.396)	1.031 (-0.417)
	NGP	0.993	0.683 (-0.310)	0.730 (-0.263)
	Raised Bog	***0.395****	1.294 ***(0.899)***	0.837 (0.442)
	Swamp	1.014	1.012 (-0.002)	1.002 (-0.012)
Tyne Gap and Hadrian's Wall	Blanket Bog	1.004	1.325 (0.321)	1.480 ***(0.476)***
	BLWP	***1.638***	1.041 ***(-0.597)***	1.043 (-0.595)
	Fen	1.255	1.035 (-0.220)	0.736 (-0.519)
	Heath	1.162	1.351 (0.189)	1.257 (0.095)
	IGP	0.889	0.576 (-0.313)	***0.564*** (-0.325)
	Marsh	1.623	1.192 (-0.431)	1.151 (-0.472)
	NGP	0.895	0.674 (-0.221)	0.804 (-0.091)
	Raised Bog	N/A	1.245 ***(1.245)***	N/A
	Swamp	0.978	0.973 (-0.005)	0.965 (-0.013)

7.3.2.3 Class Level Results (By PBVC)

Table 7.8 identifies the specific NCAs in which particular PBVCs are most and least vulnerable under each of the time slices. The results, in this regard, fall into four general groups: 1) PBVCs most vulnerable in the same NCA across all three time slices; 2) PBVCs most vulnerable in the same NCA under both future scenarios; 3) Mixed response; 4) Miscellaneous.

Group 1 consists of: Blanket Bog, which is consistently most vulnerable in the TG NCA; Marsh which is consistently the most vulnerable in the Cheviot Fringe NCA; Fen and Swamp, which are consistently the most vulnerable in the Cheviot NCA. Group 2 is comprised solely of Heath which is most vulnerable in the Cheviot Fringe under both futures scenarios. Group 3 includes: BLWP; IGP and NGP. Both IGP and NGP are most vulnerable in the same NCAs under each of the three time slices: Cheviot, NSH and TG respectively. Currently BLWP is most vulnerable within the TG NCA; under both of the future scenarios, it is most vulnerable under Cheviot Fringe and Cheviot respectively. Group 4 is comprised solely of Raised Bog. NCA results for this PBVC are unusual in that currently and under Going for Growth, it only appears in one NCA: BMF.

Considering the results for both of the future scenarios reveals some interesting trends. For instance, across both scenarios, five PBVCs are the most vulnerable in the Cheviot (Fen and Swamp under Conservation First and BLWP, Fen and Swamp under Going for Growth) and Cheviot Fringe (BLWP, Heath and Marsh under Conservation First and Heath and Marsh under Going for Growth). Four PBVCs are the most vulnerable in the TG NCA across the future scenarios (Blanket Bog under Conservation First and Blanket Bog, IGP and NGP under Going for Growth). Only two PBVCs are most vulnerable in the NSH NCA (IGP and NGP under Conservation First).

The results suggest that, in general terms, PBVCs tend to be least vulnerable within the BMF NCA under both future scenarios. For instance, apart from Raised Bog, no PBVCs are most vulnerable within that NCA in any of the time slices. Also a number of PBVCs are least vulnerable within this specific NCA (BLWP, Fen and Marsh under Conservation First and Marsh under Going for Growth).

Table 7.8: Summary of NCAs where PBVCs are most and least vulnerable in each time slice. 'Ch' = Cheviots; 'CFr' = Cheviot Fringe; 'BMF' = Border Moors and Forests; 'NSH' = Northumberland Sandstone Hills; 'TG' = Tyne Gap and Hadrian's Wall.

PBVC	Current		Conservation First		Going for Growth	
	Least	Most	Least	Most	Least	Most
Blanket Bog	BMF	TG	Ch	TG	Ch	TG
BLWP	NSH	TG	BMF	CFr	NSH	Ch
Fen	NSH	Ch	BMF	Ch	TG	Ch
Heath	BMF	NSH	Ch	CFr	Ch	CFr
IGP	CFr	Ch	TG	NSH	CFr	TG
Marsh	BMF	CFr	BMF	CFr	BMF	CFr
NGP	NSH	Ch	Ch	NSH	NSH	TG
Raised Bog	BMF*	BMF*	TG	BMF	BMF*	BMF*
Swamp	TG	Ch	TG	Ch	TG	Ch

* Only NCA in which PBVC appears under the time slice.

7.4 Discussion

7.4.1 NNP: Overall Trends

A major finding of the research is that the moderate levels of Overall Vulnerability for the national park currently are the highest across the three time slices and will decrease notably under both future scenarios. These findings may seem somewhat surprising considering the changes in climate that NNP is predicted to experience in the future and that a number of other studies have indicated that the vulnerability/local extinction risk of many communities/species in the UK is likely to increase in the future as a consequence (Araujo *et al*., 2011; Trivedi *et al*., 2008; Mitchell *et al*., 2007; Thomas *et al*., 2004; Berry *et al*., 2003). It is tempting to assume then that the decreases in Overall Vulnerability predicted within this research are due to the characteristics of the scenarios, the land use changes occurring within them and the resultant impact on the other vulnerability measures (i.e. Matrix and Geometric Vulnerability). However, Table 7.3 and preceding sections strongly indicate that this is not the case. Indeed, although average levels of Matrix and Geometric Vulnerability for the PBVCs overall often decrease under the future scenarios, the decreases are far less distinct than those observed for Climate Stress. If Climate Stress were not included as a component of VM3, reductions in overall levels of vulnerability for NNP under the scenarios would also be notably less distinct.

These results suggest that levels of Overall Vulnerability will decrease in the future, largely because of the effects of climate change, rather than in spite of them. In turn, this implies that changes in climate, rather than land use, are likely to play a more significant role in influencing the future vulnerability of the PBVCs within NNP specifically by 2050. Such results stand somewhat in contrast to those of other research, which suggest that land use is likely to continue to have a greater influence on terrestrial ecosystems by the year 2050, at least globally (e.g. MA, 2005a; 2005b; Sala *et al*., 2000). The results therefore provide some validation of Berry's (2008) suggestion that, by 2050, climate change will have replaced land use as the main factor influencing ecological systems. There is a paucity of research investigating the potential impacts of climate and land use change on ecological phenomena at the sub-regional, landscape scale (Berry, 2008; Trivedi *et al*., 2008; Pearson & Dawson, 2003). The results of this research therefore provide some indication that, although land use is typically regarded as playing a more important role in influencing the distribution of ecological phenomena at landscape scales (Pearson & Dawson, 2003), future levels and changes in community vulnerability are likely to be largely determined by climate, at least within NNP and under socio-economic conditions similar to those of the land use scenarios used within this research.

7.4.1.1 Individual PBVCs: The Role of Climate Stress

In simple terms, the trends in Overall Vulnerability at the scale of the park are largely due to the predominant trends exhibited by the majority of the PBVCs under the future scenarios. For instance, as indicated in Table 7.1, the Overall Vulnerability of most individual PBVCs notably decreases under the scenarios, whilst the vulnerability of only two PBVCs (Blanket Bog and Raised Bog) notably increases. These results are similar to those for the PBVCs taken together at the scale of NNP, in that they appear to be strongly influenced by those for Climate Stress. In most instances, trends in Overall Vulnerability for individual PBVCs closely mirror those for Climate Stress (Table 7.3).

As the discussion in Chapter Five indicates, the Climate Stress of individual PBVCs is strongly related to their particular ecological characteristics and their subsequent responses to changes in climate. For instance, many of the lowland PBVCs that are more typically associated with, or have an increased tolerance for, relatively warm and/or dry conditions (e.g. BLWP, Fen, IGP, Marsh and NGP) are generally influenced very positively by the changes in future climate. These PBVCs are also those that exhibit the most obvious decreases in Overall Vulnerability under the scenarios. Other PBVCs, more closely associated with cooler, wetter conditions (e.g. Raised Bog and Blanket Bog) generally experience a notable negative impact from future climate change. These PBVCs are also those that exhibit the greatest increase in Overall Vulnerability under both scenarios. Of all the PBVCs, Heath and Swamp exhibit the least change in Climate Stress under the scenarios. These PBVCs also exhibit the least change in terms of Overall Vulnerability.

These points highlight the important role that future climate is likely to play in influencing Overall Vulnerability in the future. However, they also demonstrate that, although the overall results suggest a generally positive future for PBVCs taken together at the scale of the park, they should be interpreted with some caution, as the vulnerability of some PBVCs (i.e. Raised Bog and Blanket Bog) is likely to increase dramatically.

Table 5.1 is also relevant in interpreting the Climate Stress results of individual PBVCs. For instance, the results for Blanket Bog and Raised Bog may be regarded as highly robust, based on the information in Table 5.1. The results of Heath are regarded as reliable based on Table 5.1. Those for BLWP, IGP and NGP are regarded as reasonably reliable. The results for Fen, Marsh and Swamp are regarded as the least reliable.

Despite these issues, the PBVC results generally agree well with those of other studies, although differences in methodology, geographical context and the spatial scale of these studies and those of this research should be noted. Berry *et al*. (2002) assessed changes in suitable climate space under the UKCIP98 2050s Low and High emissions scenarios for fifty-four species representing fifteen habitats within the UK and Ireland using an artificial neural network. As the authors point out, the use of species to infer future climate impacts on habitats is somewhat problematic. However, their results for a number of indicator species agree well with those for the specific PBVCs with which they are typically associated. For instance, cross-leaved heath (*Erica tetralix*) shows little change in its future climate space (Berry *et al*., 2002). Indeed 'lowland heath' and 'wet heath' in general are noted as exhibiting little change across the UK under the scenarios. These results are very similar to the Climate Stress results for Heath (Table 7.3).

Also, the suitable climate space of great burnet (*Sanguisorba officinalis*), a representative species of upland hay meadows, is predicted by Berry *et al*. (2002) to expand notably under the 2050 'Low' and 'High' scenarios into areas of northern England and Scotland. Again these results compare very well with those for NGP (of which upland hay meadows are a conservationally significant component) which show notable reductions in Climate Stress within NNP. Other species typically associated with NGP for which Berry *et al*. (2002) conducted simulations include globe flower (*Trollius europaeus*) and wood cranesbill (*Geranium sylvaticum*). Although these species are predicted to lose suitable climate space throughout the UK as a whole, both either retain or make gains in suitable climate space in north-eastern England, in and around NNP, under both 2050s scenarios. Overall, Berry *et al.'s* (2002) results for the north east, for species typically associated with NGP, generally concur well with those for NGP from this research.

Additionally, Berry *et al*. (2002) suggest that, although fens are predicted to lose suitable climate space in East Anglia and southern England, such communities are likely to make gains in northern areas of the UK (e.g. Scotland). Species typically associated with Fen, such as marsh helleborine (*Epipactis helleborine*) also show a marked increase in suitable climate space within north-eastern

England under both 2050s scenarios. These findings show good general agreement with the results from this research, which predict a notable decrease in the Climate Stress of Fen within NNP specifically.

Further similarities are found between the results of Berry *et al*. (2002) and Harrison *et al*. (2001) for beech woodland and upland oak woodland and those for BLWP. For instance, beech (*Fagus sylvatica*) is predicted to make significant gains in suitable climate space in northern areas of England by the 2050s (Berry *et al*., 2002; Harrison *et al*., 2001). Upland oak woodland is described as demonstrating a mixed response. However, many of the modelled species are understory plants. Oak itself is expected to expand into higher altitudes and is likely to 'continue to find suitable climate space in Great Britain' (Harrison *et al*., 2001, pp. 64).

There are however some differences between the results of Berry *et al*. (2002) and those of this research. For instance, hare's tail cotton grass (*Eriophorum vaginatum*), a species associated with Blanket Bog and Raised Bog, is predicted to experience a decrease in suitable climate space under the 2050 high emissions scenario, but mainly in southern England, East Anglia and eastern coastal areas (Harrison *et al*., 2001). This is somewhat distinct from the results from this research, which suggest that these PBVCs will experience a large to moderate increase in Climate Stress within NNP specifically. This is particularly important, as predictions of Climate Stress in this research are undertaken for the Medium emissions scenario, under which the magnitude of changes in climate may be expected to be less severe. It is possible that the differences are due to the differences in the scale of the data used to establish the bioclimatic envelopes of the ecological units utilised within the studies. It is likely that, because of the necessity of using data at the scale of the UK for this research, the bioclimatic envelopes of the BVCs/PBVCs are somewhat more restricted than those determined by Berry *et al*. (2002) which were based on European scale data. European scale ecological data at an appropriate thematic level were not readily obtainable for use within this research. It is possible that the results somewhat overestimate the future Climate Stress that the PBVCs are likely to experience. It should be noted, however, that although blanket and raised bogs are generally described as demonstrating a 'mixed response' (Berry *et al*., 2002, pp. 458), other important species typically associated with these communities, such as bog rosemary (*Andromeda perfolia*), cloudberry (*Rubus chamaemorus*) and large heath (*Coenonympha tullia*), are predicted to lose suitable climate space from north-eastern England under the 2050s high scenario. *A. perfolia* also loses suitable climate space under the 2050s Low scenario (Harrison *et al*., 2001).

In many instances, the results for particular PBVCs in terms of Climate Stress under the Medium emission scenario used within this research are broadly more similar to the findings of Berry *et al*. (2002) and Harrison *et al*. (2001) from the High scenario than the Low scenario. It is possible that the potential overestimate in the climatic stress of the PBVCs, combined with the moderate changes in climate under the Medium emissions scenario, has impacted on the Climate Stress results, so that they may be thought of as offering a more accurate assessment of the levels of stress that the PBVCs are likely to experience within NNP under High emission scenario conditions. Under conditions similar to those occurring under the Medium emissions scenario, the actual Climate Stress of Blanket and Raised Bogs may be less severe than indicated by the results of this research.

The apparent differences between some of the results of this study and those of Berry *et al*. (2002) and others also highlight some of the issues and problems with the scale of ecological organisation used to study future impacts. As the results from Berry *et al*. (2002) indicate, in some instances, the composition of established community types is likely to change as species respond individualistically to changes in climate. The model is unable to account for such changes. However, there is strong agreement between the results of many of the species modelled by Berry *et al*. (2002) and those of associated PVCs within this research. This suggests that the use of relatively simple methods with broad vegetation communities as the basic ecological units does represent a valid and potentially more straightforward approach for estimating the impacts of climate change and other stressors on whole ecological communities across entire landscapes.

7.4.1.2 Individual PBVCs: Influence of Matrix and Geometry (Land Use)

Climate evidently plays an important part in influencing the Overall Vulnerability of the PBVCs. However, Matrix and Geometric Vulnerability are also significant in the role that they play in either ameliorating or exacerbating the trends for Climate Stress (Table 7.3). In this regard, the land use change trends occurring under the scenarios are important. Generally, levels of Matrix Vulnerability are low. However, the variation that Matrix Vulnerability exhibits under the scenarios is sufficient to facilitate differences in levels of Overall Vulnerability between the future time slices. Table 7.3 also shows that levels of Geometric Vulnerability, generally, are moderate under each of the time slices and are therefore often relatively high compared to levels of Climate Stress and Matrix Vulnerability (particularly under the future scenarios). Absolute levels of Overall Vulnerability within each of the time slices are therefore strongly influenced by levels of Geometric Vulnerability. There seems therefore some potential to reduce overall levels of vulnerability through appropriate patch design and management.

The results in Table 4.16 are relevant in interpreting the results based on future simulated land use changes. Of the P/NPBVCs undergoing expansion under the scenarios, the results for Blanket Bog, Heath and Coniferous Woodland are regarded as reliable to very reliable. Those for Fen are regarded as reasonably reliable. The results for IGP, NGP and Arable are regarded as poor. Those for BLWP and Raised Bog are regarded as very poor. However, as discussed in Chapter Four, the simulation accuracies of all the P/NPBVCs are likely to be enhanced due to the inclusion of the additional management variables in producing future simulations. The significance of the low simulation accuracies for some P/NPBVCs from Table 4.16, in terms of the reliability of the results derived from future land use simulations, is likely to be less than the table initially suggests.

Matrix Vulnerability

A result highlighted by the research is that the PBVCs taken together at the scale of the National Park will be slightly less vulnerable under Going for Growth than Conservation First (Table 7.1). This result appears somewhat counterintuitive considering the differing underlying paradigms inherent within the scenarios. It may be generally expected that PBVC vulnerability would be higher under a future storyline in which environmental security and protection are relatively low on the land use agenda. Generally, the trend is related to the fact that the decrease in vulnerability associated with the majority of the PBVCs under the scenarios is often more pronounced under Going for Growth, whilst the increase in vulnerability associated with Blanket Bog and Raised Bog is more pronounced under Conservation First (Table 7.1). Examination of the trends for individual PBVCs in terms of the three measures comprising Overall Vulnerability (Table 7.3) shows that, in nearly all cases, they act to create levels of Overall Vulnerability that are less under Going for Growth than Conservation First. Where decreases in PBVC vulnerability occur under both scenarios, the decrease is often greater under Going for Growth. Where increases occur, the increase is often greater under Conservation First. In other instances where there is an increase in vulnerability under Conservation First, vulnerability under Going for Growth remains the same or actually decreases. In this regard, the trends for Matrix and Geometry are therefore also significant.

Although Going for Growth was formulated as a feasible business-as-usual storyline, the lower Overall Vulnerability it exhibits is largely due to the differing land use trends of the two scenarios and particularly the impact they appear to have on Matrix Vulnerability. For instance, in line with the general ethos of Conservation First, there is a greater increase in 'semi-natural' PBVC types, compared to Going for Growth. However, there are also greater increases in 'modified' land cover types to account for the increases in hay meadows and intensively managed grazing land that are considered feasible under the Conservation First scenario (Tables 4.6 & 4.8).

Land use change under Going for Growth is largely influenced by prevailing economic trends and regulation as well as the current and likely future economic profitability of specific land uses within the park. The major increases in coverage are associated with semi-natural P/NPBVCs, which are related to supporting the use of the park for country sports, largely for financial gain. Increases in modified types under Going for Growth are related to the increased use of the park for food and bio-fuel production deemed likely to occur under the storyline. The upshot of these characteristics is that modified land cover types tend to increase by a greater amount under Conservation First than Going for Growth. It appears that Matrix Vulnerability is more notably reduced under Going for Growth as a result. This is significant, because the greater decrease in aggregate levels of Overall Vulnerability under Going for Growth compared to Conservation First (Table 7.1) appears to be primarily influenced by the trends for Matrix Vulnerability (Table 7.3). Climate Stress is actually slightly higher under Going for Growth compared to Conservation First, whilst Geometric Vulnerability only very slightly decreases under Going for Growth in comparison to the other scenario.

These points highlight that when the characteristics of adjacent land uses are considered as a factor, the Overall Vulnerability of ecological communities is likely to be significantly influenced by the types and specific levels of land use change occurring in the future. It should be noted, however, that there is inherently a high degree of complexity and dynamism in the various factors governing land use (Chapter Four). It is quite possible that the characteristics of land use change (types and levels) may turn out somewhat differently in the future, depending on the specific interactions of these drivers. Some uncertainty is therefore associated with the scenarios and the land use changes predicted under them.

Some of the uncertainty also stems from the fact that the land use trends within the scenarios are, by necessity, based on a degree of subjective judgement. For instance, there is a lack of previous work regarding future land use change at the landscape scale, for the UK (Berry, 2008) and NNP specifically. The scenarios therefore represent a useful starting point from which to examine likely land use trends affecting the park in the future. However, some interpretation was needed in determining some of the specific types of land use expanding under the scenarios. For instance, due to the storyline trends under Going for Growth, the expansion of Heath to accommodate an increased use of the park for country sports was highlighted as a likely future land use trend. This is a novel finding. However, due to the lack of relevant secondary land use information regarding NNP under such a storyline, it was necessary to base expansion figures on those for Heath under Conservation First (Tables 4.6 & 4.8). This was considered more appropriate than simply assigning figures arbitrarily, particularly as those for BLWP under Going for Growth are based on a relatively high degree of subjective judgement. It is possible that levels of future Heath expansion under Going for Growth conditions will differ from those predicted within this research, depending on the specific interactions and characteristic trends of the prevailing land use drivers.

There are also inconsistencies between the spatial scale of this study and that of some of the secondary sources on which levels of expansion are based. For instance, the increase in some P/NPBVCs under Going for Growth (e.g. Coniferous Woodland and Arable) and Conservation First (e.g. Blanket Bog, Raised Bog and NGP) were based on expansion figures from secondary sources at the scale of the UK (Tables 4.6 & 4.8). This may have important implications in terms of the reliability of the vulnerability results. For instance, it is possible that, because the expansion figures associated with Arable are derived from UK national scale estimates, they are quite conservative (Table 4.8) and therefore somewhat underestimate levels of expansion within NNP specifically under Going for Growth. In light of the above discussion regarding the role of matrix characteristics in influencing Overall Vulnerability, this has obvious implications in terms of the apparent differences in vulnerability between the scenarios.

Despite these issues, the scenarios were formulated based on the best available secondary sources and information. For instance, the expansion figures for some P/NPBVCs undergoing expansion under Conservation First (e.g. Heath and BLWP) and Going for Growth (e.g. Heath) are based on more regionally relevant sources and may be regarded with a somewhat greater degree of certainty. The land use trends and the associated levels of land use change occurring under the respective storylines are considered, therefore, to represent feasible and realistic land use futures for the park. Based on these points, the results are regarded as a useful representation of the changes in Matrix Vulnerability that the target PBVCs are likely to experience

The scenarios are used as a way of tackling the inherently broad level of uncertainty regarding likely future land use change at the landscape scale of NNP. Therefore, they should not be considered as exhaustive but as representing a useful starting point from which to examine potential land use trends. It is recommended that future work seeks to further validate the simulation results under the scenarios within NNP. The methodology is designed so that storylines and trends may be easily formulated and run through the model according to different end-user requirements. The model may be applied elsewhere with relative simplicity to reflect different socio-economic contexts.

Geometric Vulnerability

Aggregate levels of Geometric Vulnerability for the PBVCs taken together do not change between the current time slice and future scenarios (Table 7.1). This initially suggests that land use change is largely unimportant in terms of the influence it has on PBVC vulnerability through impacts on patch size and shape. As Chapter Six's discussion indicates, this may be partly attributable to: the relatively large number of PBVCs, particularly under Going for Growth, which retain their current distribution under the scenarios; the decrease in Geometric Vulnerability associated with BLWP; and the relatively small increases in Geometric Vulnerability that many of the PBVCs experience. However, as a number of PBVCs undergo expansion under the scenarios, particularly Conservation First, these results suggest that, for the PBVCs taken together, decreases in the vulnerability of patches facilitated through an increase in area have been more or less exactly compensated for by concomitant increases in vulnerability through an increase in patch shape complexity (See: Table 6.1b). These findings generally agree with those of authors, such as Didham & Ewers (2012), who suggest a positive relationship between patch area and complexity.

The results presented in Table 6.1b provide further support for this finding. In all cases, shape complexity is shown to increase or decrease along with patch area. However, the results for individual PBVCs demonstrate some interesting trends in terms of the interrelationship between patch area, complexity and vulnerability, generally indicating that the spatial characteristics of patches (i.e. their size, complexity and therefore vulnerability) is strongly influenced by the distribution of available suitable habitat. For instance, although average patch area increases in a number of cases, Geometric Vulnerability also increases due to the associated increases in patch shape complexity. With other PBVCs, the distribution of suitable habitat generally acts to create smaller, less complex patches. However, the reduced complexity is insufficient to counteract the decreases in area and Geometric Vulnerability increases. In other instances, patch area and complexity both increase, whilst Overall Vulnerability decreases, suggesting that decreases in vulnerability through increasing patch area more than compensate for the increases in vulnerability through increasing patch complexity.

The decision rules used to allocate land under the scenarios are based on the physical characteristics of the P/NPBVCs and available land, as well as the management actions required to facilitate conversion. The results of the land use modelling therefore offer a useful prediction of the most economically viable potential patterns of future land use. These results suggest that, in order to ameliorate the increases in Geometric Vulnerability that some of the PBVCs are likely to experience in the future, additional resources may be required to facilitate the creation of larger, less complex patches through the modification of areas which represent sub-optimum conditions for particular PBVCs. For the majority of the PBVCs, this may not be so imperative, considering the positive impact that climate change is predicted to have on levels of Climate Stress (and in turn on levels of Overall Vulnerability). However, in the case of Blanket and Raised Bog, the potential to offset some of the risk posed to these communities from climate change through appropriate and sensitive changes in land use may be regarded as a priority, particularly as absolute levels of Overall Vulnerability under each of the time slices tend to be strongly influenced by levels of Geometric Vulnerability (Table 7.3).

7.4.2 NCAs

The Overall Vulnerability trends at the NCA level closely follow those for NNP. For instance, Tables 7.4 and 7.5 show that, in all instances, the moderate levels of Overall Vulnerability that each NCA exhibits currently are the highest across the three time slices and decrease notably under both future scenarios. Table 7.6 also shows that the trends for Overall Vulnerability are most strongly influenced by those for Climate Stress. All of the overall results closely mirror those of Climate Stress. In turn, levels of Matrix and Geometric Vulnerability exhibit relatively little change. However, Matrix Vulnerability generally exhibits somewhat more variation than Geometric Vulnerability.

In all instances, the PBVCs taken together within each NCA are less vulnerable under Going for Growth than Conservation First (Table 7.4). Table 7.6 also shows that the primary cause of this difference between the two future scenarios is represented by the trends for Matrix Vulnerability. Although Climate Stress decreases under both future scenarios in all cases, the decrease is greater under Conservation First. Although Geometric Vulnerability often decreases under Going for Growth and increases under Conservation First, in all instances the decrease compared to current levels is notably less than that of Matrix Vulnerability.

In terms of individual PBVCs, because of the close similarity between the trends at the NCA level and those for NNP, it may be expected that the related causes, issues and uncertainties described above for NNP are generally applicable at the NCA level. In general, it appears that the reduction in Overall Vulnerability exhibited by all NCAs under the scenarios is due to the dominant PBVC types and their specific relationship with climate. For instance, Table 4.18 shows that, in most cases, the number of patches belonging to 'lowland' PBVC types (e.g. BLWP, Fen, IGP, NGP and Marsh) equates to a very high proportion (approximately 70%; often more) of the total number of PBVC patches within each NCA. Tables A4 (a-e) show that in all NCAs the Climate Stress of most of these lowland PBVC types decreases notably under both of the future scenarios. As stated, the variation in levels of Geometric and Matrix Vulnerability between the current time slice and the scenarios within each NCA is often far less than that for Climate Stress. The trends in Overall

Vulnerability at the NCA level are predominantly determined by the climatic response of these PBVC types.

The top five overall ranks (Table 7.5) are consistently occupied by NCAs under the current time slice, which further supports the point that aggregate levels of Overall Vulnerability for the PBVCs are notably higher currently than under both future scenarios. This general pattern matches that for Climate Stress quite closely (Table 5.6), which also points towards the strong influence of Climate Stress on Overall Vulnerability.

Table 7.5 also shows some interesting trends in terms of differences in ranking of the NCAs within and between the time slices. For instance, the results suggest that Cheviot Fringe is likely to change from the least vulnerable NCA currently to the most vulnerable under both future scenarios. Examination of Tables 7.7 and 4.18 shows that this change is largely due to the trends apparent for the dominant PBVC types within the Cheviot Fringe NCA, compared to those of other NCAs, as well as the appearance of Heath, due to the land use changes occurring under the scenarios. For instance, Table 4.18 shows that the Overall Vulnerability of the first, second and third most dominant PBVCs within the Cheviot Fringe under Conservation First (Marsh, IGP and BLWP respectively) and Going for Growth (Marsh, IGP and Heath respectively) in most cases decreases by less than the dominant PBVCs from other NCAs. Heath is particularly significant, due to its expansion into the Cheviot Fringe from adjacent areas. Although Heath is less dominant than some of the other PBVCs within the Cheviot Fringe (particularly under Conservation First), patches demonstrate quite a high degree of Overall Vulnerability and therefore act to increase levels of vulnerability for the NCA overall.

The relatively large decrease in Overall Vulnerability under the scenarios associated with NSH (Table 7.4) is somewhat surprising, as the decrease in vulnerability exhibited by the majority of the dominant PBVCs within the NCA is often less than that associated with the dominant PBVCs from other NCAs (Tables 4.18 & 7.7). The notable exception to this is BLWP, which is the second and third most dominant PBVC within NSH under Conservation First and Going for Growth respectively (Table 4.18). In both cases, the PBVC exhibits the largest decreases in Overall Vulnerability of the other PBVCs with similar levels of dominance in the other NCAs (Table 7.7). The large decrease in Overall Vulnerability that NSH experiences under the future scenarios appears to be primarily influenced by the trend for this particular PBVC. However, NSH exhibits the highest level of Overall Vulnerability currently, by quite a significant margin. The decrease that it exhibits under the scenarios is insufficient to notably affect its Overall Vulnerability when compared to the majority of the other NCAs and its ranking remains high.

The particularly low ranking (relative and overall) of BMF under the scenarios is noteworthy. Generally, this is due to the moderate levels of Overall Vulnerability that the NCA exhibits currently, combined with the relatively large decreases in vulnerability that it experiences under the scenarios. The decreases associated with it are the second largest of all NCAs in each of the scenarios. In the case of Conservation First, the results for BMF appear not to be strongly associated with the trends in Overall Vulnerability for the most dominant PBVC (Marsh), as decreases of Marsh vulnerability within BMF are only moderate compared to some other NCAs. Tables 7.7 and 4.18 suggest that the relatively large decreases in Overall Vulnerability within BMF are related to the trends for Fen and BLWP, which are the second and fourth most dominant PBVCs within the NCA under the Conservation First scenario. Comparison with other PBVCs, with similar levels of dominance from the other NCAs, shows that BLWP and Fen within BMF exhibit the largest and fifth largest decreases in Overall Vulnerability respectively. The decreases in relation to BLWP are particularly great compared to those of other PBVCs from other NCAs. It appears therefore that the change in ranking associated with BMF under Conservation First is more directly related to the trends for these two PBVCs, particularly BLWP. The very low ranking of BMF under Going for Growth (lowest overall and within the scenario; Table 7.5) is somewhat more difficult to explain, as the dominant PBVCs (e.g. Marsh, Heath and IGP) generally exhibit only moderate decreases compared to the dominant PBVCs in other NCAs. BLWP and NGP, which are the fourth and sixth most dominant PBVCs within BMF, do exhibit relatively large decreases in Overall Vulnerability compared to PBVCs from other NCAs which have similar levels of dominance. It is likely that the results for BMF under Going for Growth are quite strongly influenced by the trends for these two PBVCs.

The relatively moderate decreases in Overall Vulnerability associated with TG and the relatively small changes in its ranking within each of the time slices appear to be largely related to characteristics of the three most dominant PBVCs under the scenarios. For instance, under Conservation First, Marsh (the most dominant PBVC) exhibits the largest decrease in Overall Vulnerability compared to the other NCAs. However, the decrease is only marginally greater than that within BMF and the Cheviots. Fen and IGP, the second and third most dominant PBVCs within the NCA under the scenario, exhibit only moderate levels of change compared to PBVCs from other NCAs with similar levels of dominance. Although other less dominant PBVCs within TG tend to exhibit greater levels of change, they tend to act to cancel each other out in terms of the aggregate results at the NCA level. Although the three most dominant PBVCs under Going for Growth within the NCA tend to exhibit a greater level of variation than the dominant PBVCs from other NCAs, the level of variation is only marginally greater. Overall, these trends indicate that the TG NCA is likely to be the least dynamic in terms of changes in Overall Vulnerability.

The three most dominant PBVCs within the Cheviots under Conservation First (e.g. Marsh, Heath and BLWP respectively) tend to exhibit relatively large decreases in Overall Vulnerability compared to the PBVCs from other NCAs with similar levels of dominance. These trends largely account for the decrease in ranking that the NCA exhibits under Conservation First compared to the current time slice. In all instances, the three most dominant PBVCs within the Cheviots under Going for Growth (Table 4.18) exhibit the second largest decreases in vulnerability compared to the most of the dominants from the other NCAs. In many instances, these decreases are notably larger than those of the other PBVCs within the other NCAs. This may go some way to explaining the particularly low overall ranking of the Cheviots under Going for Growth. A particularly notable result concerning the NCA is that the Overall Vulnerability of Blanket Bog is not as negatively affected as it is generally in the other NCAs under the future scenarios. Overall Blanket Bog vulnerability increases by a relatively small amount under Conservation First and slightly decreases under Going for Growth (Table 7.7). These trends diverge quite notably from those at the NNP level. Although, in terms of patches, Blanket Bog tends to exhibit relatively low levels of dominance compared to the other PBVCs, its levels of dominance within the Cheviot specifically is relatively high compared to some of the other NCAs. It is likely, therefore, that the generally low ranking of the Cheviot under the scenarios is also due to the more positive future response of Blanket Bog, and its relatively high level of dominance, within the NCA.

7.4.3 Management Recommendations

The results from this and previous chapters allow a number of specific management recommendations and considerations to be made.

7.4.3.1 PBVCs

It is possible to loosely rank the PBVCs in terms of the priority they should be afforded in terms of conservation, primarily based on the results for Overall Vulnerability at the NNP level.

Blanket and Raised Bogs are the highest priority PBVCs because both experience large increases in Overall Vulnerability under the future scenarios. Also, both PBVCs have a particularly high significance within NNP from a National and European conservation policy context (NNPA, no date[c]). Swamp and Heath are medium priority: both PBVCs experience only a small decrease in Overall Vulnerability under the scenarios compared to current levels. Of these two PBVCs, Heath may be regarded as somewhat more important, due to its high conservation status within NNP

(NNPA, no date[c]). The remaining PBVCs may be regarded as the lowest priority, as they all generally experience notable decreases in Overall Vulnerability under the scenarios.

The discussion below uses the information from this and previous chapters to identify the factors influencing vulnerability of these PBVC groups at both the NNP and NCA levels in order to provide more targeted, spatially-explicit management recommendations. The information relating to the first two groups may be regarded as more critical. However, information on the 3rd group is also provided in order to provide a more comprehensive assessment. For instance, the results for NGP are of particular interest due to the PBVC's conservation significance within NNP specifically (JNCC, 2011; NNPA, no date[c]).

High Priority

Blanket Bog

The notable increases in levels of Overall Vulnerability for Blanket Bog at the NNP level are largely related to the increases in Climate Stress it experiences, and therefore its generally negative response to the predicted future climate changes affecting the park. Because of the deterministic nature of these climate changes, subsequent changes in Climate Stress may be difficult to ameliorate in the future. Initially, this may imply that conservation efforts may be more effectively focused towards tackling levels of Geometric and Matrix Vulnerability. However, the NCA results suggest further options. For instance, Tables A4 (a-e) show that the comparatively positive response of Blanket Bog within the Cheviot NCA in terms of Overall Vulnerability under the scenarios is largely due to the trends for Climate Stress. The Cheviot is the only NCA in which Blanket Bog experiences a reduction in Climate Stress under the scenarios, decreasing to low levels from moderate levels currently. This suggests that the current climate within the NCA represents somewhat sub-optimum conditions for Blanket Bog. Blanket Bog is most abundant currently within the Cheviot NCA, in terms of areal coverage (Table 4.19). However, Blanket Bog was once more widely distributed within the park (NNPA, no date[c]). It is likely that Blanket Bog's current distribution within the study area has been highly influenced by historic land use (NNPA, no date[c]). It is feasible that the current prevailing climate of the Cheviots represents sub-optimum conditions for the PBVC. As the results suggest, these characteristics, combined with the changing climate affecting the Cheviot NCA in the future, act to reduce the Climate Stress associated with extents of Blanket Bog.

Conversely, Blanket Bog exhibits a distinctly negative climatic response within the TG and NSH NCAs under the scenarios, where Climate Stress increases by a significant margin to high levels from low levels currently (Tables A4 c & e). Tables 7.8 and Tables A4 a - e show Blanket Bog consistently exhibits its highest or second highest levels of Climate Stress and Overall Vulnerability, under the scenarios, within TG and NSH. Levels of Climate Stress for the PBVC within these NCAs are very similar and are generally notably higher compared to that within the other areas. Levels of future Climate Stress associated with Blanket Bog within the BMF NCA increase to moderate levels from low levels currently. Increases within BMF are therefore of a lower magnitude than those within NSH and TG and levels are comparable to those experienced currently within the Cheviot NCA.

Considering these points and the potential challenges in ameliorating levels of future Climate Stress, the Cheviot NCA (and to a lesser degree BMF) has the potential to act as a reserve for Blanket Bog, as well as bog communities more generally, due to the highly negative impact climate change is likely to have on such communities in some other areas of the park (i.e. within TG and NSH). Future efforts towards restoration or creation of new Blanket Bog extents, as well as the protection and enhancement of existing extents, may therefore be more usefully focused towards the Cheviots and BMF. Levels of Matrix Vulnerability are generally very low within the Cheviot and BMF NCAs across all time slices and are probably related to their relatively remote, upland characteristics. Such characteristics are therefore generally likely to persist in the future. Management of the boundary characteristics of Blanket Bog patches within these NCAs may not, therefore, be regarded as particularly necessary.

Tables A4 (a & d) show that Blanket Bog's Geometric Vulnerability exhibits a slight to moderate increase under Conservation First within Cheviot and BMF, related to the expansion of the PBVC under the scenario and the subsequent creation of smaller, more complex patches (Section 6.4.2). This suggests that additional reductions in the Overall Vulnerability of Blanket Bog within the NCAs may be gained through appropriate and sensitive patch design and management. This may be regarded as more important for BMF than the Cheviot, due to the likely negative impact of climate change on Blanket Bog within BMF. However, considering the probable distribution of available suitable habitat for Blanket Bog within both NCAs, additional planning and resources may be required to implement such changes optimally.

Table 4.19 indicates that Blanket Bog exhibits its lowest and second lowest levels of coverage within TG and NSH respectively under the scenarios. This, combined with the Climate Stress results, may suggest that these NCAs specifically will not make suitable areas in which to undertake future expansion of Blanket Bog, due to the likely problems in creating and maintaining such extents. Resources may therefore be better focused, within these areas, towards the protection of extant distributions where feasible. For instance, it is unlikely that extents of Blanket Bog within these NCAs will be lost as a direct result of climate change (i.e. none of the individual patches of Blanket Bog within the NCAs has a Climate Stress score of '1'). Table A4e shows that Blanket Bog's Matrix Vulnerability within the TG NCA is notably reduced under Conservation First compared to current conditions (and Going for Growth). This is probably due to the relatively large increase in semi-natural community types occurring under Conservation First within the area (Figure 4.4b). This suggests that improvements in the future Overall Vulnerability of Blanket Bog may be made *in situ* through improvements in boundary attributes. Because of the relatively high levels of Matrix Vulnerability that Blanket Bog exhibits currently and under Going for Growth, within the NCA, such measures are likely to be particularly important if existing distributions are to be effectively protected, within the area, in the future.

No extents of Blanket Bog occur within the Cheviot Fringe NCA currently or under Conservation First, despite the expansion that the PBVC experiences under the scenario in other NCAs. This may be indicative of unsuitable biophysical conditions within the area. Also, Cheviot Fringe is more lowland in character. Blanket Bog exhibits a highly negative climatic response within other more lowland NCAs (i.e. TG and NSH). These points suggest that the Cheviot Fringe is unlikely to make a useful target for the restoration or creation of future Blanket Bog extents.

Raised Bog

Raised Bog is unusual, in that its distribution within each of the time slices is highly restricted. Raised Bog currently and under Going for Growth only appears in the BMF NCA: it only appears in BMF and TG under Conservation First, due to the expansion it experiences under the scenario. This may suggest unsuitable biophysical conditions within other NCAs (specifically, NSH and Cheviot Fringe) and therefore their unsuitability for future efforts towards creation or restoration of Raised Bog extents.

Tables 7.7 and A4 (d & e) show that levels of Climate Stress and Overall Vulnerability for Raised Bog within BMF and TG are closely similar, suggesting that both NCAs are increasingly likely to represent marginal areas for the PBVC in the future. However, Tables A4 (d & e) also show that levels of Matrix Vulnerability within each of these NCAs are generally low. It may be possible, therefore, to ameliorate some of the increases in Overall Vulnerability caused by the increase in Climate Stress through appropriate management of boundary characteristics *in situ.* For instance, this may involve the creation of appropriately-sized buffer zones, around existing Raised Bog extents within BMF, where the inward expansion of modified community types is restricted.

However, due to the high future Climate Stress that Raised Bog is likely to experience within BMF and TG, and the close similarities between the requirements of Raised Bog and Blanket Bog communities, the Cheviot NCA is likely to represent a more useful focus for any future expansion of Raised Bog within the park. Similar points to those proposed for Blanket Bog in relation to Geometric Vulnerability within the NCA should be considered in cases where expansion of Raised Bog into the area is facilitated, particularly as expansion of Raised Bog within BMF under Conservation First is related to a notable increase in levels of Geometric Vulnerability (Table: A4d).

Medium Priority

Heath

Table 7.8 shows that Heath is most vulnerable in the Cheviot Fringe under both future scenarios. Trends for Heath within the NCA are quite unusual, due to its expansion into the area under the scenarios. Heath does not appear in the NCA currently. Tables A4 (a-e) show that the high future levels of Climate Stress and Matrix Vulnerability associated with Heath within the Cheviot Fringe are the primary cause of its high overall levels of future vulnerability within the area. These points, as well as the above discussion on Blanket and Raised Bogs, suggest that the Cheviot Fringe is unlikely to make a useful focus for future Heath expansion.

Tables 7.7 and 7.8 show that Heath is currently most and second most vulnerable within the NSH and TG NCAs, respectively, and second and third most vulnerable under the future scenarios within NSH and TG, respectively. Heath's Overall Vulnerability within these NCAs increases to similar levels under the scenarios, and therefore notably differs from the trends at the NNP level (Table 7.1). Levels of Climate Stress and Matrix Vulnerability are the main cause of these NCA results (Tables A4 a - e). The negative response that Heath exhibits to the predicted changes in climate affecting such areas implies that conservation efforts may be more beneficially focused towards protection of extant distributions. For instance, Matrix Vulnerability appears to be particularly significant in terms of the higher Overall Vulnerability Heath exhibits within NSH (Tables A4 c & e). Reductions in Overall Vulnerability may be achieved *in situ* through appropriate management of boundary characteristics where possible. Heath's Matrix Vulnerability is less within TG than the other lowland NCAs, suggesting that effective management of boundary characteristics within the area may be relatively easy to achieve.

Tables A4 (a-e) also show that Heath exhibits very low Climate Stress and Matrix Vulnerability within the BMF and (particularly) Cheviot NCAs under the scenarios. Heath's Overall Vulnerability for these NCAs generally decreases quite notably under the scenarios as a result, showing a more marked decrease than the trends for Heath at the NNP level. Creation and restoration of Heath extents may therefore be more effectively targeted within these NCAs. The trends for Heath in terms of Geometric Vulnerability under the future scenarios at the NNP level, however, should be noted (Section 6.4). These suggest that the distribution of suitable habitat within NNP acts to create larger, more complex, more vulnerable patches. Additional planning and resources may be required if the Geometric Vulnerability of Heath is to be ameliorated within the BMF and Cheviot NCAs.

Swamp

Swamp is consistently most vulnerable in the Cheviot NCA in all time slices (Table 7.8). This is largely related to its Geometric Vulnerability. Swamp's levels of Climate Stress across the time slices within the NCA are generally low. Only small differences are apparent between the low levels of Matrix Vulnerability Swamp exhibits within the Cheviot and other NCAs across the time slices (Table A4 a - e). Geometric Vulnerability, however, is very high within the Cheviots (Table A4a) and only moderate to high within the other NCAs in which it occurs (Tables A4 d & e). These results suggest that further future reductions in the vulnerability of Swamp within the Cheviots NCA, as well as BMF and TG, may be achieved through appropriate patch design and management. Certainly, in terms of climate, it appears that such areas will be quite suitable for restoration or creation of extents of Swamp. Swamp is unusual, however, in that it does not expand under either of the future scenarios. It is difficult to state whether or not such change will be easy to implement in terms of the availability of suitable habitat within these areas.

Swamp does not occur within the Cheviot Fringe or NSH NCAs in any of the time slices. As stated, these are typically lowland NCAs. The TG NCA can be similarly regarded. Based on the characteristics of Swamp within TG (e.g. low Climate Stress), restoration or creation within NSH and Cheviot Fringe, where possible, seems feasible. However, the levels of Matrix Vulnerability associated with other PBVCs within these NCAs suggest that consideration would need to be given to the boundary attributes of any new extents of Swamp within these areas. The same issues regarding Geometric Vulnerability and appropriate patch design and management, mentioned above for the Cheviots, BMF and TG NCAs, also apply. Conservation efforts may be therefore more usefully focused toward protecting and enhancing existing distributions within these areas.

Low Priority

Marsh

Marsh is consistently most vulnerable within the Cheviot Fringe NCA (Table 7.8). Tables A4 (a - e) clearly show that this is largely due to Marsh's Matrix characteristics: Levels of Climate Stress associated with the PBVC are generally lower within Cheviot Fringe than the other NCAs in each of the time slices and reduce notably in the future compared to current levels. The trends therefore closely follow those at the NNP level (Table 5.3). Marsh's Geometric Vulnerability within Cheviot Fringe is only slightly higher than other NCAs. Marsh's Matrix Vulnerability, however, is often moderately to notably higher within the NCA. Future protection and enhancement of Marsh within the Cheviot Fringe may therefore be tackled through management of matrix characteristics. However, considering the characteristics of the Cheviot Fringe NCA (e.g. size, dominant P/NPBVC types), this may prove challenging.

Marsh exhibits its second and third highest levels of Overall Vulnerability in TG and NSH, respectively, under Conservation First, and second and fourth highest levels, respectively, under Going for Growth. Future levels of Overall Vulnerability for Marsh within both NCAs are generally similar (Table 7.7). Again, Matrix Vulnerability is the primary cause of this result. However, levels of Matrix Vulnerability within TG and NSH are often notably lower than the Cheviot Fringe. Protection and enhancement of Marsh extents within TG and NSH in terms of management of boundary characteristics may therefore be more feasible. Marsh is consistently least vulnerable within the BMF NCA (Table 7.8). Its Overall Vulnerability within the Cheviot is closely similar to that within BMF (Table 7.7). This suggests that for Marsh, BMF and the Cheviot may represent a useful focus for future conservation efforts particularly as levels of Matrix Vulnerability are generally low.

The results suggest that future expansion of Marsh may be appropriate in any of the NCAs, with the possible exception of the Cheviot Fringe. However, Marsh does not expand under either of the future scenarios. It is difficult to state whether expansion will be easy to facilitate. Furthermore, the relatively low conservation status of Marsh within NNP, its highly positive response to the climate changes predicted to affect the park in the future, and its currently high level of coverage, suggests that expansion may not be regarded as a high priority.

Fen

Fen is most vulnerable within the Cheviot NCA in each of the time slices (Table 7.8). This is largely related to its levels of Climate Stress (Tables A4: a - e). Fen's Matrix Vulnerability is often lower within the NCA, whilst levels of Geometric Vulnerability do not exhibit much variation from levels in other NCAs. Although Fen's levels of Climate Stress within the Cheviot decrease under the scenarios, the decrease is often notably less than that within the other NCAs. Fen's future Climate Stress within the Cheviot is moderate and therefore consistently higher than other NCAs.

Fen's Climate Stress within the Cheviot is very high under the current time slice. The current precipitation levels within the NCA are likely to be broadly suitable for Fen. It is possible that Fen's high levels of Climate Stress currently are due to the relatively cold temperatures generally affecting this upland NCA. The decreases in Climate Stress that Fen experiences under both future scenarios are therefore likely related to the warming that is predicted to affect the NCA under ME scenario conditions. It is possible that under temperatures exceeding those predicted under the ME scenario, the Climate Stress of Fen within the Cheviots may be even further improved. These points suggest that restoration or creation of Fen extents may be feasible within the area, in addition to protection and enhancement of extant distributions. However, Fen does not expand within the NCA under Conservation First. This may suggest that biophysical conditions within the Cheviots (e.g. elevation, slope) are relatively unsuitable for expansion. Future work may be required to establish the potential for future expansion of Fen within the Cheviots.

The trends for Fen suggest that conditions within the NSH, BMF and TG NCAs are likely to be more favourable, particularly in terms of Climate Stress (Tables A4 c-e). Fen does expand its coverage within these areas under Conservation First, suggesting relatively favourable conditions for restoration and creation. However, the expansion of Fen within these areas is associated with an increase in Geometric Vulnerability, due to the creation of smaller, less complex patches (Section 6.4.2). This may suggest that the distribution of available suitable habitat within these areas is quite diffuse. Additional planning and resources may therefore be required to facilitate such expansion in order to moderate levels of Geometric Vulnerability. This is particularly relevant for NSH where levels of Geometric Vulnerability, currently, are relatively high. Although Matrix Vulnerability within the NCAs is generally low, Fen experiences a relatively large increase within TG and NSH under Conservation First. The future management of Fen within these areas might increasingly involve effective management of boundary characteristics, depending on the characteristics of future land use trends.

Fen does not occur within the Cheviot Fringe NCA in any of the time slices. This, combined with the issues associated with the other PBVCs mentioned above within the NCA, suggest that is likely to be unsuitable for future expansion efforts.

IGP and NGP

Both IGP and NGP demonstrate a mixed response across the time slices and are both most vulnerable in the same NCAs under each time slice (Cheviot, NSH and TG; Table 7.8). As suggested, the relatively high current levels of Overall Vulnerability for these lowland PBVCs within the park are largely determined by climatic stress. Their relatively high current levels of vulnerability within the Cheviots are therefore unsurprising, due to the upland characteristics of the NCA.

It is possible that the PBVCs are most vulnerable within NSH under Conservation First because of the climate changes predicted to affect the area in the future under ME scenario conditions. It is possible that these will make some areas of the NCA somewhat too warm and/or dry to represent optimum conditions for the PBVCs. For instance, the reduction in IGP and NGP's Climate Stress under Conservation First within NSH is often much less than in the other NCAs under the scenario (Tables A4 a-e). However, Climate Stress for these PBVCs within NSH is also much lower under Going for Growth compared to levels currently and Conservation First. Both PBVCs experience notable increases in coverage within the NCA under Conservation First, whilst coverage under Going for Growth decreases. It appears that the expansion under Conservation First acts to facilitate a greater degree of occurrence for these PBVCs, within more marginal, border areas of the NCA (Figures 4.4 a – c) where future temperature levels, for instance, are likely to be highest. The relatively small decrease in average levels of Climate Stress, for the PBVCs within the NCA under Conservation First, and in turn the relatively high levels of Overall Vulnerability they exhibit, are likely due to the increase of these novel, more marginal, relatively stressed extents.

A similar general trend is also observed for IGP and NGP under Conservation First within the Cheviot Fringe NCA, with a smaller decrease in Climate Stress occurring under Conservation First compared to Going for Growth apparently related to an increase in coverage within the area under the former scenario. The Climate Stress trends for both PBVCs within the TG NCA remain low under both future scenarios. However, the coverage of the PBVCs within TG does not vary much between the time slices. Due to the lowland character of TG, it is likely that, if a greater increase in coverage had occurred within the NCA under Conservation First, the Climate Stress results would be similar to those within NSH and the Cheviot Fringe.

These points suggest that climate changes of greater magnitude than those simulated for the ME scenario may act to actually increase the Climate Stress of extents of IGP and NGP within the marginal areas of these lowland NCAs (though the issues discussed in Section 7.4.4.1 in relation to the restricted nature of the bioclimatic envelope data should be noted). It may be advisable to avoid these marginal areas when creating or restoring extents of IGP and NGP within these NCAs specifically in order to reduce potential future risk. Alternatively, if expansion does occur, monitoring of extents within these marginal areas may prove useful.

Table 7.8 shows that IGP and NGP are least vulnerable under Conservation First within the TG and Cheviot NCAs, respectively. Under Going for Growth, they are least vulnerable within Cheviot Fringe and NSH, respectively. These areas may represent a potentially useful focus for conservation efforts. However, the above discussion regarding the likely impact of climate change on more marginal areas within these NCAs is relevant.

Both NGP and IGP experience quite notable increases in coverage within the BMF NCA under Conservation First. However, Climate Stress still decreases by quite a significant margin (Table A4d). This may suggest that more marginal areas within this NCA are relatively hospitable for the PBVCs under conditions of future climate change. This, in turn, suggests that the NCA may also represent a useful focus for conservation efforts.

Levels of Geometric Vulnerability for the PBVCs under each scenario are moderate (Tables A4 a-e). Considering the general decrease in future levels of Climate Stress associated with the PBVCs, any future conservation efforts may seek to focus on appropriate patch design and management to further reduce levels of Overall Vulnerability. However, the PBVCs are similar to Fen, in that expansion within NCAs is associated with an increase in Geometric Vulnerability, due to the creation of smaller less complex patches. The same considerations as those mentioned above for Fen, in terms patch creation and restoration, therefore also apply.

Due to the omission of Matrix Vulnerability for these PBVCs, it is not possible to give any recommendations on appropriate management of boundary characteristics.

BLWP

BLWP also exhibits a mixed response in terms of the NCA in which it is most vulnerable in each of the three time slices (Table 7.8). Tables A4 (a-e) show that levels of Climate Stress and Geometric Vulnerability are the primary cause of the relatively high Overall Vulnerability of BLWP within TG currently and the Cheviots under Going for Growth. Geometric and (particularly) Matrix Vulnerability are the main cause of the PBVC's high Overall Vulnerability within the Cheviot Fringe under Conservation First. However, comparison of BLWP's Climate Stress and Geometric Vulnerability within each NCA under each scenario shows that levels are broadly similar. Matrix Vulnerability exhibits somewhat more variation. BLWP's Matrix Vulnerability decreases by a relatively large amount under GFG compared to Conservation First, particularly within the more lowland NCAs (Tables A4 a-e). Levels of Climate Stress for BLWP, within these NCAs are generally quite favourable, suggesting that management of BLWP in terms of protection, enhancement and even creation and restoration is highly feasible.

Some focus may need to be afforded to effective management of BLWP's boundary characteristics, depending on the future land use trends affecting the study area, particularly within the 'lowland' NCAs. The same generally applies to the other PBVCs for which restoration and creation efforts in these areas are deemed appropriate and feasible. However, such considerations are particularly important for BLWP, due to the relatively close similarities between its physical tolerances and those of many of the modified P/NPBVCs (Section 6.5.2). This means that extents of BLWP and these modified types are very likely to occur adjacent to each other, as evidenced by the relatively high levels of Matrix Vulnerability that BLWP experiences in all NCAs across all time slices compared to the other PBVCs. These pressures on BLWP are generally true, no matter the land use context. However, pressures are likely to increase, should the land use trends affecting the park facilitate an increased expansion of modified types. The same is also generally true for BLWP for the 'upland', NCAs.

BLWP is unusual, in that it is the only PBVC which exhibits a decrease in Geometric Vulnerability under the scenarios, suggesting that available suitable habitat for this PBVC is spatially quite concentrated (Section 6.4.2). This implies that any creation and restoration of BLWP extents that may occur throughout the park in the future will be relatively easy to implement in terms of managing patch size and shape complexity.

7.4.3.2 NCAs

Dominant PBVCs

The findings suggest a number of points in terms of NCA vulnerability. Previous sections indicate that it is the dominant PBVCs that largely determine levels of Overall Vulnerability within each NCA. Vulnerability at the NCA level may therefore be more effectively managed by focusing on these PBVCs and their characteristics in terms of the individual vulnerability measures. However, this should be done with appropriate consideration of the above points and recommendations for other PBVCs. For instance, Marsh is the dominant PBVC in all NCAs (Table 4.18). Its Geometric Vulnerability, generally, is somewhat higher than the other PBVCs across the time slices (Table 6.1a). Effectively tackling vulnerability at the NCA level may therefore be achieved through appropriate management of Marsh extents to create larger, less complex, and therefore less vulnerable patches. However, doing this in a way that limits potential conservation efforts for other 'High' or 'Medium' priority PBVCs (e.g. Blanket Bog, Raised Bog and Heath) should be avoided. Creation or restoration of Marsh extents that restricts the availability of suitable habitat for potential expansion of Blanket Bog is not likely to be a desirable outcome.

Climate Stress

The results also show a general split between the upland and lowland NCAs and appropriate management actions for specific PBVC types. The lowland NCAs are unlikely to be suitable for creation or restoration efforts for the more upland PBVCs (Blanket Bog, Raised Bog and Heath), partially because of the future levels of Climate Stress that the PBVCs are likely to experience within these areas. This is perhaps particularly relevant to the more extreme lowland Cheviot Fringe. Although Blanket Bog and Raised Bog do not occur within the Cheviot Fringe NCA in any of the time slices, it is very likely that levels of Climate Stress for both PBVCs will be very high, based on their responses to climate in the other lowland NCAs. Heath's high levels of Climate Stress within the Cheviot Fringe under both future scenarios are also relevant. Expansion is likely to be much more appropriate for these PBVCs in terms of Climate Stress within the upland NCAs.

Conversely, management options for the lowland PBVCs, in terms of Climate Stress, are likely to be less restricted. For instance, both lowland and upland NCAs are generally likely to be suitable for expansion of lowland PBVCs. These results, particularly those for Cheviot Fringe, NSH and TG, are perhaps unsurprising. However, the research also suggests that the future climate of more marginal areas within these lowland NCAs will become increasingly unsuitable, even for some of the more lowland PBVC types, particularly if the magnitude of climate changes exceeds those predicted under the ME scenario. It is likely that the relatively small decrease in Climate Stress often exhibited by IGP and NGP within these NCAs under Conservation First compared to Going for Growth is probably due to their expansion into more marginal areas under the former scenario. Other lowland PBVCs that undergo expansion under Conservation First (i.e. Fen and BLWP) appear not to be similarly affected. This may be due to a greater climatic tolerance associated with BLWP compared to IGP. In the case of Fen, however, this is questionable. Table A1.2 clearly shows that the bioclimatic envelope of Fen (see: 'Fen, Marsh and Swamp'), in terms of most of the climatic parameters, is more restricted than that of IGP and NGP (as well as BLWP). Figures 4.4a-c show that the expansion of Fen within the lowland NCAs under Conservation First tends to occur in less marginal areas. However, a greater amount of expansion into marginal areas tends to be associated with IGP, NGP and BLWP. This suggests that Climate Stress for Fen may become more of an issue if expansion is undertaken within these marginal areas or with a greater magnitude of climate change than that predicted within this research.

Based on these results, it is recommended that additional planning and research be conducted if expansion of Fen, IGP and NGP is undertaken within lowland NCAs. Monitoring of existing and potential novel distributions may also prove beneficial. Although the other lowland PBVCs (Marsh and Swamp) do not expand within the NCAs, the same recommendations are likely to apply due to their established climatic tolerances (Table A1.2: 'Fen, Marsh and Swamp').

Because of the apparently greater climatic sensitivity of Raised Bog, Blanket Bog and Heath, similar recommendations are also proposed for current and potential future distributions of these PBVCs within the more marginal areas of the upland NCAs. For instance, Raised Bog experiences a notably greater increase in Climate Stress within BMF under Conservation First (where it experiences expansion), compared to Going for Growth (where expansion does not occur). The expansion of Blanket Bog under Conservation First within Cheviot and BMF is also associated with a somewhat higher level of Climate Stress than Going for Growth.

Matrix Vulnerability

The upland and lowland NCA division is also relevant for effective management in terms of Matrix Vulnerability. The results show that all PBVCs typically exhibit their lowest levels of Matrix Vulnerability within the upland NCAs, suggesting that expansion within these areas is generally suitable for all PBVCs, in terms of potential impacts from the boundary characteristics of patches. Due to the characteristics of these NCAs (remote, upland), the pressures from modified P/NPBVC types on semi-natural PBVCs is likely to be relatively reduced compared to the other NCAs, regardless of the land use scenario. However, the amount of expansion of modified P/NPBVCs under the scenarios may be regarded as quite low. Significant divergence from the land use trends indicated under the scenarios may lead to a more notable expansion of modified P/NPBVC types within the park and therefore an increased pressure on semi-natural types. In such instances, appropriate planning for, and monitoring of, all PBVC extents will be required, even in the upland NCAs.

Matrix Vulnerability for the PBVCs is often higher in the lowland NCAs. This is unsurprising considering their characteristics, particularly the relative dominance of modified types currently compared to the other NCAs (Table 4.19 & Figure 4.4a). However, appropriate management (including expansion) of at least some semi-natural PBVC types within these NCAs is likely to be desirable under a range of possible land use futures. Recommendations therefore have to be made. The findings point to a number of possibilities. For instance, despite the high *relative* levels of Matrix Vulnerability within the lowland NCAs, no PBVCs exhibit high levels of vulnerability within these areas in terms of the applied matrix index. Indeed, all PBVCs (with the exception of

BLWP) exhibit low levels of Matrix Vulnerability within NSH and TG within each time slice when they are present. In the case of Blanket Bog (and to a lesser degree Heath), management in terms of boundary attributes may simply focus on extant distributions, due to the highly negative impact climate change is likely to have on these PBVCs within these areas. However, management of Fen, Marsh and Swamp within the NCAs may more feasibly involve restoration or creation because of their low levels of Climate Stress. There exists therefore a potential 'win-win' (Berry, 2008; Morecroft et al., 2012) situation within NSH and TG whereby the likely desired decreases in levels of Matrix Vulnerability associated with Blanket Bog and Heath are at least partially achieved through expansion of Fen, Marsh and Swamp. Although the feasibility of this requires further investigation, it is an attractive option as it potentially provides an opportunity to offset some of the climate impacts Blanket Bog and Heath are likely to experience, by providing a more supportive surrounding matrix network.

Levels of Matrix Vulnerability of all semi-natural PBVC types that appear within Cheviot Fringe are moderate, and therefore notably higher than the other NCAs. This generally suggests that future expansion of semi-natural PBVC types within (or into) the area may be undesirable, particularly if prevailing future land use trends act to increase the coverage of modified P/NPBVCs by an amount significantly greater than that simulated under the scenarios. Such changes are quite feasible, as some sources advocate an increase in more intensive agriculture (including more intensive grazing) in some areas of the park, in order to minimise potential impacts elsewhere (e.g. NE, 2009). The Cheviot Fringe, and to a lesser degree NSH and TG, represent an obvious potential focus in this regard. However, appropriate consideration will need to be given to balance the potential demands for more intensive agriculture within these areas and the potential negative impacts on extant or novel PBVC patches.

BLWP exhibits notably higher Matrix Vulnerability than the other PBVCs in all NCAs across the time slices for reasons already provided. However, a number of management possibilities exist. For instance, the relevance of the decrease in Matrix Vulnerability under Going for Growth, compared to Conservation First, in terms of potential management of boundary attributes within the lowland NCAs, has already been covered. Also, levels of Matrix Vulnerability within Cheviot, NSH, BMF and TG may be generally classed as low to moderate. The potential to reduce further the vulnerability of BLWP through appropriate management of boundary characteristics within Cheviot, NSH, BMF and TG is high. Such management may include the reduction of boundary pressures on existing extents, or the restoration or creation of novel BLWP extents, where possible, in more isolated areas of the NCAs, where the impact from modified P/NPBVC types is likely to be minimised.

Considering the comparatively high levels of Matrix Vulnerability that BLWP exhibits within Cheviot Fringe currently and under Conservation First, as well as the potential land use pressures regarding the NCA (see above), expansion of BLWP within the area may be somewhat less feasible or desirable. However, as the results for Going for Growth indicate, some potential exists for reducing the impacts of boundary attributes on extant BLWP patches *in situ* though appropriate management.

Geometric Vulnerability

The trends for Geometric Vulnerability indicate that, in general, it will be difficult to minimise pressures on the PBVCs through the management of patch shape and complexity in all NCAs. The most obvious exception to this is BLWP. However, it is also true that Geometric Vulnerability for some PBVCs within specific NCAs does decrease with expansion. This may suggest a somewhat greater viability for restoration or creation of extents for these PBVCs within these particular locales. However, these results should be balanced with the recommendations provided above. For instance, Heath's Geometric Vulnerability within TG decreases somewhat under both future scenarios (Table A4e). However, as suggested above, expansion of Heath within the NCA is likely be less desirable, due to the future Climate Stress that Heath is likely to experience within the area, compared to the upland NCAs. However, it is possible that Heath expansion, within upland areas will be, for whatever reason, insufficient to meet expansion goals for the PBVC at the NNP level under a given set of socio-economic conditions. TG may therefore, under certain circumstances, represent a more useful focus for Heath expansion than the other lowland NCAs.

7.5 Critique and Conclusions

7.5.1 Summary of Main findings

The model provides a novel approach for providing spatially-explicit assessments of the vulnerability of vegetation communities to changes in both climate and land use at the landscape scale. The results clearly indicate that, within NNP at least, climate rather than land use, is likely to play a much more significant role in influencing the vulnerability of vegetation communities. The research therefore provides valuable evidence suggesting that climate change is likely to have replaced land use change as the most significant driver influencing community vulnerability at the landscape scale as early as 2050. Although this represents a positive change for the majority of the PBVCs (BLWP, Fen, IGP, Marsh and NGP), others, that are particularly significant within NNP in terms national and European conservation policy, are generally unaffected, i.e. Heath (NNPA, no date[c]). Crucially, Blanket Bog and Raised Bog are also of particular conservation significance within NNP (NNPA, no date[c]) and experience highly negative impacts due to climate change.

The model also proved useful in providing targeted and spatially-explicit management recommendations for the study area. For instance, due to the way in which vulnerability is constructed, applied and analysed, it has been possible to identify specific sources of vulnerability for individual PBVCs both at the national park level and for individual NCAs. This has shown that, despite the negative impacts that climate change is likely to have on some upland PBVCs (such as Blanket Bog and Raised Bog) overall, there exists some potential for expansion of these PBVCs within specific NCAs (i.e. Cheviots and BMF) due to the relatively reduced climate and matrix related impacts they are likely to experience in these areas. However, it is also suggested that appropriate patch design and management may be required if expansion of these PBVCs does occur within these NCAs to tackle the levels of Geometric Vulnerability effectively. The results also indicate that management of these PBVCs within other (lowland) NCAs may be more usefully focused towards protection of existing distributions. Similar recommendations are identified for Heath.

The expansion of the lowland BVCs (Marsh, IGP, NGP, Fen, Swamp and BLWP) is generally likely to be feasible throughout NNP, due to the positive response of these communities to predicted future climate change. However, it is also shown that expansion of BLWP, Marsh, Swamp and Fen in the lowland NCAs is likely to require more sensitive management, particularly in terms of managing matrix characteristics and within the Cheviot Fringe. Additional care may also need to be taken in managing expansion of the lowland PBVCs in the lowland NCAs, due to the negative impacts that climate change is likely to have on these communities in more marginal locales within these areas. The Geometric Vulnerability results also suggest that expansion of the majority of the lowland PBVCs generally, will require some consideration of patch shape and complexity if the vulnerability associated with the spatial attributes of patches is to be reduced. BLWP is unusual in that it is the only PBVC which exhibits a decrease in Geometric Vulnerability under the scenarios. This suggests that expansion of BLWP is likely to be relatively straightforward in terms of the design and management of patch size and shape complexity. Additionally, it is also demonstrated that expansion of lowland 'semi-natural' PBVCs (e.g. BLWP, Marsh, and Fen) within the TG and NSH NCAs is likely to be a particularly attractive management option, due to the potential that exists to reduce some of the Matrix Vulnerability associated with existing distributions of Blanket Bog, Raised Bog and Heath within these areas.

The maps presented in Chapters Five, Six and Seven go some way in highlighting further the usefulness of the model in providing spatially-explicit assessments of vulnerability and for identifying relevant causes. The maps presented in the thesis do not provide information for individual PBVCs in order to simplify the presentation and subsequent analysis of results. However, this information is available upon request and should prove highly useful in providing even more targeted spatial information for relevant stakeholders.

7.5.2 Vulnerability Construct

The vulnerability construct developed within this research facilitates a more holistic spatial assessment of vulnerability than many previous impact assessments, in which vulnerability constructs may be regarded as either less holistic or do not represent vulnerability in a spatially-explicit way (e.g. Mitchell *et al*., 2007; Matsui *et al*., 2004; Berry *et al*., 2003). Considering the relevance of the vulnerability concept for investigating overall ecological responses to environmental change, and the value of spatially-explicit assessments for conservation planning and sustainable management (Preston *et al*., 2011; Griffiths *et al*., 2011), the findings of this research are regarded a useful contribution to these previous efforts.

Questions have been raised over the use of more generic vulnerability indicators, particularly within a 'social vulnerability' context (Preston, *et al*., 2011). The measures employed here, particularly VM2a and VM2b, are quite generic. For instance, although these indicators enable implicit assessment of the vulnerability of community patches in terms of relevant factors such as population size, genetic diversity and species richness, they do not measure these factors directly. However, the use of these generic measures is regarded as both necessary and advantageous for providing timely, reasonably comprehensive vulnerability assessments for complex ecological communities across entire regions. In many instances, detailed ecological data for species, and particularly whole communities, are not currently available and are impractical to obtain directly (Klausmeyer *et al*., 2011; Thuiller *et al*., 2005; Pearson & Dawson, 2003; Guisan & Zimmerman, 2000). Also, from a methodological perspective, it is extremely difficult to accurately model changes in factors such as genetic diversity, directly for whole communities and under conditions of environmental change (Tremblay-Boyer & Anderson, 2007; Pearson & Dawson, 2003; Guisan & Zimmerman, 2000; Zimmerman & Kienast, 1999). These issues mean that the use of more generic indicators for estimating the vulnerability of numerous complex species assemblages, at larger spatial scales, at present remains the most appropriate approach, particularly considering the broad array of pressures these communities face and the imperative need for spatially-explicit impact assessments in helping to manage the 'biodiversity crisis' (Morecroft *et al*., 2012; Preston *et al*., 2011; Scherer-Lorenzen, 2005; Hooper *et al*., 2005; Guisan & Zimmerman, 2000). Furthermore, the relative simplicity of the vulnerability indicators used within the research means that they may be easily understood and applied. It is hoped therefore that the vulnerability construct developed and applied within this research (as well as the methodology more generally) provides users with a convenient framework for providing meaningful vulnerability assessments at larger spatial and ecological scales that may also be used to guide and complement more detailed or targeted assessments if required (Klausmeyer *et al*., 2011).

Although this research specifically focuses on the exposure and vulnerability of communities to climate and land use, the characteristics of the vulnerability construct means that it is also likely to be useful for providing implicit assessments of vulnerability in terms of other pressures, such as introduced/invasive species, over-exploitation and pollution (e.g. nutrient loading). Invasive species have the potential to significantly disrupt the dynamics, properties and functioning of existing ecological communities and therefore the goods and services they provide (Morecroft *et al*., 2012; MA, 2005a; 2005b; Scherer-Lorenzen, 2005). The threat posed to existing communities from invasive species tends to be greatest for communities which experience greater disturbance and stress (Keller *et al*., 2011; Thuiller *et al*., 2005; MA, 2005a). On balance therefore, healthier community patches (i.e. those that are less climatically stressed, less complex, larger in size, and experience less pressure from adjacent land covers) are likely to be less susceptible to invasion. This is likely to contribute to stability in the dynamics of local populations within these patches, and therefore that of the properties, functions and ecosystem services with which they are typically associated (Scherer-Lorenzen, 2005; Hooper *et al*., 2005; Fridely, 2001). This is also likely to contribute to the stability of existing properties, functions and services at broader scales. Chapter Two highlights the important role that the composition of the species pool at landscape scales can play in influencing BEF characteristics locally. Due to the greater resistance to invasion provided by healthier patches at local scales, the capacity of invasive species to establish themselves within the landscape as a whole, is also likely to be reduced (Scherer-Lorenzen, 2005; Fridely, 2001). The species pool is more likely to contain those species currently associated with maintaining existing ecological properties, functioning and services.

Healthier patches (as defined above) may also be likely to be better able to cope with, or recover from, the pressures of over-exploitation and pollution. On balance, larger, less complex patches should be less sensitive to over-exploitation than smaller ones, simply as a functioning of their size as well as the amount of interior habitat that they contain. Also, the increased diversity associated with larger patches (e.g. in terms of genetic variation or species richness) means that they are more likely to contain those individuals and/or species that are capable of coping with or adapting to changes in nutrient load or levels of exploitation. Similarly, the increased habitat heterogeneity associated with these patches should enable constituent populations to recover more effectively in the event that these pressures are alleviated or removed. It is also probable that communities which are less climatically stressed (i.e. further from the limits of their climatic tolerances) will be better able to cope with increased levels of resource exploitation and pollution without changing state.

Some additional work may be required to refine the model and further establish the validity of these points. However the issues raised above provide an indication of the model's wider potential as a tool for providing holistic impact assessments for whole ecological communities across entire landscapes in terms of the broad array of pressures these communities face.

7.5.3 Reliability Issues

As with any other technique, the reliability and accuracy of the approach adopted here is influenced by issues associated with the availability of data and methods of simulation and analysis. There are a number of problems associated with the bioclimatic envelope data and the methods subsequently used in their spatially-explicit application. For instance, the bioclimatic modelling may be improved through the use of broader scale (e.g. European) data to establish the bioclimatic envelopes. However, appropriate (community level) ecological data at this scale are not readily available. Issues are also apparent with the frequency distributions of the bioclimatic envelopes and the Gaussian methods subsequently employed to estimate probabilities of occurrence for the BVCs (Chapter Three) and the P/NPBVCs (Chapter Five). There are also thematic differences between the ecological units used to establish the bioclimatic envelopes (i.e. BVCs) and those units for which the bioclimatic envelope data were used to gauge Climate Stress (i.e. PBVCs) which potentially influences the reliability of the results. However, despite these difficulties, there is close agreement between the Climate Stress results for the PBVCs and the results of other research (e.g. Berry *et al*., 2002; Harrison *et al*., 2001) investigating the impacts of climate change on species typically associated with these PBVCs. The methods of bioclimatic modelling adopted here are therefore regarded as generally robust.

Although the use of bioclimatic envelope modelling for investigating climate change impacts on ecological phenomena has been questioned, particularly for assessments at the landscape scale (Pearson & Dawson, 2003; Guisan & Zimmerman, 2000), this research suggests that, when used appropriately, the approach can be useful for investing potential climate impacts at these scales. The methods adopted here for estimating the Climate Stress of plant communities represent a novel approach to bioclimatic modelling at the landscape scale and are regarded as an improvement on those of other research which have attempted to assess community vulnerability in terms of climate change based largely on the climatic conditions that local individual community patches have historically experienced (e.g. Klausmeyer, *et al*., 2011; Tremblay-Boyer &

Anderson, 2007). The approach adopted here therefore offers a less relative, more biologically-realistic, technique for incorporating the potential impacts of climate change on community vulnerability.

Issues are also apparent in terms of the reliability of the land use model and associated results. The uncertainty regarding the future direction of land use change is tackled through the use of two robust, regionally-relevant land use scenarios, which themselves represent unique and useful research outputs. However, the strength of the main findings of the research could be improved through the use of additional land use scenarios to investigate the impact of land use changes on community vulnerability under different socio-economic conditions to those prevalent under Conservation First and Going for Growth and so build a more comprehensive picture of potential land use trends affecting the park. Time constraints made it impractical to do so for this research.

Inaccuracies in the land use modelling results have been identified. A number of relevant P/PNBVCs (e.g. NGP, IGP and BLWP and Raised Bog) demonstrate poor or very poor simulation accuracies with potential implications for the reliability of the results in terms of Matrix and Geometric Vulnerability. However, overall simulation accuracies are good and exceed those of other research simulating community distributions (e.g. Zimmerman & Kienast, 1999; Brzeziecki *et al*., 1995). Also, a number of relevant P/NPBVCs (e.g. Heath, Blanket Bog and Coniferous Woodland) are simulated very accurately. Furthermore, the inclusion of the additional management variables means that the future simulations of future P/NPBVC distributions should be regarded as more robust than the results in Table 4.16 initially suggest. Overall, the adopted approach is therefore regarded an accurate and useful tool for assessing the exposure and vulnerability of communities to both climate and land use change at the landscape scale.

7.5.4 Model Refinement and Further Application

The various characteristics of the adopted methodology suggest that it has good potential for further application. The relative simplicity and transparency of many aspects of the approach mean that the various sources, underlying assumptions and techniques are well conveyed and readily understood, enabling the model to be applied with relative ease. For instance, the data, sources of information and methods used to establish the bioclimatic envelopes of the BVCs and the various P/NPBVC suitability indices are widely available, explicit and may be easily understood and employed by a wide range of potential users, including non-specialists. Similarly, the data, methods and techniques subsequently employed to make spatially-explicit simulations based on this information are also relatively accessible, straightforward and easy to implement. The application of the model described in this thesis is therefore regarded as a useful first step towards the provision of more comprehensive assessments of community vulnerability within NNP (as well as other regions of the UK).

There are undoubtedly aspects of the approach that could be improved. As stated, running additional land use scenarios through the model may help to further strengthen the results and recommendations of this research. Some of the underlying biophysical data used in the land use simulations (e.g. soil pH, soil water), although the best available at relatively little cost, could also be improved upon. Also, some of the thresholds used to delineate P/NPBVC suitability indices for factors used within the land use model, although generally robust, may represent an oversimplification of real-world ecological relationships. Due to the characteristics of the approach, however, many of these issues could be easily tackled in future applications. For instance, once formulated, additional scenarios may be run through the model with relative ease and speed. The model may be applied quite readily within NNP (or elsewhere), to investigate potential impacts under different socio-economic conditions to those considered here. The model may also be easily applied using more robust underlying biophysical data for those with larger research budgets. Furthermore, the nature of the suitability indices means that they may be easily adapted, for instance to account for different interpretations of the source information or to incorporate more robust, up-to-date information regarding the relationships they describe. Because of the sources of information used in delineating the elevation suitability indices and the 'law of relative site constancy' (Guisan & Zimmerman, 2000), this is likely to be particularly relevant in utilising the elevation suitability indices to produce land use simulations in areas outside of the north east of the UK.

The inclusion of the additional variables of distance and cross-suitability are interesting and novel aspects of the methodology. Griffiths *et al*. (2011) highlight the relevance of these variables in determining the suitability of land for the occurrence of vegetation communities. However, to date, such variables have not been used to provide spatially-explicit simulations of community distributions. These variables, as well as contributing to the robustness of future predictions of land use change, also provide the potential to incorporate more localised considerations into the land use simulations. For instance, some of the scoring for cross-suitability for particular P/NPBVCs was used to account for more scenario-specific characteristics and considerations. The high score assigned to Modified Bog in terms of its suitability for conversion to Blanket Bog and/or Raised Bog under Conservation First (Table A2.7a) provides a useful example and reflects the fact that under the prevailing socio-economic characteristics of the scenario, conversion of patches of Modified Bog to Blanket Bog and/or Raised Bog is likely to be favoured from a policy perspective. The inclusion of cross-suitability and distance therefore provide users with a simple tool for incorporating more locally-relevant factors and considerations into the simulated outputs. Their use within the model therefore further highlights the wider potential and applicability of the adopted approach.

The basic model presented here could also be easily adapted to incorporate additional data that may become available to provide more comprehensive assessments. For instance, the potential impacts of particular introduced/invasive species are not explicitly simulated, due to the broad focus of the research and the paucity of relevant information on specific invasive species, their ecological traits (e.g. dispersal characteristics) and potential interactions with, or impacts on, native taxa. However, more explicit assessments of vulnerability in terms of such pressures could be made using the model in the event that relevant data become available and by focusing investigations on a single or limited number of community types. Such future work may prove especially useful for providing more comprehensive vulnerability assessments for PBVCs (e.g. Blanket Bog and Raised Bog), which have been identified within this research as being at particular risk.

This research has provided Information for a range of vegetation communities relevant to the UK. Although the PBVCs are the particular focus of this research, the information provided could be used to produce vulnerability assessments for any one of these community types. The results of this research (e.g. bioclimatic envelope data, suitability indices) may be applied quite readily throughout the UK, wherever relevant ecological and biophysical data are available. The BVC and P/NPBVC categories used within the research represent just one treatment of the available ecological data. Other users may wish to treat the data differently, or have different ecological data at their disposal. Because of the relative simplicity and accessibility of many aspects of the approach (e.g. creation and application of suitability indices and bioclimatic envelope data), it is felt that the general methodology offers a convenient and relevant framework for a wide range of potential users, regardless of their particular focus and resources. It is hoped that these methods prove useful in providing meaningful, spatially-explicit vulnerability assessments for a range contexts within the UK, and elsewhere, and so assist in effective management of biodiversity and environmental change.

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Appendix 1 (appendices to Chapter 3)

Table A1.1: Results of Pearson's correlation analysis of the selected seasonal temperature parameters (used as independent variables in the model) and a selection of other climatic variables (which represent other proposed bioclimatic controls on species distributions) available from the UKCIP for the 1961-90 period.

Summer Variables (all p-values = 0.000)		Winter Variables (all p-values = 0.000)	
	Summer Temperature (Coefficient)		Winter Temperature (Coefficient)
Mean Summer Maximum Temperature	0.969	Mean Winter Maximum Temperature	0.976
Mean Summer Minimum Temperature	0.915	Mean Winter Minimum Temperature	0.973
Mean Summer Air Frost	-0.667	Mean Winter Air Frost	-0.959
Mean Summer Ground Frost	-0.786	Mean Winter Ground Frost	-0.894
Mean Summer Sunshine	0.852	Mean Winter Sunshine	0.687
Growing Degree Days	0.978	Growing Degree Days	0.834
Consecutive Dry Days	0.940	Consecutive Dry Days	0.656
Summer Cloud Cover	-0.893	Winter Cloud Cover	-0.546
Growing Season Length	0.827	Growing Season Length	0.971
Cooling Degree Days	0.822	Cooling Degree Days	0.364
Heating Degree Days	-0.916	Heating Degree Days	-0.940

Table A1.2: Bioclimatic envelopes of the BVCs as established through the spatial correspondence between climate cells from 5km resolution UKCIP climate grids, and BVC distribution data for England and Wales from Landcover Map 2000.

Output Class (BVC)	**Summer Temperature (^oC)**			**Winter Temperature (^oC)**			**Summer Precipitation (mm)**			**Winter Precipitation (mm)**		
	Min	**Max**	**Mean** (SD)	**Min**	**Max**	**Mean** (SD)	**Min**	**Max**	**Mean** (SD)	**Min**	**Max**	**Mean** (SD)
Bracken	9.23	16.23	12.80 (±1.13)	-0.42	6.50	2.45 (±1.01)	45.86	259.20	104.35 (±37.69)	39.14	360.56	147.40 (±62.22)
Heath	9.23	17.21	12.69 (±1.24)	-0.42	7.57	2.33 (±1.12)	42.09	289.71	87.99 (±26.50)	39.28	394.41	122.05 (±48.57)
Fen, Marsh & Swamp	9.86	17.21	15.40 (±0.87)	1.22	6.03	4.03 (±0.58)	41.14	203.45	56.54 (±17.46)	39.02	311.68	62.35 (±35.02)
Bog	9.33	16.10	12.19 (±1.10)	-0.42	5.87	1.83 (±1.09)	47.48	228.48	97.74 (±22.14)	39.14	328.72	130.73 (±42.66)
Improved Grassland	9.23	17.21	14.58 (±0.96)	-0.42	7.57	3.81 (±0.91)	41.14	289.71	67.67 (±16.49)	39.02	394.41	87.62 (±32.79)
Acid Grassland	9.23	17.21	13.25 (±1.36)	-0.42	7.45	2.81 (±1.16)	41.14	289.71	89.61 (±30.12)	39.02	394.41	125.31 (±54.05)
Neutral & Calcareous Grassland	9.80	17.21	14.66 (±1.02)	-0.41	7.57	3.63 (±0.89)	41.14	259.20	63.51 (±14.87)	39.02	350.51	78.38 (±30.98)
Broadleaved Woodland	9.23	17.21	14.83 (±0.94)	-0.41	7.57	3.80 (±0.80)	41.14	298.71	64.48 (±17.45)	39.02	394.41	82.52 (±34.92)
Coniferous Woodland	9.23	17.21	13.51 (±1.36)	-0.42	7.57	2.96 (±1.06)	41.38	289.71	84.00 (±26.42)	39.28	944.41	115.20 (±49.27)
Arable & Horticulture	9.23	17.21	15.06 (±0.71)	-0.41	7.57	3.77 (±0.64)	41.14	289.71	56.47 (±8.56)	39.02	394.41	62.07 (±21.20)

Normality Tests (Figures A1.1a-A1.10d)

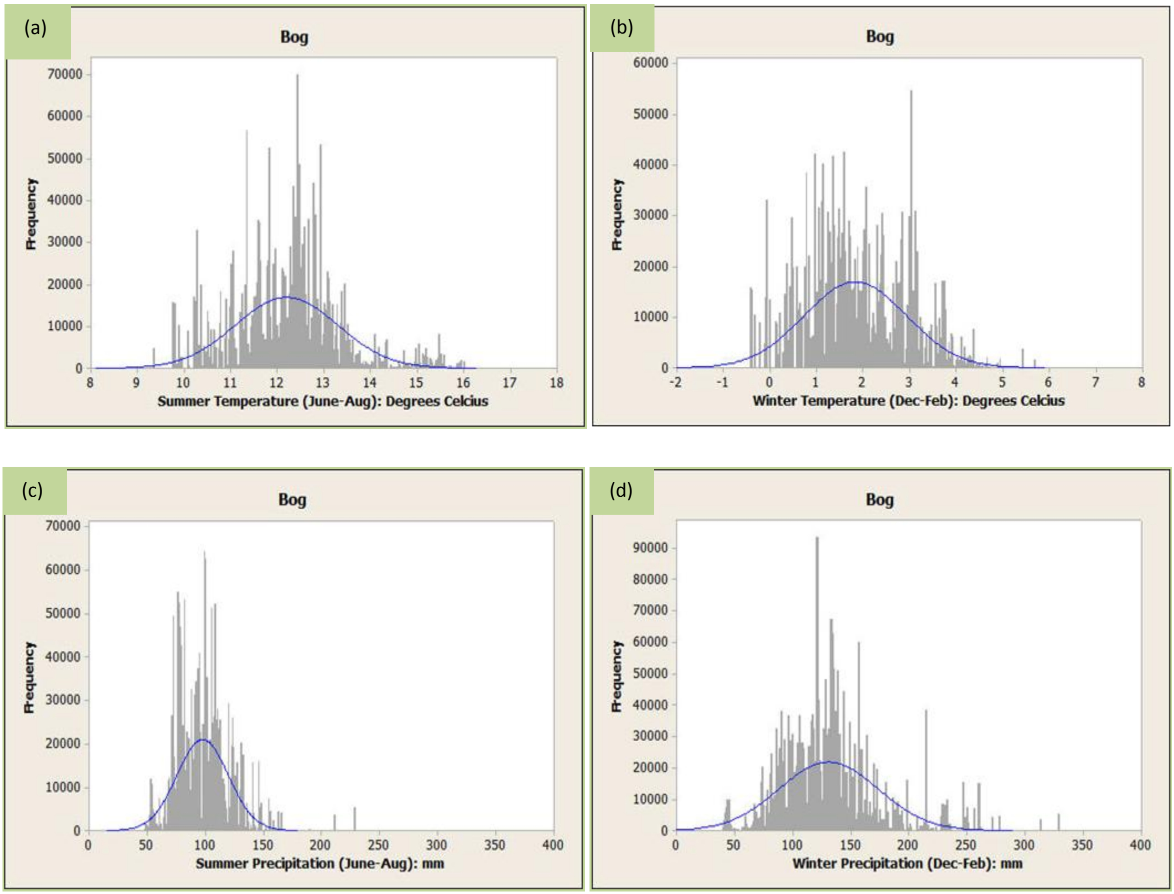
The individual BVC frequency distributions for each climate variable (Figures A1.1a-A1.10d) were gauged using visual analysis. Three basic types of frequency distribution were identified: normally distributed data (1), slightly skewed data (2) and highly skewed (3). Fifteen datasets are of Type 1 (highlighted green), fourteen are Type 2 (yellow) and eleven are Type 3 (orange).

For Type 1, because the data are normally distributed, the Bayesian approach is regarded as an accurate model of the bioclimatic envelope of the BVCs. For Types 2 and 3, the Bayesian approach is regarded as a less accurate model of the bioclimatic envelope data. However, it is likely that these data are not normally distributed due to the influence of other; non-climatic factors such as land use history (see Section 3.7). In all of these cases the means are not accurate representations of the optimum conditions suggested by the skewed data. For instance, in terms of summer temperature for Broadleaved Woodland (Fig A1.2a), the data (grey bars), suggest optimum conditions to be approximately 15.5^{o}C. The optimum conditions suggested by the mean are slightly less than 15^{o}C. However, it is likely that the optimum conditions suggested by the skewed data are not an accurate representation of the 'true' realised optimum climatic tolerances of the BVCs, because of the influence of other factors. As such, the optimum conditions suggested by the imposed normal curves are, in some instances, regarded as a reasonable model of the 'true' optimum tolerances of the BVCs (i.e. in cases where the bioclimatic envelope data is of Type 2). For instance, in the case of Broadleaved Woodland and summer temperature, it is feasible that the negative skew of the data is related to a reduction in Broadleaved Woodland occurrence, due to non-climatic factors, in areas characterised by summer temperatures between approximately 14-15^{o}C. Without the influence of these confounding factors, the observed response would include a higher frequency of Broadleaved Woodland occurrences within this temperature range. As such, the data would be normally distributed, with greater symmetry between 14-16^{o}C. In this instance, the optimum conditions suggested by the imposed normal curve *around* 15^{o}C are thought to represent the BVC's 'true' realised optimum climatic tolerance more accurately than the skewed data. The Bayesian approach is therefore regarded as a reasonably accurate model of the BVC's 'true' tolerance in terms of summer temperature and for other BVCs which exhibit Type 2 responses for particular variables.

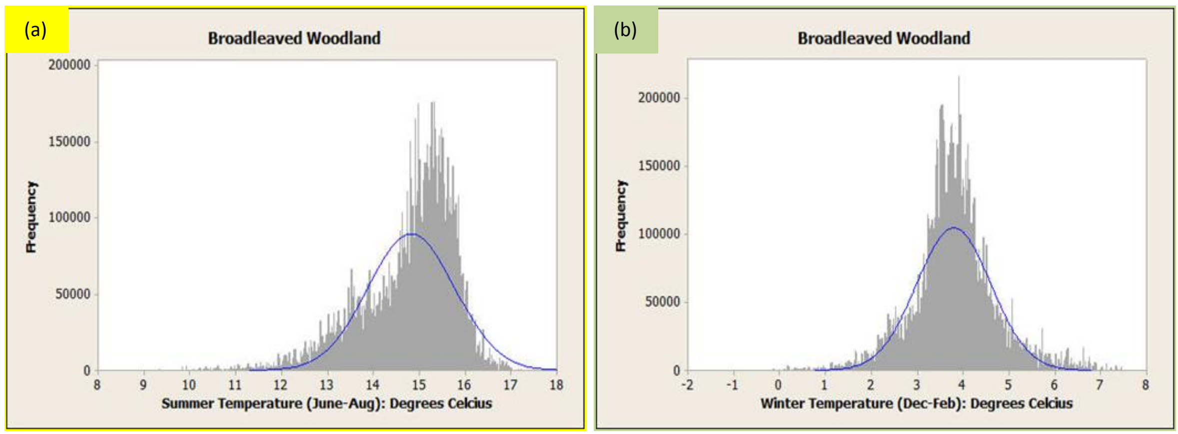
It should be noted, however, that in cases where observed responses are positively skewed the derived means are likely to slightly underestimate the BVCs 'true' mean. Responses that are negatively skewed are likely to slightly overestimate the BVCs 'true' mean. Similar issues are relevant in instances where Type 3 responses are exhibited. However, because of the greater skew in these data, the Bayesian approach is likely to offer a less accurate model of actual BVC tolerances than for data of Type 2.

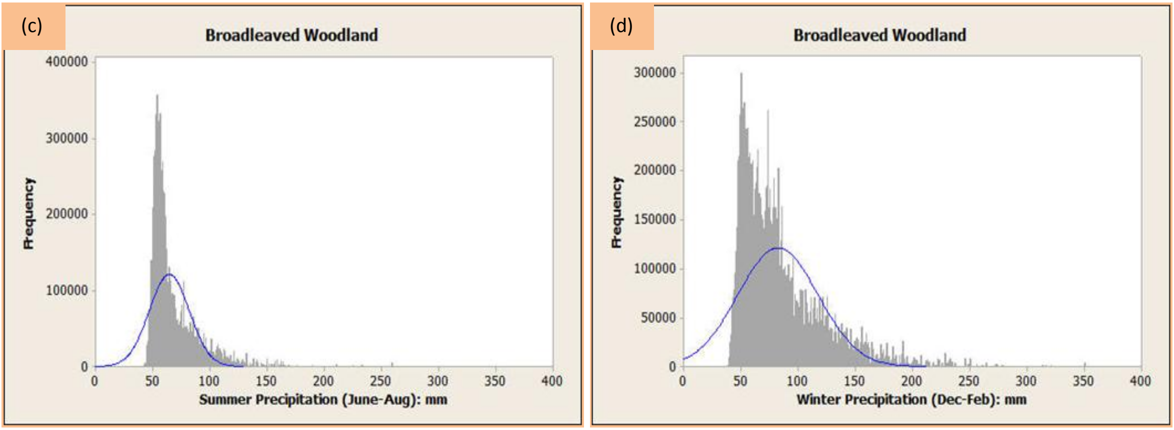
More than two thirds of the bioclimatic envelope data were either normally distributed or only slightly skewed. As such, the application of the Bayesian approach was regarded as generally appropriate for investigating the specific role of climate in influencing BVC distributions.

Figures A1.1a-d: Frequency distributions of the bioclimatic envelope data for Bog. Summer Temperature (a), Winter Temperature (b), Summer Precipitation (c), Winter Precipitation (d).

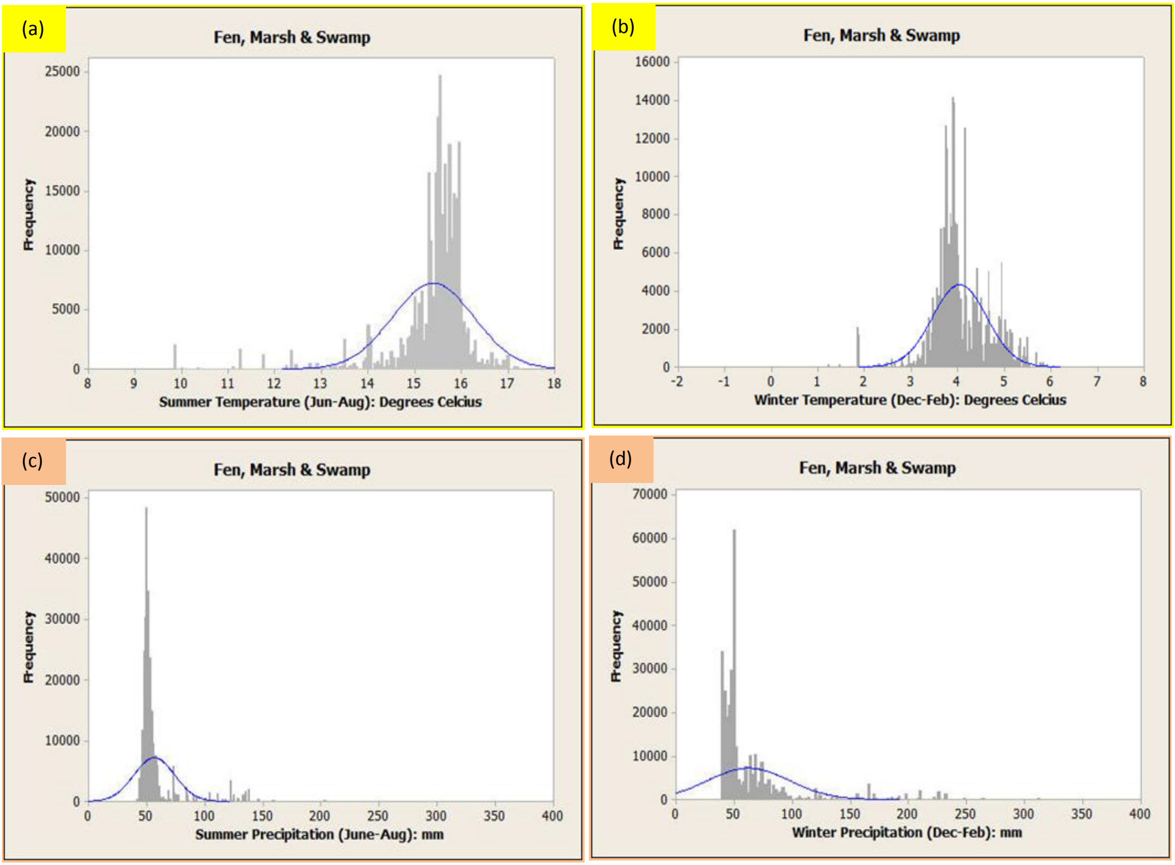


Figures A1.2a-d: Frequency distributions of the bioclimatic envelope data for Broadleaved Woodland

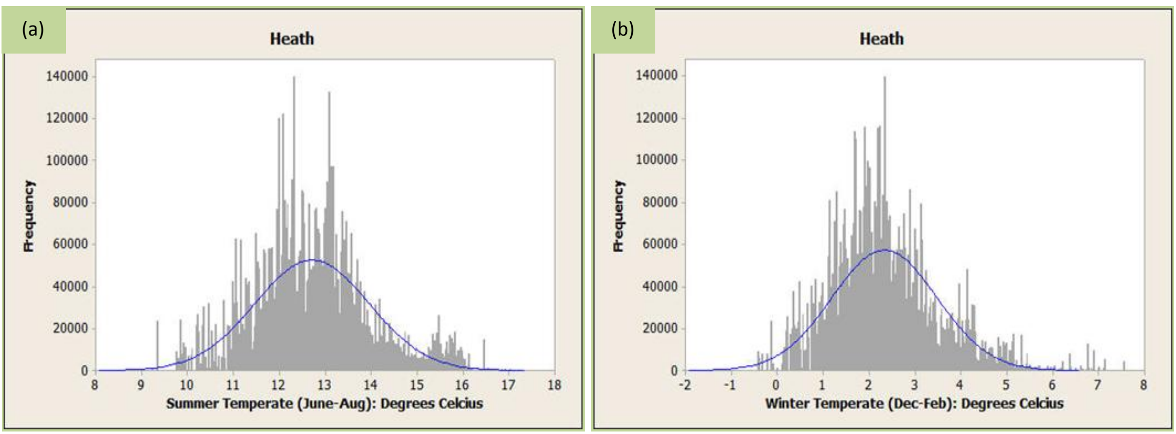


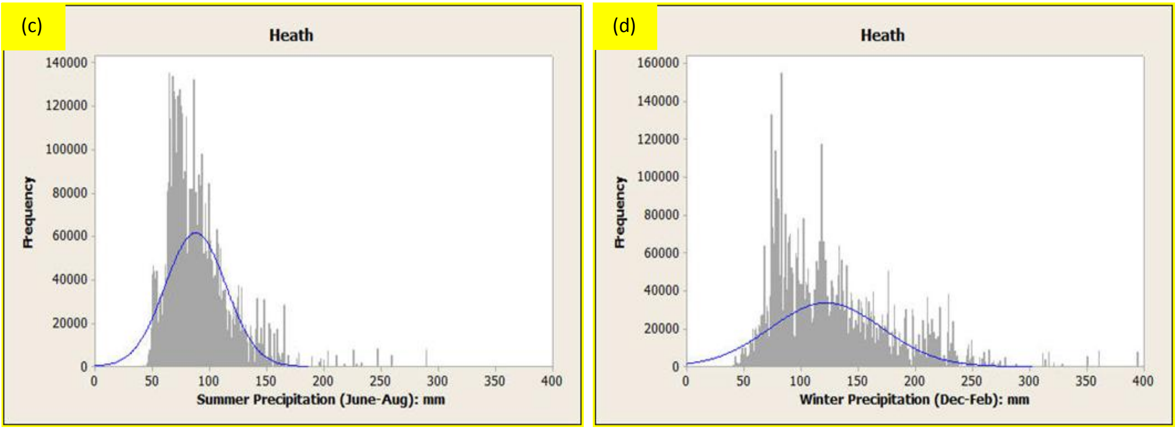


Figures A1.3a-d: Frequency distributions of the bioclimatic envelope data for FMS

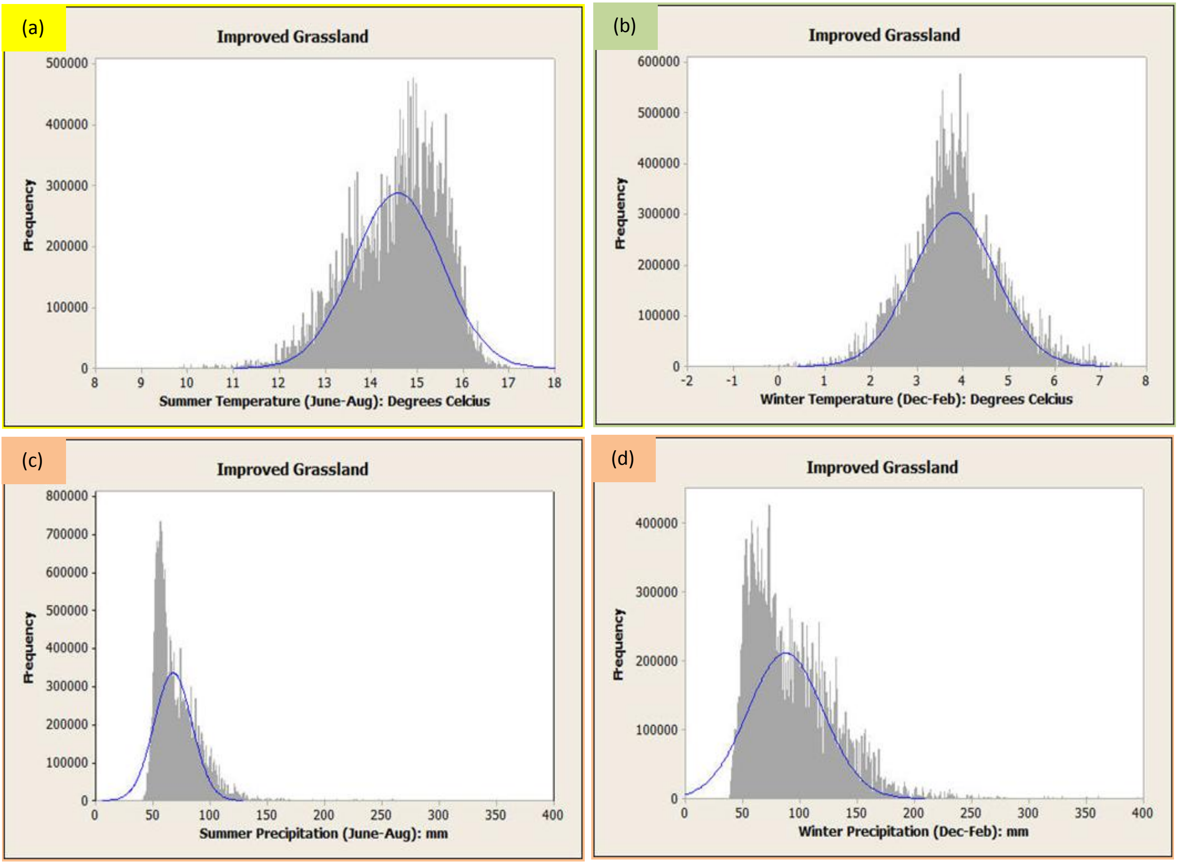


Figures A1.4a-d: Frequency distributions of the bioclimatic envelope data for Heath

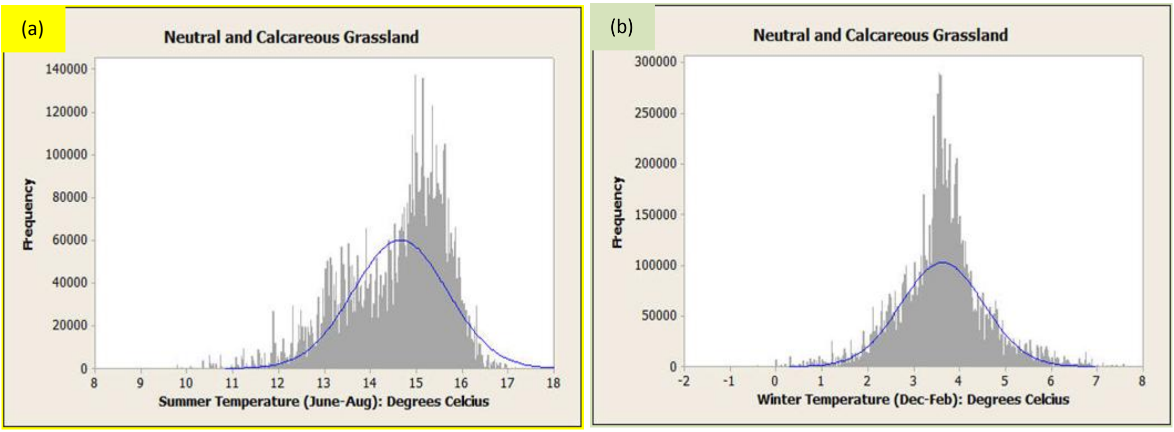


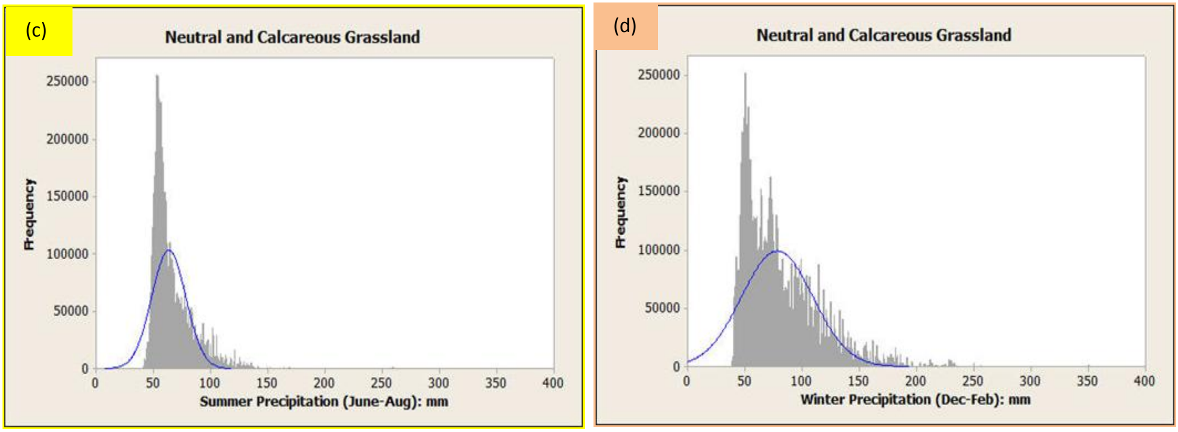


Figures A1.5a-d: Frequency distributions of the bioclimatic envelope data for Improved Grassland

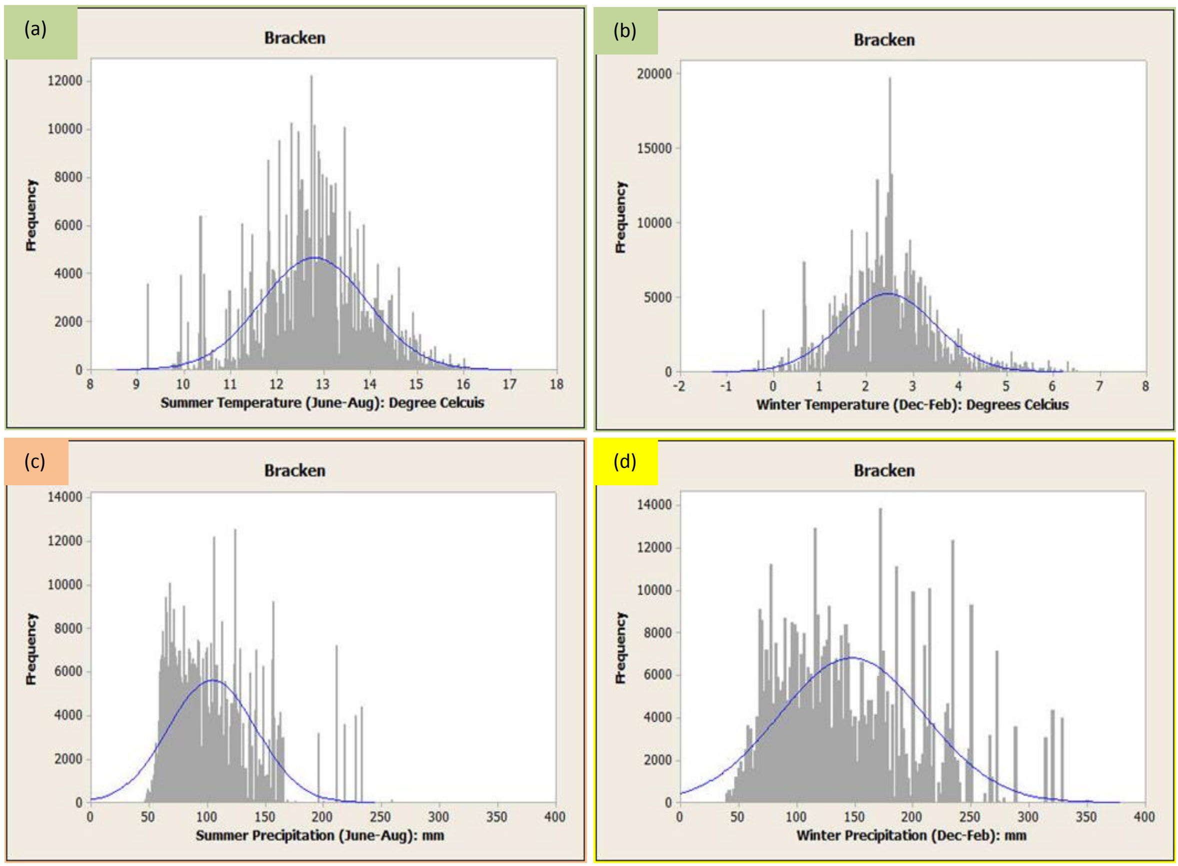


Figures A1.6a-d: Frequency distributions of the bioclimatic envelope data for Neutral & Calcareous Grassland

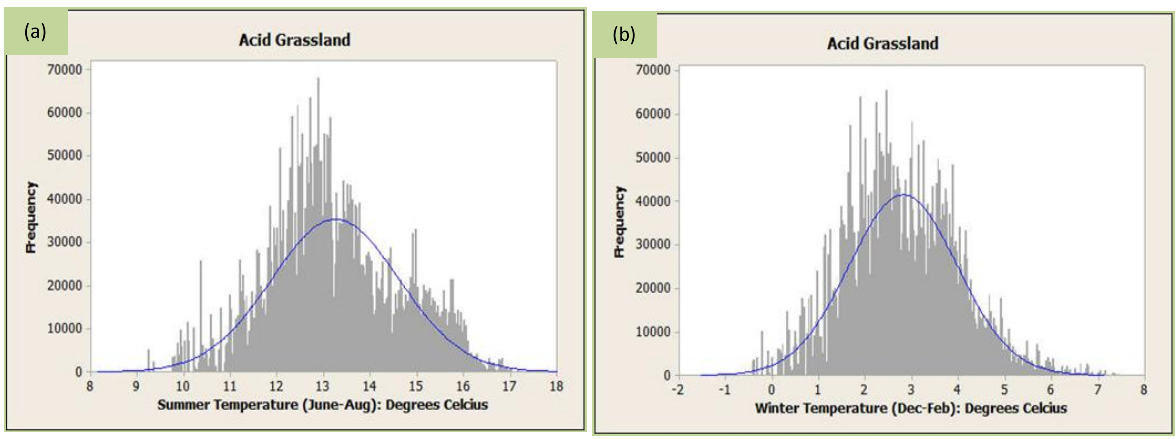


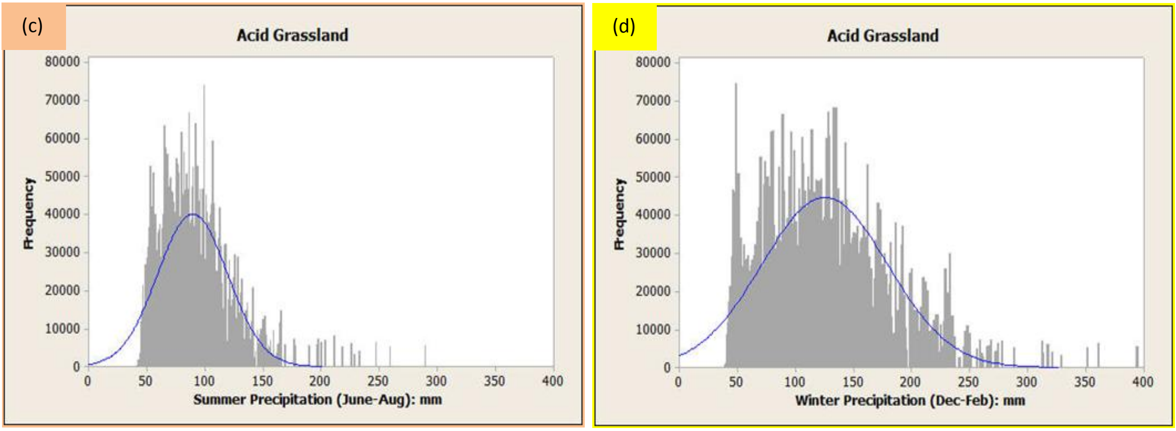


Figures A1.7a-d: Frequency distributions of the bioclimatic envelope data for Bracken

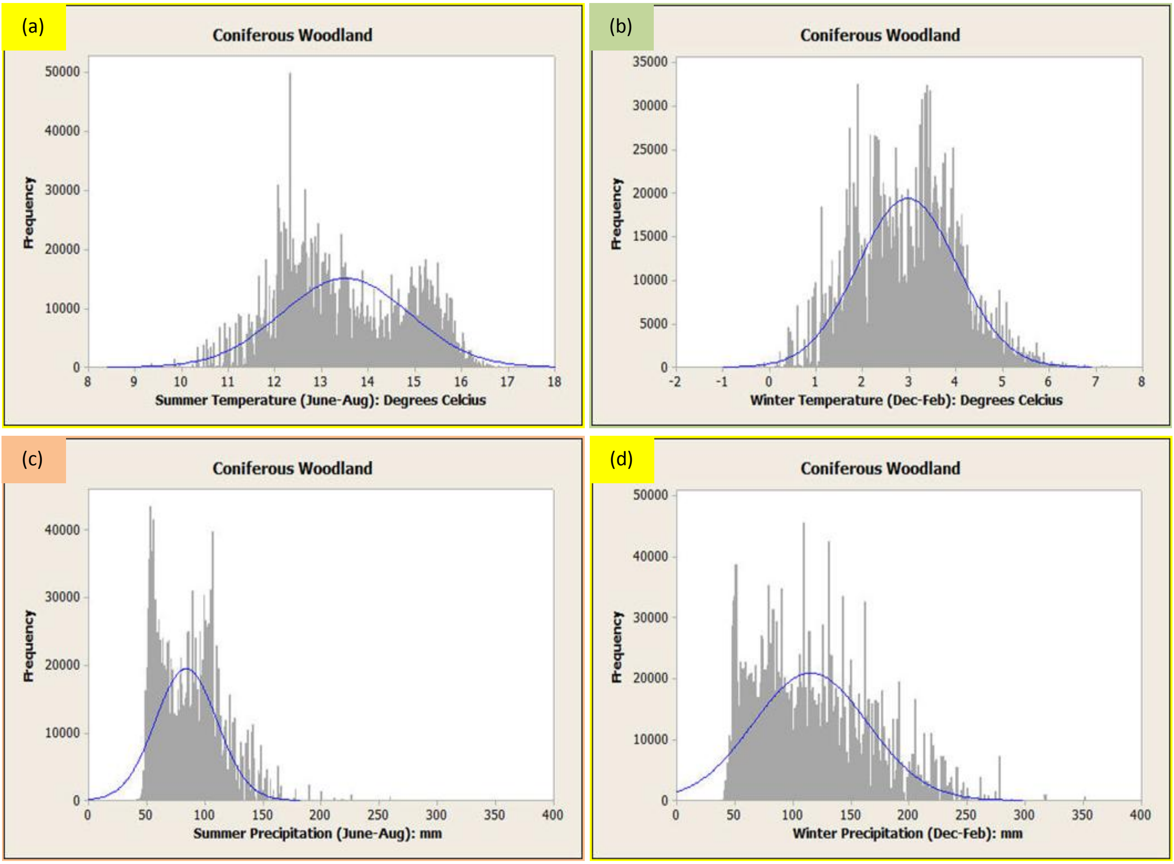


Figures A1.8a-d: Frequency distributions of the bioclimatic envelope data for Acid Grassland

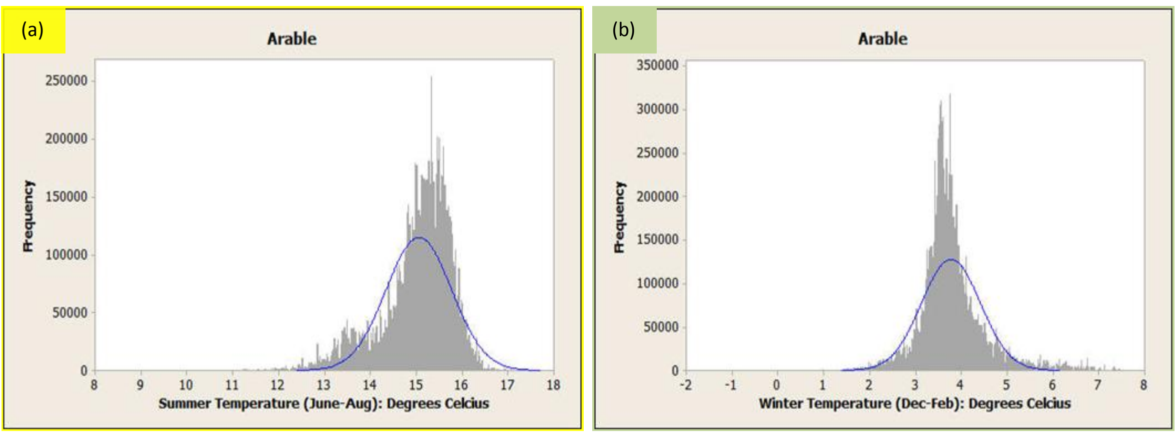


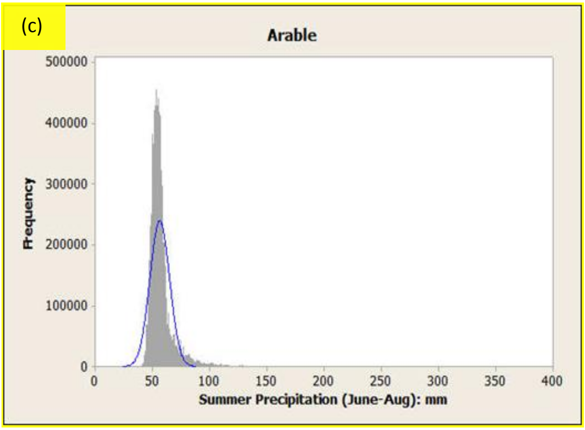


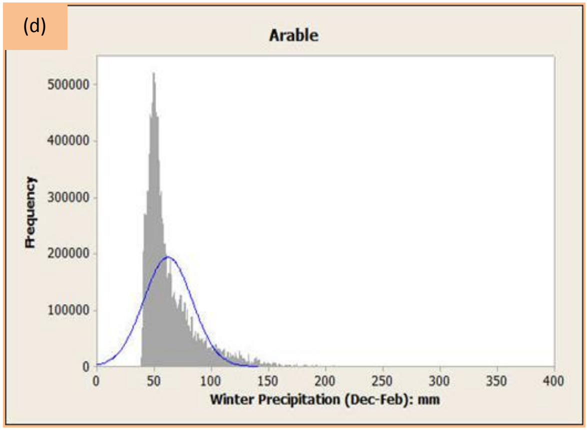
Figures A1.9a-d: Frequency distributions of the bioclimatic envelope data for Coniferous Woodland



Figures A1.10a-d: Frequency distributions of the bioclimatic envelope data for Arable and Horticulture




(c)
Arable
Frequency
Summer Precipitation (June-Aug): mm


(d)
Arable
Frequency
Winter Precipitation (Dec-Feb): mm

Appendix 2 (appendices to Chapter 4)

Appendix 2 is split into two parts. The first part, Appendix 2a explains the selection of biophysical and management-related variables for determining P/NPBVC distributions. The general methodology, sources and rationale for determining P/NPBVC requirements/suitability in terms of these variables are also provided, as well as the methods used to represent these requirements spatially. Particular focus is given to Blanket Bog (and other PBVCs, where appropriate) to further demonstrate the methodology. Appendix 2b includes relevant information, e.g. classification schemes for soil water, soil pH and slope, used to provide more comprehensive quantification of P/NPBVC suitability. Appendix 2b concludes by providing full details of the suitability scoring for the other P/NPBVCs not covered in Appendix 2a.

Appendix 2a

A2.1 Introduction

Appendix 2a is organised as follows: Section A2.2 introduces the concept of habitat suitability and its relevance for modelling P/NPBVC occurrence. General details of the methods used to represent the suitability of land for P/NPBVC occurrences spatially are also provided. Section A2.3 explains the selection of the biophysical variables and provides details of the spatial data for NNP in relation these variables. Section A2.4 provides information on the sources used to determine requirements of the P/NPBVCs in terms of the selected biophysical variables and also explains the standardisation of suitability scoring and indices. Section A2.5 provides full details of the suitability scoring for Blanket Bog (and other PBVCs, where appropriate) in terms of the selected biophysical variables (Section A2.5.1). Section A2.5.2 provides details of the suitability scoring for the two management variables, cross-suitability and distance, for all P/NPBVCs undergoing expansion under the scenarios. These variables are used along with the biophysical variables to model future P/NPBVC distributions within NNP.

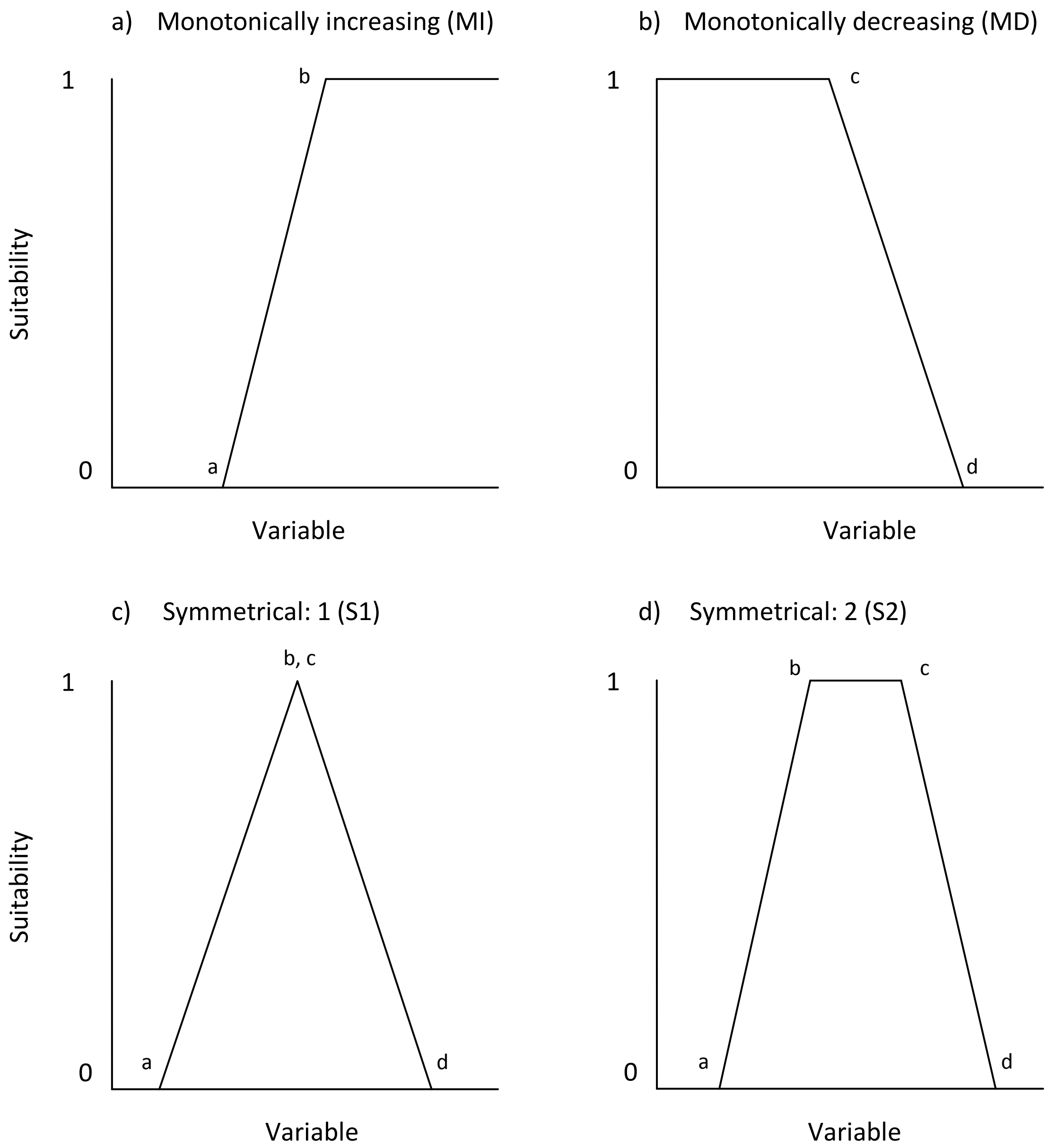
A2.2 Habitat suitability

A technique that is commonly used to determine the likelihood of occurrence of species is the Habitat Evaluation Procedure (Oldham, *et al*., 2000). The method assumes that for any given species (or group of species) the characteristics of particular habitat conditions, deemed important for maintaining viable populations, can be quantified. This quantification process usually involves the establishment of a Habitat Suitability Index (HSI) for the organisms under investigation. Specifically, the HSI is a numeric index, typically ranging from 0.0 to 1.0 (representing unsuitable and optimal habitat, respectively) (Oldham *et al*. 2000). Typically, the method assumes that 'there is a direct correlation, usually a linear relationship, between the index and the species carrying capacity of the habitat' (Oldham *et al*. 2000, pp. 144). The method has been used successfully to gauge the habitat suitability of a wide range of species (e.g. mammals: Mitchell *et al*., 2002; birds: Uhmann *et al*., 2001; Prosser & Brooks, 1998; amphibians: Oldham *et al*. 2000; fishes: Vinagre *et al*. 2006; and plants: Williams *et al*., 2008). Here the approach is applied in a novel way to determine suitability for plant species assemblages, specifically, P/NPBVC types. The traditional focus on species is likely related to the current thinking regarding the community/continuum debate (see: Section 2.4.2). This research is more closely affiliated with community theory, in that it assumes that predictable species assemblages occur because of shared environmental requirements (Guisan & Zimmerman, 2000; Zimmerman & Kienast, 1999; Franklin, 1995; Begon *et al*., 1990).

A2.2.1 Spatial Application of HSIs

Ultimately the HSIs are used here to facilitate spatial predictions of future land use change under different scenarios (see: Section 4.2). A method is therefore required to facilitate their spatially explicit application. *IDRISI Taiga's* 'Fuzzy Set Membership Function' (FSMF) module was employed here to achieve this. Specifically, a 'Linear membership function' was used. This allows suitability, for each P/NPBVC in terms of each of the key variables, to be represented spatially by applying the defined HSI to raster grids depicting the spatial characteristics of these variables (Figure 4.1: 'Suitability Layer 'A''). For each pixel within a grid, a score is returned from 0-1 in terms of its suitability for a given P/NPBVC. The HSI is parameterised by the input of 'control points' delineating lower optimum, upper optimum and absolute maximum and minimum thresholds. Linear interpolation is then used to determine suitability for intermediate values. The thresholds are derived from the literature review of P/NPBVC biophysical requirements (Section 4.2). Further details of the delineation of suitability indices using the 'Linear membership function' are provided in Figures A2.1a-d. The method was chosen because of the ease with which it allows spatially-explicit application of HSIs. HSIs based on linear interpolations have also been successfully employed in other ecological research (e.g. Oldham *et al*., 2000). The characteristics of the procedure mean it cannot adequately represent non-linear community-environment relationships that may be characterised, statistically, by polynomial distributions. Such relationships are apparent in nature (Begon *et al*., 1990). However, adequate data and information for the P/NPBVCs, and the species of which they are comprised, to accurately parameterise such relationships is not currently available.

Figures A2.1 a-d: Four basic types of suitability function and the control points required to define them in IDRISI's FSMF module. Within the module, parameters and thresholds are assigned to 'control points' which allow a suitability function to be defined in terms of four basic types. These are: 'monotonically increasing', 'monotonically decreasing', and two types of 'symmetrical' function. The figures provide a diagrammatic representation of the characteristics of these suitability functions. The control points associated with the functions are also included. Control point 'a' marks the point at which suitability begins to rise above 0 (lowest suitability). Point 'b' indicates the point at which the suitability reaches 1 (highest suitability). 'c' marks the point at which suitability drops below 1. Control point 'd' indicates the point where suitability reaches 0. For monotonically-increasing types only control points 'a' and 'b' need to be defined. For monotonically-decreasing types only points 'c' and 'd' are needed. For the symmetrical types all four control points are required (Clark Labs, IDRISI Taiga, N/K).



A2.3 Variables

Ten generic factors are typically regarded as key determinants of vegetation occurrence. They are: climate, geology, soil pH, soil depth, soil type, soil water, landform, vegetation, human management and fauna (Di Gregorio & Jansen, 2000; Zimmerman & Kienast, 1999; Franklin, 1995).

From these variables a limited selection was made for determining the suitability for P/NPBVC occurrence. The selection used three criteria: established or perceived importance to P/NPBVC occurrence; the availability of relevant information; availability of spatially explicit data. Four variables were selected from the ten listed above following these criteria. They were: soil pH, soil water, soil type and landform (represented here separately by elevation and slope). Table A2.1 provides summary details of these variables and the data for NNP used in the spatially-explicit application of the HSIs. A general rationale for the choice of biophysical variables is provided below. Specific details of how the selected biophysical variables were utilised in the research is provided in Sections A2.4 and A2.5. Section A2.5 also provides details of the suitability scoring for the two management-related variables used alongside the biophysical variables to produce predictions of future P/NPBVC distributions under the land use scenarios.

Table A2.1: Summary characteristics of the biophysical data used in the spatially explicit application of the HSIs. All data used is in raster format at a resolution of 50m.

Variable	Source	Data type	Unit	Derivation
Soil water	Soils map	Categorical	6 categories	A 'soil series' map for NNP was obtained from Northumberland National Park Authority in polygon format. The water class of each soil series polygon was input based on information from Jarvis *et al*. (1984). The polygon layer was then converted to raster format
Soil type	Soils map	Categorical	3 categories	The soil type of each soil series polygon was input based on information from Jarvis *et al*. (1984) and Nobel-de Lange (2009). The polygon layer was then converted to raster format.
Soil pH	Soils map	Pseudo-continuous	pH	The pH value of each soil series polygon was input based on information from Jarvis *et al*. (1984). The polygon layer was then converted to raster format.
Elevation	Digital Elevation Model (DEM)	Continuous	Metres	Average height in meters above sea level for each 50m raster cell within the study area. Interpolated from digital Ordinance Survey (OS) data.
Slope angle	Derived from DEM	Continuous	Degrees	Derived from DEM

A2.3.1 Soil Water

Water is crucial for plant survival and growth. Firstly, it is the principal medium for the chemical and biochemical processes that support plant metabolism (Gurevitch *et al*. 2002; Jeffrey, 1987; Bannister, 1976). Water plays a direct role in photosynthesis and is therefore imperative for plant cell development and regeneration. Water also provides physical support for plant cells. In plants suffering from water stress, the structure and shape of plant cells are affected in such a way that vital processes such as photosynthesis and evapotranspiration are decreased, so that overall plant growth is reduced (Gurevitch *et al*. 2002; Jeffrey, 1987; Bannister, 1976). Water also transports important minerals and nutrients within soils to plant roots (Gurevitch *et al*. 2002; Begon *et al*., 1990; Jeffrey, 1987; Bannister, 1976). In short, an inadequate supply of water can lead to diminished plant growth and ultimately death. The primary source of water for most terrestrial plants is the soil and it is the properties of soil (particularly its structure and texture) which largely determine the water available to plants (Begon *et al*., 1990; Jeffrey, 1987; Bannister, 1976). Studies modelling vegetation distributions often include measures representing soil water characteristics as predictor variables (e.g. Liu *et al*. 2005; Berry *et al*. 2002; Pearson *et al*. 2002; Zimmerman & Kienast, 1999).

The results of Berry *et al*. (2002) provide some indication of the importance of soil water in determining distributional differences between particular species indicative of different community types within the UK (e.g. wet heath and blanket bog). Further evidence of the link between soil water conditions and community occurrence is provided by Gurnell (1981) whose research demonstrated that the species composition of different heath and mire communities in the New Forest, Hampshire was a good indicator of local scale soil moisture conditions. Gurnell *et al*. (1998) point out that, because of the relative ease with which maps of vegetation and land cover are accessed and complied, they are often used as surrogates when data relating directly to the hydrological characteristics of the soil are unavailable. JNCC (2007), Furniss & Lane (1999); Lane (1999), Rodwell *et al*. (1991a; 1991b; 1992) and Tansley (1949) used soil water characteristics to distinguish between particular community and habitat types. The use of some measure of soil water characteristics to gauge P/NPBVC suitability was therefore essential.

A2.3.2 Soil pH

Soil pH has an important effect on the growth and occurrence of plant species generally, due to the influence it has on the toxicity of certain minerals within soils, as well as the availability of nutrients essential for growth (Begon *et al*., 1990; Grime *et al*. 1988; Jeffrey, 1987; Tansley, 1949). For instance, in moderately to highly acidic soils (ca. pH <5.5) levels of macronutrients such as phosphorus (P) are reduced so low that they can adversely affect plant productivity (Jeffrey, 1987). Aluminium (Al) and hydrogen (H) toxicity is a particular problem for many plants in highly acidic soils (ca. pH <4.5). In alkaline soils, the availability of nutrients such as phosphorus is also reduced to levels detrimental to the vigour and growth of some species (Jeffrey, 1987).

Different species are adapted to survive and/or thrive at different ranges of soil pH (Begon *et al*., 1990; Grime *et al*. 1988; Tansley, 1949). For instance, many of the Sphagnum moss species typical of raised bog and blanket bog communities can only survive in acidic conditions (Richardson, 1981; Tansley, 1949). They are poisoned by conditions outside of this range that different species, more typical of other community types, can easily tolerate (Richardson, 1981; Tansley, 1949). A number of studies have demonstrated the importance of pH in influencing plant distributions (e.g. Coudun *et al*. 2006; Critchley *et al*. 2002; Roem & Berendse, 2000; Eldridge & Tozer, 1997; Steele, 1955), including plant communities (e.g. Brzeziecki *et al*. 1993). Many distinct plant communities are defined in terms of soil pH requirements (Rodwell *et al*., 1991a; 1991b; 1992; Tansley, 1949). Soil pH was therefore regarded as useful for determining community distributions.

A2.3.3 Soil Type

Classifications of soil type are typically based on textural, structural and pH characteristics (Gurevitch *et al*. 2002; Jeffrey, 1987; Bannister, 1976; Tansley, 1949). Soil texture and structure typically correlate strongly with soil water characteristics (Tansley, 1949). A comprehensive assessment of P/NPBVC suitability in terms of soil type was therefore deemed unnecessary because of the inclusion of soil water and soil pH as separate variables within the model. However, JNCC (2007) place particular significance on defining particular habitat types according to associations with peat. Some habitat types are defined according to whether or not they are associated with deep peat (>0.5m) or thin peat (<0.5m). Others are defined by their association with thin peat and non-peat soils. For instance, a peat depth of >0.5m is one of the defining characteristics of blanket bog (JNCC, 2007). Heath is distinguished from blanket bog (and some other 'wetland' types) in that it is more typically associated with thin peat *or* non-peat soils.

The development of peat is due to the partial decomposition of vegetation under the anaerobic conditions typically associated with permanently waterlogged soils (Tansley, 1949). Development can be checked due to increased aeration associated with drying of the soil (Tansley, 1949). Deep peats are therefore indicative of waterlogged conditions occurring, more or less uninterrupted, over large temporal scales. These points and the discussion on the apparent differences between the soil water characteristics of blanket bog and heath communities (Section A2.5.1) suggest that the method of distinguishing blanket bog (and some other 'wetland' types) from closely associated terrestrial types (e.g. heath) on the basis of peat depth has a sound theoretical underpinning. In determining suitability in terms of soil water characteristics, every effort was made to meaningfully represent such differences. However, because of the methods employed in assigning suitability for the P/NPBVCs in terms of soil water, it is possible that inaccuracies were introduced. Nevertheless, the consideration of suitability in terms of the basic categories of soil type (Section A2.5.1.2) was deemed useful as a secondary edaphic measure.

A2.3.4 Topographic Variables (Elevation and Slope)

Topographic variables, such as elevation, slope and aspect are commonly used as independent variables in studies investigating relationships between vegetation and the environment. This is mainly because of the relative ease with which reasonably accurate data can be obtained and that they often strongly correlate with other environmental factors, which are thought to have a more direct, physiological significance to the biological units under investigation (Guisan & Zimmerman, 2000).

The topographic variables slope and elevation were chosen to model P/NPBVC suitability in part because data relating to these variables for the study area were readily available. However, it was also thought that these variables would be useful as surrogates for a combination of other factors deemed important in determining P/NPBVC occurrence (Guisan & Zimmerman, 2000). For instance, Brzeziecki *et al*. (1995) used elevation as a surrogate for mean annual temperature to simulate present and future distributions of forest community types in Switzerland. Zimmerman & Kienast (1999) used slope angle as a way of representing the potential impact of gravitational disturbance processes (e.g. rockslides) in their model also simulating the distributions of Swiss forest communities. Other studies have employed topographic factors indirectly to derive more physiologically relevant variables (e.g. soil moisture) which are then applied directly within the model as predictor variables (e.g. Skov & Svenning, 2003).

Much of the relevant literature highlights the important role that human land use plays in influencing the distribution of different vegetation communities generally within the UK. For instance, in relation to neutral grassland communities specifically, factors related to their use as pastures, such as grazing, regular mowing and the application of fertilisers, are important in creating and sustaining occurrence (JNCC, 2007; Lane, 1999; Rodwell *et al*, 1992: Tansley, 1949). NNP is typically regarded as a 'semi-natural' landscape (NNPA, 2009; no date[c]; no date[e]). It therefore consists of a mixture of different vegetation community and land cover types which have been influenced by human management to greater or lesser degrees (Bridgewater, 1998). Indeed, it is possible to consider many of the P/NPBVCs within the park in terms of their degree of naturalness. For instance, there are P/NPBVCs (such as Blanket Bog) for which, generally, the influence of anthropogenic activities is minimal and therefore exhibit a relatively high degree of naturalness. As suggested above, other P/NPBVCs (such as Neutral Grassland: Priority and Non-Priority) are, generally, quite strongly influenced by human management. Therefore, although occurrences of Neutral Grassland (Priority and Non-Priority) are by no means entirely dependent upon anthropogenic influence, they may be regarded as less natural P/NPBVC types. Previous stages of the research had suggested land use to be a major determinant of community distributions within the study area. However, meaningful information on the characteristics of land use within the park is not readily available.

In general terms anthropogenic influences on ecosystems tend to increase with increasing soil depth and ease of access (Zimmerman & Kienast, 1999). They tend to decrease with increasing slope angle and elevation (Zimmerman & Kienast, 1999). Because of the apparent relationship between topography, human management and community occurrence, it was felt that the inclusion of elevation and slope would be useful in determining suitability for the various P/NPBVCs. Elevation is also included as a way of representing differences in climate deemed relevant to P/NPBVC occurrence. For instance, the prevalence of strong winds at higher elevations is an important factor preventing the establishment of trees in more upland areas (Grime *et al*. 1988; Tansley, 1949).

A2.4 Sources of Information and Standardisation of Suitability

A2.4.1 Sources

In determining the relationship between suitability for P/NPBVC occurrence and each of the variables, the study adopts a knowledge-based approach (Aspinall, 1998) (e.g. Store & Kangas, 2001). The suitability patterns defined are therefore essentially based on subjective judgement, informed by a number of relevant sources. Two texts in particular were especially important: JNCC (2007) and Tansley (1949). These were chosen because they provide descriptions of relevant biophysical habitat characteristics at a level of ecological organisation that closely matches that of P/NPBVC type. Indeed, the P1HS categories as defined in JNCC (2007) were used as a partial basis for the P/NPBVC categories used in this research (Table 4.1). Furthermore, P1HS data for NNP are used as a partial basis for the modelling of future land use change. Additionally, the geographical scale of the information provided by both sources is focused at the UK national level. As such, it was hoped that by utilising them to define P/NPBVC suitability, a model could be formulated with the potential to be applied outside of NNP and so aid conservation efforts elsewhere in the UK.

A2.4.1.1 Other (secondary) sources

Wherever possible the information from JNCC (2007) and Tansley (1949) was used directly to determine the thresholds used to parameterise the HSIs. However, a general issue in relation to both these sources is the lack of quantitative information for some key variables for particular P/NPBVC types. This is due to the fact that the provision of quantitative information was largely outside of the remit of the two sources. Providing comprehensive accounts of the likely tolerances of the P/NPBVCs in terms of the selected variables is an important goal of this research. Thus, it was necessary to refer to other sources in order to determine suitability in cases where the provision of information by JNCC (2007) and Tansley (1949) was inadequate.

In some instances, this meant establishing a correspondence between the qualitative descriptions given by JNCC (2007) and Tansley (1949) and quantitative values delimiting the thresholds of categories from classification schemes used by other sources. For instance, JNCC (2007, pp. 57) states that raised bog is typically associated with flat ‘level’ ground. In a scheme used by Jarvis *et al*. (1984) to categorise the angle of slopes, the upper threshold associated with level ground is 1^{o}. By using information from JNCC (2007) and Jarvis *et al*. (1984), it was therefore possible to establish optimum suitability for Raised Bog in terms of slope angle as $0 - 1^{o}$. Classification schemes relating to soil water, soil pH and slope (Tables A2.9a-c) from Jarvis *et al*. (1984) were utilised in a similar way to define other suitability thresholds.

In other instances, additional sources of secondary information were used where appropriate to provide quantitative information more directly. For instance, information from Rodwell *et al*. (1991a), where adequate, was used to provide quantitative information for key variables for specific National Vegetation Classification (NVC) community types associated with particular P/NPBVCs (Tables A2.10a&b). Information from Grime *et al*. (1988) and Fitter & Peat (1994) were used, where appropriate, to provide quantitative information for key variables for selected species indicative of particular P/NPBVCs (Table A2.11). The use of these sources was necessary in order to provide more comprehensive quantification of P/NPBVC suitability.

A2.4.1.2 Other (primary) sources

As a final source of information, descriptive statistics (mean, minimum and maximum), relating to the elevation and slope characteristics of the P/NPBVCs within the study area (Table A2.12), were obtained using *Idrisi Taiga’s* ‘Extract’ module (Clarke Labs, IDRISI Taiga, no date). In some cases, these data were used as a basis for determining thresholds of absolute maximum and minimum suitability, where information from the secondary sources was inadequate. However, this information was only used when absolutely necessary to enable a degree of generality to be incorporated into the model and avoid making it overly specific to the study area (Guisan & Zimmerman, 2000).

A2.4.2 Standardisation of suitability

A2.4.2.1 Absolute maximum and minimum suitability

The essential premise of modelling habitat suitability is to standardise the suitability indices generally (i.e. suitability for all ecological units is scored between 1 and 0). However, it is also important to standardise the suitability scores returned for specific thresholds of particular ecologically significance. For instance, optimal conditions are universally represented by a suitability score of 1.0. This is quite easily achieved by entering quantitative values directly from the literature for the relevant control points within the FSMF module. However, the process of standardising thresholds representing sub-optimal conditions associated with infrequent or unusual occurrences was more complex. This is because of the characteristics of the suitability indices (i.e. the assumption of linear relationships represented by interpolated regression lines) and the way they are able to be defined within the FSMF module. The relevance of this is best illustrated using a specific example.

Descriptive statistics for the study area suggest that the absolute maximum slope threshold observed for extents of Blanket Bog is 33^{o}. Defining the absolute maximum slope threshold as 33^{o} within the suitability index would return a suitability value of 0 (i.e. unsuitable) in relation to Blanket Bog for all areas with this gradient. Clearly, this is inappropriate, as the empirical evidence demonstrates that Blanket Bog can and does occur on such gradients. In order to derive a more meaningful suitability score, the threshold representing Blanket Bog's absolute maximum slope tolerance within the suitability index was therefore defined as 36^{o} so that a suitability score of 0.1 is returned for slopes with a gradient of 33^{o}.

The above example highlights a generally relevant issue in defining absolute maximum and minimum thresholds for the P/NPBVCs in terms of the continuous or pseudo-continuous variables (Table A2.1). In these cases every effort was made to define the absolute maximum and minimum thresholds within the suitability index so that a suitability score of 0.1 is returned for absolute maximum and minimum tolerances defined by the sources. The suitability score of 0.1 is used to quantify suitability associated with infrequent or unusual P/NPBVC occurrences for soil pH, elevation and slope. Some justification for using the 0.1 value in this way is provided by Oldham *et al*. (2000), who utilise the same value to represent absolute maximum suitability for crested newt populations in terms of the periodicity of drought. In instances where the suitability value of 0.1 is not used to represent absolute minimum or maximum suitability, the rationale for doing so is provided.

A2.4.2.2 'Moderate' suitability

In most cases (particularly for the categorical variables: Table A2.1), a suitability score of 0.5 is used to represent moderate suitability. The use of the 0.5 value in this way is based on Oldham *et al*. (2000), who represented 'moderate' suitability for crested newt populations in terms of a number of relevant habitat variables, by a SI value of approximately 0.5.

A2.5 Suitability Indices

The specific sources and rationale for determining the suitability indices for the P/NPBVCs for each of the key biophysical variables is provided in Sections A2.5.1.1 – A2.5.1.5. Information on the two management variables used to produce predictions of future P/NPBVC distributions are provided in Sections A2.5.2.1 – A2.5.2.2 Focus is given to Blanket Bog (and other PBVCs, where appropriate) to further demonstrate the methodology. The suitability indices for other P/NPBVCs are provided in Appendix 2b (Tables A2.13a - A2.14r and Figures A2.6a - A2.8a-j). The three continuous/pseudo-continuous biophysical variables (Table A2.1), as well as distance, are expressed quantitatively in graphical form. The two categorical biophysical variables (Table A2.1) and the management variable cross-suitability are expressed in tabular format.

A2.5.1 Biophysical Variables

A2.5.1.1 Soil Water

Adequate quantitative information relating to the soil water characteristics of the P/NPBVCs was not available from the various sources. The scheme used by Jarvis *et al*. (1984) classifies soils into six different 'wetness classes' (WC) according to their overall duration of water logging and therefore provides a useful indication of a soil's water availability and hydrological regime. Under the scheme, wetness class six refers to the most waterlogged soils and wetness class one relates to the least waterlogged soils (see: Table A2.9a in Appendix 2b for full details of the classification). Descriptions of the soil water characteristics for a number of relevant community types in JNCC (2007) and Tansley (1949) have a good general correspondence with the descriptions of Jarvis *et* *al's.* (1984) soil wetness classes. Furthermore, Jarvis *et al*. (1984) establish a link between wetness class and the occurrence of particular species, vegetation communities and land use types for soils within northern England. It was therefore possible to use this information to validate the information from JNCC (2007) and Tansley (1949).

A general issue in gauging the soil water characteristics of the P/NPBVCs was the reliance upon qualitative descriptions within the literature. Terms such as 'dry', 'damp', 'moist', 'wet' and 'waterlogged' are commonly used when describing the soil water conditions associated with particular community types. Sometimes they are used interchangeably. The use of these terms is subjective and using them to describe variations along what in reality is a continuous environmental gradient is problematic. However, they provided a way of gauging typical soil water characteristics of specific P/NPBVCs and therefore relative differences between them. In considering P/NPBVC suitability the terms were loosely ranked in the following order according to the overall water content that they describe: 'waterlogged', 'wet', 'damp/moist', 'dry'. The terms 'damp' and 'moist' are considered interchangeable.

The establishment of P/NPBVC suitability also relied on determining a correspondence between the soil water characteristics of the P/NPBVCs as determined by JNCC (2007) and Tansley (1949) and the WC descriptions offered by Jarvis *et al*. (1984). The vegetation and community descriptions for particular soil types provided by Jarvis *et al*. (1984) were useful in this regard.

'Wetland' and 'Terrestrial' P/NPBVCs

A useful distinction is made by JNCC (2007) Lane (1999), Furniss & Lane (1999) and Tansley (1949) between 'wetland' and 'terrestrial' community types. The distinction is also used here to broadly categorise the various P/NPBVCs. Table A2.2 describes the categorisation scheme and the rationale behind it.

Table A2.2: Generalised categorisation scheme of P/NPBVCs according to typical soil water characteristics.

Broad type	P/NPBVCs	Notes
Wetland	**Blanket Bog** **Raised Bog** **Fen** **Marsh** **Swamp** **Flush & Spring**	Although taxonomic and terminological differences are apparent between Tansley (1949), Furniss & Lane (1999), Lane (1999) and JNCC (2007) their general nomenclature and community descriptions make a strong case for regarding these P/NPBVCs as typically 'wetland' types. Modes of development differ, however all types may be rudimentarily defined as a broad range of plant communities which are associated with conditions transitional between those of aquatic/open water habitats (e.g. pools, ponds, lakes and streams) and those of terrestrial habitats (e.g. grasslands, woodlands and heaths). Specifically, their occurrence is primarily dependent on more or less permanently waterlogged or inundated conditions. For instance, JNCC (2007, pp. 56) describe 'mires' (i.e. Fen, Blanket Bog, Raised Bog and Flush & Spring) as having 'a water table at or just below the surface'. Marsh is described in similar terms (JNCC, 2007, pp. 53). Swamp is a type where the water level is typically above the surface for most of the year (JNCC, 2007, pp. 53 & 60). Tansley (1949, pp. 634 & 675) and Furniss & Lane (1999, pp. 8) provide much the same treatment.
Terrestrial	**Heath** **Broadleaved Woodland (BLW)** (Inc. BLW: Priority; BLW: Non-Priority; BLW: Recently Felled) **Acid Grassland** **Heath/Acid Grassland Mosaic** **Calcareous Grassland** **Modified Bog** **Arable** **Coniferous Woodland** (Inc. Coniferous Woodland and Coniferous Woodland: Recently Felled) **Improved Grassland: Non-Priority** **Bracken**	The categorisation of the majority of these P/NPBVCs as 'terrestrial' types is based on the nomenclature of Tansley (1949), Furniss & Lane (1999), Lane (1999) and JNCC (2007). In the general taxonomy of these sources all of the P/NPBVCs are treated separately to the 'wetland' types listed above. Heaths are generally regarded as occurring on well-drained soils (Tansley, 1949, pp. 724; Lane, 1999, pp. 8; JNCC, 2007, pp. 55). Acid grasslands tend to occur on soils which are either 'well-drained' or of 'medium' dampness. (Tansley, 1949, pp. 494). This definition excludes *Molinia* grasslands, which are included in the 'Marsh/marshy grassland' habitat category according to JNCC (2007, pp. 52, 53) nomenclature and are therefore included under the Marsh PBVC (Table 4.1). BLW is included as a terrestrial type as descriptions by Grime *et al*. (1988) and Fitter & Peat (1994), for some of the more water-tolerant of the broadleaved species considered in the analysis, e.g. *Alnus glutinosa* (Table A2.11), suggest that they have only a moderate tolerance for waterlogged soils. The inclusion of Calcareous Grassland is based on Tansley (1949, pp. 495; Lane, 1999, pp. 32). Coniferous Woodland is included based on Fitter & Peat's (1994) data for *P. sylvestris*. The inclusion of Arable is based on information from Jarvis *et al*. (1984). The inclusion of Modified Bog is based on JNCC (2007, pp. 57); Bracken is included based on the data for *Pteridium aquilinum* from Grime *et al*. (1988). Improved Grassland: Non-Priority is essentially amenity grasslands (JNCC, 2007, pp. 66; e.g. golf courses) and is therefore unlikely to be associated with high soil water content.
Broad	**Neutral Grassland: Priority** **Improved Grassland: Priority** **Neutral Grassland: Non-Priority**	These P/NPBVCs are those whose occurrence may be associated with more or less dry to permanently waterlogged soils. The inclusion of Neutral Grassland (Priority and Non-Priority) is based on descriptions by JNCC (2007, pp. 52). The inclusion of Improved Grassland: Priority is based on JNCC (2011), who state that improved grasslands encompass floodplain grazing marsh which is defined as 'periodically inundated pasture, or meadow with ditches which maintain the water levels, containing standing ... fresh water....Sites may contain seasonal water-filled hollows and permanent ponds'.

The categorisation presented in Table A2.2 is somewhat problematic, as it suggests that sharp boundaries exist between these types which do not necessarily occur in the natural world (Begon *et al*., 1990; Tansley, 1949). Indeed this is a general issue when dealing with any system which seeks to define ecological units in terms of environmental tolerances above the species level of ecological organisation (Begon *et al*., 1990; Tansley, 1949). The investigation and subsequent establishment of suitability in terms of soil water characteristics in relation to Blanket Bog and Heath provides a useful exemplar.

Both PBVCs demonstrate vegetative similarities. Heath is typically characterised by an abundance of dwarf shrub species such as *Calluna vulgaris*, *Erica cinerea* and *E. tetralix*. However, such species are also recorded as constituents of blanket bog communities (as well as those of other 'mire' habitats). Similarly, mosses (particularly *Sphagna*: e.g. *Sphagnum papillosum*) form the typical vegetation of blanket bogs. However, this vegetation is also common within heath communities (particularly 'wet heaths'. See: JNCC, 2007, pp. 55).

The taxonomy within the literature also demonstrates the problems in delineating sharp definitional boundaries between bog and heath, particularly in terms of their soil water characteristics. For instance, in Rodwell *et al*.'s (1991a) nomenclature, NVC communities M15 ('*Scirpus cespitosus – Erica tetralix* wet heath') and M16 ('*Ericetum tetralicis* wet heath') are both treated as particular types of mire. Under JNCC (2007) nomenclature, M15 is treated as representative of blanket bog, wet modified bog, wet dwarf shrub heath and wet heath/acid grassland! Descriptions in the literature add to the uncertainty. For instance, Tansley (1949) and Furniss & Lane (1999) also commonly refer to the soils associated with bog communities as 'permanently wet' as well as 'waterlogged'. This contrasts to the description of the soil water characteristics of blanket bog (and other 'wetland' community types) offered by JNCC (2007) (Table A2.2). Tansley (1949, pp. 734) also suggests that 'wet heath communities' typically occur on constantly 'wet' *or* 'waterlogged' areas within a heath and have a 'great deal in common' with 'valley bog' communities.

Clearly then bog and heath communities are very closely affiliated. They often naturally occur in mosaic with a subtle gradation of one type to another along a continuous soil water gradient (JNCC, 2007; Lane, 1999, Furniss & Lane, 1999; Tansley, 1949). Considering these points, any attempt to determine differences between them in terms of their soil water characteristics is undoubtedly problematic, particularly considering the broad nature of the soil water categories (Table A2.9a). However, the treatment from the various sources is sufficient to conclude that meaningful differences between such communities do exist. For instance, despite the vegetative similarities, a transition from blanket bog to heath is marked by a notable increase in the abundance of dwarf shrubs and concomitant decrease in the proportion of *Sphagna* (JNCC, 2007;

Tansley, 1949). This is related to significant physiological differences between the species (Rodwell *et al*. 1991a; Tansley, 1949). Also, Jarvis *et al*. (1984) suggest that *E. Tetralix*, a species indicative of wet heath communities, only occurs abundantly on the drier types of WC 6 soils.

In assigning suitability scores, an effort was made to represent the typical soil water characteristics of the P/NPBVCs, whilst also taking some account of the apparent variations associated with the community types. However, the characteristics of the WC categories, the reliance on qualitative descriptions from a number of sources and the close association between 'wetland' and some 'terrestrial' community types means that the representations of the soil water characteristics for the P/NPBVCs are likely to be somewhat oversimplified. Nevertheless, for the purposes of modelling, distinctions had to be made.

The SI values representing P/NPBVC suitability in terms of soil water follow a subjective scale and are defined as: 1 = optimum suitability; 0.5 = moderate suitability; 0 = unsuitable. Table A2.3 presents the soil water suitability index for Blanket Bog and the rationale underpinning it. The soil water suitability indices for other P/NPBVCs are available in Appendix 2b (Tables: A2.13a-r).

Table A2.3: Soil water suitability index for Blanket Bog.

WC	SI value	Derivation of SI value
6	1	The description of WC6 (Table A2.9a) suggests that it encompasses some soils whose surface is likely to experience some drying. However, it is assumed that the majority will be more or less permanently waterlogged. Such conditions are deemed optimal for Blanket Bog. Some validation of this is provided by Jarvis *et al*. (1984), who describe characteristic bog vegetation (e.g. *Sphagna*) occurring abundantly on WC 6 soils.
5	0.5	WC 5 encompasses soil types whose surface may be more or less waterlogged approximately all year. However, the category also includes types that maybe more or less dry for approximately half of the year. As such, Blanket Bog suitability for WC 5 soils is likely to range from about 0-1 depending on the specific type. To account for this, WC 5 is regarded as representing moderately suitable conditions for Blanket Bog. Some validation of this is provided by Jarvis *et al*. (1984), who suggest that characteristic Blanket Bog vegetation occurs abundantly on the wetter types of WC 5 soils.
4	0	WC 4 refers to soil types whose surface is potentially waterlogged for less than half the year. Such conditions are deemed to be too dry for blanket bog communities. Vegetation descriptions from Jarvis *et al*. (1984) for WC 4 soils validate this assumption. WCs 1-3 refer to even drier soil types. WCs 1-4 are therefore deemed unsuitable for Blanket Bog.
3		
2		
1		

A2.5.1.2 Soil type

Suitability scoring in terms of soil type was made in terms of the following basic types: Thin peat (peat depth <0.5m); Deep peat (>0.5m) and Non-peat. These categories follow relevant JNCC (2007) criteria (see: Section A2.3.3). The SI values used to represent P/NPBVC suitability in terms of soil type are defined as follows: 1 = optimum suitability; 0.5 = moderate suitability; 0 =

unsuitable. Table A2.4 presents the suitability index for Blanket Bog. The suitability indices for other P/NPBVCs are available in Appendix 2b (Tables: A2.14a-r).

Table A2.4: Soil type suitability index for Blanket Bog.

Soil type	SI value	Derivation of SI value
Deep peat	1	Blanket bogs typically occur on 'deep peat (over 0.5m thick)' (JNCC, 2007, pp. 56)
Thin peat	0.5	The occurrence of thin peat is likely to be generally indicative of conditions unsuitable for blanket bog communities. However, there is no agreed minimum peat depth supporting blanket bog vegetation (JNCC, 2011). The JNCC threshold is defined arbitrarily (JNCC, 2007, pp. 55). It is likely that some occurrences of peat with a depth less than 0.5m are able to support the development of blanket bog communities. Thin peat soils are therefore regarded as moderately suitable for Blanket Bog
Non-peat	0	Peat will always tend to develop under water logged conditions. The absence of peat in a soil is likely to be indicative of conditions entirely unsuitable for the occurrence of blanket bog communities. Non-peat soils are regarded as unsuitable for Blanket Bog.

A2.5.1.3 Soil pH

The pH range of most soils in the UK is 3 – 8 (NSRI, 2011; 2002; Grime *et al*. 1988). The horizontal axis of the soil pH graphs is formatted to include this range.

JNCC (2007) provides useful information on the soil pH typically associated with a number of grassland P/NPBVCs on which to base optimum thresholds. For instance, a pH of about 5.4 represents the upper limit of optimum tolerance for acid Grasslands (JNCC, 2007). Other quantitative values provided by JNCC (2007) of optimum soil pH requirements are: neutral grasslands (pH 5.5 – 7.0) and calcareous grasslands (pH >7.0).

JNCC (2007) provides no quantitative (and in some cases no qualitative) information for some relevant P/NPBVCs in relation to their optimum soil pH requirements. An important aim when determining P/NPBVC suitability was to maintain consistency with the information provided in the two main sources as far as possible, particularly the JNCC (2007) system. Furthermore, quantitative information in relation to soil pH for a number of relevant NVC community types is not available from Rodwell *et al*. (1991a; 1991b; 1992). The approach taken was to use Tansley (1949) and JNCC (2007) to establish a reasonable correspondence in terms of optimum soil pH requirements between particular community types and then use the quantitative information provided by JNCC (2007) to assign optimum P/NPBVC thresholds accordingly.

Using this approach, P/NPBVCs were grouped into four basic types: 'acidic'; 'neutral'; 'calcareous' and 'broad'. Table A2.5 provides details on these groupings and the underlying rationale.

Specific information was not available from Tansley (1949) and JNCC (2007) on which to base sub-optimum thresholds. The approach adopted was to use the general descriptions from the main sources and establish a reasonable correspondence between the quantitative thresholds delimiting categories of pH from the scheme used by Jarvis *et al*. (1984; see: Table A2.9b).

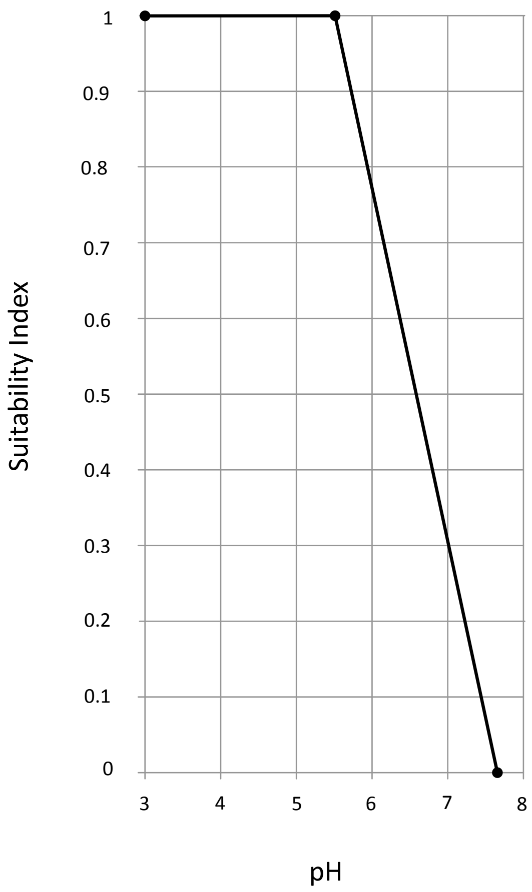
The general approach adopted here may represent an oversimplification of ecological reality. Rodwell *et al*.'s (1991a; 1991b; 1992) data (where available) suggest some variation between the pH tolerances for particular NVC community types and those defined within this research for some of the 'acidic' P/NPBVCs (See: Table A2.5). However, their data, as well as that of Fitter & Peat (1994) for indicator species associated with specific P/NPBVCs (Table A2.11), also demonstrates a good general correspondence with the thresholds employed. It is therefore felt that the applied approach represents a useful representation of the biophysical interactions occurring within the natural world.

The soil pH suitability indices for Blanket Bog, Heath and Raised Bog are presented in Figure A2.2. The written annotations accompanying the figure detail the rationale behind their formulation, the thresholds applied and relevant sources used. The soil pH suitability indices for other P/NPBVCs are available in Appendix 2b (Figures A2.6a-g).

Table A2.5: Generalised categorisation scheme of P/NPBVCs according to typical soil pH tolerances.

pH Type	Optimum pH range	P/NPBVCs	Notes
Acidic	<5.5	**Heath** **Blanket Bog** **Acid Grassland** **Raised Bog** **Heath/Acid Grassland Mosaic** **Modified Bog**	Acid grasslands, heaths and bogs represent the typical communities of upland moors where conditions tend to favour the development of acidic soils (Lane, 1999; Tansley, 1949). This suggests a broad similarity in terms of pH requirements. JNCC (2007) suggest a very close similarity between the soil pH of Acid Grassland and Heath. The upper optimum pH tolerance for Acid Grassland is 5.4 (JNCC, 2007). Rodwell *et al*. (1991a, pp. 432 & 210) suggest a slightly higher upper optimum threshold of 5.8 for typical heath NVC community types and 4.7 for some types associated with Raised Bog and Blanket Bog. Because of these general similarities the upper optimum thresholds for Blanket Bog, Heath, Acid Grassland and Raised Bog were all defined as 5.4. An upper optimum threshold of 5.4 is also assigned for Heath/Acid Grassland Mosaic and Modified Bog due to their obvious associations with the relevant P/NPBVCs referred to above.
		Bracken **Coniferous Woodland**	The upper optimum pH tolerance of Bracken (*P. aquilinum*) was investigated using data from Grime *et al*. (1988). They suggest an upper optimum pH of 5. However, their data do not account for variations on a continuous pH scale. The pH tolerance of Coniferous Woodland was investigated using Scots pine (*P. sylvestris*)) (Table A2.11). Fitter & Peat (1994) provide an Ellenberg indicator value of 2 for the species in relation to soil pH, suggesting that it is indicative of acidic conditions. Because of these points, the upper optimum pH threshold of 5.4 used for other acidic P/NPBVCs was regarded as suitable for Bracken and Coniferous Woodland.
Neutral	5.5 – 7.0	**Neutral Grassland: Priority** **Improved Grassland: Priority** **Neutral Grassland: Non-Priority** **Improved Grassland: Non-Priority** **Arable**	Neutral grasslands encompass a wide range of grassland communities occurring on soil with a pH range of 5.5 - 7.0 (JNCC, 2007, pp. 52). No information is provided by JNCC (2007) on the pH tolerances of improved grasslands. Improved grasslands are a particular type of neutral grassland which has been subject to such intensive management that agricultural species such as *Lolium perenne* and *Trofolium repens* dominate (Tansley, 1949). The treatment by JNCC (2007) is similar. Arable is included here as a 'neutral' type; however, optimum pH for this NPBVC was based on DEFRA (2010), due to its more specific pH requirements.
Basic	>7.0	**Calcareous Grassland**	Calcareous grasslands are typically associated with a soil pH over 7.0 (JNCC, 2007, pp. 52)
Broad	3 – 8	**Broadleaved Woodland (BLW)**	Adequate information was not available from Tansley (1949) and JNCC (2007) on the pH requirements of broadleaved woodlands. Grime *et al*. (1988) suggest an overall optimum soil pH tolerance range of 3 – 8 for the broadleaved species considered in the analysis (Table A2.11).
		Fen **Marsh** **Swamp** **Flush & Spring**	Tansley (1949) suggests that the soil pH associated with Fen, Marsh, Swamp and Flush & Spring is largely determined by the nature of the surrounding geology and therefore may include acidic, neutral and basic types. JNCC (2007) define acidic *and* basic types of Fen and Flush & Spring. The optimum pH range for these P/NPBVCs is therefore assumed to be 3 – 8.

Figure A2.2: Soil pH suitability index for 'acidic' priority BVCs: Blanket Bog, Raised Bog and Heath.



Optima: (SI = 1)
Lower = 3
Upper = 5.4

Source(s) and rationale: Table A2.5 describes the rationale for determining the upper optimum limit of the 'acidic' BVCs.

Adequate information to establish lower optimum thresholds for Blanket Bog, Raised Bog and Heath was not available from JNCC (2007) and Tansley (1949). Rodwell *et al*. (1991a, pp. 217) suggests a lower optimum limit of 3.1 in relation to some Blanket and Raised Bog communities (A2.10 a & b). Information on soil pH associations for a number of heath communities is lacking from Rodwell *et al*. (1991a) (Table 2.10a). Species commonly associated with Heath (e.g. *C. vulgaris, E. cinerea*) (Table: A2.11) occur more or less abundantly on strongly acidic soils (Fitter & Peat, 1994), suggesting Heath has very similar lower optimum pH requirements to Blanket and Raised Bog. This is partially confirmed by the classification of strongly acidic soils from Jarvis *et al*. (1984) (Table A2.9b) and the lower limit of such soils used by NSRI (2002). For simplicity the lower optimum pH limit for all of the acidic priority BVCs is defined as 3.0.

Absolute maxima = 7.6 (SI = 0)

Source(s) and rationale: Jarvis *et al*. (1984) define an upper threshold of 7.5 for 'neutral' soils. The absolute maximum threshold used for the acidic priority BVCs is defined as 7.6 returning a SI value of 0.1 for a pH of 7.5. This limit may seem questionable considering the acidophilic characteristics of the communities. However, the communities appear to be generally tolerant of more or less neutral conditions. For instance, Rodwell *et al*. (1991a, pp. 155 & 181) suggest an absolute maximum threshold of 7.4 for Heath and 6.7 for Blanket and Raised Bog, respectively. The absolute maximum of 7.6 therefore is also regarded as broadly appropriate for all of the acidic priority BVCs (also see: Figure A2.6c).

A2.5.1.4 Elevation

The horizontal axis of the elevation graphs is formatted to encompass elevations of 0 – 900m to incorporate the highest areas of NNP (815m).

Upland and lowland P/NPBVCs

It is common within the literature to refer to communities as either 'upland' or 'lowland' types. The distinction is linked to how complex interactions in factors such as altitude, climate, soils and human management influence vegetation patterns (Tansley, 1949). It was possible to use qualitative descriptions from Tansley (1949) and JNCC (2007) to classify the P/NPBVCs into 'upland' and 'lowland' types to partially determine optimum thresholds.

Typically 'upland' is defined as any area above the upper limit of agricultural enclosure (JNCC, 2011). This limit varies within the UK. Definitions of what constitutes an upland area in terms of elevation therefore also vary. This research utilises 300m as the lower limit of upland areas. The threshold is largely defined arbitrarily but has good general agreement with elevational thresholds used by JNCC (2011) and others (e.g. Thompson *et al*., 1995).

Table A2.6 provides details of the P/NPBVCs regarded as either ‘upland’ or ‘lowland’ for the purposes of this research and the rationale behind the distinction.

Table A2.6: Generalised categorisation scheme of P/NPBVCs as 'upland' and 'lowland' types.

Type	P/NPBVCs	Notes
Upland (Lower optimum: 300m)	**Blanket Bog**	Blanket bog is described as an 'upland' community type by JNCC (2007). This association is largely due to the prevailing climate (e.g. increased precipitation and decreased temperatures) and relatively low levels of human management/disturbance at higher elevations which generally create conditions favourable to its occurrence (Tansley, 1949).
	Heath	Heath is included here as an upland type in part because it depends on broadly similar climatic conditions to blanket bog, particularly in terms of its requirement for moist air (Tansley, 1949, pp. 200). Also heaths tend to occur most abundantly above the limit of agricultural enclosure (Tansley, 1949, pp. 763).
	Acid Grassland	Acid grassland primarily occurs on 'unenclosed...land' (JNCC, 2007, pp. 52) and is most common above 300m (Tansley, 1949, pp 499).
	Heath/Acid Grassland Mosaic	Heath/Acid Grassland Mosaic simply relates to a specific mixture of Heath and Acid Grassland. Altitudinal associations are therefore regarded as the same.
	Bracken	The inclusion of Bracken is based on Grime *et al*. (1988, pp. 468), who state that 'suitable habitats are more frequent and abundant in upland areas'.
	Modified Bog	Modified Bog is also included as an upland type for suitability modelling. However, elevation characteristics of Raised Bog (see below) as well as the tendency for more intensive management to occur at lower elevations mean the assumption is potentially spurious.
Lowland (Upper optimum: 300m)	**Raised Bog**	Raised bogs are typically associated with 'levels areas with impeded drainage in the lowlands...' (JNCC, 2007, pp. 57). Although raised bogs may also occur at moderate elevations, they tend to be most closely associated with lowland areas (JNCC, 2011). Raised Bog is therefore included here as a lowland type.
	Neutral Grassland: Priority	Neutral grasslands typically occur on enclosed land (JNCC, 2007, pp. 52; Tansley, 1949, pp. 559). The association with lowland areas is largely due to the tendency for more productive soils to occur at lower elevations and the associated influence of human management. Improved grasslands are a particular type of neutral grassland (Table A2.5). Both neutral and improved grasslands are regarded as essentially lowland types. Improved Grassland: Non-Priority mainly comprises amenity grasslands such as parks and golf courses (JNCC, 2007) and is therefore likely to be restricted to very low elevations to facilitate access. This is partially confirmed by the descriptive statistics (Table A2.12), which show a maximum recorded occurrence for this NPBVC of 275m within NNP. Parameterisation of the suitability index for Improved Grassland: Non-Priority is based entirely on the descriptive statistics.
	Improved Grassland: Priority	
	Neutral Grassland: Non-Priority	
	Improved Grassland: Non-Priority	
	Broadleaved Woodland (BLW)	Tansley (1949) essentially treats broadleaved woodlands as a lowland type. Grime *et al.'s* (1988) data also show that all of the tree species considered in the analysis of BLW suitability (Table A2.11) occur most abundantly below 300m within the UK.
	Fen	Swamp, Fen, Marsh and Flush & Spring have a close association with water courses (JNCC, 2007, pp. 56; Tansley, 1949, pp. 634). This suggests some proclivity for lowland locales. This is somewhat validated by the descriptive statistics for NNP, which describe mean altitudinal occurrences of 224m, 237m, 260m and 334m for Swamp, Fen, Marsh, Flush & Spring respectively (Table A2.12).
	Marsh	
	Swamp	
	Flush & Spring	
	Calcareous Grassland	Due to the lack of adequate information from most of the sources for Calcareous Grassland, it is classed as a lowland type based on Fitter & Peat's (1994) information regarding the typical minimum occurrence of a number of species associated with the NPBVC, e.g. *S. Minor*, *H. Nummularium*, *K. Macrantha* (Table A2.11).
	Arable	Arable is included as a lowland type because of its association with productive soils and human management. However, parameterisation of the suitability index for Arable is based entirely on information from Leeds University (no date).
	Coniferous Woodland	Tansley (1949) suggests that *P. sylvestris* has very similar requirements to the birches (*B. pendula* and *B. pubescens*). Grime *et al.'s* (1988) data suggest these species occur most abundantly below 300m.

Optimum thresholds

300m was used as the lower optimum threshold for all of the 'upland' P/NPBVCs (Table A2.6). With the exception of Improved Grassland: Non-Priority and Arable (Table A2.6), 300m was used as the upper optimum threshold for the 'lowland' P/NPBVCs. The lower optimum threshold for all of the 'lowland' P/NPBVCs was assigned as 0m.

Information from the main secondary sources (JNCC, 2007; Tansley, 1949) was used where possible to determine upper optimum thresholds for the upland P/NPBVCs. However the lack of quantitative information from these sources proved problematic. Quantitative information from Rodwell *et al*. (1991a) and Grime *et al*. (1988) was used where available, as well as the descriptive statistics for NNP (Table A2.12) where appropriate.

Absolute maximum thresholds

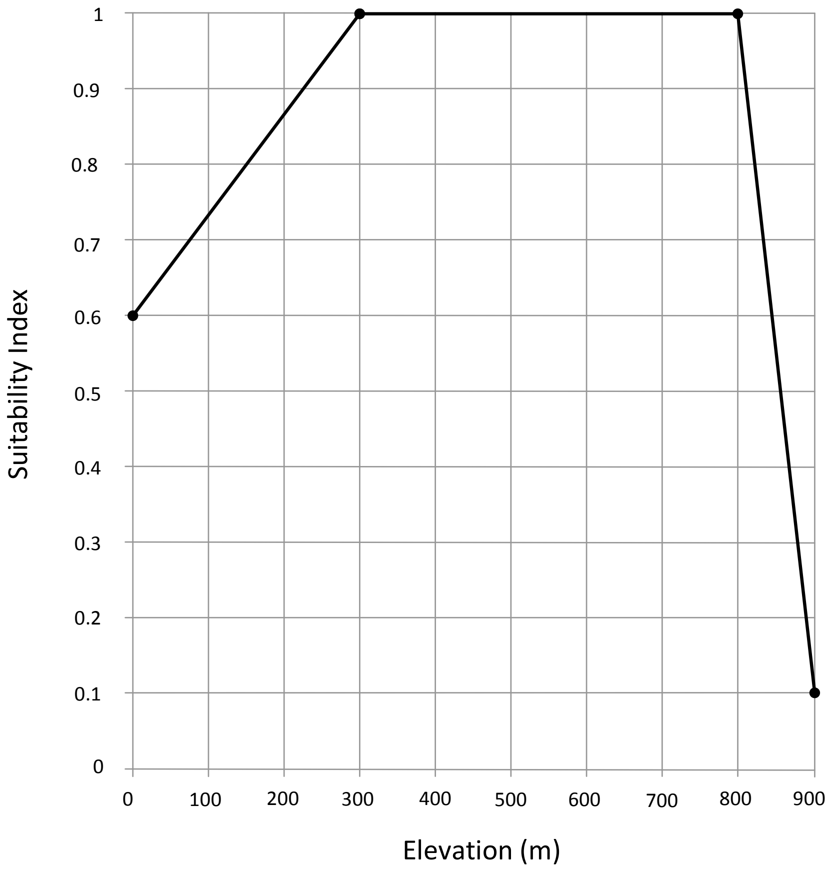
With the exception of Bracken (Figure A2.7g), the absolute maximum threshold for the upland P/NPBVCs was assigned as 900m (see: Figures A2.3 & A2.7e). Absolute maximum thresholds for the 'lowland' P/NPBVCs (with the exception of Arable) are based on their maximum recorded elevational occurrences from the descriptive statistics for NNP (Table: A2.12), due to the lack of relevant quantitative information from the various secondary sources.

Absolute minimum thresholds

All of the upland P/NPBVC types are most suited to conditions (e.g. low temperatures, high precipitation, low soil pH) typically found at higher elevations in the UK. However, this does not preclude their occurrence at lower elevations. For instance, although the typical climate in low-lying areas of the UK tends to be less favourable for blanket bog communities, extents can and do occur abundantly at lower elevations under appropriate conditions (Furniss & Lane, 1999; Rodwell *et al*., 1991a; Tansley, 1949). Rodwell *et al*. (1991a, pp. 55) associate a mean elevation of about 70m with a limited number of Blanket Bog extents in the north-eastern UK, suggesting a relatively low absolute minimum altitudinal tolerance for these communities within the region. In light of this information, an SI value of 0.6 is assigned for elevations of 0m. The value is largely conjectural but has good general agreement with the value used by Oldham *et al*. (2000, pp. 154) to represent 'moderate' suitability for occurrences of amphibian populations in terms of water quality. The SI value of 0.6 is also used to represent suitability at elevations of 0m for the other 'upland' P/NPBVCs (Figures A2.3 and A2.7 e & g). The suitability index between 0 – 300m is interpolated linearly. No absolute minimum thresholds are associated with the lowland P/NPBVCs (see above).

The elevation suitability indices Blanket Bog and Heath are presented in Figure A2.3. Elevation suitability indices for other P/NPBVCs are available in Appendix 2b (Figures: A2.7a-l).

Figure A2.3: Elevation suitability index for the 'upland' PBVCs: Blanket Bog and Heath



Optima: (SI)

Lower = 300
Source(s) and rationale: See Section A2.5.1.4 (main text) and Table A2.6.

Upper = 800
Source(s) and rationale: Rodwell *et al*. (1991a, pp. 210 & 563) suggest a mean elevational occurrence of approximately 800m for some blanket bog and heath occurrences in the north and north eastern UK.

Absolute minima = -450* (SI = 0)
Source(s) and rationale:
Blanket Bog: See Section A2.5.1.4 (main text).
Heath: Rodwell *et al*. (1991a, pp. 155, 481, 503) suggest an absolute minimum occurrence of about 10-80m for heath in northern areas of the UK. However, a number of species commonly associated with Heath, e.g. *C. vulgaris, E. cinerea, E. tetralix* (Table A2.11) occur frequently at 0m (Fitter & Peat, 1994). Because of these ambiguities the SI of 0.6 for elevations of 0m is also regarded as appropriate for Heath.

Absolute maxima = 920* (SI = 0)

Source(s):
Blanket Bog: Rodwell *et al*. (1991a, pp. 57, 181, 209, 217)
Heath: Rodwell *et al*. (1991a, pp. 481, 502, 554).

Rationale: Rodwell *et al*. (1991a, see above) suggest a maximum occurrence of about 800-1000m for a number of bog and heath communities in northern and north-eastern areas of the UK. Many occur at approximately 900m. 900m is therefore regarded as a reasonable threshold representing marginal suitability for Blanket Bog and Heath (SI = 0.1). The threshold also generally corresponds to the lower limit of the 'alpine zone' (Tansley, 1949, pp. 781,784, 787) and is an important constraint influencing the occurrence of upland community types at high elevations (Brown et al., 1993). The suitability index between 800 – 900m is interpolated linearly.

* Linear interpolation, within *IDRISI Taiga's* FSMF module, was used in the spatial application of the suitability indices (see: Section A2.2.1 in Appendix 2b). Because of these methods -450m and 920m were assigned, respectively, as the absolute minimum and maximum thresholds for the upland priority BVCs. This was done in order to assign appropriate SI values for elevations of 0m and 900m. Specifically, to ensure a SI value of 0.6 was assigned for elevations of 0m it was necessary to use -450m as the value for control point 'a', within the FSMF module. Similarly, to ensure a SI value of 0.1 was assigned for elevations of 900m, 920m was used as the value for control point 'd'.

A2.5.1.5 Slope

The horizontal axis of the slope graphs is formatted to encompass slopes of 0 – 50^o in order to incorporate the steepest slopes within NNP (46^o).

Wherever possible, qualitative descriptions from the main secondary sources (JNCC, 2007; Tansley, 1949) were used to determine the optimum slope characteristics of the P/NPBVCs. These descriptions were then corresponded with quantitative thresholds delimiting categories of slope angle in the classification scheme used by Jarvis *et al*. (1984) (Table A2.9c).

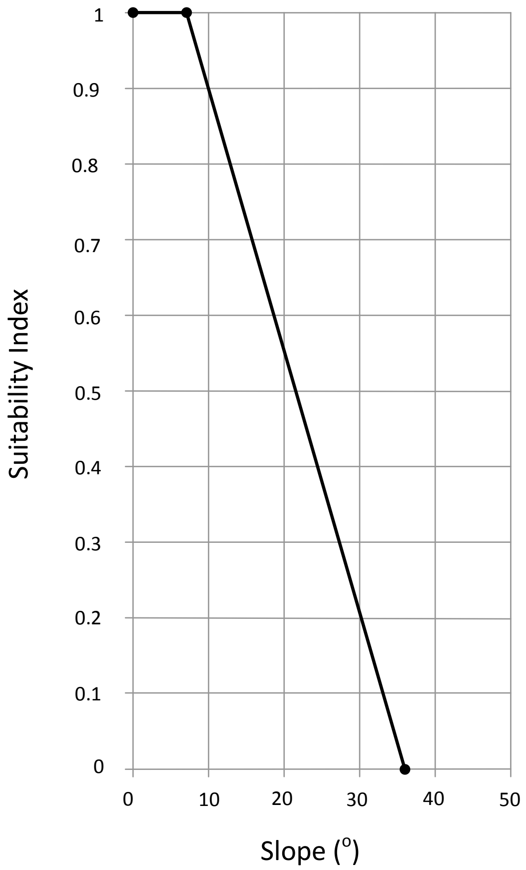
In some instances this was not possible. Some interpretation of the typical habitat and landform characteristics of particular P/NPBVCs was necessary in order to determine a correspondence between the qualitative information from the main sources with the category descriptions from Jarvis *et al*. (1984). Typical associations with human management were also used for some P/NPBVCs in the same way. For instance, Neutral and Improved Grasslands (Priority and Non-Priority) and Arable are associated with more intensive agricultural management than many other P/NPBVCs (JNCC, 2007; Tansley, 1949). In determining their optimum slope thresholds, the British Land Capability Classification (BLCC) system was also used. This system uses slope, along with other factors, to assess land according to its capacity for agricultural production (Leeds University, no date). The slope categorisation scheme used within the system closely corresponds to that of Jarvis *et al*. (1984).

Descriptive statistics (Table A2.12) were also used to assign absolute maximum and minimum thresholds for some P/NPBVCs.

The 0-50^o slope range was deemed to be unimportant in influencing suitability for Heath, Acid Grassland, Broadleaved Woodland: Priority and Non-priority and Coniferous Woodland. This was based on general qualitative descriptions from Tansley (1949), as well as quantitative data from Grime *et al*. (1988) in relation to particular species indicative of these community types (Table A2.11).

The suitability index for Blanket Bog is presented in Figure A2.4. The slope suitability indices for other P/NPBVCs are available in Appendix 2b (Figures: A2.8a-j).

Figure A2.4: Slope suitability index for Blanket Bog



Optima: (SI = 1)
Lower = 0
Upper = 7

Source(s) and rationale: Blanket Bog is typically associated with 'level to moderately sloping ground' (JNCC, 2007, pp. 56). 7° represents the upper limit of moderate slopes according to Jarvis *et al*. (1984) (Table A2.9c).

Absolute maxima = 36 (SI = 0)

Source(s) and rationale: Blanket bogs may occur on relatively steep slopes in areas with a sufficiently moist climate. The descriptive statistics for NNP (Table A2.12) suggest that the maximum recorded gradient associated with Blanket Bog is 33°. The absolute maximum threshold assigned for Blanket Bog within the suitability index is therefore 36° so that an SI value of 0.1 is returned for slopes of 33°. The suitability index between 7° and 36° is interpolated linearly.

A2.5.2 Management Variables

A2.5.2.1 Cross-Suitability

It is possible to establish the suitability of an area of land for a particular P/NPBVC type based on the characteristics of the existing P/NPBVC comprising that area (Griffiths *et al*. 2011) and the human management actions that would be required in order for conversion to occur. Information on the key physical characteristics of the P/NPBVCs, the vegetation typically associated with them and the human management actions associated with their occurrence were therefore used to consider the potential for conversion from an existing P/NPBVC type to each of the P/NPBVCs undergoing expansion under each of the scenarios. The scoring of cross-suitability is flexible and may be easily adapted and applied to reflect changed circumstances, particularly different socio-economic contexts (Griffiths *et al*. 2011).

The highest suitability score (1) is assigned where conversion may occur naturally through the process of succession or through minimal human action. Minimal human action in this context assumes that no modification of the P/NPBVC patch is required prior to conversion. For instance, conversion from Acid Grassland to Broadleaved Woodland: Priority may require afforestation. However, no human action is necessary before trees could be planted. The second highest suitability score (0.67) is assigned when some modification is required to facilitate conversion, e.g. the raising soil pH to facilitate conversion from Acid Grassland to Neutral Grassland: Priority. The third highest suitability score (0.33) is assigned where more elaborate modifications of the environment are required, e.g. the raising of soil pH and ploughing required for conversion from Acid Grassland to Arable. The lowest suitability score (0) is used where the conversion from one P/NPBVC type to another is regarded as inappropriate, e.g. due to the characteristics of the Conservation First scenario, conversion from one PBVC type to another as deemed inappropriate. Similarly, existing patches of a type undergoing expansion under a particular scenario were regarded as unsuitable for conversion to other types also undergoing expansion under that scenario. For instance, the conversion of existing patches of Heath to Broadleaved Woodland: Priority (and vice versa) are regarded as inappropriate under both scenarios.

The scoring of cross-suitability also allowed P/NPBVC suitability indices to be based on the particular characteristics of each of the scenarios. For instance, the additional information regarding UKBAP expansion targets relevant to Blanket Bog (i.e. T2 & T3: DEFRA, 2013c) suggest that they will be partially met through restoration of Modified Bog under Conservation First. Therefore, although some management (i.e. 'rewetting') is likely to be required, Modified Bog is regarded as highly suitable (1) for conversion to Blanket Bog, due to the prevailing socio-economic conditions and conservation policy under the scenario.

Due to the thematic resolution of some of the P/NPBVCs and the P1HS categories from which they are derived, it was necessary to make some assumptions in order to assign suitability scores. For instance, 'Neutral Grassland: Non-Priority' can include dry, wet and permanently waterlogged types (JNCC, 2007). It is not possible to distinguish between these different types from the P1HS nomenclature. Although the Heath PBVC encompasses both wet and dry types, it is a general assumption of this research (supported by the literature) that wet heaths have a lower tolerance for permanently waterlogged soils (Table A2.2). In determining the suitability score for the P/NPBVCs, it was assumed that extents of Neutral Grassland: Non-Priority within NNP are drier types. This is because visual analysis of existing extents of Neutral Grassland: Non-Priority with the soil water data for NNP showed that the majority of patches occurred on soils with a water class of 1-5. The vast majority of Neutral Grassland: Non-Priority patches within the park would not require drainage for conversion to Heath.

Tables A2.7a and A2.7b provide details of the cross-suitability scores for those target P/NPBVCs undergoing expansion under Conservation First and Going for Growth, respectively. Details of the alphabetic superscripts in Tables A2.7a&b refer to Table A2.7c, which provides information on the potential for conversion from each of the existing P/NPBVC types to each of the target P/NPBVCs undergoing expansion under the scenarios.

Table A2.7a: Cross-suitability scoring for target P/NPBVCs under Conservation First

Existing P/NPBVC	Target P/NPBVC						
	Broadleaved Woodland: Priority	Heath	Blanket Bog	Raised Bog	Neutral Grassland: Priority	Fen	Improved Grassland: Priority
Bracken	0.67[a]	0.67[a]	0.67[b]	0.67[b]	0.33[a, c]	0.67[b]	0.33[a, c]
Heath	0	0	0	0	0	0	0
Improved Grassland (IG): Priority	0	0	0	0	0	0	0
Acid Grassland	1[d]	1[d]	0.67[b]	0.67[b]	0.67[c]	0.67[b]	0.67[c]
Neutral Grassland (NG): Priority	0	0	0	0	0	0	0
Fen	0	0	0	0	0	0	0
Blanket Bog	0	0	0	0	0	0	0
Broadleaved Woodland (BLW): Non-Priority	0	0	0	0	0	0	0
Coniferous Woodland (CW)	0	0	0	0	0	0	0
Arable	1[d]	1[d]	0.67[b]	0.67[b]	0.67[c]	0.67[b]	0.67[c]
Other	0	0	0	0	0	0	0
Calcareous Grassland	1[d]	0.67[e]	0.33[b,e]	0.33[b,e]	0.67[e]	0.67[b]	0.67[e]
BLW: Priority	0	0	0	0	0	0	0
BLW: Felled woodland	1[d, g]	1[d]	0.67[b]	0.67[b]	0.67[c]	0.67[b]	0.67[c]
Modified Bog	1[d]	1[d]	1[g]	1[g]	0.33[a, c]	0.67[b]	0.33[a, c]
Heath/Acid Grassland Mosaic	1[d]	1[d, g]	0.67[b]	0.67[b]	0.33[a, c]	0.67[b]	0.33[a, c]
IG: Non-Priority	1[d]	1[d]	0.67[b]	0.67[b]	0.67[c]	0.67[b]	0.67[c]
NG: Non-Priority	1[d]	1[d]	0.67[b]	0.67[b]	1[g]	0.67[b]	0.67[c]
CW: Recently Felled	1[d, g]	1[d]	0.67[b]	0.67[b]	0.67[c]	0.67[b]	0.67[c]
Flush & Spring	0	0	0	0	0	0	0
Marsh	0	0	0	0	0	0	0
Swamp	0	0	0	0	0	0	0
Raised Bog	0	0	0	0	0	0	0

Table A2.7b: Cross-suitability scoring for target P/NPBVCs under Going for Growth

Existing P/NPBVC	Target P/NPBVCs			
	Heath	Coniferous Woodland	Broadleaved Woodland (BLW): Priority	Arable
Bracken	0.67[a]	0.67[a]	0.67[a]	0.33[c,f]
Heath	0	0	0	0
IG: Priority	1[d]	1[d]	1[d]	1[g]
Acid Grassland	1[d]	1[d]	1[d]	0.33[c,f]
NG: Priority	1[d]	1[d]	1[d]	1[g]
Fen	0	0	0	0
Blanket Bog	0	0	0	0
BLW: Non-Priority	0	0	0	0
CW	0	0	0	0
Arable	0	0	0	0
Other	0	0	0	0
Calcareous Grassland	0.67[e]	0.67[e]	1[d]	0.33[e,f]
BLW: Priority	0	0	0	0
BLW: Recently Felled	1[d]	1[d, g]	1[d, g]	0.33[c,f]
Modified Bog	1[d, g]	1[d]	1[d]	0.33[c,f]
Heath/Acid Grassland Mosaic	0	0	0	0
IG: Non-Priority	0	0	0	0
NG: Non-Priority	1[d]	1[d]	1[d]	1[g]
CW: Recently Felled	1[d]	1[d, g]	1[d, g]	0.33[c,f]
Flush & Spring	0	0	0	0
Marsh	0	0	0	0
Swamp	0	0	0	0

Table A2.7c: Alphabetic superscripts from Tables A2.7a&b.

Superscript	Description
a	Removal of original vegetation is likely to be required for conversion.
b	Rewetting required. It is assumed that the vegetation of the original P/NPBVC will be unable to tolerate the new water regime.
c	It is assumed that most soils within NNP have a tendency towards acidification if left unmanaged. Raising of soil pH is likely required for conversion.
d	Natural conversion likely.
e	Existing P/NPBVC is a natural type. Lowering of soil pH is likely required for conversion
f	Ploughing required.
g	Existing P/NPBVC highly suitable (1) for conversion due to the socio-economic characteristics of the scenario.

A2.5.2.2 Distance

Distance assigns a suitability score for a given target P/NPBVC (i.e. a P/NPBVC undergoing expansion under a given scenario) for each 50m cell within the study area based on the Euclidean distance of that cell to the boundary of the nearest patch of the target P/NPBVC. Higher suitability scores for a particular target P/NPBVC are assigned for cells in closer proximity to existing patches of that P/NPBVC. Lower suitability scores are assigned for cells further away. It is likely that area increases in a particular target P/NPBVC under the scenarios are likely to occur in close proximity to existing extents. In other words, expansion of existing patches, where possible, is likely to be a characteristic. The suitability scoring for distance is therefore useful, as it favours the spatial concentration of target P/NPBVCs adjacent to existing extents when producing future predictions of distributions (Griffiths *et al*. 2011).

Under Conservation First, the spatial concentration of target P/NPBVC patches is likely to enhance their quality, value and overall resilience and is therefore likely to be regarded as a desirable management goal (Griffiths *et al*. 2011; FLUFP, 2010; KanKaanpaa & Carter, 2004). Under Going for Growth, area increases in the target P/NPBVCs are likely to occur in closer proximity to existing extents, primarily for economic reasons. In terms of Coniferous Woodland and Arable, for instance, the suitability of land for conversion is likely to be strongly determined by factors such as proximity to roads, access to markets and distance to existing occurrences, generally related to the accessibility of that land and its suitability for conversion in terms of existing infrastructure (Swetnam *et al*, 2010; Verburg *et al*., 2006; Busch, 2006; KanKaanpaa & Carter, 2004). Distance is therefore regarded as a useful generic, indirect measure of the suitability of land for conversion to a particular target P/NPBVC, in terms of a range of factors (related to the accessibility of that land and the level of existing infrastructure in place), that are relevant in influencing human decisions regarding the appropriateness for conversion. For instance, it is assumed likely that future extents of Coniferous Woodland are more likely to occur in closer proximity to existing patches as the appropriate infrastructure to justify this conversion is more likely to already be in place. Swetnam *et al*. (2010) utilise a measure of the distance of land to existing occurrences of agriculture to determine its suitability for conversion to agriculture, specifically. Furthermore, current UK land use trends (FLUFP, 2010), as well as the prevailing socio-economic trends under Going for Growth, suggest that increases in the coverage of P/NPBVCs, such as Arable and Coniferous Woodland, are likely to favour increased coverage and spatial concentration adjacent to existing extents, as farmers and landowners attempt to maximise production and profits through increased 'economies of scale' (FLUFP, 2010; Creedy *et al*., 2009; Busch, 2006; KanKaanpaa & Carter, 2004).

The applied distance suitability indices ensure that cells immediately adjacent to existing extents of a particular P/NPBVC are assigned highest suitability scores (1). The lowest suitability score (0) for a particular P/NPBVC is equal to the largest observable distance between an individual patch (from that P/NPBVC's current distribution) and the nearest neighbouring patch or the boundary of NNP. For instance, 50m raster grids depicting the Euclidean distance of each cell within NNP to the nearest current patch of Blanket Bog (derived using *IDRISI Taiga's* 'Distance' module) showed that the maximum distance between two extant patches of Blanket Bog to be 9.3km. 9.3km was therefore used as the threshold delineating zero suitability for expansion of Blanket Bog within the study area. Values intermediate between 0 and 9.3km are interpolated linearly. Suitability in terms of each of the target P/NPBVCs was worked out separately using the same method described above for Blanket Bog. For illustrative purposes, Figure A2.5 shows the suitability index for Blanket Bog. Table A2.8 provides details of the thresholds used to delineate the suitability indices for all target P/NPBVCs.

Figure A2.5: Distance suitability index for Blanket Bog

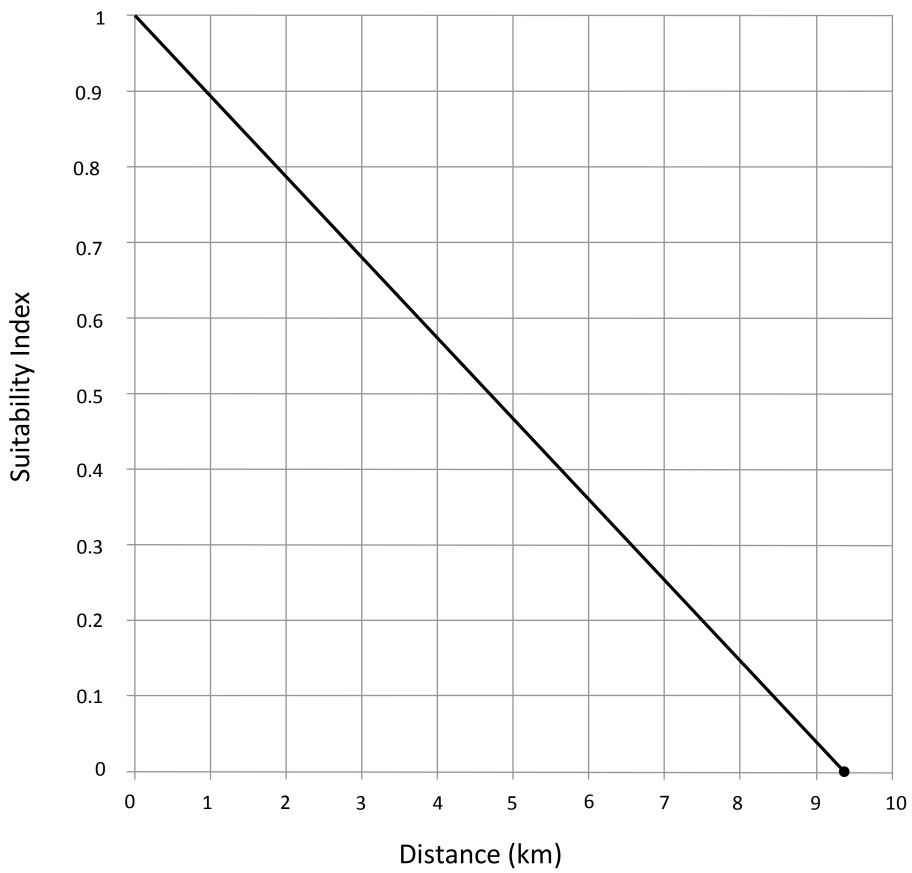


Table A2.8: Quantitative values used to delineate suitability thresholds in terms of distance for all target P/NPBVCs. Key: 'Min' = minimum; 'Max' = maximum; 'LO' = lower optimum; 'UO' = upper optimum.

Target P/NPBVC	Thresholds (km)			
	Min	LO	UO	Max
Conservation First				
Blanket Bog	-	-	0	9.3
Broadleaved Woodland: Priority	-	-	0	11.4
Fen	-	-	0	20.6
Heath	-	-	0	8.8
Improved Grassland: Priority	-	-	0	6.7
Neutral Grassland: Priority	-	-	0	13.9
Raised Bog	-	-	0	30.1
Going for Growth				
Arable	-	-	0	20.4
Broadleaved Woodland: Priority	See above	See above	See above	See above
Coniferous Woodland	-	-	0	4.9
Heath	See above	See above	See above	See above

Appendix 2b

Tables A2.9a, b & c: Classification schemes relating to soil water (a) soil pH (b) and slope (c) from Jarvis *et al*. (1984) used to define suitability thresholds.

Table A2.9a: Classification scheme of soil water characteristics (duration of water logging) (Source: Jarvis *et al*. 1984)

Wetness/Water Class (WC)	Duration of water logging
1	The soil profile is not waterlogged within 70cm depth for more than 30[1] days in most years[2]
2	The soil profile is waterlogged within 70cm depth for 30-90 days in most years
3	The soil profile is waterlogged within 70cm depth for 90-180 days in most years
4	The soil profile is waterlogged within 70cm depth for more than 180 days, but not waterlogged within 40cm depth for more than 180 days in most years
5	The soil profile is waterlogged within 40cm depth for 180-335 days, and is usually waterlogged within 70 for more than 335 days in most years
6	The soil profile is waterlogged within 40cm depth for more than 335 days in most years

[1] The number of days specified is not necessarily a continuous period

[2] *In most years* is defined as more than 10 out of 20 years

Table A2.9b: Classification scheme of soil pH (Source: Jarvis *et al*. 1984).
The lower limit of 'strongly acid' soils is based on NSRI (2002).

Description	**pH (in water)**
Strongly acid	3.1 – 4.5
Moderately acid	4.5 – 5.5
Slightly acid	5.6 – 6.5
Neutral	6.6 – 7.5
Alkaline	>7.5

Table 2.9c: Classification scheme of slope angle (Source: Jarvis *et al*. 1984)

Description	**Slope Angle (degrees)**
Level	0 – 1
Gently sloping	2 – 3
Moderately sloping	4 – 7
Strongly sloping	8 – 11
Moderately steeply sloping	12 – 15
Steeply sloping	16 – 25
Very steeply sloping	26 – 35
Precipitous	> 35

Table A2.10a: Summary of the relevant NVC communities associated with Blanket Bog, Raised Bog and Heath from JNCC (2007, pp. 99, 100) and the availability of data for these NVC types in relation to soil pH and elevation from Rodwell *et al*. (1991a). Shaded cells indicate that the particular NVC community type is not associated with the PBVC according to JNCC (2007). Ticks and crosses indicate data availability and unavailability, respectively. Bold ticks indicate that the data relating to that NVC was used to determine PBVCs thresholds. NVC communities M15 and M16 are regarded as a types associated with Blanket Bog and Heath according to JNCC (2007, pp. 99, 100). Information from Rodwell *et al*. (1991a) in relation to pH and elevation for M16 is not available. Descriptions for M15 from Rodwell *et al*. (1991a, pp. 147) suggest that, in terms of vegetation, soil water characteristics and peat depth, it has more in common with wet heath, than blanket bog. M15 was therefore only used in assigning thresholds for Heath. Although elevation data were available for a number of NVC communities associated with Blanket Bog and Heath, not all of these were regarded as suitable for determining elevation thresholds, due to the potential bias that could be introduced into the suitability functions as a result. For instance, NVC communities H 1-4 were not considered suitable because sampling for these communities was concentrated in the far south of the UK. Similarly, types H 20-22 were also regarded as unsuitable as the sampling was mainly concentrated in northern Scotland. Although the selection of relevant NVC communities on which to base suitability functions for Heath and Blanket Bog therefore involved some subjective judgement, every effort was made to select those NVCs for which sampling had a relatively diffuse geographical distribution. See Table A2.10b for page references for relevant NVC communities.

PBVC	NVC Community																												
	M									H																			
	1	2	3	15	16	17	18	19	20	1	2	3	4	5	6	8	9	10	12	13	14	15	16	17	18	19	20	21	22
Soil pH																													
Blanket & Raised Bog	✓	✓	✓	✓		**✓**	✓	✓	**✓**																				
Heath				**✓**	X					X	X	X	X	✓	✓	✓	X	X	✓	X	X	X	X	X	X	X	X	X	X
Elevation																													
Blanket Bog	✓	**✓**	**✓**	✓		**✓**	✓	**✓**	**✓**																				
Heath				**✓**	X					✓	✓	✓	✓	X	X	✓	✓	**✓**	**✓**	✓	✓	✓	✓	✓	**✓**	**✓**	✓	✓	✓

Table A2.10b: Page references for relevant NVC communities from Table A2.10a.

PBVC	NVC Community (and page reference from Rodwell *et al*., 1991a)
Soil pH	
Blanket Bog & Raised Bog	**M20** (pp. 217); **M17** (pp. 181)
Heath	**M15** (pp. 155)
Elevation	
Blanket Bog	**M2** (pp. 55); **M3** (pp. 59); **M17**; **M19** (pp. 209); **M20**
Heath	**M15**; **H10** (pp. 481); **H12** (pp. 502); **H18** (pp. 554) **H19** (pp. 563)

Table A2.11: Indicator species used to provide a more comprehensive quantification of P/NPBVC suitability in instances where adequate data from the other sources were not available. Numeric codes in the 'indicator species' column refer to the main sources used to establish the species indicative of a particular P/NPBVC: 1 = Tansley (1949); 2 = JNCC (2007). Alphabetic codes in the 'variable' column relate to sources used to establish P/NPBVC suitability based on the indicator species: a = Fitter & Peat (1994); b = Grime *et al*. (1988). Ticks indicate that quantitative data from either Fitter & Peat (1994) or Grime *et al*. (1988) were used more or less directly in establishing relevant P/NPBVC suitability thresholds. Crosses indicate that for a particular variable either the indicator species was not necessary in establishing P/NPBVC suitability or the information on the indicator species was used from sources other than Fitter & Peat (1994) and Grime *et al*. (1988) (e.g. Tansley, 1949; JNCC, 2007). The '†' symbol used for Coniferous Woodland in relation to elevation or slope is used due to the lack of quantitative information for these variables for *P. sylvestris* from Fitter & Peat (1994) and Grime *et al*. (1988). This meant that the suitability index for the NPBVC was based on the information for *Betula pendula* and *Betula pubescens* from Grime *et al*. (1988) because of the close association between these species and *P. sylvestris* (Tansley, 1949).

P/NPBVC	**Indicator species**	**Variable**				
		Soil Water	**Soil Type**	**Soil pH**	**Elevation**	**Slope**
Heath	*Calluna vulgaris* [1, 2]	X	X	✓[a]	✓[a]	✓[b]
	Erica cinerea [1, 2]	X	X	X	✓[a]	X
	E. tetralix [1, 2]	X	X	X	✓[a]	X
Broadleaved Woodland	*Alnus glutinosa* [1]	✓[a]	X	✓[b]	✓[b]	✓[b]
	Betula pendula [1]	✓[a]	X	✓[b]	✓[b]	✓[b]
	B. *pubescens* [1]	✓[a]	X	✓[b]	✓[b]	✓[b]
	Fagus sylvatica [1]	✓[a]	X	✓[b]	✓[b]	✓[b]
	Fraxinus excelsior [1]	✓[a]	X	✓[b]	✓[b]	✓[b]
	Querbus robur [1]	✓[a]	X	✓[b]	✓[b]	✓[b]
	Q. petraea [1]	✓[a]	X	✓[b]	✓[b]	✓[b]
Bracken	*Pteridium aquilinum* [2]	✓[b]	✓[b]	✓[b]	✓[b]	✓[b]
Coniferous Woodland	*Pinus sylvestris* [1]	X	X	✓[a]	†[b]	†[b]
Acid Grassland	*Deschampia flexuosa* [1, 2]	X	X	✓[a]	X	X
	Juncus squarrosus [1, 2]	X	X	✓[a]	X	X
	Festuca rubra [1]	X	X	✓[a]	X	X
	Anemone nemorosa [1]	X	X	✓[a]	X	X
Modified Bog	*Eriophorum vaginatum* [2]	X	X	✓[a]	X	X
Calcareous Grassland	*Sanguisorba minor* [2]	X	X	X	✓[a]	X
	Brachypodium pinnatum [2]	X	X	X	X	X
	Helianthemum nummularium [2]	X	X	X	✓[a]	X
	Koeleria macranth [2]	X	X	X	✓[a]	X

Table A2.12: P/NPBVC slope and elevation statistics (minimum, maximum and mean) derived for NNP. Specifically, slope and elevation statistics for NNP were extracted from 50m resolution slope and elevation raster grids for P/NPBVC categories. The spatial data representing the current distribution of the P/NPBVCs within the study area was based on 50m resolution P1HS data reclassified to represent the P/NPBVC categories.

P/NPBVC	**Variable**					
	Slope (°)			**Elevation (m)**		
	Min	**Max**	**Mean**	**Min**	**Max**	**Mean**
Acid Grassland	0	38	8.17	71	779	299.36
Arable	0	26	5.65	57	371	151.20
Blanket Bog	0	33	6.21	152	815	474.75
Bracken	0	32	11.60	89	570	278.95
Broadleaved Woodland	0	33	8.06	58	435	182.50
Calcareous Grassland	1	20	8.83	160	267	240.81
Coniferous Woodland	0	38	5.92	70	561	297.19
Fen	0	18	1.96	166	531	237.10
Flush & Spring	0	35	6.15	153	688	334.49
Heath	0	4	6.57	109	618	322.20
Heath/Acid Grassland Mosaic	0	41	7.30	114	805	332.86
Improved Grassland: Non-Priority	0	11	3.95	59	275	162.88
Improved Grassland: Priority	0	26	4.83	50	391	189.88
Marsh	0	31	4.64	65	558	260.04
Modified Bog	0	27	6.03	165	609	437.54
Neutral Grassland: Non-Priority	0	29	4.96	59	480	208.99
Neutral Grassland: Priority	0	27	4.40	76	448	192.66
Raised Bog	0	11	1.88	240	523	337.51
Swamp	0	10	1.26	163	329	224.54

A5.2.3 Suitability Indices for All P/NPBVCs Not Covered in Appendix 2a

A2.5.3.1 Soil Water

Table A2.13: Summary of soil water suitability indices for all P/NPBVCs from a classification of soil wetness from Jarvis *et al*. (1984) (Table A2.9a). The information is presented in alphabetical order. Cells are colour coded to correspond to the general categorisation scheme of P/NPBVC soil water characteristics tolerances in Table A2.2. Blue cells: 'wetland'; green cells: 'terrestrial'; clear cells: 'broad'. Broadleaved Woodland includes: Broadleaved Woodland: Priority, Broadleaved Woodland: Non-Priority and Broadleaved: Recently Felled Woodland). Coniferous Woodland includes: Coniferous Woodland and Coniferous: Recently Felled Woodland

P/NPBVC	Soil Water Class						Table reference
	1	2	3	4	5	6	
Acid Grassland	1	1	1	1	1	0.5	A2.13i
Arable	1	1	1	0.5	0	0	A2.13j
Blanket Bog	0	0	0	0	0.5	1	A2.3
Bracken	1	1	1	1	1	0.5	A2.13k
Broadleaved Woodland	1	1	1	1	1	0.5	A2.13a
Calcareous Grassland	1	1	1	0.5	0	0	A2.13l
Coniferous Woodland	1	1	1	1	0.5	0	A2.13m
Fen	0	0	0	0	0.5	1	A2.13b
Flush & Spring	0	0	0	0	0.5	1	A2.13n
Heath	1	1	1	1	1	0.5	A2.13c
Heath/Acid Grassland Mosaic	1	1	1	1	1	0.5	A2.13o
Improved Grassland: Non-Priority	1	1	1	0.5	0	0	A2.13p
Improved Grassland: Priority	1	1	1	1	1	1	A2.13d
Marsh	0	0	0	0	0.5	1	A2.13e
Modified Bog	1	1	1	1	1	0.5	A2.13q
Neutral Grassland: Priority	1	1	1	1	1	1	A2.13f
Neutral Grassland: Non-Priority	1	1	1	1	1	1	A2.13r
Raised Bog	0	0	0	0	0.5	1	A2.13g
Swamp	0	0	0	0	0	1	A2.13h

The tables for the PBVCs are provided first, followed by the tables for the NPBVCs.

A2.13a: Soil water suitability scoring for PBVC: Broadleaved Woodland

WC	SI value	Derivation of SI value
6	0.5	Fitter & Peat (1994) and Tansley (1949) suggest broad overall tolerances in terms of soil water when the various tree species indicative of the Broadleaved Woodland P/NPBVCs (Table A2.11) are taken together. *A. glutinosa* (common alder) may be regarded as the most water tolerant of the broadleaved tree species considered in the analysis (Tansley, 1949). Fitter & Peat (1994) provide an Ellenberg indicator value of 8 for *A. glutinosa* in relation to soil moisture suggesting that the species is moderately tolerant of waterlogged soils. A SI value of 0.5 is assigned for soils with WC 6.
5	1	WC 1 soils are generally highly suitable for the broadleaved species considered in the analysis (Jarvis *et al*. 1984). WC 5 soils are also suitable for Broadleaved Woodland (Jarvis *et al*. 1984). It is assumed that soil WCs 1 - 5 are optimal for Broadleaved Woodland (SI = 1).
4		
3		
2		
1		

A2.13b: Soil water suitability scoring for PBVC: Fen

WC	SI value	Derivation of SI value
6	1	The suitability scoring for Fen in terms of soil water is exactly the same as Blanket Bog (as well as the other 'wetland' P/NPBVCs: Excluding Swamp; See Tables A2.2 & A2.13h). Fen is regarded as a typical 'mire' community by JNCC (2007). Jarvis *et al*. (1984) describe vegetation commonly associated with Fen (e.g. *Sphagna*) occurring abundantly on WC 6 soils. Such vegetation only occurs abundantly on the wetter areas of WC 5 soils (Jarvis *et al*., 1984). Similarly to Blanket Bog (and most of the other 'wetland' types), WC 1-4 soils are deemed unsuitable for Fen.
5	0.5	
4	0	
3		
2		
1		

A2.13c: Soil water suitability scoring for PBVC: Heath

WC	SI value	Derivation of SI value
6	0.5	There are some differences between Bog and the wetter types of Heath in relation to soil water requirements. Bog is more typically associated with wetter soils which favour the development of Sphagnum mosses indicative of the community type (JNCC, 2007; Furniss & Lane, 1994; Tansley, 1949). However, Sphagnum mosses will often be present to some degree within a wet heath and will increase in abundance in transition to mire. Similarly, the ericaceous vegetation, typical of heath, is often present on the drier parts of a bog (JNCC, 2007; Tansley, 1949). Clearly there is a close association between the two community types and drawing sharp definitional boundaries between them in terms of soil water content is somewhat problematic. Here a SI value of 0.5 is assigned for WC 6 soils in relation to Heath in order to take some account of its moderate suitability for waterlogged soils.
5	1	Heath generally occurs on well-drained soils (JNCC, 2007; Tansley, 1949). This description corresponds well with descriptions offered by Jarvis *et al*. (1984) in relation to soils with a WC of 1. Heath incorporates both wet and dry types suggesting a broad overall tolerance in relation to soil water. Descriptions of semi-natural vegetation types typically occupying WC 5 soils from Jarvis *et al*. (1984) suggest a preponderance of ericaceous vegetation and a relative lack of sphagnum mosses compared to WC 6 soils. These vegetative descriptions are very similar to those offered by JNCC (2007) in relation to Wet Dwarf Shrub Heath. A SI value of 1 for WC 5 soils is therefore deemed valid. All intermediate WCs (2 – 4) are also deemed suitable for Heath (SI = 1).
4		
3		
2		
1		

A2.13d: Soil water suitability scoring for PBVC: Improved Grassland: Priority

WC	SI value	Derivation of SI value
6	1	WC 1 soils are highly suitable (JNCC, 2007; Jarvis *et al*. 1984). According to JNCC (2011) and Jackson (2000), Improved Grassland: Priority may include extents of floodplain grazing marsh. Such extents are likely to be permanently waterlogged in places (JNCC, 2011). WC 6 soils are therefore also likely to be suitable for this PBVC. All intermediate WCs are also deemed to be suitable (SI = 1).
5		
4		
3		
2		
1		

A2.13e: Soil water suitability scoring for PBVC: Marsh

WC	SI value	Derivation of SI value
6	1	Marsh communities commonly occur on waterlogged soils (JNCC, 2007; Furniss & Lane, 1999; Tansley, 1949), suggesting a high suitability for WC 6 soils. Such communities typically diminish in abundance in transition to the drier soil types (Jarvis *et al*., 1984; Tansley, 1949). This is similar to the way the drying of bogs leads to the reduction of species typical of the community. The suitability scoring for Marsh in terms of soil water is therefore the same as Blanket Bog (as well as most of the other 'wetland' P/NPBVCs).
5	0.5	
4	0	
3		
2		
1		

A2.13f: Soil water suitability scoring for PBVC: Neutral Grassland: Priority

WC	SI value	Derivation of SI value
6	1	Neutral Grassland (Priority and Non-Priority) include some grasslands which are associated with permanently water logged soil (JNCC, 2007, pp. 52). Permanently waterlogged soils are typical of conditions associated with WC 6 soils (SI = 1). Neutral grasslands also consist of a range of types that may be ‘periodically inundated and permanently moist’ (JNCC, 2007, pp. 52) as well as those that are ‘well drained and fairly dry throughout the year’ (Tansley, 1949, pp. 559). Soil WCs 1-5 are therefore also regarded as suitable for Neutral Grassland (SI = 1).
5		
4		
3		
2		
1		

A2.13g: Soil water suitability scoring for PBVC: Raised Bog

WC	SI value	Derivation of SI value
6	1	Blanket Bog and Raised Bog have very similar vegetative characteristics (JNCC, 2007; Tansley, 1949). The soil water characteristics of Raised Bog are also very similar to Blanket Bog (as well as other communities classified as ‘mire’ by JNCC, 2007; Table A2.2). The suitability scoring for Raised Bog in terms of soil water requirements is therefore the same as Blanket Bog.
5	0.5	
4	0	
3		
2		
1		

A2.13h: Soil water suitability scoring for PBVC: Swamp

WC	SI value	Derivation of SI value
6	1	Swamps are generally associated with water that is above the soil surface for most of the year (Table A2.2). However, swamp represents a transitional stage between open water and land. There may be some instances in which the soil surface is not immersed (JNCC, 2007). It is assumed, however, that where this is the case the soil will remain water logged all year round. WC 6 soils are deemed suitable for Swamp (SI = 1).
5	0	The characteristics of WC5 soils (Table A2.9a) suggest that they are unlikely to provide characteristics able to support Swamp communities (SI = 0). WC’s 1-4 represent types of increasing dryness.
4		
3		
2		
1		

A2.13i: Soil water suitability scoring for NPBVC: Acid Grassland

WC	SI value	Derivation of SI value
6	0.5	Acid grasslands are typically regarded as a terrestrial community (JNCC, 2007; Furniss & Lane, 1999; Lane, 1999; Tansley, 1949). The Acid Grassland NPBVC excludes types dominated by *Molinia* communities, which are represented within the Marsh ‘wetland’ PBVC (Table A2.2). However, it is problematic to draw sharp definition between the two. A SI value of 0.5 is therefore assigned for WC 6 soils to account for this.
5	1	Acid grasslands tend to occur on soils which are either ‘well drained’ or of ‘medium’ dampness. (Tansley, 1949, pp. 494). ‘Well-drained’ soils correspond well with descriptions offered by Jarvis *et al*. (1984) in relation to soils with a WC of 1 (SI = 1). Descriptions of semi-natural vegetation types typically occupying WC 5 soils from Jarvis *et al*. (1984) are closely similar to types typical of acid grassland communities (e.g. *Nardus stricta*) according to Tansley (1949) and JNCC (2007). A SI value of 1 is therefore assigned for WC 5 soils. All intermediate WCs (2 – 4) are also deemed suitable for Acid Grassland (SI = 1).
4		
3		
2		
1		

A2.13j: Soil water suitability scoring for NPBVC: Arable

WC	SI value	Derivation of SI value
6	0	Soil WCs 5 and 6 are deemed too wet and therefore entirely unsuitable for arable purposes based on Jarvis *et al*. (1984) (SI = 0).
5		
4	0.5	Jarvis *et al*. (1984) suggest moderate suitability for arable farming in relation to WC 4 soils with arable crops generally being grown on the drier areas of these soils. A SI value of 0.5 is therefore assigned for WC4 soils.
3	1	WCs 1 – 3 are deemed most suitable (SI = 1) for arable purposes based on information from Jarvis *et al*. (1984)
2		
1		

A2.13k: Soil water suitability scoring for NPBVC: Bracken

WC	SI value	Derivation of SI value
6	0.5	Grime *et al*. (1988) state that *P. aquilinum* is occasionally found on the margins of soligeneous mire. A SI value of 0.5 is therefore assigned for WC 6.
5	1	WCs 1 – 5 are deemed most suitable (SI = 1) based on information from Grime *et al*. (1988).
4		
3		
2		
1		

A2.13l: Soil water suitability scoring for NPBVC: Calcareous Grassland

WC	SI value	Derivation of SI value
6	0	Calcareous Grassland generally requires free draining soils and has a lower tolerance of wet soils than the other grassland P/NPBVCs (Lane, 1994; Tansley, 1949, pp. 494). The literature provides little specific information on the soil water characteristics on which to base maximum, minimum and optimum thresholds. The suitability scoring in relation to this NPBVC is largely conjectural.
5		
4	0.5	
3	1	
2		
1		

A2.13m: Soil water suitability scoring for NPBVC: Coniferous Woodland

WC	SI value	Derivation of SI value
6	0	Some WC 5 soils require drainage in order to support Coniferous Woodland species. Many WC 6 soils are unsuitable even with appropriate management (Jarvis *et al*. 1984). WCs 5 and 6 are regarded as moderately suitable (SI = 0.5) and unsuitable (SI = 0), respectively, for Coniferous Woodland.
5	0.5	
4	1	It is assumed that drainage of WC 5 soils is necessary to facilitate a change to WC 1-4 (SI = 1). Jarvis *et al*. (1984) describe *P. sylvestris* achieving growth sufficient to support commercial forestry on WC 1 – 4 soils.
3		
2		
1		

A2.13n: Soil water suitability scoring for NPBVC: Flush & Spring

WC	SI value	Derivation of SI value
6	1	Due to the classification of Flush & Spring as 'mire' under JNCC (2007) nomenclature the suitability scoring of this NPBVC follows that of other mire community types (e.g. Blanket Bog; Fen etc.).
5	0.5	
4	0	
3		
2		
1		

A2.13o: Soil water suitability scoring for NPBVC: Heath/Acid Grassland Mosaic

WC	SI value	Derivation of SI value
6	0.5	Heath/Acid Grassland Mosaic represents a common mixture of Heath and Acid Grassland with less than 25% coverage of ericoid or small gorse species (JNCC, 2007). Due to the very close similarities between the soil water tolerances of these two P/NPBVC types in terms of soil water, the suitability scoring for Heath/Acid Grassland Mosaic is the same as that for Heath and Acid Grassland.
5	1	
4		
3		
2		
1		

A2.13p: Soil water suitability scoring for NPBVC: Improved Grassland: Non-Priority

WC	SI value	Derivation of SI value
6	0	There is little information in the literature concerning the water characteristics of Improved Grassland: Non-Priority. The suitability scoring is largely conjectural and is based on the assumption that the use of this NPBVC for amenity purposes will necessitate drier ground than that associated with some types of Improved Grassland: Priority.
5		
4	0.5	
3	1	
2		
1		

A2.13q: Soil water suitability scoring for NPBVC: Modified Bog

WC	SI value	Derivation of SI value
6	0.5	Modified Bog is essentially Blanket or Raised Bog which is drying and degraded (JNCC, 2007). Such modification may initiate the transition from bog to heath discussed in Table A2.13c. Descriptions of the vegetative characteristics of Wet Modified Bog and Dry Modified Bog from JNCC (2007) are very similar to their descriptions for Wet Heath and Dry Heath. Similarly to Heath, Modified Bog is therefore deemed to have a moderate association with WC 6 soils.
5	1	Due to the close similarities between Heath and Modified Bog, WCs 1-5 are also regarded as having a strong association with Modified Bog (SI = 1).
4		
3		
2		
1		

A2.13r: Soil water suitability scoring for NPBVC: Neutral Grassland: Non-Priority

WC	SI value	Derivation of SI value
6	1	See: Table A2.13f.
5		
4		
3		
2		
1		

A2.5.3.2 Soil Type

Table A2.14: Summary of soil type suitability indices for all P/NPBVCs. The information is presented in alphabetical order. Broadleaved Woodland includes: Broadleaved Woodland: Priority, Broadleaved Woodland: Non-Priority and Broadleaved: Recently Felled Woodland. Coniferous Woodland includes: Coniferous Woodland and Coniferous: Recently Felled Woodland

P/NPBVC	Soil Type			Table reference
	Deep Peat	Thin Peat	Non-peat	
Acid Grassland	0.5	1	1	A2.14i
Arable	0	0.5	1	A2.14j
Blanket Bog	1	0.5	0	A2.4
Bracken	0	0.5	1	A2.14k
Broadleaved Woodland	0.5	1	1	A2.14a
Calcareous Grassland	0	0	0.5	A2.14l
Coniferous Woodland	0.5	1	1	A2.14m
Fen	1	0.5	0	A2.14b
Flush & Spring	0.5	1	1	A2.14n
Heath	0.5	1	1	A2.14c
Heath/Acid Grassland Mosaic	0.5	1	1	A2.14o
Improved Grassland: Non-Priority	0	0	1	A2.14p
Improved Grassland: Priority	0.5	1	1	A2.14d
Marsh	0.5	1	1	A2.14e
Modified Bog	1	0.5	0	A2.14q
Neutral Grassland: Priority	0.5	1	1	A2.14f
Neutral Grassland: Non-Priority	0.5	1	1	A2.14r
Raised Bog	1	0.5	0	A2.14g
Swamp	0	0.5	1	A2.14h

The tables for the PBVCs are provided first, followed by the tables for the NPBVCs.

Table A2.14a: Soil type suitability scoring for PBVC: Broadleaved Woodland

Soil Type	SI value	Derivation of SI value
Deep Peat	0.5	It is assumed that Grime *et al*. (1988) and Tansley (1949) define 'deep' and 'thin' in a broadly similar way as JNCC (2007). Many of the broadleaved species considered in the analysis tend to avoid deep acidic peats; although they are do occur less frequently in drier areas of these soils (Grime *et al*., 1988; Tansley, 1949). A SI value of 0.5 is therefore assigned to 'Deep Peat' to take some account of the moderate overall potentiality for the broadleaved species to occur on such soils.
Thin Peat	1	The various broadleaved species can occur on soils with a thin layer of peat (Grime *et al*., 1988; Tansley, 1949). Jarvis *et al*. (1984) suggest that many of the 'Thin peat' soils within NNP are highly suitable for some of the broadleaved species considered in the analysis. As such, 'Thin peat' is assigned a SI value of 1. The majority of the broadleaved species considered in the analysis occur abundantly on brown earths and podsols (Tansley, 1949). Some of the broadleaved species considered in the analysis also occur readily on rendzina soils (Tansley, 1949). A SI value of 1 is therefore also assigned for 'Non-peat'.
Non-peat		

Table A2.14b: Soil type suitability scoring for PBVC: Fen

Soil Type	SI value	Derivation of SI value
Deep Peat	1	Although the specific modes of development of Fen differ from those of Blanket Bog and Raised Bog all three PBVCs are closely associated, exhibit very similar vegetation characteristics and have strong associations and requirements in terms of soil water and type (JNCC, 2007; Tansley, 1949). As such, Fen is most closely associated with and occurs most readily upon 'Deep peat' soils (JNCC, 2007, pp. 58).
Thin Peat	0.5	The lack of an agreed minimum peat depth associated with bog communities (Table A2.4) also likely applies to the specific depth of peat typically associated with fen communities. 'Thin peat' is therefore regarded as having a moderate association with Fen.
Non-peat	0	Due to the close similarities between Blanket and Raised Bogs and Fen (Table A2.2), non-peat soils are regarded as unsuitable for Fen (Also see: A2.4 & A2.14g).

Table A2.14c: Soil type suitability scoring for PBVC: Heath

Soil Type	SI value	Derivation of SI value
Deep Peat	0.5	Due to the difficulties in establishing an agreed maximum peat depth distinguishing blanket bog communities and other types (e.g. heath) (See: Table A2.4), a SI value of 0.5 in relation to 'Deep peat' is used to represent the reduced potentiality for Heath to occur on drying or degraded peat with a depth greater than 0.5m.
Thin Peat	1	JNCC (2007) suggests that heath generally occurs on peat less than 0.5m thick. Heath also occurs frequently on podsols and can potentially occur readily on other types of soil (e.g. brown earth and rendzina soils) which the 'Non-peat' category encompasses (Tansley, 1949). A SI value of 1 is therefore assigned for 'Thin peat' and 'Non-peat' soils.
Non-Peat		

Table A2.14d: Soil type suitability scoring for PBVC: Improved Grassland: Priority

Soil Type	SI value	Derivation of SI value
Deep Peat	0.5	Little information is available from the various sources (e.g. JNCC, 2007; Tansley, 1949 etc.) with regard associations between soil peat and Improved Grassland: Priority. The inclusion of floodplain grazing marsh within the Improved Grassland: Priority PBVC (See: Table A2.2) suggests that some extents may be associated with the accumulation of deep peat. However, because these extents are likely to be relatively localised, general associations between 'Deep Peat' and Improved Grassland: Priority are likely to be moderate (SI = 0.5).
Thin Peat	1	Soil water characteristics for some types of Improved Grassland: Priority (see above) are likely to be associated with more wide spread accumulations of thin peat (SI = 1). In general terms Improved Grassland: Priority is assumed to have the same relationship with 'Non-peat' soils as Neutral Grassland (Priority and Non-Priority) (Table A2.14f). These P/NPBVCs are highly suited to some soils (e.g. brown earth) and may occur readily on others (e.g. rendzina soils and podsols) with appropriate management (Tansley, 1949).
Non-peat	1	

Table A2.14e: Soil type suitability scoring for PBVC: Marsh

Soil Type	SI value	Derivation of SI value
Deep Peat	0.5	Marsh is a community type typically associated with mainly mineral (inorganic) soils (Furniss & Lane, 1999; Tansley, 1949). A SI value of 1 is therefore assigned in relation to 'Non-peat' soils. However, the waterlogged conditions that are characteristic of Marsh will tend to lead to the accumulation of some peat within the soil (Tansley, 1949). Indeed, some marshes are associated with peat less than 0.5m thick (JNCC, 2007). A SI value of 1 is assigned for 'Thin peat'. Although the depth of peat associated with Marsh is likely to be thin, it is feasible that a minority of Marsh occurrences will be associated with a peat depth greater than 0.5m. A SI value of 0.5 is therefore assigned in relation to 'Deep peat'.
Thin Peat	1	
Non-peat	1	

Table A2.14f: Soil type suitability scoring for PBVC: Neutral Grassland: Priority

Soil Type	SI value	Derivation of SI value
Deep Peat	0.5	Neutral Grassland (Priority and Non-Priority) may be associated with periodically inundated or permanently waterlogged conditions (Table A2.2) (JNCC, 2007). The characteristics of such soils are likely to lead to the accumulation of peat. However, in many instances this accumulation is likely to be checked by aeration and/or the influence of water carrying silt (Tansley, 1949). A SI value of 0.5 is assigned in relation to 'Deep peat' to take some account of the moderate association Neutral Grassland is likely to have with such soils.
Thin Peat	1	Neutral grasslands are more likely to occur on soils with a thinner layer of peat (see above). A SI value of 1 is assigned for 'Thin peat' soils. Jarvis *et al*. (1984) and Tansley (1949) suggest that neutral grassland communities are highly suited to some soils (e.g. brown earth) incorporated within the 'Non-peat' category and can occur on others (e.g., rendzina soils and podsols) with appropriate management. 'Non-peat' soils are therefore also assigned a SI value of 1.
Non-peat	1	

Table A2.14g: Soil type suitability scoring for PBVC: Raised Bog

Soil Type	SI value	Derivation of SI value
Deep Peat	1	Although specific forms and structures differ between Raised Bog and Blanket Bog, they have very similar associations in terms of soil type (JNCC, 2007; Tansley, 1949). Raised Bog is also typically associated with deep peat soils (JNCC, 2007, pp. 57).
Thin Peat	0.5	Due to the lack of an agreed minimum peat depth associated with bog communities (Table A2.4), 'Thin peat' is regarded as only moderately suitable for Raised Bog.
Non-peat	0	Non-peat soils are regarded as unsuitable for Raised Bog (Table A2.4).

Table A2.14h: Soil type suitability scoring for PBVC: Swamp

Soil Type	SI value	Derivation of SI value
Deep Peat	0	Swamp may be associated with either 'peat or mineral soils' (JNCC, 2007, pp. 60; Tansley, 1949). As with other P/NPBVCs associated with constantly waterlogged soils the conditions may lead to the accumulation of some peat. However, a significant build up is associated with transition to either Marsh or Fen (Tansley, 1949). It is likely therefore that Swamp is not typically associated with deep peat. As such, a SI value of 0 is assigned for 'Deep peat'.
Thin Peat	0.5	The fact that increasing accumulation of peat is likely to lead to transition to either Marsh or Fen suggests a moderate association with soils with a thin layer of peat.
Non-peat	1	The above points suggest that swamps have a proclivity for mainly mineral soils. Tansley (1949) also, specifically suggests that swamps are most likely to be associated with mainly mineral soils.

Table A2.14i: Soil type suitability scoring for NPBVC: Acid Grassland

Soil Type	SI value	Derivation of SI value
Deep Peat	0.5	Acid grasslands are typically associated with sandy and siliceous soils that are well drained or of medium dampness (Tansley, 1949, pp. 494). In these latter types, conditions are likely to favour the development of some peat. However, accumulation is likely to be limited due to the relative dryness of the soil when compared with wetter, permanently water logged types (Tansley, 1949, pp. 494). The issue concerning the lack of consensus on the specific depth of peat used to distinguish particular community types is also relevant. It is likely therefore that Acid Grassland has a moderate association with 'Deep peat'.
Thin Peat	1	Acid grasslands, particularly specific types (see above), are likely to be closely associated with soils with a thin accumulation of peat. Acid grasslands may frequently occur on a number of soils encompassed by the 'Non-peat' category (e.g. podsols, brown earths), particularly where such soils are characterised by low to intermediate levels of pH (Tansley, 1949).
Non-peat		

Table A2.14j: Soil type suitability scoring for NPBVC: Arable

Soil Type	SI value	Derivation of SI value
Deep Peat	0	Descriptions by Jarvis *et al*. (1984) suggest that the majority of 'Deep peat' soils are not suited for arable use, even with appropriate management. A SI value of 0 is therefore assigned for 'Deep peat'.
Thin Peat	0.5	Some types of soils with a thin layer of peat may become highly suitable for arable purposes relatively easily with appropriate management (Jarvis *et al*., 1984).
Non-peat	1	Some soil types incorporated under the 'Non-peat' category are highly suitable for arable purposes. For instance, brown earth soils naturally support arable land use. Other soil types such as Podsols also have some value in terms of potential conversion. A SI value of 1 is therefore assigned for 'Non-peat' (Jarvis *et al*., 1984; Tansley, 1949).

Table A2.14k: Soil type suitability scoring for NPBVC: Bracken

Soil Type	SI value	Derivation of SI value
Deep Peat	0	Although *P. aquilinum* is not a wetland species and is absent from most mire types (suggesting unsuitability for peat soils), the species may occur on marginal areas of mires particularly on peat which is drying and degraded (Grime *et al*., 1988). A SI value of 0.5 is assigned for 'Thin peat' to account for this moderate suitability.
Thin Peat	0.5	
Non-peat	1	*P. aquilinum* can occur on a wide variety of other soil types (Grime *et al*. 1988; Tansley, 1949). A SI value of 1 is therefore assigned for 'Non-peat'.

Table A2.14l: Soil type suitability scoring for NPBVC: Calcareous Grassland

Soil Type	SI value	Derivation of SI value
Deep Peat	0	The soil water characteristics of Calcareous Grassland (See: Table A2.13l) suggest that it is unlikely to be associated with 'Deep Peat' or 'Thin-Peat' (SI = 0). Tansley (1949, pp. 494, 553) also suggests that Calcareous Grassland is largely confined to well drained soils and notable increases in soil water is associated with the accumulation of peat and transition to other community types.
Thin Peat		
Non-peat	0.5	Calcareous Grassland is most closely associated with rendzina soils (Tansley, pp. 525). Although other soils feasibly included in the 'Non-peat' category are likely to be unsuitable for Calcareous Grassland (Tansley, 1949, pp. 88, 89) the characteristics of other soils (e.g. brown earths) are generally likely to support calcareous vegetation (Tansley, 1949, pp. 86). In light of these points Calcareous Grassland is deemed to have an overall moderate association with 'Non-peat' soils (SI = 0.5).

Table A2.14m: Soil type suitability scoring for NPBVC: Coniferous Woodland

Soil Type	SI value	Derivation of SI value
Deep Peat	0.5	The requirements of *P. Sylvestris* are very similar to those of the birches (*B. pendula* and *B. pubescens)* (Tansley, 1949, pp. 255). These species can dominate on drying bogs (Tansley, 1949, pp. 251) suggesting a moderate association with 'Deep peat' (SI = 0.5).
Thin Peat	1	The above described relationship between *P. sylvestris* and bogs suggests a closer association with 'Thin-peat' (SI = 1). *P. Sylvestris* typically prefers 'lighter and drier' soils, however, it is a relatively hardy species and can occur even on some rendzina soils (Tansley, 1949, pp. 251, 253-5). Tansley (1949, pp. 255) suggests that the species is generally suited to 'better, more loamy soils' but may suffer from competition from other species. Overall 'Non-peat' soils are assumed to be suitable for *P. sylvestris* (SI = 1).
Non-peat		

Table A2.14n: Soil type suitability scoring for NPBVC: Flush & Spring

Soil Type	SI value	Derivation of SI value
Deep Peat	0.5	'Flushes and springs may or may not form peat, but where they do; the peat is *often* less than 0.5m deep' (JNCC, 2007, pp. 57). This suggests only a moderate association between Flush & Spring and deep peat (SI = 0.5). It also implies that there is likely to be a close association between thin peat and Flush & Spring (SI = 1).
Thin Peat	1	
Non-peat		The above information suggests that with sufficiently high water levels a variety of 'Non-peat' soils are highly suitable for Flush & Spring (SI = 1).

Table A2.14o: Soil type suitability scoring for NPBVC: Heath/Acid Grassland Mosaic

Soil Type	SI value	Derivation of SI value
Deep Peat	0.5	Heath/Acid Grassland Mosaic represents a mixture of Heath and Acid Grassland. Suitability scoring for Heath/Acid Grassland Mosaic is therefore exactly the same as that for Heath and Acid Grassland (Tables: A2.14c & A2.14i)
Thin Peat	1	
Non-Peat		

Table A2.14p: Soil type suitability scoring for NPBVC: Improved Grassland: Non-Priority

Soil Type	SI value	Derivation of SI value
Deep Peat	0	Little information is available from the various sources from which to draw conclusions regarding soil associations with Improved Grassland: Non-Priority. Suitability scoring is largely conjectural and is based on the assumption that extents of the NPBVC are generally associated with drier conditions than Improved Grassland: Priority (Table A2.2), as well as other grassland P/NPBVC types. It is likely that Improved Grassland: Non-Priority is too dry to be associated with the accumulation of peat due to its soil water characteristics (SI =0). It is assumed that Improved Grassland: Non-Priority has the same associations with 'Non-peat' soil types as Neutral Grassland (Priority and Non-Priority) and Improved Grassland: Priority (Tables A2.14d & A2.14f).
Thin Peat		
Non-peat	1	

Table A2.14q: Soil type suitability scoring for NPBVC: Modified Bog

Soil Type	SI value	Derivation of SI value
Deep Peat	1	The peat on which modified bog occurs is typically subject to greater drying and degradation than that associated with more natural types of bog (JNCC, 2007). However, JNCC (2007) suggests that this modification is insufficient to significantly reduce the original depth of peat. Modified Bog is most closely associated with 'Deep peat' soils (SI = 1).
Thin Peat	0.5	
Non-peat	0	By definition bogs will not be associated with Non-peat soils (JNCC, 2007, pp. 56).

Table A2.14r: Soil type suitability scoring for NPBVC: Neutral Grassland: Non-Priority

Soil Type	SI value	Derivation of SI value
Deep Peat	0.5	See: Table A2.14f
Thin Peat	1	
Non-peat		

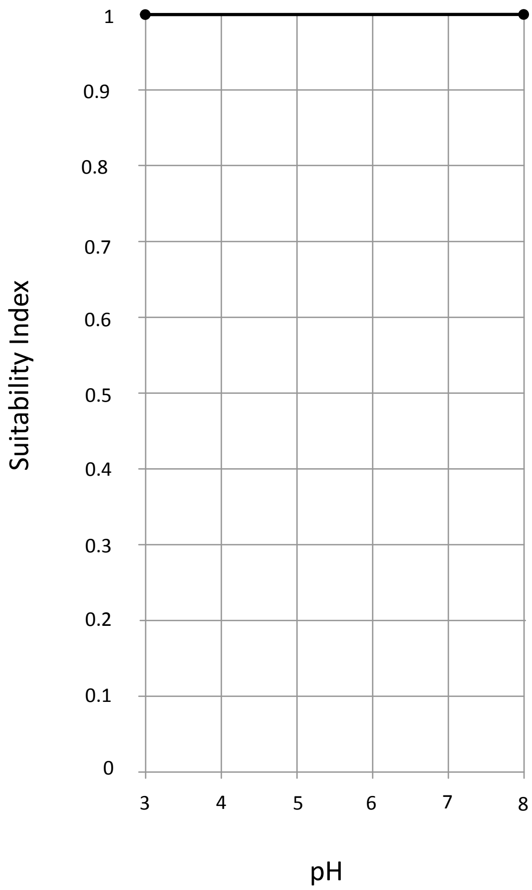
A2.5.3.3 Soil pH

Table A2.15: Summary of soil pH suitability indices for all P/NPBVCs. The information is presented in alphabetical order. Cells are colour coded to correspond to the general categorisation scheme of P/NPBVC soil pH tolerances in Table A2.5. Red cells: 'acidic'; yellow cells: 'neutral'; green cells: 'basic'; clear cells: 'broad'. Broadleaved Woodland includes: Broadleaved Woodland: Priority, Broadleaved Woodland: Non-Priority and Broadleaved Recently Felled Woodland. Coniferous Woodland includes: Coniferous Woodland and Coniferous Recently Felled Woodland

P/NPBVC	Thresholds				Figure reference
	Min	LO	UO	Max	
Acid Grassland	-	3.0	5.4	7.6	A2.6c
Arable	4.4	5.8	6.5	7.8	A2.6d
Blanket Bog	-	3.0	5.4	7.6	A2.2
Bracken	-	3.0	5.4	7.6	A2.6c
Broadleaved Woodland	-	3.0	8.0	-	A2.6a
Calcareous Grassland	4.8	7.1	8.0	-	A2.6e
Coniferous Woodland	-	3.0	5.4	7.6	A2.6c
Fen	-	3.0	8.0	-	A2.6a
Flush & Spring	-	3.0	8.0	-	A2.6f
Heath	-	3.0	5.4	7.6	A2.2
Heath/Acid Grassland Mosaic	-	3.0	5.4	7.6	A2.6c
Improved Grassland: Non-Priority	4.4	5.5	7.0	8.0	A2.6g
Improved Grassland: Priority	4.4	5.5	7.0	8.0	A2.6b
Marsh	-	3.0	8.0	-	A2.6a
Modified Bog	-	3.0	5.4	7.6	A2.6c
Neutral Grassland: Non-Priority	4.4	5.5	7.0	8.0	A2.6g
Neutral Grassland: Priority	4.4	5.5	7.0	8.0	A2.6b
Raised Bog	-	3.0	5.4	7.6	A2.2
Swamp	-	3.0	8.0	-	A2.6a

The figures for the PBVCs are provided first, followed by the figures for the NPBVCs.

Figure A2.6a: Soil pH suitability index for the 'broad' PBVCs: Broadleaved Woodland: Priority, Fen, Marsh and Swamp



Optima: (SI = 1)

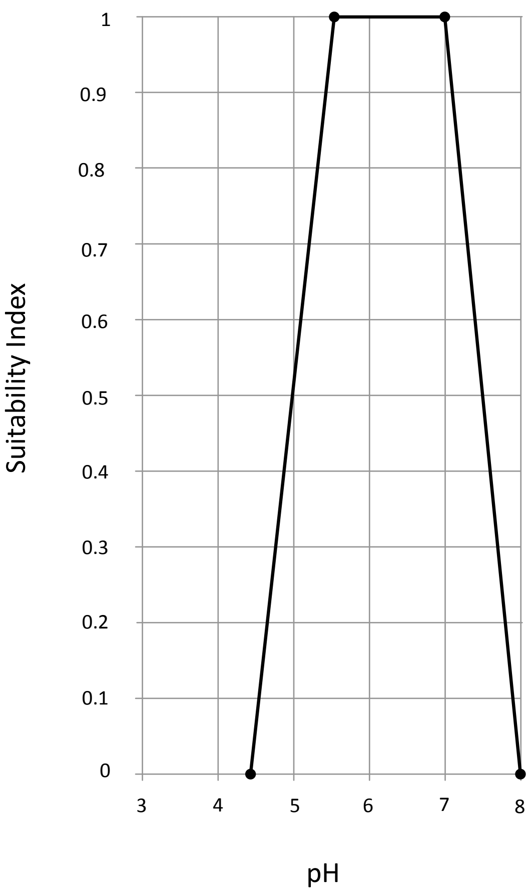
Lower = 3.0
Upper = 8.0

Source(s) and rationale:

Broadleaved Woodland: Priority: See Table A2.5

Fen, Marsh and Swamp: See Table A2.5

Figure A2.6b: Soil pH suitability index for the 'neutral' PBVCs: Improved Grassland: Priority and Neutral Grassland: Priority



Optima: (SI = 1)

Lower = 5.5
Upper = 7.0

Source(s): JNCC (2007). See Table A2.5

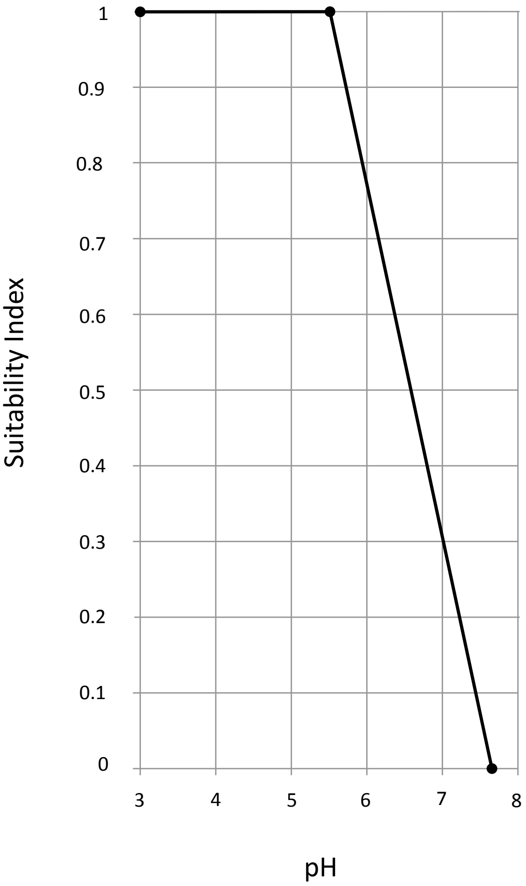
Absolute minima = 4.4 (SI = 0)

The pH range for a great majority of plant species within the UK typically 'extends across the neutral point, usually for a greater distance on the acid than the alkaline side' (Tansley 1949, pp. 82). This suggests some tolerance of moderate acidity for 'neutral' PBVC types. Jarvis *et al*. (1984) describe a minimum pH threshold of 4.5 for moderately acidic soils (Table A2.9b). An absolute minimum pH threshold of 4.4 is assigned, so that a SI value of 0.1 is returned at the 4.5 pH level. SI values between pH 4.4 and 5.5 are interpolated linearly.

Absolute maxima = 8.0 (SI = 0)

Jarvis *et al*. (1984) define an upper pH threshold of 7.5 for 'neutral' soils. 8.0 is assigned as the absolute maximum pH threshold for the 'neutral' PBVCs so that a SI value of 0.5 is returned for the mid-seven pH level. The value is largely conjectural. However, it ensures that a higher suitability score to be returned for the 'neutral' PBVCs at the 'neutral'/'alkaline' soil pH boundary than for the 'acidic' P/NPBVC types.

Figure A2.6c: Soil pH suitability index for 'acidic' NPBVCs: Acid Grassland, Bracken, Coniferous Woodland, Heath/Acid Grassland Mosaic, Modified Bog.



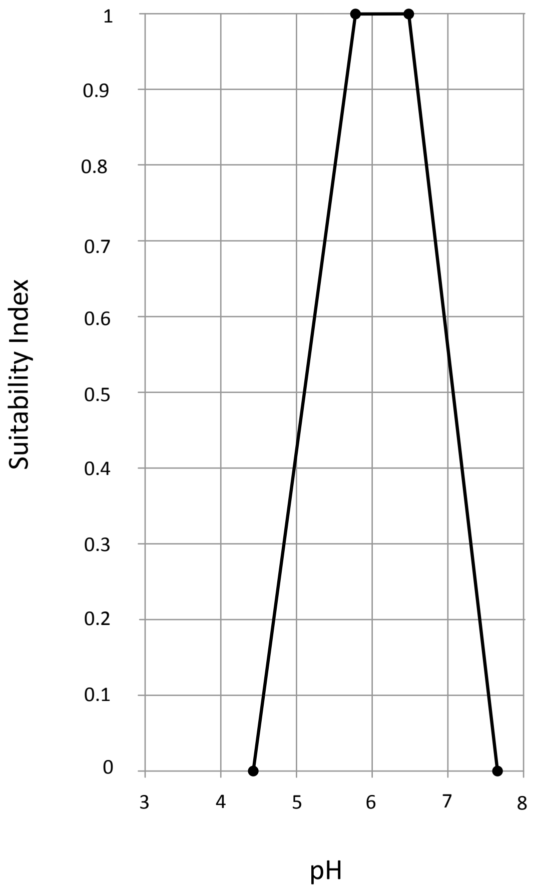
Optima: (SI = 1)
Lower = 3
Source(s) and rationale: Adequate information to establish lower optimum thresholds for Acid Grassland, Heath/Acid Grassland Mosaic, Bracken, and Coniferous Woodland was not available directly from JNCC (2007), Tansley (1949) or Rodwell *et al*. (1991a; 1991b; 1992). JNCC (2007, pp. 52) and Tansley (1949, pp. 494; 515) state that species such as *Deschampia flexuosa* and *Juncus squarrosus* commonly dominate more acidic grasslands. These species, as well as those indicative of Heath/Acid Grassland Mosaic (e.g. *C. vulgaris, E. cinerea*) and Coniferous Woodland (*P. sylvestris*), occur more or less abundantly on strongly acidic soils (Fitter & Peat, 1994). This suggests a lower optimum pH tolerance of approximately 3 (See: Figure A2.2 for rationale). Grime *et al*.'s (1988) data also suggest a lower optimum pH tolerance of 3 for Bracken (*P. aquilinum*). Rodwell *et al*. (1991a, pp. 217) indicate a lower optimum tolerance of 3.1 for some NVC types associated with of Blanket and Raised Bogs that will qualify as Modified Bog if drying or degraded. Also, species (e.g. *Eriophorum vaginatum*) commonly associated with Modified Bog (JNCC, 2007, pp. 57), are most abundant on strongly acidic soils (Fitter & Peat, 1994).

Upper = 5.4
Source(s) and rationale: see Table A2.5: 'acidic' P/NPBVCs.

Absolute maxima = 7.6 (SI = 0)

Source(s) and rationale: The 7.6 absolute maximum threshold used for the 'acidic' PBVCs (Figure A2.2) is also used for the 'acidic' NPBVCs. Species (e.g. *Festuca rubra*; *Anemone nemorosa*) which are commonly associated with relatively weak acidic grasslands (Tansley, 1949, pp. 494; 500-1) also occur infrequently on 'basic soils' (Fitter & Peat, 1994). As the lower limit of basic soils used in this research is 7 (See: Table A2.5), this suggests a maximum tolerance slightly higher than this level. An absolute maximum value of 7.6 is therefore for Acid Grassland. 7.6 is also regarded as appropriate for Heath/Acid Grassland Mosaic based on the rationales for Acid Grassland (above) and Heath (Figure A2.2), respectively. Grime *et al*. (1988) indicate an absolute maximum threshold of 7-8 for *P. aquilinum*. However, their data do not account for variations on a continuous pH scale. 7.6 is therefore also regarded as generally appropriate for Bracken. Due to its close association with Blanket and Raised Bogs, 7.6 is also applied as the absolute maximum threshold for Modified Bog (Figure A2.2). Although Fitter & Peat (1994) suggest that *P. sylvestris* is restricted to more acidic soils, Tansley (1949, pp. 445) argues that *P. sylvestris* has very similar requirements to the birches (*B. pendula* and *B. pubescens)*. Both birch species have a broad overall tolerance (i.e. 3 – 8), but occur most frequently below a pH of about 5. This suggests a marginal association with basic soils. The absolute maximum threshold of 7.6 is therefore also regarded as appropriate for Coniferous Woodland based on Tansley's (1949) descriptions.

Figure A2.6d: Soil pH suitability index for 'neutral' NPBVC: Arable.



Optima: (SI = 1)

Lower = 5.8
Upper = 6.5

Source(s) and rationale: The optimum pH range is based on information from DEFRA (2010, pp. 19) for continuous cropping systems.

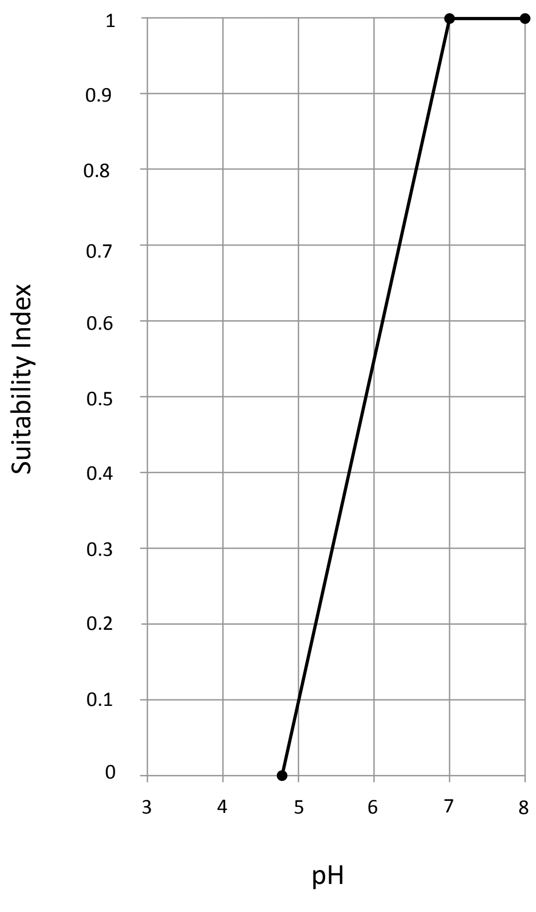
Absolute minima = 4.4 (SI = 0)

Source(s) and rationale: DEFRA (2010, pp. 19) suggests that most crops will fail in strongly acidic soils. An absolute minimum pH threshold of 4.4 is therefore assigned for Arable. This returns a SI value of approximately 0.1 at the 4.5 pH level, the lower limit of 'moderately' acidic soils (Jarvis et al. 1984).

Absolute maxima = 7.8 (SI = 0)

DEFRA (2010, pp. 19) suggests that maintaining a pH between 6.5 and 7.0 is justified for some types of continuous cropping system growing some acid sensitive species in rotation. An absolute maximum pH threshold of 7.8 is assigned returning a SI value of about 0.6 at pH 7.0 to account for the NPBVCs apparent moderate overall suitability for soils with relatively high pH.

Figure A2.6e: Soil pH suitability index for 'basic' NPBVC: Calcareous Grassland.



Optima: (SI = 1)

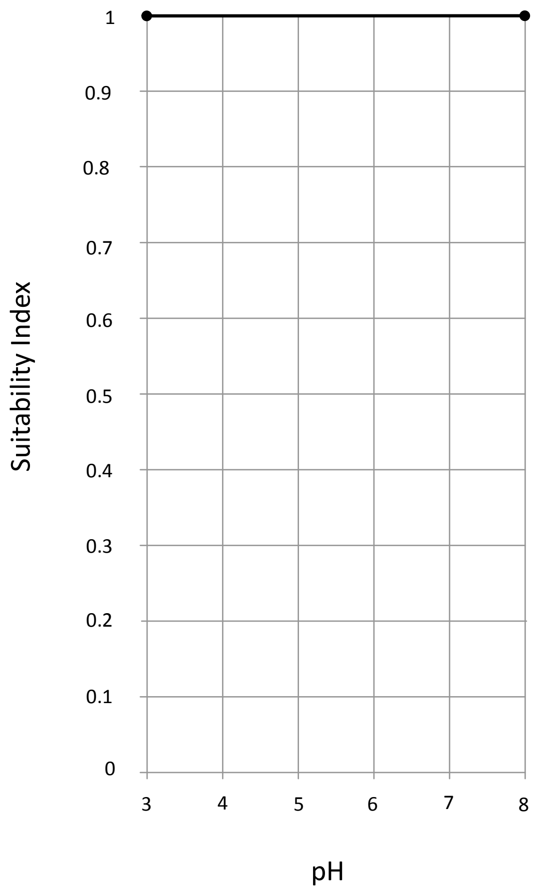
Lower = 7.1
Upper = 8.0

Source(s) and rationale: The lower optimum is based on JNCC (2007, pp 52). The upper optimum is based on Fitter & Peat (1994), who indicate that a number of species commonly associated with Calcareous Grassland, e.g. *Sanguisorba minor*, *Brachypodium pinnatum* (Table A2.11), are very tolerant of relatively high levels of soil pH (i.e. 7–8) .

Absolute minima = 4.8 (SI = 0)

Source(s) and rationale: JNCC (2011) states that calcareous grassland communities can occur on soils with a pH as low as 5. An absolute minimum pH threshold of 4.8 is assigned, returning a SI value of 0.1 for pH 5.

Figure A2.6f: Soil pH suitability index for 'broad' NPBVC: Flush & Spring



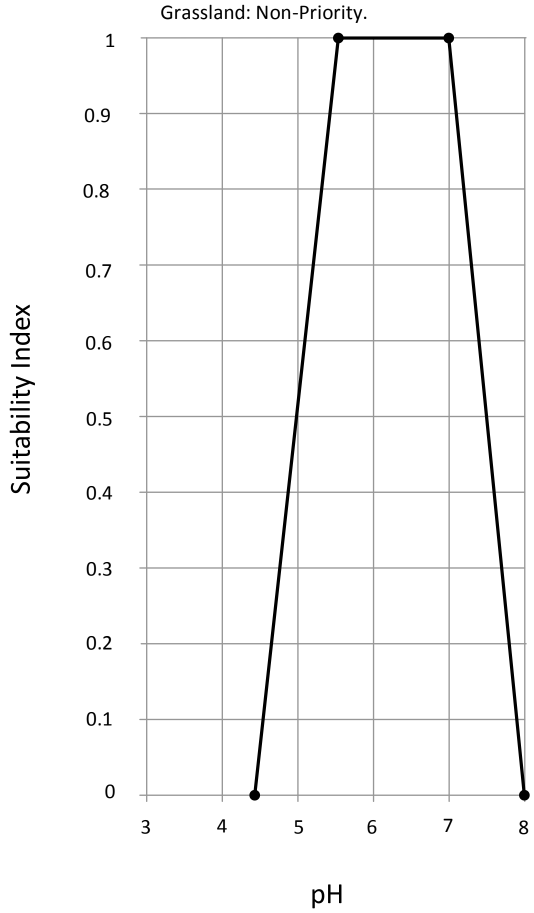
Optima: (SI = 1)

Lower = 3.0
Upper = 8.0

Source(s) and rationale:

See table A2.5

Figure A2.6g**:** Soil pH suitability index for 'Neutral' NPBVCs: Neutral Grassland: Non-Priority and Improved Grassland: Non-Priority.



Optima: (SI = 1)

Lower = 5.5
Upper = 7.0

Source(s) and rationale: JNCC (2007). See: Table A2.5 &Figure A2.6b

Absolute minima = 4.4 (SI = 0)

Source(s) and rationale: See: Table A2.5 &Figure A2.6b

Absolute maxima = 8.0 (SI = 0)

Source(s) and rationale: See: Table A2.5 &Figure A2.6b

A2.5.3.4 Elevation

Table A2.16: Summary of elevation suitability indices for all P/NPBVCs. The information is presented in alphabetical order. Cells are colour coded to correspond to the general categorisation scheme of P/NPBVC elevation characteristics in Table A2.6. Red cells: 'upland'; green cells: 'lowland'. Broadleaved Woodland includes: Broadleaved Woodland: Priority, Broadleaved Woodland: Non-Priority and Broadleaved Recently Felled Woodland. Coniferous Woodland includes: Coniferous Woodland and Coniferous Recently Felled Woodland

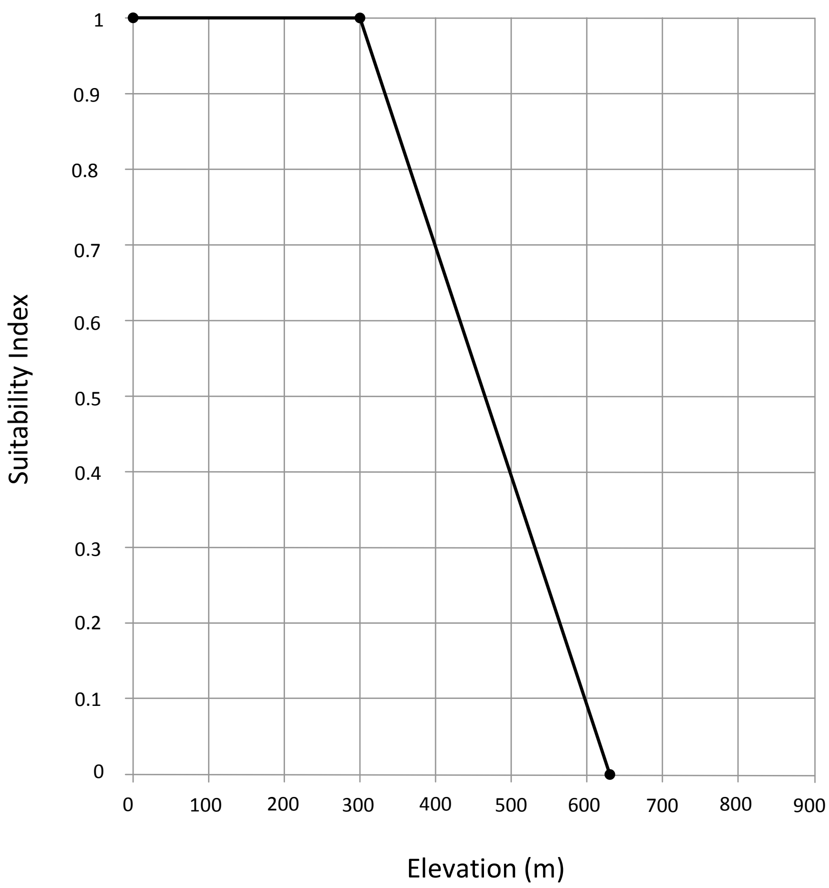
P/NPBVC	Thresholds (m)				Figure reference
	Min	LO	UO	Max	
Acid Grassland	-450*	300	800	920*	A2.7e
Arable	-	0	150	490	A2.7f
Blanket Bog	-450*	300	800	920*	A2.3
Bracken	-450†	300	500	600	A2.7g
Broadleaved Woodland	-	0	300	630	A2.7a
Calcareous Grassland	-	0	300	610	A2.7h
Coniferous Woodland	-	0	300	630	A2.7i
Fen	-	0	300	560	A2.7b
Flush & Spring	-	0	300	730	A2.7j
Heath	-450*	300	800	920*	A2.3
Heath/Acid Grassland Mosaic	-450*	300	800	920*	A2.7e
Improved Grassland: Non-Priority	-	0	160	280	A2.7k
Improved Grassland: Priority	-	0	300	400	A2.7c
Marsh	-	0	300	590	A2.7b
Modified Bog	-450*	300	800	920*	A2.7e
Neutral Grassland: Priority	-	0	300	500	A2.7c
Neutral Grassland: Non-Priority	-	0	300	500	A2.7l
Raised Bog	-	0	300	550	A2.7d
Swamp	-	0	300	360	A2.7b

*Due to the methods applied, -450m and 920m were assigned, respectively, as the absolute minimum and maximum thresholds for the upland P/NPBVCs in order to assign appropriate SI values for elevations of 0m and 900m

† Due to the methods applied, -450m was assigned, as the absolute minimum thresholds for Bracken in order to assign an appropriate SI value for elevations of 0m.

The figures for the PBVCs are provided first, followed the figures for the NPBVCs.

Figure A2.7a: Elevation suitability index for Broadleaved Woodland: Priority



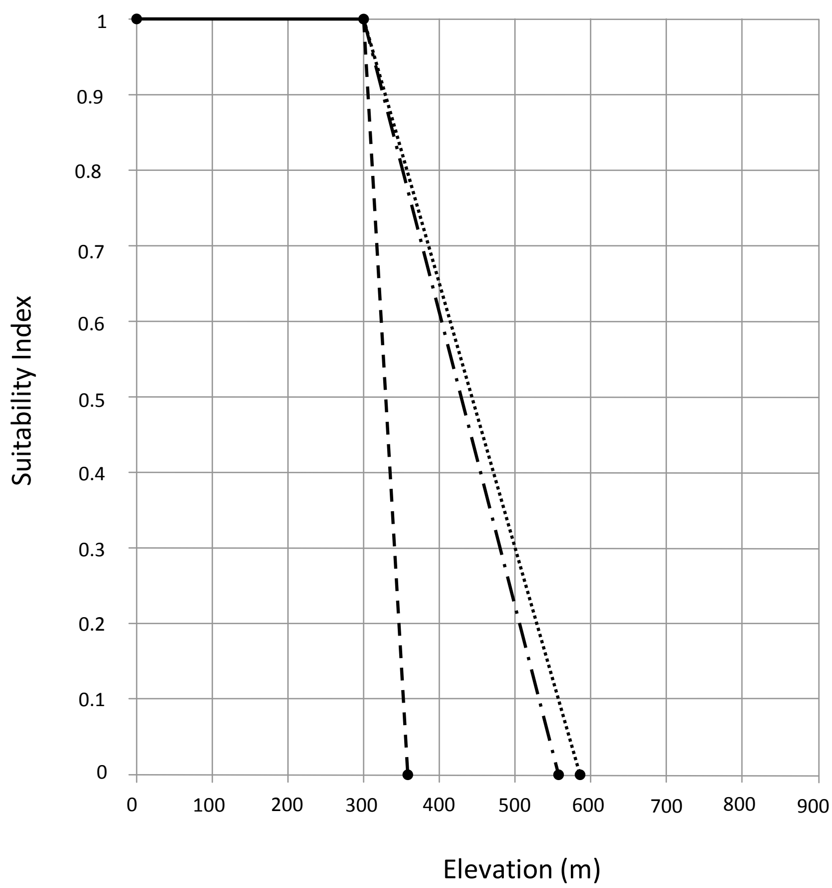
Optima: (SI = 1)
Lower = 0
Upper = 300

Source(s) and rationale: See: Section A2.5.1.4 and Table A2.6.

Absolute maxima = 630 (SI = 0)

Source(s) and rationale: The action of strong winds at higher elevations (ca. >600m) is an important factor preventing the establishment of trees (Tansley, 1949). 600m represents the natural tree line in the UK (Tansley, 1949, pp. 775). Brown *et al*. (1993) use an elevation of 600m to approximate the natural tree line of the Scottish uplands. *Fraxinus excelsior* (Ash) is an important component of a number of the semi-natural broadleaved woodland types occurring within NNP (NNPA, no date[c]). Grime *et al*. (1988) suggest an upper altitudinal limit of 600m associated with *F. excelsior*. 630m is assigned as the absolute maximum elevation threshold. The suitability index between 300 and 630m is interpolated linearly returning a SI value of 0.1 for elevations of 600m.

Figure A2.7b: Elevation suitability indices for the 'lowland' PBVCs: Fen, Marsh and Swamp



Key: — · — **= Fen**
.... **= Marsh**
— — **= Swamp**

Optima: (All PBVCs) (SI = 1)
Lower = 0
Upper = 300

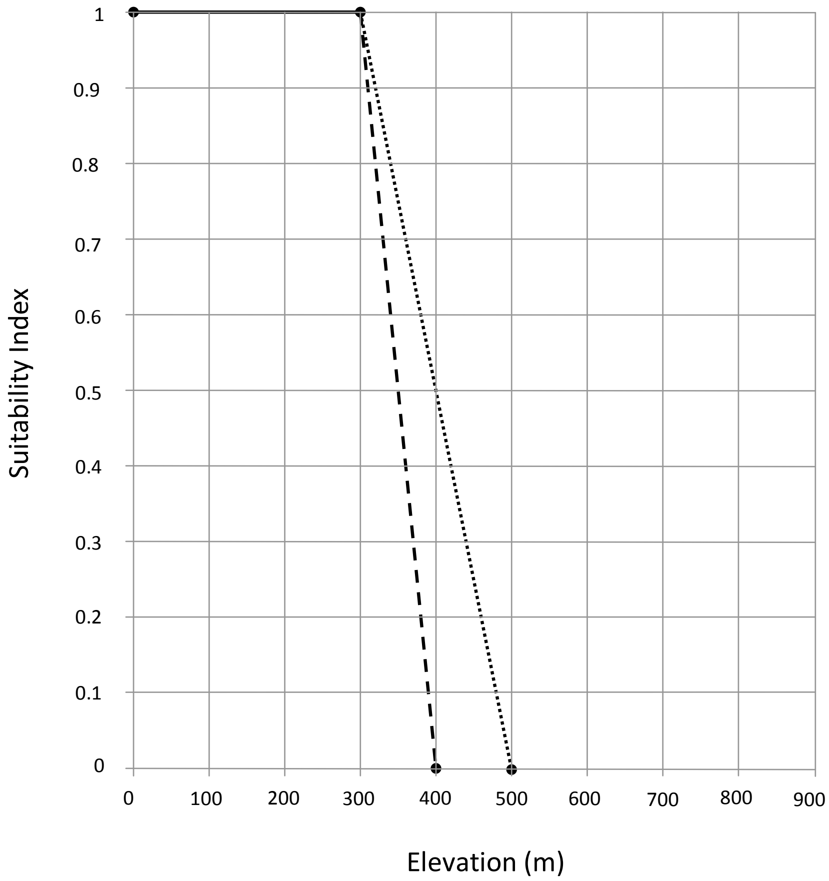
Source(s) and rationale: See Section A2.5.1.4 and Table A2.6

Absolute maxima (SI = 0)

Fen = 560
Marsh = 590
Swamp = 360

Source(s): Descriptive statistics: NNP (Table A2.12)

Figure A2.7c: Elevation suitability indices for the 'lowland' PBVCs: Improved Grassland: Priority; Neutral Grassland: Priority.



Key: ·········· = **Neutral Grassland: Priority**
– – – = **Improved Grassland: Priority**

Optima: (Both PBVCs) (SI = 1)
Lower = 0
Upper = 300

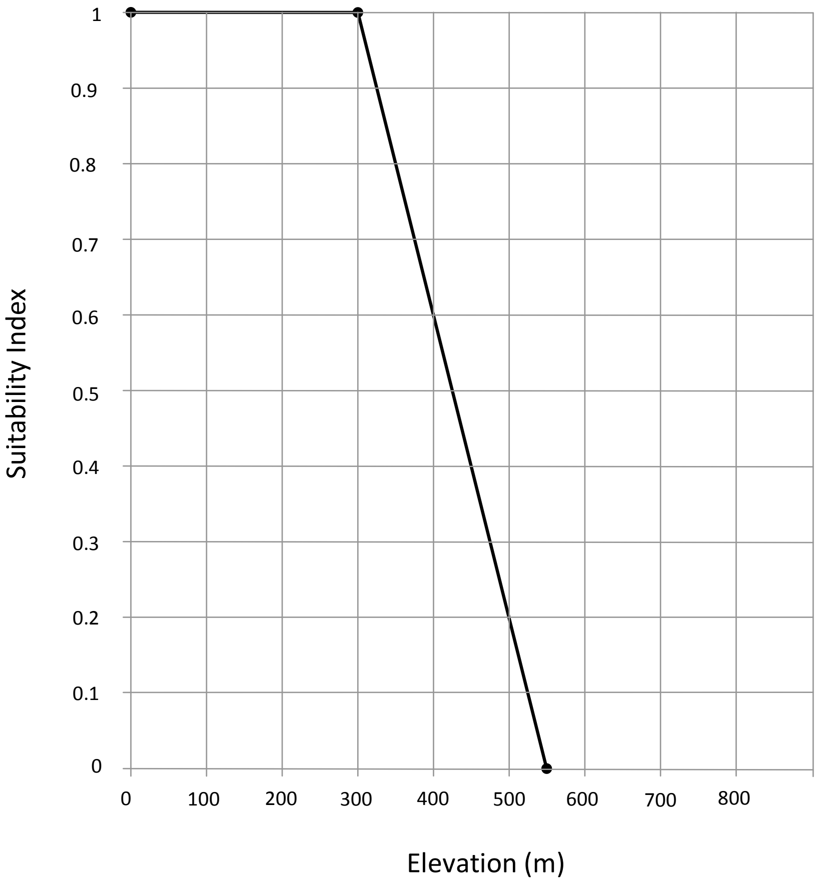
Source(s): See Section A2.5.1.4 and Table A2.6

Absolute maxima: (SI = 0)

Neutral Grassland: Priority = 500
Source(s) and rationale: The descriptive statistics for NNP show a maximum recorded occurrence of 448m and 480m for Neutral Grassland: Priority and Non-Priority, respectively. Neutral Grassland: Non-Priority is simply a type of Neutral Grassland: Priority that has undergone particularly intensive management (JNCC, 2007). It is likely that extents of Neutral Grassland: Non-Priority were originally Neutral Grassland: Priority. 500m is assigned as the absolute maximum elevation threshold for Neutral Grassland: Priority returning a SI value of 0.1 for elevations of 480m.

Improved Grassland: Priority = 400
Source(s): Descriptive statistics: NNP (Table A2.12)

Figure A2.7d: Elevation suitability index the 'lowland' PBVC: Raised Bog



Optima: (SI)

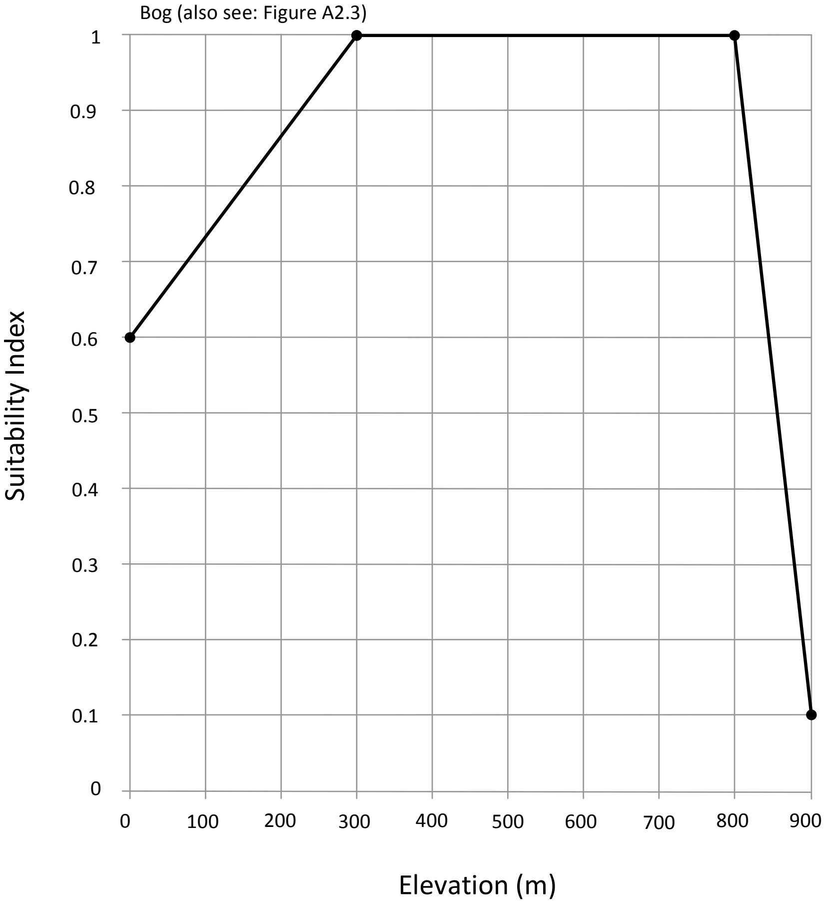
Lower = 0
Upper = 300

Source(s): See Section A2.5.1.4 and Table A2.6

Absolute maxima = 550 (SI = 0)

Descriptive statistics (Table A2.12) show that the maximum recorded occurrence of Raised Bog within NNP is at 520m. An absolute maximum elevation threshold of 550m is assigned returning an SI value of 0.1 for elevations of 520m.

Figure A2.7e: Elevation suitability index for the 'upland' NPBVCs Acid Grassland, Heath/ Acid Grassland Mosaic and Modified Bog (also see: Figure A2.3)



Optima: (SI)

Lower = 300
Source(s) and rationale: See Section A2.5.1.4, Table A2.6 and Figure A2.3.

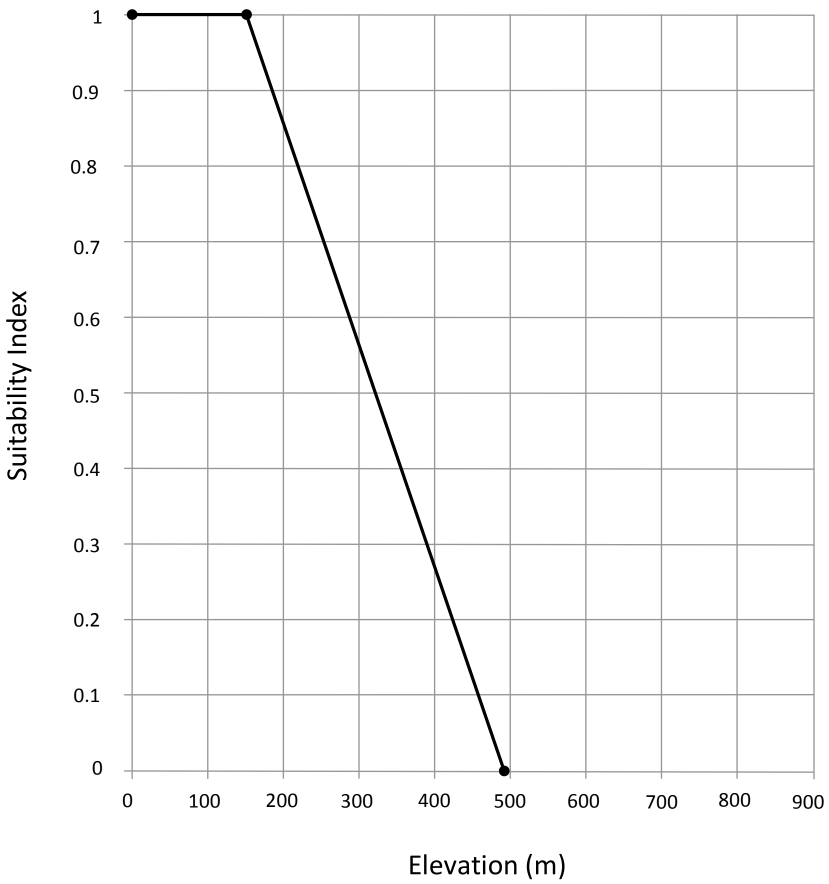
Upper = 800
Source(s) and rationale:
Acid Grassland: A number of acid grassland communities (e.g. *Nardus stricta*) occur frequently up to about 800m in the UK (Tansley, 1949, pp. 784-5).
Heath/Acid Grassland Mosaic: Based on the rationales for Acid Grassland (above) and Heath (Figure A2.3).
Modified Bog: Based on the rationale for Blanket Bog (Figure A2.3).

Absolute minima = -450* (SI = 0)
Source(s) and rationale:
Acid Grassland: Although primarily an upland type, acid grasslands occur less frequently in lowlands areas of the UK, in some places down to sea level (Tansley, 1949, pp. 515). The SI value of 0.6 for elevations of 0m is assigned to take account of this apparently moderate suitability.
Heath/Acid Grassland Mosaic: Based on the rationales for Acid Grassland (above) and Heath (Figure A2.3)
Modified Bog: Based on the rationale for Blanket Bog (Figure A2.3).

Absolute maxima = 920* (SI = 0)
Source(s) and rationale:
Acid Grassland: Grasslands dominated by *N. stricta* occur up to about 900m in the UK (Tansley, 1949, pp. 515).
Heath/Acid Grassland Mosaic: Based on the rationales for Acid Grassland (above) and Heath (Figure A2.3).
Modified Bog: Based on the rationale for Blanket Bog (Figure A2.3)

* Linear interpolation, within *IDRISI Taiga's* FSMF module, was used in the spatial application of the suitability indices (see: Section A2.2.1 in Appendix 2b). Because of these methods, -450m and 920m were assigned, respectively, as the absolute minimum and maximum thresholds for the upland P/NPBVCs. This was done in order to assign appropriate SI values for elevations of 0m and 900m. Specifically, to ensure a SI value of 0.6 was assigned for elevations of 0m it was necessary to use -450m as the value for control point 'a', within the FSMF module. Similarly, to ensure a SI value of 0.1 was assigned for elevations of 900m, 920m was used as the value for control point 'd'.

Figure A2.7f: Elevation suitability index for the 'lowland' NPBVC: Arable.



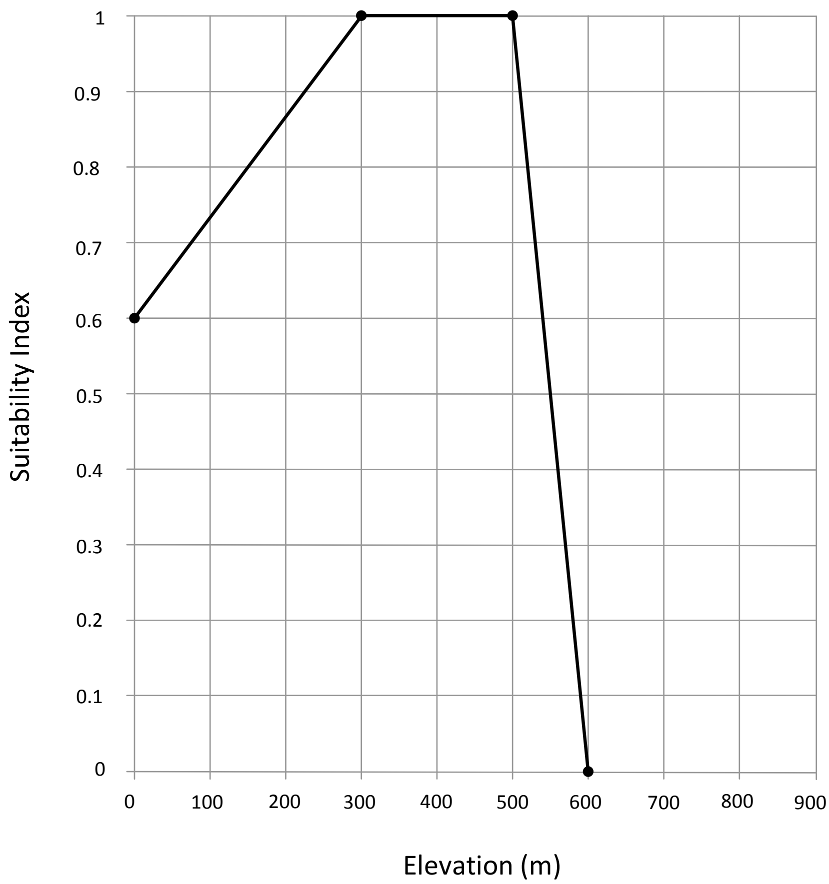
Optima: (SI = 1)
Lower = 0
Upper = 150

Source(s) and rationale: Leeds University (no date) suggest that land below 150m is most suitable for arable use.

Absolute maxima = 490 (SI = 0)

Source(s) and rationale: At higher elevations the interrelationships between crop production, management and various physical factors are likely to reduce land's suitability for arable use (Leeds University, no date). Leeds University (no date) suggest a maximum upper altitudinal threshold of 460m in relation to arable land. Here an absolute maximum elevation threshold of 490m is assigned returning a SI value of 0.1 for elevations of 460m.

Figure A2.7g: Elevation suitability index for 'upland' priority BVC: Bracken (*P. aquilinum*)



Optima: (SI = 1)
Lower = 0
Upper = 300

Source(s) and rationale: Grime et al. (1988, pp. 468) record *P. aquilinum* occurring most abundantly at elevations between 300-500m.

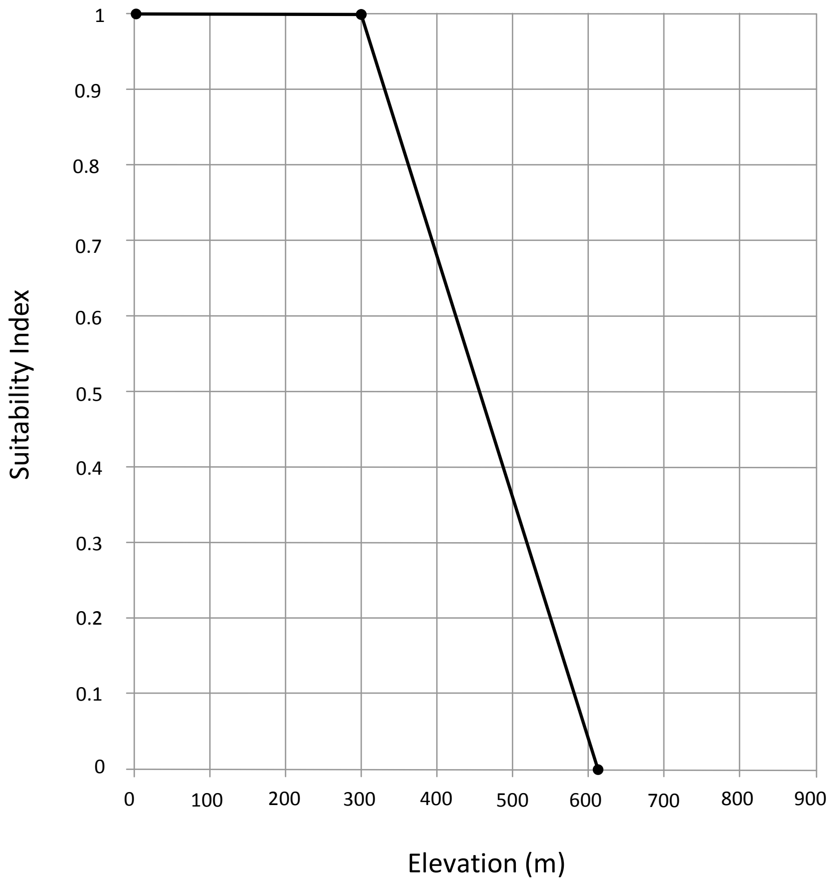
Absolute minima = 0 (SI = 0.6)

Source(s) and rationale: Grime et al. (1988, pp. 468) state that *Pteridium aquilinum* is 'common at all altitudes but suitable habitats are more frequent and abundant in upland areas'. A SI value of 0.6 is assigned for elevations of 0 to take some account of this and provide correspondence with the suitability index between 0-300m defined for other 'upland' BVCs.

Absolute maxima = 600 (SI = 0)

Source(s) and rationale: Grime et al. (1988) recorded a maximum altitudinal occurrence for *P. aquilinum* of 590m. 600m is assigned as the absolute maximum elevational threshold so that SI values of 0.1 are returned for elevations of 590m

Figure A2.7h: Elevation suitability index for the 'lowland' NPBVC: Calcareous Grassland



Optima: (SI)

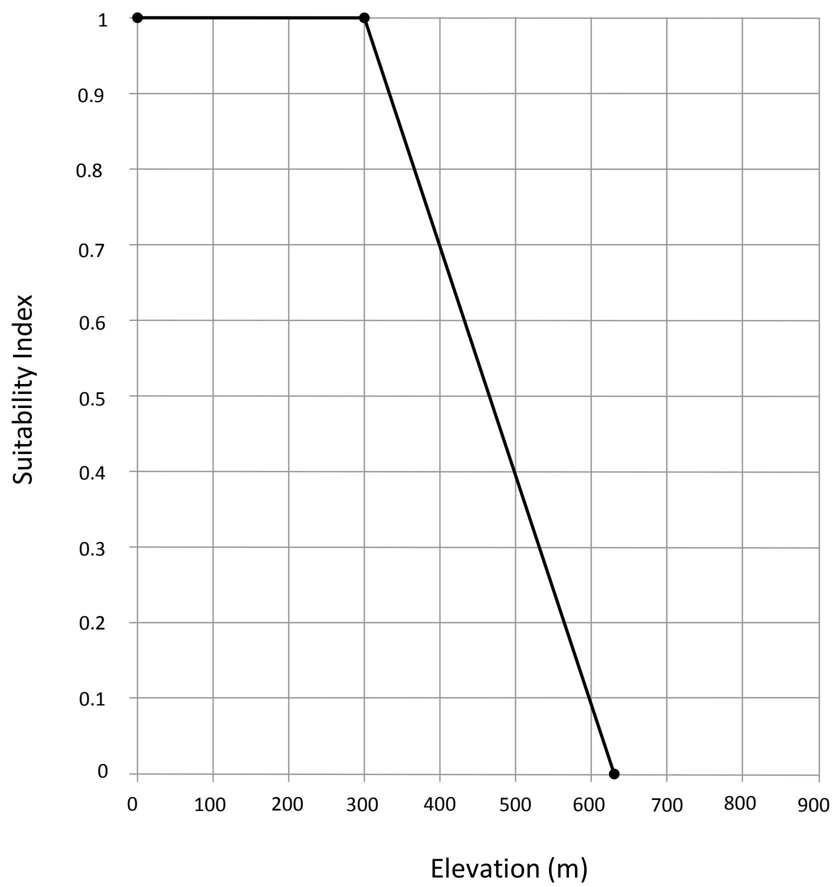
Lower = 0
Upper = 300

Source(s) and rationale: See Section A2.5.1.4 and Table A2.6

Absolute maxima = 900 (SI = 0.1)

Source(s) and rationale: Information from Fitter & Peat (1994) suggests that the average maximum recorded altitudinal occurrence of *H. nummularium, K. macrantha* and *S. minor* is approximately 580m. Here 610m is assigned as the absolute maximum elevation threshold returning a SI value of 0.1 for elevations of 580m.

Figure A2.7i: Elevation suitability index for the 'lowland' NPBVC: Coniferous Woodland



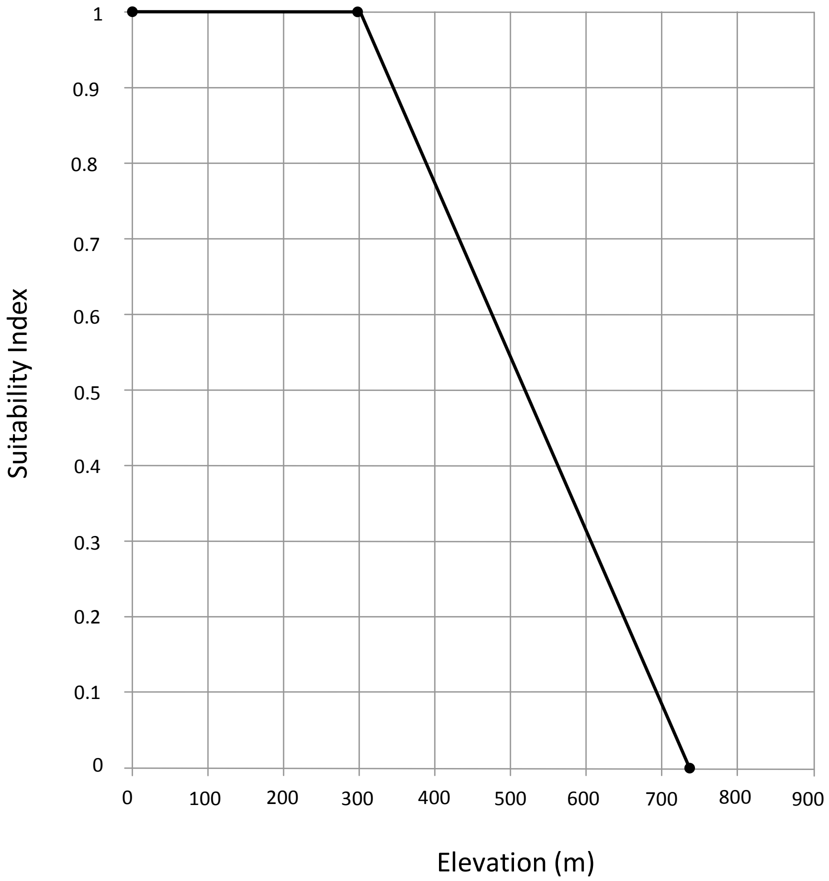
Optima: (SI = 1)
Lower = 0
Upper = 300

Source(s) and rationale: See Section A2.5.1.4 and Table A2.6

Absolute maxima = 630 (SI = 0)

Source(s) and rationale: Based on the rationale for Broadleaved Woodland: Priority (Figure A2.7a). Also, *P. Sylvestris* generally forms, along with *B. pendula* and *B. pubescens,* an elevational woodland limit, of 600m in the UK (Tansley, 1949, pp. 454).

Figure A2.7j: Elevation suitability index for 'lowland' NPBVC: Flush & Spring.



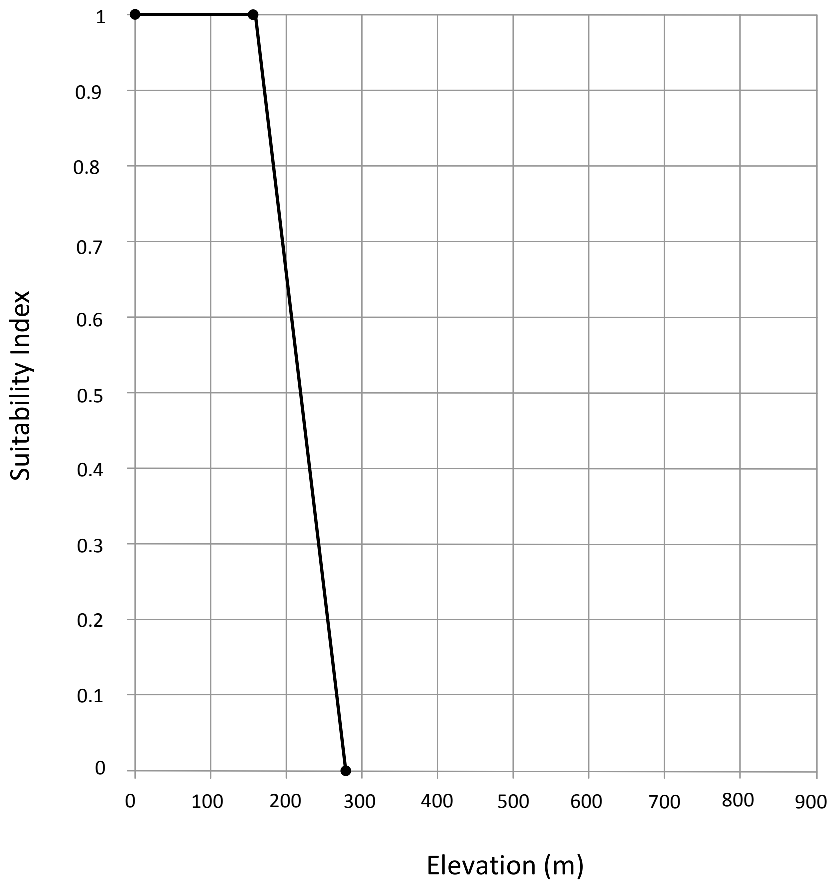
Optima: (SI = 1)
Lower = 0
Upper = 300

Source(s) and rationale: See Section A2.5.1.4 and Table A2.6

Absolute maxima: 730 (SI = 0)

Source(s): Descriptive statistics: NNP (Table A2.12)

Figure A2.7k: Elevation suitability index for lowland NPBVC: Improved Grassland: Non-Priority

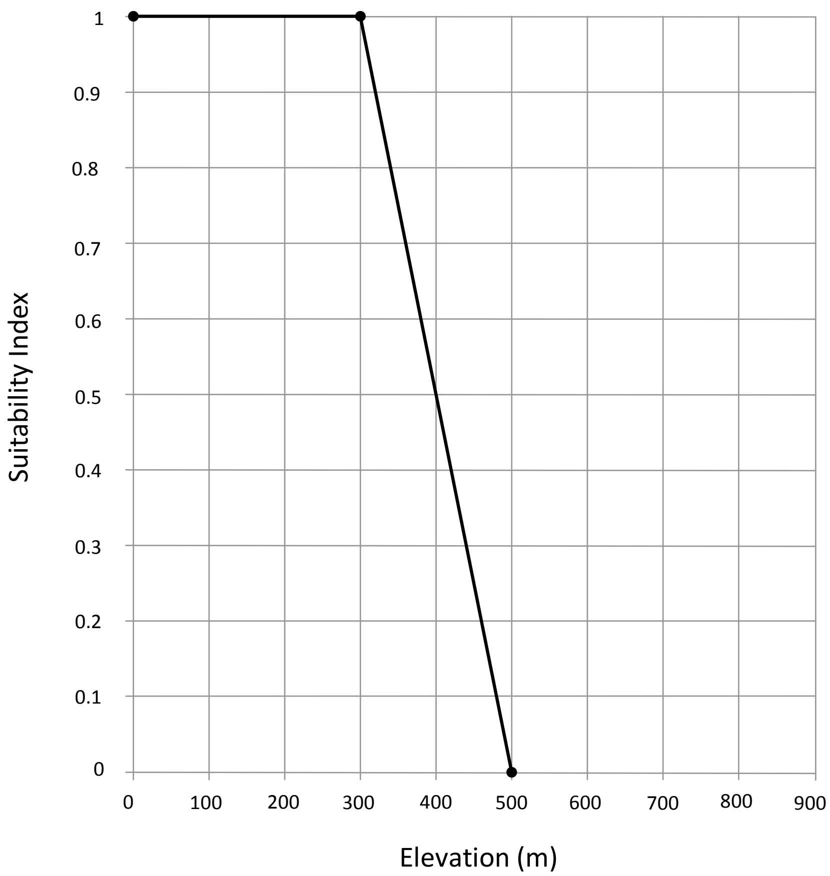


Optima: (SI = 1)
Lower = 0
Source(s) and rationale: See Section A2.5.1.4 and Table A2.6

Upper = 160
Source(s) and rationale: Based on the mean elevation associated with Improved Grassland: Non-Priority from the descriptive statistics (Table A2.12)

Absolute maxima: 280 (SI = 0)
Source(s) and rationale: Descriptive statistics: NNP (Table A2.12)

Figure A2.7l: Elevation suitability index for lowland NPBVC: Neutral Grassland: Non-Priority



Optima: (SI = 1)
Lower = 0
Upper = 300

Source(s): See Section A2.5.1.4 and Table A2.6.

Absolute maxima: 500 (SI = 0)

Source(s): Descriptive statistics: NNP (Table A2.12).

A2.5.3.5 Slope

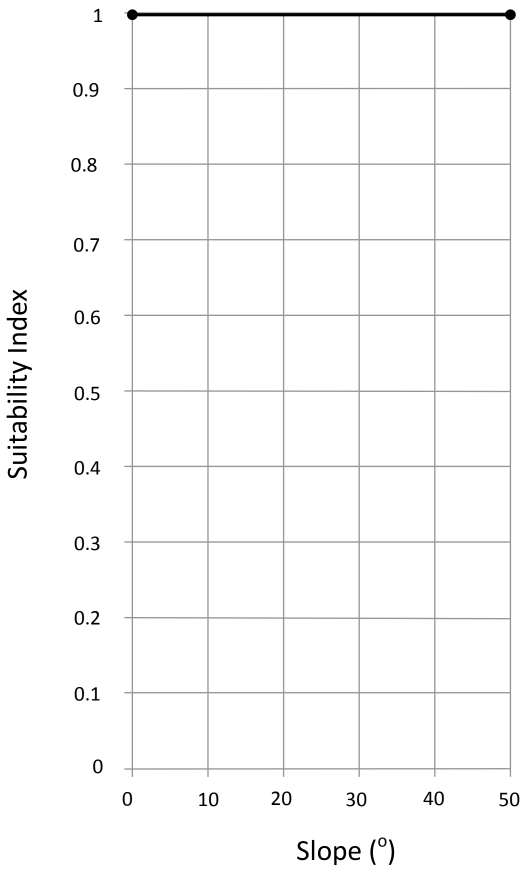
Table A2.17: Summary of slope suitability indices for all P/NPBVCs. The information is presented in alphabetical order. Broadleaved Woodland includes: Broadleaved Woodland: Priority, Broadleaved Woodland: Non-Priority and Broadleaved Recently-Felled Woodland. Coniferous Woodland includes: Coniferous Woodland and Coniferous Recently-Felled Woodland

P/NPBVC	Thresholds (^{o})				Figure reference
	Min	LO	UO	Max	
0	-	0	50	-	A2.8e
Arable	-	0	3	29	A2.8f
Blanket Bog	-	0	7	36	A2.4
Bracken	-	0	50	-	A2.8e
Broadleaved Woodland	-	0	50	-	A2.8a
Calcareous Grassland	-2*	3	50	-	A2.8g
Coniferous Woodland	-	0	50	-	A2.8e
Fen	-	0	3	20	A2.8b
Flush & Spring	-	0	3	38	A2.8h
Heath	-	0	50	-	A2.8a
Heath/Acid Grassland Mosaic	-	0	50	-	A2.8e
Improved Grassland: Non-Priority	-	0	7	12	A2.8i
Improved Grassland: Priority	-	0	7	28	A2.8c
Marsh	-	0	3	34	A2.8b
Modified Bog	-	0	7	36	A2.8j
Neutral Grassland: Priority	-	0	7	32	A2.8c
Neutral Grassland: Non-Priority	-	0	7	32	A2.8i
Raised Bog	-	0	1	12	A2.8d
Swamp	-	0	3	11	A2.8b

* Due to the methods applied, -2^o was assigned as the absolute minimum threshold for Calcareous Grassland in order to assign appropriate SI values for slopes of 0^o.

The figures for the PBVCs are provided first, followed the figures for the NPBVCs.

Figure A2.8a: Slope suitability index for PBVCs: Broadleaved Woodland: Priority and Heath



Optima: (SI = 1)

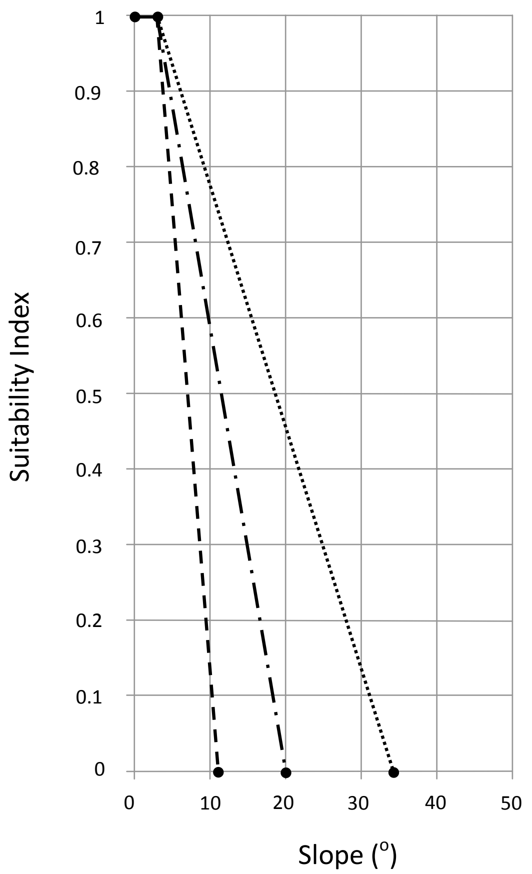
Lower = 0
Upper = 50

Source(s) and rationale:

Broadleaved Woodland: *Priority*: All of the broadleaved species considered in the analysis (Table A2.11) are recorded by Grime *et al*. (1988) as occurring abundantly on slopes between 0-50^o.

Heath: Upland heaths occur frequently on steep and gentle slopes as well as level ground (Tansley, 1949, pp. 763). Species commonly associated with Heath (e.g. *C. vulgaris*) occur abundantly on slopes between 0-50^o (Grime *et al*., 1988).

Figure A2.8b: Slope suitability indices for PVCs: Fen, Marsh and Swamp



Key: — · — · = **Fen**
············ = **Marsh**
— — — = **Swamp**

Optima: (All PBVCs) (SI = 1)
Lower = 0
Upper = 3

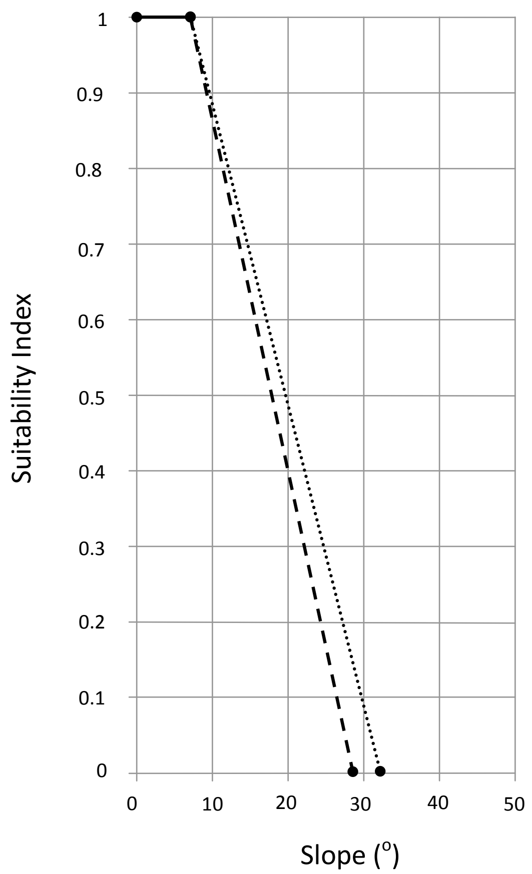
Source(s) and rationale: Fen, Marsh and Swamp are closely related PBVC types whose occurrence is associated with water courses and/or waterlogged hollows and depressions (JNCC, 2007; Tansley, 1949). In relation to Fen specifically, JNCC (2007, pp. 59) states that it is associated with the lower slopes of valleys, waterlogged basins and stream flood plains. Marsh 'occurs on *more or less* level areas' (JNCC, 2007, pp. 53). Swamp is a type 'in which the ...water level is above the soil surface' (Tansley, 634). These points suggest a proclivity for flat to gently sloping ground. 3^o marks the upper limit of gentle slopes (Table 2.9c).

Absolute maxima (SI = 0)

Fen = 20
Marsh = 34
Swamp = 11

Source(s): Descriptive statistics: NNP (Table A2.12)

Figure A2.8c: Slope suitability index for PBVCs: Improved Grassland: Priority and Neutral Grassland: Priority.



Key: ………… = **Neutral Grassland: Priority**
– – – – = **Improved Grassland: Priority**

Optimum: (Both PBVCs) (SI = 1)
Lower = 0
Upper = 7

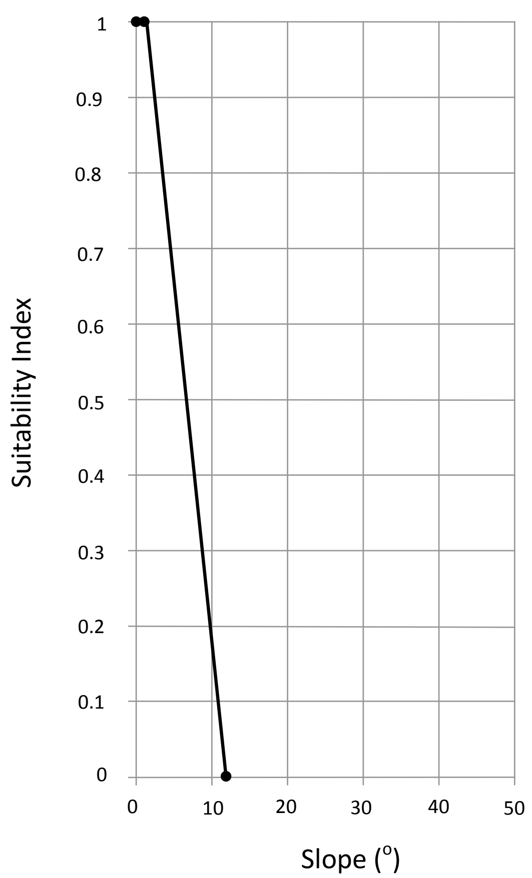
Source(s) and rationale: Both PBVCs are typically associated with more mature, productive soils and more intensive management for agriculture (JNCC, 2007; Tansley, 1949). Such soils tend to develop, and associated management occurs most readily, on low slopes. 7^{o} is assigned as the upper limit of optimum suitability to correspond with the upper limit of 'moderate' slopes defined by Jarvis *et al*. (1984). 7^{o} also corresponds to the upper slope limit associated with land capability class 2, which has only minor limitations for *arable* use (Leeds University, No date). It is assumed that such land represents optimum conditions for productive grassland pastures which are generally less demanding than arable crops (DEFRA, 2010).

Absolute maxima (SI =0)

Neutral Grassland: Priority = 32
Improved Grassland: Priority = 28

Source(s): Descriptive statistics: NNP (Table A2.12)

Figure A2.8d: Slope suitability index for PBVC: Raised Bog

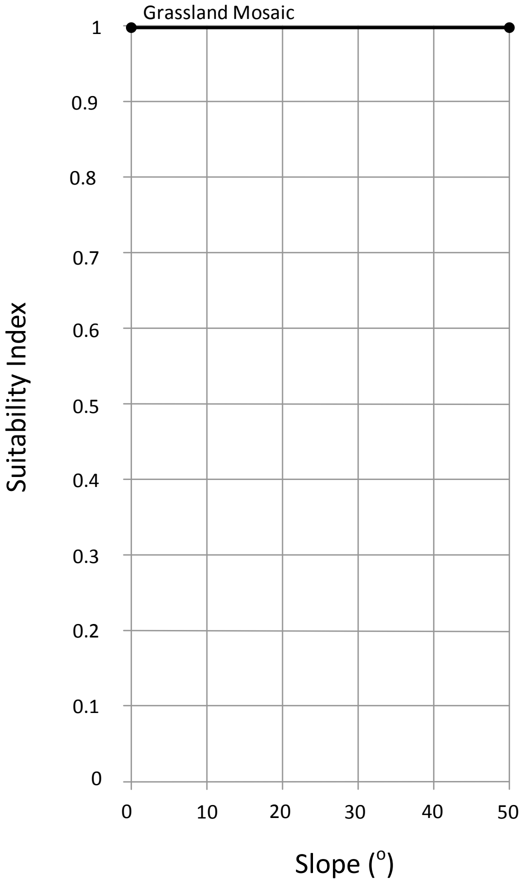


Optima: (SI = 1)
Lower = 0
Upper = 1

Source(s) and rationale: 'Raised bogs are found on estuarine flats, river flood plains and other level areas with impeded drainage in the lowlands' (JNCC, 2007, pp. 57). 1^{o} marks the upper limit of 'level' ground (Table A2.9c).

Absolute maxima = 12 (SI = 0)
Source(s): Descriptive statistics: NNP (Table A2.12)

Figure A2.8e: Slope suitability index for NPBVCs: Acid Grassland, Bracken, Coniferous Woodland and Heath/Acid Grassland Mosaic



Optima: (SI = 1)

Lower = 0
Upper = 50

Source(s) and rationale:

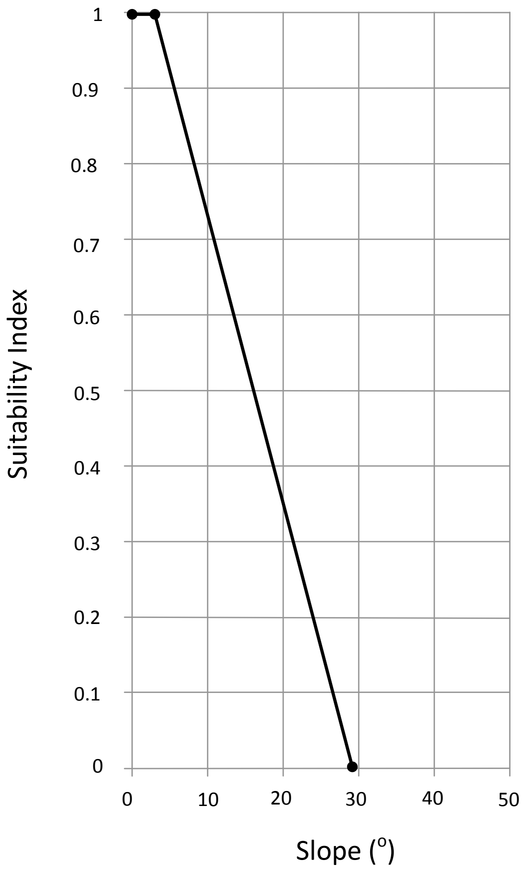
P. aquilinum occurs on a variety of slopes up to 80° and appears most abundantly on slopes between 0-60° (Grime *et al*., 1988).

Acid grasslands can occur abundantly on hillsides and mountain slopes (Tansley, 1949, pp. 494; 499), as well as more gentle slopes and level areas (Tansley, 1949, pp. 515). Slopes between 0-50° are therefore regarded as suitable for Acid Grassland.

Heath/Acid Grassland Mosaic is also likely to occur frequently on slopes between 0-50°, based on the rationales for Acid Grassland (above) and Heath (Figure A2.8a).

Quantitative information on slope for Coniferous Woodland (*P. Sylvestris*) from Grime et al. (1988) and Fitter & Peat (1994) was not available. *P. sylvestris* has very similar habitat requirements to those of Birch (Table A2.6). *B. pubescens* and *B. pendula* can occur on a variety of slopes up to 80° and frequently on slopes of 50° or less (Grime *et al*., 1988).

Figure A2.8f: Slope suitability index for NPBVC: Arable

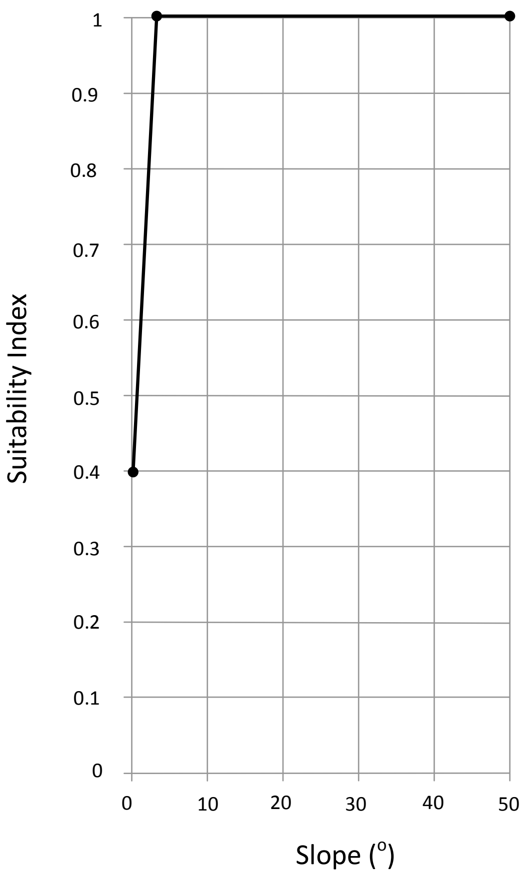


Optima: (SI = 1)
Lower = 0
Upper = 3

Source(s) and rationale: Land with a gradient of 0 –3° is most suitable for arable use (Leeds University, no date).

Absolute maxima = 29 (SI = 0)
Source(s): Descriptive statistics: NNP (Table A2.12)

Figure A2.8g: Slope suitability index for NPBVC: Calcareous Grassland



Optima: (SI = 1)
Lower = 3
Upper = 50

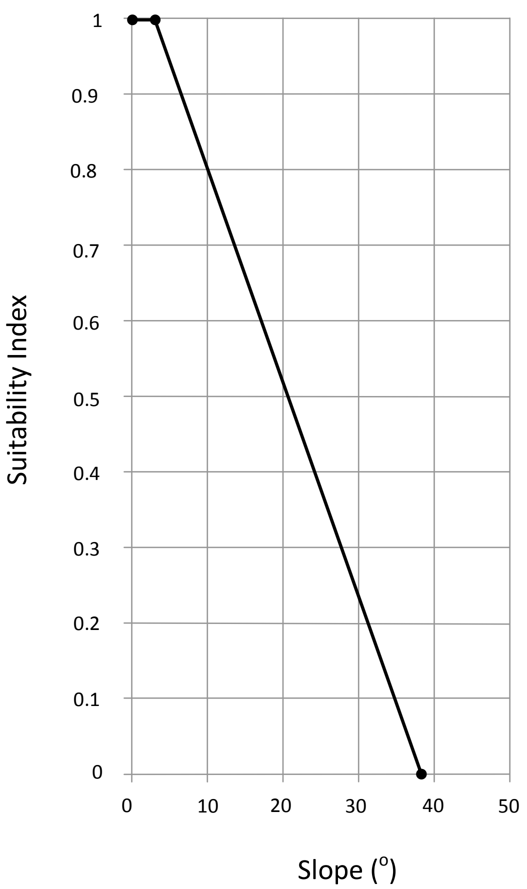
Source(s) and rationale: Calcareous grasslands are typically associated with rounded hills and contours (Lane, 1994; Tansley, 1949). Calcareous grasslands have a requirement for basic, relatively dry, conditions. Such conditions are unlikely to occur on level to gently sloping ground (Tansley, 1949). A lower optimum slope threshold of 3^{o} is assigned to coincide with the lower limit of 'moderate' slopes (Table A2.9c). This is largely conjectural but coincides with the upper limit of optimum suitability in terms of slope for the 'wetland' PBVCs (e.g. Fen, Marsh and Swamp).

Absolute minima = -2* (SI = 0)

Calcareous grasslands may occur on flat or gently sloping ground with sufficiently permeable geology and dry climate (Tansley, 1949). A SI value of 0.4 is assigned to slopes of 0^{o} to take some account of this. The SI value is largely conjectural. The suitability index between 0 – 3^{o} is interpolated linearly.

* Due to the methods applied, -2^{o} was assigned as the absolute minimum threshold for Calcareous Grassland in order to assign appropriate SI values for slopes of 0^{o}.

Figure A2.8h: Slope suitability index for NPBVC: Flush & Spring



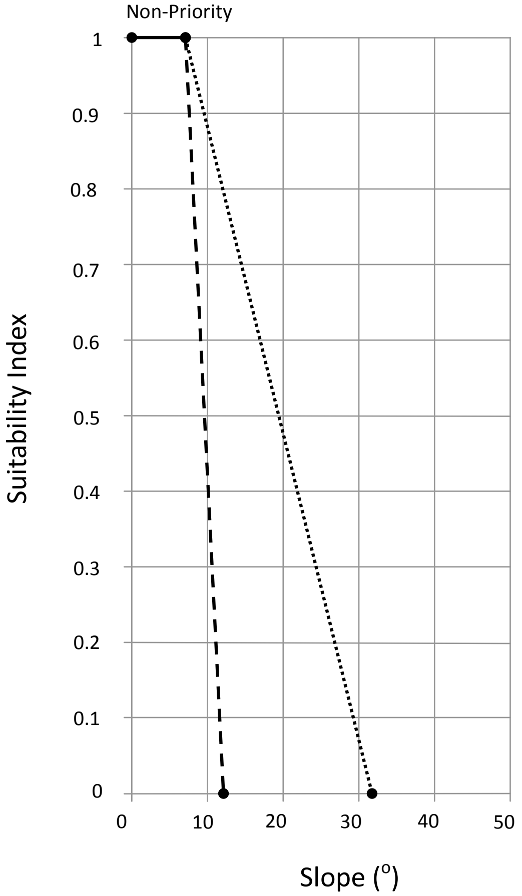
Optima: (SI = 1)

Lower = 0
Upper = 3

Source(s) and rationale: Flushes and springs typically occur on gently sloping ground (JNCC, 2007, pp. 57). The upper limit of gently sloping ground from Jarvis *et al*. (1984) is 3^{o}. However, flushes and springs are often integral components of marshes and fens (JNCC, 2007, pp. 53; 59). This and the soil water characteristics of Flush & Spring (Table A2.2) imply that the NPBVC is also likely to be associated with level ground. The suitability index between 0 and 3^{o} is interpolated linearly.

Absolute maxima = 38 (SI = 0)
Source(s): Descriptive statistics: NNP (Table A2.12)

Figure A2.8i: Slope suitability index for NPBVCs: Improved Grassland: Non-Priority and Neutral Grassland: Non-Priority



Key: ··········· = **Neutral Grassland: Non-Priority**
– – – – = **Improved Grassland: Non-Priority**

Optima: (Both NPBVCs) (SI = 1)
Lower = 0
Upper = 7

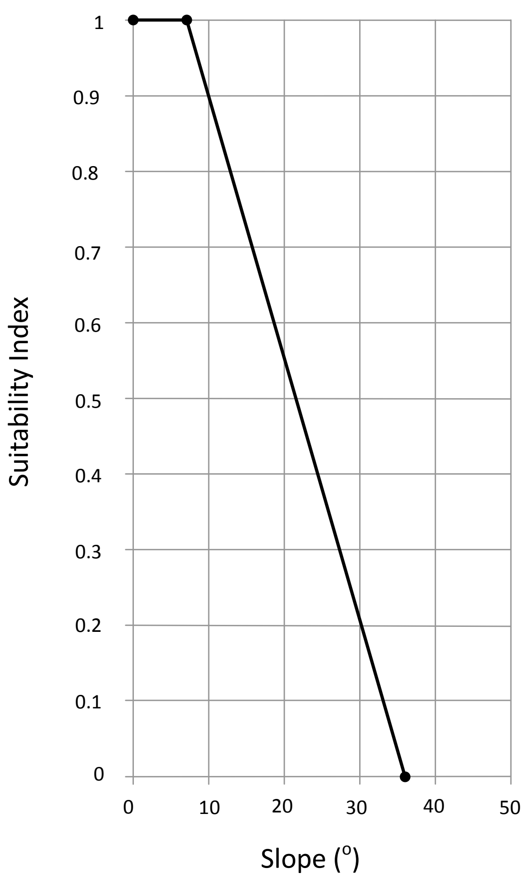
Source(s) and rationale: Both NPBVCs are typically associated with more intensive management (Tansley, 1949; JNCC, 2007). This is for agricultural or amenity purposes for Neutral Grassland: Non-Priority and Improved Grassland: Non-Priority, respectively. It is assumed that flat to moderately sloping ground is most suited to such purposes. 7° marks the upper limit of moderate slopes (Jarvis *et al*., 1984) and also corresponds to the upper slope limit associated with land capability class 2, which has only minor limitations for *arable* use (Leeds University, No date) (Also see: Figure A2.8c).

Absolute maxima: (SI = 0)

Neutral Grassland: Non-Priority = 32
Improved Grassland: Non-Priority = 12

Source(s): Descriptive statistics: NNP (Table A2.12)

Figure A2.8j: Slope suitability index for NPBVC: Modified Bog



Optima: (SI = 1)
Lower = 0
Upper = 7

Source(s) and rationale: Modified bogs are blanket or raised bogs that are drying or degraded (JNCC, 2007, pp. 57). The suitability index for Blanket Bog in relation to slope is therefore used for Modified Bog (See: Figure A2.4).

Absolute maxima = 36 (SI = 0)

Source(s) and rationale: See Blanket Bog (Figure A2.4).

Appendix 3 (appendices to Chapter 5)

Table A3: Categorisation of P/NPBVCs into 'Modified' and 'Semi-natural' types for analysis of Matrix Vulnerability. The 'Other' category includes a mixture of P1HS categories regarded as either 'Modified' or 'Semi-natural' types. The 'Other' category was therefore disaggregated and reclassified as appropriate. * Bracken is categorised as a 'Modified' type due to its invasive characteristics.

Code	P/NPBVC	P1HS Category	Categorisation	Current Coverage (cells)	CF Coverage (cells)	GFG Coverage (cells)	Current Proportion of Total	CF Proportion of Total	GFG Proportion of Total
1	Bracken	C11	M*	13336	12983	13336	3.24	3.15	3.24
2	Heath	D1, D2	SN	29619	79717	79819	7.20	19.36	19.39
3	Improved Grassland: Priority	B4	M	18510	20582	12102	4.50	5.00	2.94
4	Acid Grassland	B11, B12	SN	104249	70594	60736	25.32	17.15	14.75
5	Neutral Grassland: Priority	B21	M	974	3478	591	0.24	0.84	0.14
6	Fen	E31, E32, E33	SN	1939	6179	1939	0.47	1.50	0.47
7	Blanket Bog	E161	SN	13373	24180	13373	3.25	5.87	3.25
8	Broadleaved Woodland (BLW): Non-Priority	A112, A21, J14, A131, A132	SN	3140	3140	3140	0.76	0.76	0.76
9	Coniferous Woodland	A121, A122	SN	74552	74552	82007	18.11	18.11	19.92
10	Arable	J11	M	2364	1554	3782	0.57	0.38	0.92
11	Other	A22	N	911	911	911	0.22	0.22	0.22
		A31	N	1914	1914	1914	0.46	0.46	0.46
		A32	N	547	547	547	0.13	0.13	0.13
		A33	N	176	176	176	0.04	0.04	0.04
		B6	N	7	7	7	0.00	0.00	0.00
		C12	M	5987	5987	5987	1.45	1.45	1.45
		C31	N	143	143	143	0.03	0.03	0.03
		C32	N	282	282	282	0.07	0.07	0.07
		E4	N	27	27	27	0.01	0.01	0.01

		G1	N	617	617	617	0.15	0.15	0.15
		G2	N	605	605	605	0.15	0.15	0.15
		I	N	1521	1521	1521	0.37	0.37	0.37
		J13	N	7	7	7	0.00	0.00	0.00
		J2	N	54	54	54	0.01	0.01	0.01
		J3	M	180	180	180	0.04	0.04	0.04
		J4	N	134	134	134	0.03	0.03	0.03
		J5	N	440	440	440	0.11	0.11	0.11
12	Calcareous Grassland	B31, B32	SN	31	31	31	0.01	0.01	0.01
13	BLW: Priority	A111	SN	3461	16140	6922	0.84	3.92	1.68
14	BLW: Recently Felled	A41, A43	SN	5	5	5	0.00	0.00	0.00
15	Modified Bog	E17, E18	SN	3594	28	3559	0.87	0.01	0.86
16	Heath/Acid Grassland Mosaic	D5, D6	SN	52369	19531	52369	12.72	4.74	12.72
17	Improved Grassland: Non-Priority	J12	M	180	49	180	0.04	0.01	0.04
18	Neutral Grass: Non-Priority	B22	M	24653	14200	16082	5.99	3.45	3.91
19	Coniferous: Recently Felled	A42	SN	4674	3460	1050	1.14	0.84	0.26
20	Flush & Spring	E21, E22, E23	SN	328	328	328	0.08	0.08	0.08
21	Marsh	B5	SN	46284	46284	46284	11.24	11.24	11.24
22	Swamp	F1	SN	170	170	170	0.04	0.04	0.04
23	Raised Bog	E162	SN	311	931	311	0.08	0.23	0.08
Totals				**411668**	**411668**	**411668**	**100**	**100**	**100**
Total proportion of 'Modified' P/NPBVCs							**16.08**	**14.33**	**12.69**

Appendix 4 (appendices to Chapter 7)

Tables A4a-e: Summarising results and trends for Climate Stress, Matrix, Geometric and Overall Vulnerability for each PBVC for each time slice for the Cheviot (a); Cheviot Fringe (b); NSH (c); BMF (d); and TG (e). The formatting of cells and arrows follows the same as that used for Tables 7.3 and 7.6.

(a) Cheviot

PBVC	Climate Stress					Matrix					Geometry					Overall				
	C	CF	T	GFG	T	C	CF	T	GFG	T	C	CF	T	GFG	T	C	CF	T	GFG	T
BB	0.424	0.277	↘	0.256	↘	0.056	0.043	↘	0.026	↘	0.479	0.578	↗	0.479	→	0.928	1.075	↗	0.856	↘
BLWP	0.400	0.178	↘	0.204	↘	0.377	0.436	↗	0.369	↘	0.636	0.605	↘	0.673	↗	1.484	1.158	↘	1.145	↘
Fen	0.790	0.540	↘	0.540	↘	0.008	0.008	→	0.008	→	0.564	0.564	→	0.564	→	1.417	1.088	↘	1.088	↘
Heath	0.501	0.317	↘	0.341	↘	0.089	0.148	↗	0.072	↘	0.573	0.602	↗	0.562	↘	1.151	1.045	↘	1.059	↘
IGP	0.367	0.257	↘	0.038	↘	-	-	-	-	-	0.496	0.529	↗	0.521	↗	0.954	0.653	↘	0.523	↘
Marsh	0.687	0.268	↓	0.268	↓	0.182	0.143	↘	0.131	↘	0.664	0.664	→	0.664	→	1.496	1.085	↘	1.072	↘
NGP	0.463	0.067	↘	0.008	↓	-	-	-	-	-	0.590	0.528	↘	0.606	↗	1.028	0.564	↘	0.601	↘
RB	N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A	
Swamp	0.250	0.250	→	0.250	→	0.059	0.055	↘	0.055	↘	0.853*	0.853*	→	0.853*	→	1.162	1.157	↘	1.157	→

(b) Cheviot Fringe

PBVC	Climate Stress					Matrix					Geometry					Overall				
	C	CF	T	GFG	T	C	CF	T	GFG	T	C	CF	T	GFG	T	C	CF	T	GFG	T
BB	N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A	
BLWP	0.413	0.130	↘	0.198	↘	0.560*	0.535	↘	0.372	↘	0.633	0.632	↘	0.592	↘	1.610	1.331	↘	1.142	↘
Fen	N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A	
Heath	N/A	0.688	N/A	0.665	N/A	N/A	0.427	N/A	0.308	N/A	N/A	0.562	N/A	0.571	N/A	N/A	1.701	N/A	1.570	N/A
IGP	0.353	0.187	↘	0.005	↘	-	-		-		0.462	0.489	↗	0.462	→	0.832	0.690	↘	0.469	↘
Marsh	0.508	0.250	↘	0.250	↘	0.487	0.468	↘	0.405	↘	0.680	0.680	→	0.680	→	1.653	1.398	↘	1.335	↘
NGP	0.263	0.168	↘	0.145	↘	-	-		-		0.668	0.594	↘	0.665	↘	0.978	0.690	↘	0.790	↘
RB	N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A	
Swamp	N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A	

(c) NSH

PBVC	Climate Stress					Matrix					Geometry					Overall				
	C	CF	T	GFG	T	C	CF	T	GFG	T	C	CF	T	GFG	T	C	CF	T	GFG	T
BB	0.252	0.755	↑	0.756	↑	0.064	0.048	↘	0.031	↘	0.437	0.485	↗	0.437	→	0.760	1.297	↗	1.241	↗
BLWP	0.424	0.114	↘	0.130	↘	0.352	0.351	↘	0.180	↘	0.621	0.620	↘	0.600	↘	1.413	1.090	↘	0.894	↘
Fen	0.500	0.250	↘	0.250	↘	0.000	0.092	↗	0.000	→	0.576	0.644	↗	0.576	→	1.076	0.986	↘	0.826	↘
Heath	0.500	0.528	↗	0.556	↗	0.231	0.218	↘	0.176	↘	0.602	0.597	↘	0.611	↗	1.333	1.412	↗	1.403	↗
IGP	0.382	0.200	↘	0.002	↘	-	-		-		0.530	0.556	↗	0.555	↗	0.886	0.776	↘	0.558	↘
Marsh	0.468	0.250	↘	0.250	↘	0.321	0.228	↘	0.149	↘	0.663	0.663	→	0.663	→	1.454	1.141	↘	1.062	↘
NGP	0.251	0.193	↘	0.020	↘	-	-		-		0.398	0.569	↗	0.517	↗	0.651	0.728	↗	0.580	↘
RB	N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A	
Swamp	N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A		N/A	N/A		N/A	

(d) BMF

PBVC	Climate Stress					Matrix					Geometry					Overall				
	C	CF	T	GFG	T	C	CF	T	GFG	T	C	CF	T	GFG	T	C	CF	T	GFG	T
BB	0.266	0.619	↗	0.593	↗	0.056	0.053	↘	0.052	↘	0.452	0.547	↗	0.452	→	0.671	1.291	↗	1.227	↗
BLWP	0.436	0.080	↘	0.109	↘	0.331	0.307	↘	0.264	↘	0.647	0.614	↘	0.625	↘	1.418	0.968	↘	0.977	↘
Fen	0.714	0.267	↓	0.293	↓	0.053	0.061	↗	0.043	↘	0.432	0.600	↗	0.432	→	1.182	0.926	↘	0.743	↘
Heath	0.493	0.422	↘	0.449	↘	0.093	0.103	↗	0.096	↗	0.544	0.577	↗	0.571	↗	1.129	1.097	↘	1.132	↗
IGP	0.397	0.101	↘	0.005	↘	-	-		-		0.525	0.548	↗	0.554	↗	0.934	0.608	↘	0.554	↘
Marsh	0.624	0.269	↘	0.269	↘	0.178	0.144	↘	0.123	↘	0.641	0.641	→	0.641	→	1.448	1.052	↘	1.031	↘
NGP	0.386	0.101	↘	0.117	↘	-	-		-		0.568	0.587	↗	0.592	↗	0.993	0.683	↘	0.730	↘
RB	0.125	0.735	↑	0.568	↑	0.000*	0.026	↗	0.000*	→	0.270	0.541	↗	0.270	→	0.395	1.294	↑	0.837	↗
Swamp	0.264	0.264	→	0.264	→	0.012	0.009	↘	0.000*	↘	0.669	0.669	→	0.669	→	1.014	1.012	↘	1.002	↘

(e) TG

PBVC	Climate Stress					Matrix					Geometry					Overall				
	C	CF	T	GFG	T	C	CF	T	GFG	T	C	CF	T	GFG	T	C	CF	T	GFG	T
BB	0.250	0.753	↑	0.750	↑	0.325	0.099	↘	0.301	↘	0.429	0.445	↗	0.429	→	1.004	1.325	↗	1.480	↗
BLWP	0.467	0.063	↓	0.067	↓	0.498	0.386	↘	0.246	↘	0.692	0.618	↘	0.692	→	1.638	1.041	↘	1.043	↘
Fen	0.718	0.270	↓	0.283	↓	0.088	0.139	↗	0.015	↘	0.452	0.634	↗	0.452	→	1.255	1.035	↘	0.736	↘
Heath	0.443	0.571	↗	0.561	↗	0.094	0.191	↗	0.100	↗	0.623	0.621	↘	0.613	↘	1.162	1.351	↗	1.257	↗
IGP	0.398	0.077	↘	0.000	↘	-	-		-		0.507	0.507	→	0.564	↗	0.889	0.576	↘	0.564	↘
Marsh	0.664	0.256	↓	0.256	↓	0.335	0.281	↘	0.240	↘	0.650	0.650	→	0.650	→	1.623	1.192	↘	1.151	↘
NGP	0.347	0.022	↘	0.055	↘	-	-		-		0.574	0.559	↘	0.638	↗	0.895	0.674	↘	0.804	↘
RB	N/A	0.775	N/A	N/A	N/A	N/A	0.008	N/A	N/A	N/A	N/A	0.483	N/A	N/A	N/A	N/A	1.245	N/A	N/A	N/A
Swamp	0.250	0.250	→	0.250	→	0.067	0.062	↘	0.053	↘	0.661	0.661	→	0.661	→	0.978	0.973	↘	0.965	↘