Changes in Soil Characteristics Under Different Aged Plantations of Corsican Pine (*Pinus nigra*) at Chopwell Woodland Park, Gateshead, UK.

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ABSTRACT

This study examines the pedogenic processes and temporal changes occurring in soils across six different aged plantations of Corsican pine (*Pinus nigra*), which were otherwise similar in their environmental characteristics, including geology, slope angle and aspect, altitude and land use history.

A representative soil profile was sampled, on a horizon basis, and a further 10 topsoil samples were collected, on a grid basis, from each plantation. Properties determined in the laboratory included pH, organic carbon content, particle size distribution, exchangeable base content (Ca, Mg, K, Na), total free and organically-bound iron content, and lead and zinc concentrations. Morphological and chemical changes within the soil profiles were examined to shed light on the processes and pathways of soil formation, and one-way analysis of variance (ANOVA) was used to compare topsoil characteristics between the different plantations.

Morphological and chemical changes within the soil profiles indicated that organic matter accumulation and mor humus formation, acidification, clay translocation (lessivage) and incipient podzolisation were the dominant pedogenic processes. There are very few systematic age-related changes in soil morphological or physical and chemical characteristics, possibly due to a combination of young stand ages, high topsoil variability, soil mixing due to drainage operations and silvicultural practices. There are, however, a number of statistically significant but non-systematic differences in soil properties between the different aged plantation blocks. Possible associations between these differences and age-related litter production and root growth, and silvicultural operations such as understory control, plantation thinning and selective harvesting are explored.

Key Words: Corsican pine, plantation age, silviculture soil formation.

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INTRODUCTION

About 1.5 million ha of land in Britain is covered by coniferous forest (Malcolm *et al.*, 2001), composed almost entirely of plantations of non-native species and established since 1900 on previously un-wooded ground or, as at Chopwell Woodland Park, on sites converted from ancient semi-natural woodland (Ferris *et al.,* 2000). McCarthy (2006) argues that of all land uses, conifer afforestation has had the biggest visual impact on the British landscape. The acidifying effects of conifers on soils is also well documented (e.g. Messenger, 1980; Miles, 1986; Howard and Howard, 1989; Peterken, 2001) and some studies have shown this to be age-related (e.g. Birkeland, 1984; Mellor, 1987; Alriksson and Olsson, 1995). Stutzer (1998), for example, found that top soil pH values decreased from 5.0 to 4.0 within 30 years of planting in response to high rates of acid litter accumulation, whilst Griffiths and Swanson (2001) found no significant stand age related differences in soil pH. Certini *et al.,* (1998) found that soil acidification was more rapid under Corsican pine than under other species such as Douglas fir or Silver birch, although changes in soil pH became less marked with increasing distance from the trunks. Soil acidity is closely related to other properties including organic content, exchangeable base content and metal contents such as iron, lead and zinc, which often show similar age-related trends (Mellor, 1987; Ellis and Mellor, 1995).

Podzolisation is prevalent in soils under coniferous plantations on base-deficient parent materials and can become evident through eluvial bleaching and corresponding redistribution of humus and sesquioxides after only a few decades (Certini *et al.,* 1998; Stutzer, 1998; Peterken, 2001; Mokma *et al.,* 2004). In some podzolised soils, however, the eluvial horizon is absent due to masking by strong parent material colours or anthropogenic mixing of soil horizons (Blaser *et al.,* 1997; Stutzer, 1998). Nevertheless, Mellor (1987) found decreases in total iron content in eluvial horizons and corresponding increases in illuvial horizons, with surface age over a 250 year period on wooded neoglacial moraines in Norway. Similarly, Alriksson and Olsson (1995) and Mokma *et al.,* (2004) found increases in topsoil organic carbon content with stand age. In subsoils, however, changes in organic carbon content were found to be less regular (Stutzer, 1998; Peichl and Arain, 2006).

Relatively few studies of soil changes in relation to stand age exist within the UK, perhaps due to the relatively young age of many forestry plantations, the complexity of local soil variability and soil disturbance resulting from forestry operations. However, detailed and accurate recording of species and planting dates on UK forestry stock maps, consistency of management practices and the relatively small size of plantation blocks ensure that variations in environmental influences on soil development, such as parent material, topography, biota and climate are minimal. Such a high degree of environmental control means that UK forestry plantations may, in fact, be well suited to studies of soil changes in relation to stand age. In this study, we examine changes in soil profile and topsoil characteristics across six different aged plantations of Corsican pine (*Pinus nigra*) at Chopwell Woodland Park in Gateshead, UK.

STUDY AREA

Chopwell Woodland Park is an area of 360 ha of mixed conifer and broadleaved woodland managed by the Forestry Commission (Fig. 1). The area is 150-200 m above sea level and is dominated by sandstones, shales and mudstones of the Carboniferous Coal Measures Series, also containing coal seams of varying thicknesses. Although most of the site is drift free, deposits of glacial till occur on the lower slopes and the River Derwent flows along its southern margin. Dominant soils include surface water gleys, and forest brown earths (Cooke, 1987). Climate is cool, humid and temperate in nature with relatively mild winters and cool summers. Mean annual rainfall and temperature are 750 mm and 8.0 ^{o}C, respectively (Jarvis, 1977).

Figure 1 near here

Chopwell forest dates back to the 12th century when it consisted mainly of deciduous trees dominated by oak. Many of these trees were felled in the 17th and 18th centuries for ship building and bridge construction and the area was re-planted with oak and larch; much of this was subsequently felled as part of the First World War effort. The Forestry Commission took over management of the area in 1923 and began a major replanting programme with emphasis on conifer species. During the 1930s and 1940s, the area was used for training purposes by a local drainage school and, despite being freely drained, linear drains were cut at 5-6 m intervals rather than the more usual spacing of 20 m; the drainage lines can be seen clearly in aerial photographs of the area. Drains were constructed manually by hand digging with a cutter and turning the topsoil over; trees were then planted in the inverted turf. This was a very labour intensive practice and is now largely mechanised. Following planting, the first thinning phase takes place after about 20-25 years, with subsequent thinning phases every 6-7 years. After the fourth thinning phase, only the final crop trees remain and tree density is reduced from the original planting density of around 2700 trees per hectare to 1200 trees per hectare. Clear-felling then takes place after about 50-55 years with another planting cycle following after 12-18 months. As soil quality in the area is good and yield classes are relatively high (18-20 for Corsican pine), fertilisers are not required. However, herbicides are sometimes used to remove competing ground flora such as bracken, brambles and other weed species.

The area was recognised as a Woodland Park in 1993 and more recently as a Plantation on Ancient Woodland (PAWS), with emphasis now being placed on natural regeneration of broad-leaved species and thinning out of the conifer species. Today the park is dominated by Corsican pine (*Pinus nigra*), Scots pine (*Pinus sylvestris*), Japanese larch (*Larix kaempferi*) and Oak (*Quercus robur*) with some mixed broadleaf and conifer plantations. Only a few remnants of the ancient woodland survive on some of the steeper crags above the River Derwent. Whilst relatively rural in character, Chopwell Woodland Park is only a few km away from Gateshead and Newcastle upon Tyne, both major centres of urban and industrial activity.

MATERIALS AND METHODS

As part of the site selection process, Forestry Commission stock maps were examined with a view to finding a number of plantation blocks containing the same tree species but with a range of planting dates. In addition, the plantation blocks should have the same land use history and be in close proximity to each other in order to minimise variations in soil parent material, slope steepness, aspect and altitude, and climatic characteristics. Six plantation blocks consisting of Corsican pine (*Pinus nigra*), planted between 1920 and 1990 were thus selected for investigation (Fig. 1). These stands were first cycle Corsican pine plantations, planted on mixed oak and larch woodland, located at altitudes of 165-180 m above sea level with slope angles of 0-3 ^{o}

and on parent materials consisting predominantly of weathered sandstone from the Carboniferous Coal Measures Series. It proved difficult to find a suitable control site under ancient, predominantly oak woodland because remnants of this vegetation type exist only on steeper slopes adjacent to the River Derwent. Consequently, whilst parent materials and altitudes are broadly similar, slope angles are steeper at around 15 ^{o}.

Following preliminary exploration using a screw auger, a representative soil profile was selected for description and sampling from within each stand, and from a nearby area of ancient woodland; samples were collected from each identifiable soil horizon (Mellor, 1987). In addition, 10 topsoil samples (0-10 cm) were collected, using a systematic grid based approach, from each stand (Echeverria *et al.*, 2004).

Soil samples were oven-dried at 105 ^{o}C, ground using a pestle and mortar and passed through a 2 mm sieve prior to laboratory analysis. Soil properties determined included reaction (pH), organic carbon, exchangeable base (Ca, Mg, K, Na) content, texture, total and organically-bound iron contents and lead and zinc concentrations (Avery and Bascomb, 1974; Rowell, 1994). Soil pH was determined in distilled water using a 1:2.5 w/v ratio and organic carbon was determined using the Walkley-Black digestion. Exchangeable base content was determined by flame emission and atomic absorption spectrometry following ammonium acetate extraction. Texture was determined by sieving and laser diffraction following treatment with hydrogen peroxide and sodium hexa-meta phosphate (calgon). Total free iron and organically-bound iron were determined by atomic absorption spectrometry following dithionite and pyrophosphate extraction, respectively. Lead and zinc concentrations were determined by atomic absorption spectrometry following aqua-regia digestion. These properties have been used in other forest soil studies, thus enabling comparisons to be made. They can also change rapidly over relatively short timescales and are useful indicators of the operation of a range of pedogenic processes (Alriksson and Olsson, 1995; Dahlgren *et al.*, 1997). Lead and zinc concentrations were determined with a view to investigating the changing nature of urban and industrial pollution in the area.

One-way analysis of variance (ANOVA) was used to compare topsoil characteristics between the different plantations and therefore to establish the significance of any age-related differences (Paul *et al.*, 2002). Changes in soil profile morphology were used to shed light on the processes and pathways of soil formation.

RESULTS

The first two sections will focus on findings from the soil profiles, whereas the third section will focus largely on the topsoil analyses.

Soil physical characteristics

No systematic changes in soil profile morphology were observed in relation to stand age. At all sites, soil profiles were characterised by a very dark brown to black Ah horizon of about 10 cm in thickness containing abundant woody roots, bleached sand grains and a sharp lower boundary. Below was a brown to yellowish brown Bw horizon of about 20 cm in thickness, with a predominantly sandy texture, containing few stones and with a diffuse lower boundary leading into the yellowish brown weathered sandstone parent material. The soil profile from the control site, although located on a steeper slope, was remarkably similar in morphology and colour to those under the plantation stands, although the horizons were rather deeper with an Ah horizon of 18 cm and a Bw horizon of 30 cm. In all cases, the soils are classified as acid brown earths of the Rivington 1 series (Jarvis *et al.*, 1984).

In all six soil profiles, organic carbon contents decrease with increasing depth, ranging from about 4 % to 10 % in the surface Ah horizon to mostly less than 2 % in the subsurface Bw and C horizons (Fig. 2a). Values were similar in the control site profile ranging from 9.5 % in the Ah horizon to 5.8 % and 3.5 % in the Bw and C horizons, respectively. There are no systematic variations in organic carbon contents with stand age, with values in the Ah horizon being greatest in the youngest stand, followed by a slight decrease, then a slight increase with increasing stand age and then a marked decrease in the oldest stand. In the subsurface Bw and C horizons, organic carbon contents appear to be greatest in the middle aged stands, with lowest values in the youngest and oldest stands. The textural characteristics of all profiles are similar being predominantly sandy loam, with medium and fine sand together comprising approximately 50 % by weight of the soil mineral fraction. The Ah horizon has a slightly coarser sandy texture than the Bw and C horizons, with highest clay and fine silt contents found mainly in the Bw horizon (Fig. 2b).

Figures 2 and 3 near here

Soil chemical characteristics

Total exchangeable base contents are highest in the Ah horizon of each profile with the exception of the 1970 and 1920 stands where they are highest in the C and Bw horizons, respectively (Fig. 2c). This pattern was mirrored in the control profile although total exchangeable base contents were somewhat higher, ranging from 2.1 me/100g in the Ah horizon to 1.2 me/100g and 1.0 me/100g in the Bw and C horizons, respectively. In the Ah horizon, variations in total exchangeable base content with stand age appear to mirror those of organic carbon. This is not the case in the subsurface Bw and C horizons, however, where total exchangeable base contents show no clear association with stand age. In all stand profiles, soil pH values are acidic and decrease with increasing depth, ranging from about 2.9 in the Ah horizon to about 4.3 in the C horizon (Fig. 2d). Values in the control profile, however, are higher in the Ah horizon with a value of 3.8 but similar in the subsurface horizons. Although variations are small, pH values in the Ah horizons appear to mirror those of organic carbon and total exchangeable base contents. In the Bw and C horizons, pH values decrease with stand age in the three youngest stands but then appear to level out with further increases in stand age.

In all but the two oldest stands, organically-bound iron (Fep) contents decrease with increasing depth in the soil (Fig. 3a). Conversely, in all but the youngest stand, total free iron (Fed) contents increase with increasing depth (Fig 3b). Inorganic iron contents (Fed – Fep) are about three to six times higher than organically-bound iron contents. Only Fe(d) contents were determined in the control profile where values increase from 0.51 % in the Ah horizon to 0.70 % and 0.76 % in the Bw and C horizons, respectively; this pattern is remarkably similar to the stand profiles. In the Ah horizons, variations in organically bound iron content with stand age appear to mirror those of organic carbon and total exchangeable bases; in the Bw and C horizons contents are greatest in the youngest and oldest stands. Total free iron contents in the Ah horizon are consistently low in all but the youngest stand, while contents in the Bw horizon increase systematically with stand age in all but the two oldest stands; C horizon contents are similar across all but the oldest stand where the highest content of 1.5 % is found. In all profiles, lead and zinc concentrations are relatively low with generally lower values in the Ah horizons than in the subsoil Bw and C horizons (Figs. 3c and d). Although no clear variations in metal content with stand age were observed, for either metal, concentrations appeared to be somewhat lower in soils of the oldest stands.

Statistical analyses

Descriptive statistics for the 10 topsoil samples collected from each stand are shown in Table I. All samples are characteristically acidic with high organic carbon contents and generally low exchangeable base contents. Total free iron contents are relatively high, whilst lead and zinc contents are mostly low. Organic carbon, lead and zinc contents show particularly high variability.

Table I near here

One-way ANOVA was carried out to test for significance of difference in topsoil properties between the six stands (Table II). With the exception of organically-bound iron, all properties displayed statistically significant differences, although like the soil profile results, these were not systematically related to age. For topsoil pH, the two oldest stands had noticeably lower values than the remaining four stands. Lead concentrations were highest in the middle of the age range, whilst total free iron contents were highest at the oldest and youngest stands. Organic carbon, exchangeable base and zinc contents all showed the same pattern with noticeably lower values in the 1940 and 1990 stands than in the other stands, all of which had similar values.

Table II near here

DISCUSSION

Pedogenic processes

Despite disturbance resulting from drainage and thinning operations, there is clear morphological evidence for soil formation within the soil profiles, and whilst some of this may be inherited from the woodland soils prior to planting, particularly in the subsoil, changes in the topsoil are likely to have occurred following planting of the

Corsican pine stands. The key pedogenic processes identified are organic matter accumulation and decomposition, acidification, lessivage and, with the exception of the control site, incipient podzolisation. These processes operate together and should not be seen as mutually exclusive (Ellis and Mellor, 1995). Evidence of organic matter accumulation can be seen from the extensive litter cover and dark brown to black topsoil Ah horizons, present in all six profiles, and the high organic carbon contents in these horizons. The dark colour and sharp lower boundary, characteristic of these Ah horizons, suggests a degree of decomposition to form an acidic mor humus with limited bioturbation (Alriksson and Olsson, 1995; Lilienfein *et al.,* 2003). The control site profile is somewhat different from the conifer stand profiles, being located under mature deciduous woodland. Here, whilst organic matter accumulation and decomposition, acidification and lessivage are evident, incipient podzolisation and mor humus formation are not. Podzolisation fails to occur due to greater faunal mixing, microbial degradation and adsorption of chelating organic substances onto clay surfaces thus preventing iron movement (Payton and Rimmer, 1992). These authors also suggest that increased faunal mixing and bacterial decay lead to mull rather than mor humus formation in soils under well established deciduous woodland.

Acidification is common in acid brown soils on freely draining, sandy and base-deficient parent materials such as those found at Chopwell Woodland Park (Jarvis *et al.* 1984). Acidification is particularly evident in the topsoil Ah horizons, where pH values are 3.1 or less, due to high rates of acidic litter supply from conifer plantations (Alriksson and Olsson, 1995). Even in the control profile, under well established deciduous woodland, the Ah horizon has a pH value of 3.8. In all six stand profiles, pH values increase with increasing depth, often by more than 0.5 of a pH unit, a trend that is characteristic of leached, acidified soils (Stutzer, 1998; White, 2006). As expected in such acidic soils, exchangeable base contents are relatively low but are greatest in the upper soil horizons due to their association with organic matter (Rosberg *et al.,* 2006). There is little evidence of downward translocation of exchangeable bases into the Bw horizons, although it is possible that they could be leached out of the profile altogether in such coarse, freely drained parent materials (Franzmeier and Whiteside, 1963; Alriksson and Olsson, 1995).

In all six stand profiles, and in the control profile, clay content increases markedly with depth from the Ah to the Bw horizon. In four of the stand profiles clay content in the Bw horizon is also noticeably greater than in the C horizon. Maximum clay content in the Bw horizon is indicative of clay translocation or lessivage, a common process in acidified brown soils (Ellis and Mellor, 1995; Gardiner and Miller, 2004).

Organically-bound iron contents are greatest in topsoil Ah horizons due to the abundance of organic matter (Lilienfein *et al.,* 2003). However, the presence of bleached quartz grains in the Ah horizon and evidence of downward translocation of both organically-bound and total free iron, but only in the older soil profiles, indicates incipient podzolisation. This finding is supported in other studies of young soils including Mellor (1987), Stutzer (1998) and Munroe *et al.* (2007).

Both lead and zinc contents are low, corresponding with background concentrations found elsewhere in the UK (Thornton, 1991). Lowest concentrations are found in topsoil Ah horizons indicating low levels of atmospheric deposition from urban and industrial sources in the region. This is not surprising given that Chopwell Woodland Park is located to the southwest, and therefore up-wind, of the major sources of pollution in Tyneside, prevailing winds being mainly from the west or southwest. Highest metal concentrations are in fact found in the subsoil mineral horizons, suggesting that lead and zinc are derived either from weathering of coal bearing soil parent materials or from downward translocation, both of which have been reported from elsewhere in the region (Mellor and Bevan, 1999; Mellor, 2001).

Temporal patterns and pathways

There are no systematic changes in profile morphology with plantation age in the soils at Chopwell Woodland Park. Despite the apparent lack of systematic temporal trends, however, ANOVA reveals that almost all topsoil properties show statistically significant but non-systematic differences with plantation age. Such non-systematic or irregular, age-related changes in soil properties have also been reported in a number of other similar studies (Certini *et al.,* 1998; Stutzer, 1998; Griffiths and Swanson, 2001; Paul *et al.,* 2002; Zinn *et al.,* 2002; Lilienfein *et al.,* 2003; Peichl and Arain, 2006).

The irregular age-related changes might be explained by the young plantation ages, soil disturbance due to drainage operations and silvicultural practices. Mokma *et al*., (2004) estimated that podzols require between a few hundred and a few thousand years to develop, a time span that is considerably greater than that available in the soils of this study. Moreover, Certini *et al.*, (1998) indicated that chemical evidence of eluviation is not evident in young soils under Corsican pine. Morphological and chemical evidence for soil development may be further masked by profile homogenisation resulting from ground preparation and ploughing prior to planting (Stutzer, 1998). Profile disturbance is likely to be particularly significant at Chopwell Woodland Park as a result of the intensive drainage operations practiced as part of the drainage school training programmes. The young surface ages and profile mixing may also account for the high degree of spatial variability observed in relation to most of the topsoil properties determined.

Irregular age-related changes in topsoil properties, particularly organic carbon, may also be explained by age-related changes in litter production, root growth and organic matter decomposition rates, and silvicultural practices, particularly thinning operations (Paul *et al*., 2002). At Chopwell Woodland Park, highest organic carbon contents are found in topsoils from the second youngest (1980) and oldest (1920) stands, with lowest contents in the second oldest (1940) and youngest (1990) stands (Table I). Although one might expect highest and lowest organic carbon contents in the oldest and youngest stands, respectively, in response to age-related changes in litter supply, decomposition and root development (Paul *et al*., 2002), it is more difficult to account for the progressive decline in topsoil organic carbon contents between the 1980 and 1940 stands. One possible explanation for the decline is reduced litter supply in response to thinning operations (Henderson, 1995), which began about 20 years after planting and every 6-7 years thereafter until the fourth and final thinning phase. Consequently, the 1990 stand has not yet been subjected to thinning, the 1980 stand has only recently experienced its second thinning phase, whilst the remaining stands have all experienced four thinning phases. The oldest stand, however, has had almost 50 years to recover from its last phase of thinning. Interestingly, temporal changes in total exchangeable base contents and pH closely follow the changes in organic carbon contents, indicating a strong association between these properties. In the subsoil horizons (Fig. 2), particularly the C horizon, soil pH shows a regular decrease with increasing stand age reflecting progressive leaching and acidification (Mellor, 1987; Alriksson and Olsson, 1995; Certini *et al*., 1998).

The longer term pathway of soil formation in Chopwell Woodland Park might be viewed as follows: Prior to the 18th century, the dominant vegetation was semi-natural, mixed oak woodland, documented as far back as the 12th century. Dominant soils under this type of woodland, relicts of which still exist elsewhere in the region, are brown forest soils, which are slightly acidified with well mixed mull humus in the topsoil and evidence of clay translocation in illuvial Bt horizons (Jarvis *et al.*, 1984). Large scale re-planting with oak and larch in the 19th century is likely to have enhanced the process of acidification, favouring mor humus formation. It is also likely that re-planting allowed lessivage to continue and led to the initiation of podzolisation. In 1923 the Forestry Commission took over management of the area and implemented wholesale harvesting and drainage programmes. Consequent site disturbance probably obliterated earlier phases of soil development and horizonation, and caused extensive mixing of the acidified soil materials (Stutzer, 1998). Subsequent planting of conifers then led to the re-establishment of organic matter accumulation with mor humus formation, lessivage and podzolisation. The latter two processes, however, are very much in the early stages of their development (Certini *et al.*, 1998). Management at Chopwell Woodland Park now favours a gradual replacement of conifer species with more native broadleaved species such as oak, which is likely to allow soils to revert back to their original pathway of development towards the brown forest soils found at the control site and elsewhere in northern England under this woodland regime (Payton and Rimmer, 1992).

CONCLUSIONS

This study aimed to investigate the pedogenic processes and temporal changes occurring in soils beneath six Corsican pine (*Pinus nigra*) stands ranging in age from 17 to 87 years. The key pedogenic processes operating within the soils studied were found to be a combination of organic matter accumulation and mor humus formation, acidification, clay translocation (lessivage) and incipient podzolisation. Lead and zinc contents were found to be low and to be derived principally from natural weathering of coal-bearing soil parent materials or downward translocation, rather than from airborne urban and industrial pollution.

Very few systematic, age related changes in soil properties were observed, although ANOVA revealed a number of statistically significant but non-systematic differences with stand age. These non-systematic differences were argued to result from the young plantation ages and short time-scale available for soil formation, soil profile mixing resulting from drainage operations prior to planting, and silvicultural operations such as understory control, plantation thinning and selective harvesting.

A longer term pathway of soil formation in Chopwell Woodland Park was suggested in relation to historical changes in vegetation cover and land management, highlighting periods of stability, with associated phases of soil development, interspersed with short phases of instability brought about by the drainage operations and silvicultural practices outlined above. This study, however, focuses on changes in soil characteristics following the most recent phase of ground preparation and replanting commencing in the early 1920s.

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	1920	1940	1960	1970	1980	1990
pH	3.0 (0.13)	2.9 (0.04)	3.1 (0.28)	3.2 (0.10)	3.1 (0.16)	3.1 (0.14)
OC (%)	15.3 (4.70)	10.2 (2.89)	13.5 (3.18)	13.8 (4.22)	15.5 (3.34)	10.6 (3.58)
Ca (me/100g)	1.04 (0.54)	0.32 (0.15)	0.99 (0.41)	0.80 (0.39)	1.16 (0.63)	0.55 (0.18)
Mg (me/100g)	0.22 (0.03)	0.16 (0.04)	0.22 (0.02)	0.23 (0.07)	0.23 (0.03)	0.19 (0.02)
K (me/100g)	0.39 (0.15)	0.19 (0.09)	0.36 (0.07)	0.44 (0.16)	0.56 (0.27)	0.32 (0.07)
Na (me/100g)	0.63 (0.30)	0.47 (0.17)	0.59 (0.25)	0.63 (0.23)	0.56 (0.12)	0.32 (0.07)
Fep (%)	0.12 (0.03)	0.15 (0.03)	0.16 (0.05)	0.14 (0.04)	0.14 (0.05)	0.16 (0.04)
Fed (%)	0.85 (0.23)	0.69 (0.17)	0.70 (0.25)	0.77 (0.23)	0.90 (0.34)	1.18 (0.61)
Pb (mg/kg)	42.0 (30.11)	58.1 (24.55)	71.4 (49.3)	76.0 (20.11)	49.6 (26.45)	30.1 (23.38)
Zn(mg/kg)	29.5 (7.84)	20.7 (10.24)	33.4 (5.70)	26.4 (10.95)	33.9 (8.80)	20.2 (13.46)

Table 1. Means and standard deviations (in parentheses) for topsoil samples collected from each dated stand (n = 10). OC = organic carbon; Fep = pyrophosphate-extractable (organically-bound) iron; Fed = dithionite-extractable (total free) iron.

Soil property	**F ratio**	**p value**
pH	4.35	0.002 **
OC	3.74	0.006 **
Ca	5.86	< 0.001 ***
Mg	5.13	0.001 ***
K	8.06	< 0.001 ***
Na	3.58	0.007 **
Fep	1.59	0.180 NS
Fed	2.96	0.020 *
Pb	3.30	0.011 *
Zn	3.75	0.005 **

Table 2. One-way ANOVA results for topsoils (n = 10 from each stand). OC = organic carbon; Fep = pyrophosphate-extractable (organically-bound) iron; Fed = dithionite-extractable (total free) iron.

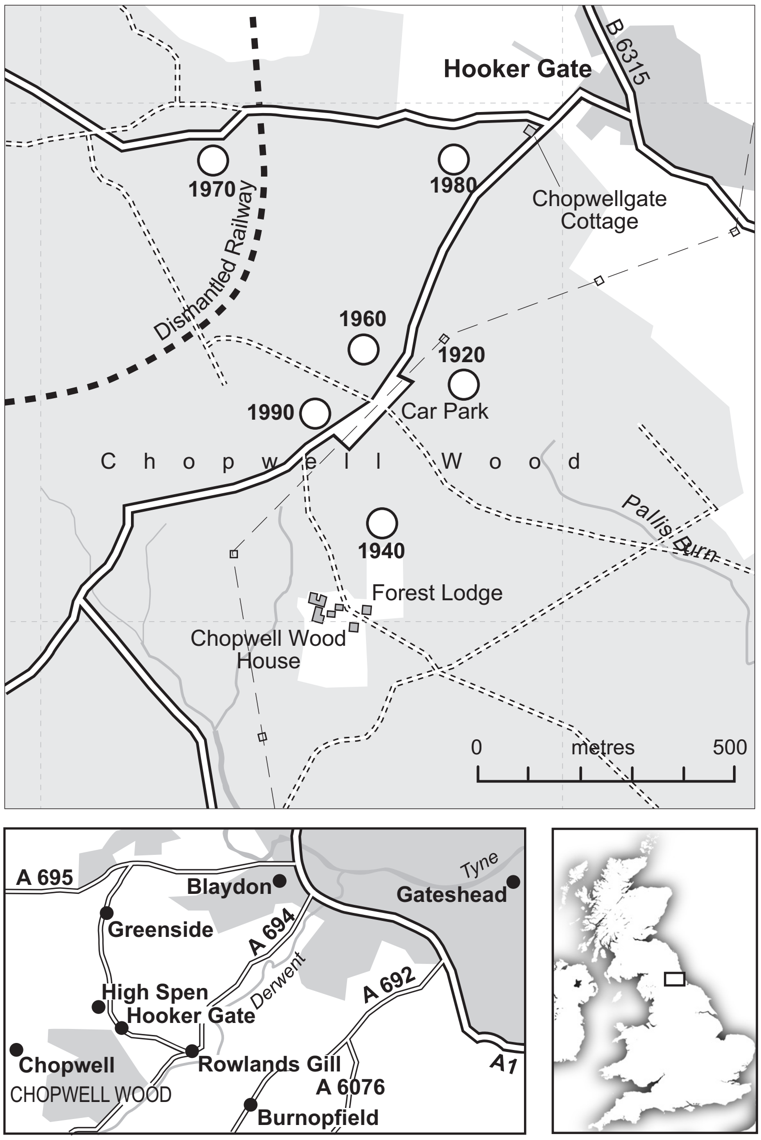

Figure 1. Map showing location of study area with sampled plantation blocks (all Corsican Pine) and their planting dates

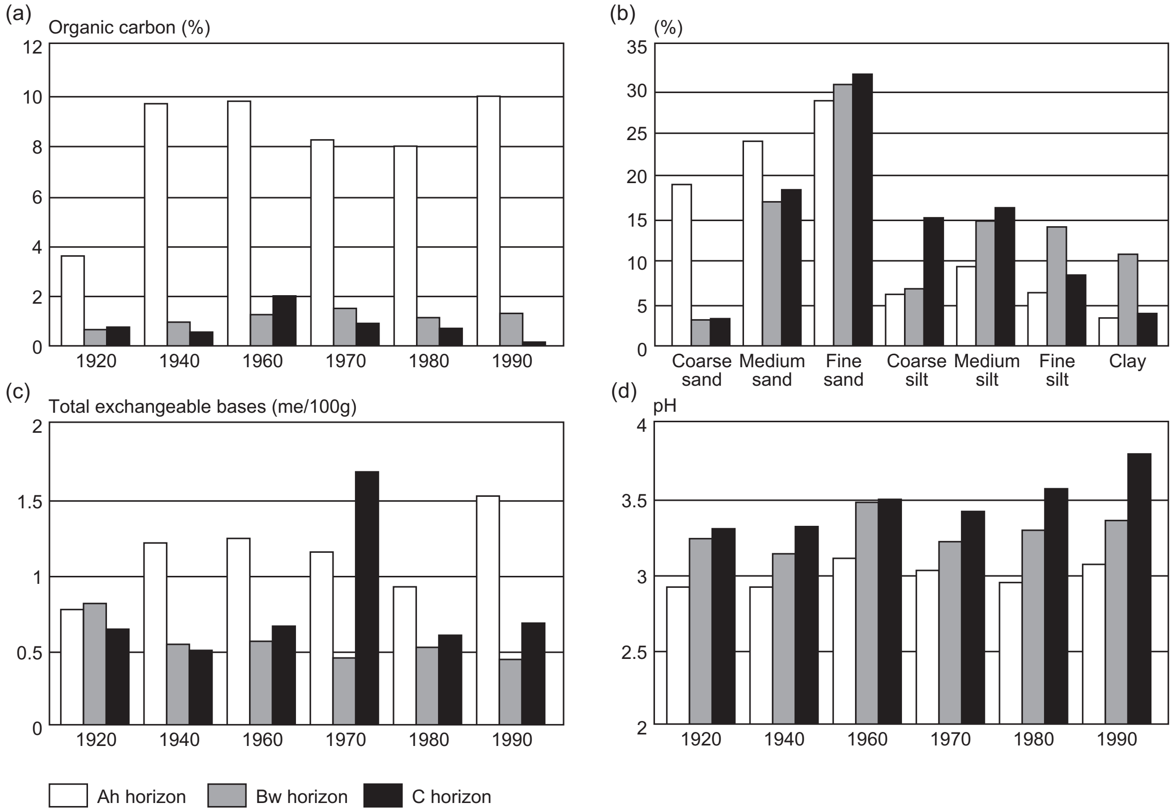

Figure 2. Soil property variations in profiles from the different aged plantations at Chopwell Woodland Park. Graph (b) shows variations in texture within the 1920 soil profile

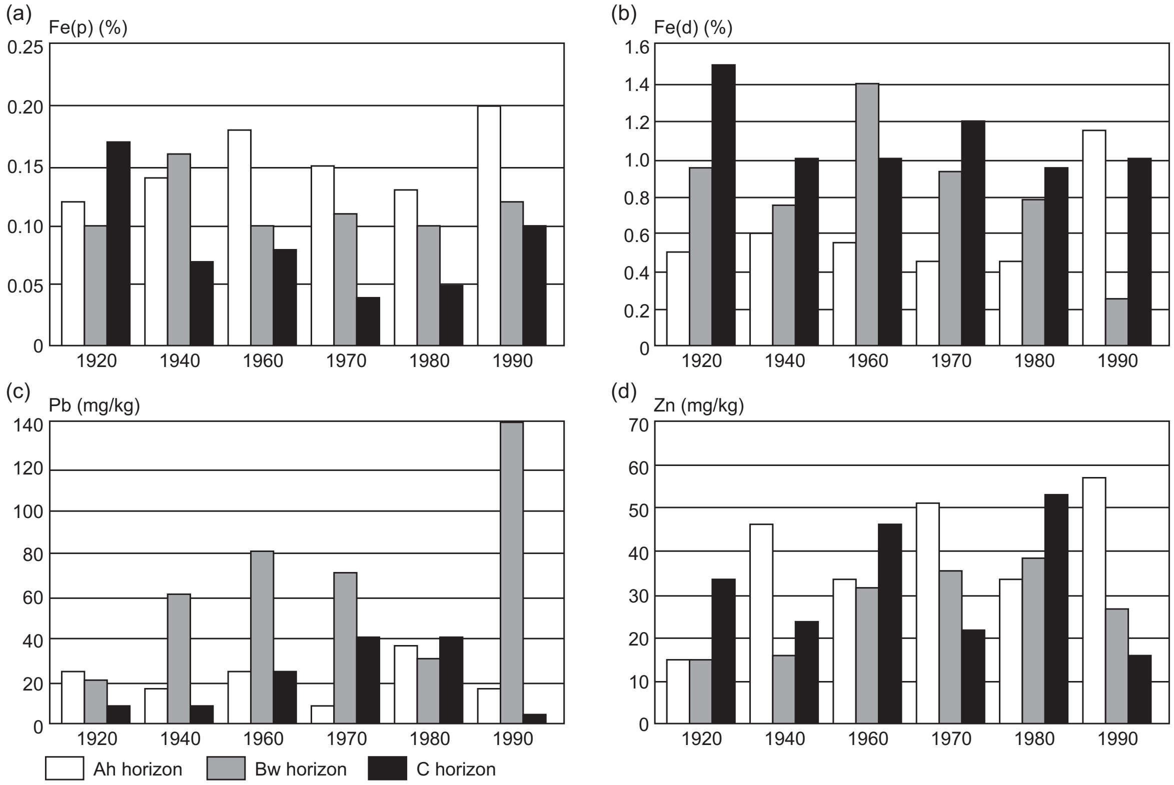

Figure 3. Soil property variations in profiles from the different aged plantations at Chopwell Woodland Park.