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Complete List of Authors:	Tew, Nicholas; University of Bristol, Life Sciences Baldock, Katherine; Northumbria University, Department of Geography and Environmental Sciences; University of Bristol, Life Sciences Vaughan, Ian; Cardiff University, School of Biosciences Bird, Stephanie; Royal Horticultural Society, Plant Health Memmott, Jane; University of Bristol, Life Sciences
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Turnover in floral composition explains species diversity and temporal stability in the nectar supply of urban residential gardens

Authors: Nicholas E. Tew[1,*], Katherine C.R. Baldock[1,2,3], Ian P. Vaughan[4], Stephanie Bird[5], Jane Memmott[1,2]

[1] School of Biological Sciences, University of Bristol, Bristol, United Kingdom

[2] Cabot Institute, University of Bristol, Bristol, United Kingdom

[3] Department of Geography and Environment Sciences, Northumbria University, Newcastle upon Tyne, United Kingdom

[4] Cardiff School of Biosciences, Cardiff University, Cardiff, United Kingdom

[5] Royal Horticultural Society, RHS Garden Wisley, Woking, United Kingdom

Corresponding author: Nicholas E. Tew; nicholas.tew@bristol.ac.uk;

School of Biological Sciences, Life Sciences Building, University of Bristol, 24 Tyndall Avenue, Bristol, BS8 1TQ

Abstract

1. Residential gardens are a valuable habitat for insect pollinators worldwide, but differences in individual gardening practices substantially affect their floral composition. It is important to understand how the floral resource supply of gardens varies in both space and time so we can develop evidence-based management recommendations to support pollinator conservation in towns and cities.
2. We surveyed 59 residential gardens in the city of Bristol, UK, at monthly intervals from March to October. For each of 472 garden surveys, we combined floral abundances with nectar sugar data to quantify the nectar production of each garden, investigating the magnitude, temporal stability, and diversity and composition of garden nectar supplies.
3. We found that individual gardens differ markedly in the quantity of nectar sugar they supply (from 2 g to 1662 g), and nectar production is higher in more affluent neighbourhoods, but not in larger gardens. Nectar supply peaks in July (mid-summer), when more plant taxa are in flower, but temporal patterns vary among individual gardens. At larger spatial scales, temporal variability averages out through the portfolio effect, meaning insect pollinators foraging across many gardens in urban landscapes have access to a relatively stable and continuous supply of nectar through the year.
4. Turnover in species composition among gardens leads to an extremely high overall plant richness, with 636 taxa recorded flowering. The nectar supply is dominated by non-natives, which provide 91% of all nectar sugar, while shrubs are the main plant life form contributing to nectar production (58%). Two thirds of nectar sugar is only available to relatively specialised pollinators, leaving just one third that is accessible to all.
5. *Synthesis and applications*. Our study demonstrates that pollinator-friendly management, affecting garden quality, is more important than the size of a garden, giving every gardener an opportunity to contribute to pollinator conservation in urban areas. For gardeners interested in increasing the value of their land to foraging pollinators we recommend planting nectar-rich shrubs with complementary flowering periods and prioritising flowers with an open structure in late summer and autumn.

Keywords: Floral resources, Flowering phenology; Gardens; Landscape; Nectar; Pollinators; Pollinator conservation; Urban ecology

1. Introduction

Flower-visiting insects including bees and hoverflies are crucial pollinators of many wild plants and agricultural crops (Klein et al., 2007; Ollerton et al., 2011). Increasing evidence for pollinator declines (e.g. Biesmeijer et al., 2006; Powney et al., 2019; Soroye et al., 2020) has led to a focus on designing and implementing strategies for conserving pollinators (Potts et al., 2016). Urban areas could play a surprisingly important role in such conservation strategies for two main reasons. First, they already cover 2-3% of the world's land (Liu et al., 2014) and are expanding (Gao and O'Neill, 2020). Second, urban green spaces can support substantial pollinator diversity (Baldock et al., 2019; Normandin et al., 2017), which may be higher than that in surrounding rural areas (Baldock et al., 2015; Theodorou et al., 2020, 2017).

Privately-owned residential gardens or yards (hereafter referred to as 'gardens') are a particularly valuable type of urban green space for insect pollinators as they are often (but not always) actively managed by gardeners to provide ornamental displays of flowering plants, which provide pollinators with food in the form of nectar and pollen. As a result, diverse pollinator communities can be found in gardens throughout the world (Baldock et al., 2019; Fetridge et al., 2008; Marín et al., 2020; Martins et al., 2017; Staab et al., 2020). Despite their small individual size, residential gardens collectively cover 16-36% of cities in different countries (Baldock et al., 2019; Colding et al., 2006; Loram et al., 2007; Mathieu et al., 2007; Ossola et al., 2021) and provide an estimated 85% of nectar in urban areas in the UK (Tew et al., 2021). Consequently, gardens offer a unique opportunity for pollinator conservation where the combined action of many individuals can have a major impact on foraging resources at a landscape scale (Goddard et al., 2010).

Gardens vary substantially in size, shape, topography, amount of sunlight and soil type (Loram et al., 2007; Matteson and Langellotto, 2010). In addition, management by gardeners differs due to the many and diverse motivations for gardening, this being explained in part by demographic and socio-economic factors (Goddard et al., 2013; Lindemann-Matthies and Marty, 2013; Philpott et al., 2020). As a result, the abundance and composition of flowering plants is very variable among gardens, with some comprised of flower-rich borders and others dominated by short mown grass or hard surfaces (Goddard et al., 2013; Loram et al., 2008b). Consequently, the quantity of floral resources available to insect pollinators is likely to differ substantially from one garden to the next, as is the temporal pattern of resource production due to differences in flowering phenology among species. The seasonal timing of floral resources is often overlooked, but is an important factor determining the success of insect pollinators in temperate climates (Guezen and Forrest, 2021; Timberlake et al., 2020). To understand the quality of the garden habitat for foraging pollinators and identify opportunities for its enhancement we need to quantify variation in the supply of floral resources among individual gardens.

In this study we investigate for the first time how the nectar supply of residential gardens varies in space and time and use our results to develop evidence-based management recommendations for pollinator conservation in urban areas. Nectar sugar is the main energy source for adult pollinators, particularly important for powering their flight muscles (McCallum et al., 2013), but nectar resources have declined in rural areas due to land use change (Baude et al., 2016). We focus on three characteristics of the nectar supply in gardens. (1) Magnitude: we predict substantial variation in nectar sugar production among gardens and an overall peak in summer when we expect more plants to be in flower. (2) Temporal stability: we predict that individual gardens will vary in their seasonal patterns of nectar sugar production such that not all gardens will peak at the same time of year. However, complementarity among gardens will produce a relatively stable supply of nectar throughout the year at the scale of an urban landscape. (3) Diversity and composition: given gardeners can choose from a wide variety of species when planting, we predict substantial turnover in species composition among gardens.

2. Materials and Methods

2.1. Selecting gardens to survey

We surveyed residential gardens in Bristol, a city of around 460,000 inhabitants (Office for National Statistics, 2019) in Southwest England, UK, and stratified our sampling by both geographical location and neighbourhood income. Six separate regions of the city were chosen for garden surveys (Appendix S1), with each region corresponding to an Output Area (a census reporting unit containing 101-123 households). Two regions were each chosen to represent areas of relatively low (band one: £19,149 and £21,215), intermediate (band two: £25,357 and £28,677) and high (band three: £41,308 and £44,992) median annual income (Baldock et al., 2019).

We obtained permission to survey residential gardens by posting a flyer advertising the study to all properties in our chosen six regions and subsequently visiting properties to talk to residents (Appendix S2). Following this, we obtained permission to survey 59 gardens continuously from March to October, these encompassing a wide range of sizes and planting styles. Although we tried to ensure we surveyed an equal number of gardens in each income band, there were differences in the number of properties we gained permission to access (band one: 12; band two: 23; band three: 24), but this imbalance did not affect our conclusions (Appendix S3).

2.2. Surveying gardens

We visited each of the 59 gardens once per calendar month between 04 March and 29 October 2019 to record floral abundance. Thus, each garden was visited eight times, with 472 garden surveys conducted. The period from March (early spring) to October (mid-autumn) covers the vast majority of the UK pollinator flight season. Although some gardens contain floral resources in late autumn and winter (November-February), pollinator activity is low at these times (Ball & Morris, 2015; Falk, 2015). We ensured gaps between visits to the same garden were close to one calendar month, with a mean gap of 30.7 days (n=413; range=25-42 days; 97% of gaps 25-35 days inclusive). For logistical reasons we usually visited multiple gardens in the same region on the same day, but we visited each region on two to six days spread across each month to ensure there was no systematic bias in sampling date among regions.

On the first visit we mapped each garden to measure its total area. On this and each subsequent visit we identified all plant taxa in flower as far as possible (to species, species aggregate, hybrid or genus) and counted all open floral units within the boundaries of each garden (with no height limit and including flowers on plants hanging over boundaries into gardens). We excluded grasses (Poaceae) as they offer no nectar resources. Floral units were defined as a single flower or collection of flowers (e.g. a capitulum for Asteraceae) that a pollinator can walk within but must fly between (e.g. Baldock et al., 2015; Carvalheiro et al., 2008; Appendix S4). Floral units were either counted individually in a garden using a handheld tally counter or estimated by sub-sampling and then multiplying up (e.g. for flowering shrubs and trees). For flower-rich lawns, we estimated floral units using quadrats (0.5 × 0.5 m) to quantify floral abundance for a fixed area, which we then scaled up to the area of the entire lawn.

2.3. Nectar sugar production data

Each of the 636 plant taxa we recorded flowering in gardens was assigned a daily nectar sugar production value (mass of sugars produced per floral unit per 24 hours) derived either from empirical values reported in the published literature (181 taxa; Baude et al., 2016; Hicks et al., 2016; Timberlake et al., 2019), measurements we made in the field (263 taxa), or predictive modelling where empirical values could not be obtained (192 taxa). Our approach for assigning nectar sugar values to plant taxa (Appendix S5) followed that of Tew et al. (2021).

We measured nectar sugar production at field sites in Southern England (not the 59 gardens we surveyed; Appendix S6) for 263 taxa in March-October 2018 and February-April 2019 using the same methods as Baude et al. (2016), Hicks et al. (2016) and Timberlake et al. (2019). We enclosed flowers with mesh bags (pore size 1.4 mm × 1.7 mm) for 24 ± 2 hours and subsequently extracted accumulated nectar using glass microcapillaries (0.5, 1, 5, 10 and 20 μl Minicaps, Hirshmann, Eberstadt, Germany), rinsing nectaries with distilled water to dissolve sugar residues where necessary. The concentration of the solution (C; g of sugars per 100 g solution) was measured using a handheld refractometer modified for small volumes (Eclipse, Bellingham and Stanley, Tunbridge Wells, UK) and the mass of sugar produced (s; μg of sugars per 24 hours) calculated with the formula $s = 10dvC$, where v is the volume collected (μl) and d is the density of a sucrose solution at concentration C and obtained by the formula $d = 0.0037921C + 0.0000178C^2 + 0.9988603$ (Corbet et al., 2001). We sampled 10-52 flowers for 255 plant taxa (1-9 for 8 taxa) and focused our field sampling of nectar on plants commonly found in UK gardens, which we selected in part based on data from Baldock et al. (2019).

Where the floral unit was defined as a collection of flowers (125 taxa), nectar sugar production was scaled from flower to floral unit level by multiplying by the mean number of open flowers per floral unit (Appendix S5). For the 192 taxa which lacked published empirical nectar sugar values, and which could not be found in sufficient numbers for sampling in the field, we estimated nectar sugar production using the predictive modelling approach employed by Tew et al. (2021). Variation in nectar sugar production per floral unit for the empirically measured taxa was analysed using a linear model, which contained plant family, floral unit type, flower shape and floral unit size as explanatory variables (Appendix S7). The estimates from this model ($N = 318$; $R^2_{adj} = 0.537$) were subsequently used to predict the nectar sugar production values for the plant taxa for which no empirical data were available (validation in Appendix S8). Finally, daily nectar sugar production per monthly visit was calculated for each garden by multiplying the number of floral units of each taxon by its corresponding value of daily nectar sugar production.

2.4. Data analysis

All analyses were performed using R v.4.0.3 (R Core Team, 2020). Generalised additive mixed models (GAMMs) were fitted using R package 'mgcv' (v.1.8-33; Wood, 2017) and diagnostic plots (generated with R function 'gam.check') were inspected to validate models against assumptions of heteroscedasticity and normality of the residuals. The degree of smoothness of the regression spline was selected by comparing Akaike's information criterion (AIC) among candidate models (Appendix S9).

2.4.1. Magnitude of the nectar supply through the year

To estimate 'annual' (March-October) nectar sugar production for each garden, we multiplied the mean daily nectar sugar mass for the eight survey visits by the number of days between 01 March and 31 October inclusive. To describe the non-linear trend in nectar sugar production through the sampling period we fitted a GAMM with day of the year modelled with a thin-plate regression spline. A Gamma error family with log link function gave the best fit for the data. The model also included median household income (a numeric value for each of the six sampled regions in Bristol) and garden area as fixed effects (linear fits) and the code for each garden as a random effect, this accounting for the repeated sampling of gardens (Appendix S9).

2.4.2. Temporal stability of the nectar supply

To investigate how the temporal stability of the garden nectar supply (i.e. consistency between months of the year) varied with the flowering plant richness of individual gardens, we regressed the coefficient of variation (standard deviation / mean) in monthly nectar sugar production onto flowering plant richness. The coefficient of variation (CV) is commonly used as a measure of instability in ecology (Doak et al., 1998), with a smaller value indicating greater stability. Next, we investigated how the total number of gardens a pollinator can visit affects the temporal stability of the overall nectar supply, using a simulation approach. We drew random combinations of gardens from the 59 we surveyed (with replacement, so gardens could be selected multiple times) to give samples of 1-100 gardens and iterated this process 1000 times for each sample size (1-100 gardens). For each iteration we summed across gardens to give total nectar sugar per month and calculated CV for this aggregated supply. A pollinator flying 100 m from a central point within each of our six surveyed regions of Bristol can visit 60 to 181 gardens (mean of 93; data from inspecting satellite imagery). Thus, 100 gardens are accessible well within the typical foraging ranges of flower-visiting insects (Greenleaf et al., 2007; Wratten et al., 2003).

2.4.3. Diversity and composition of the nectar supply

To describe the non-linear trend in flowering plant richness through the sampling period, we fitted a GAMM as described above (Section 2.4.1; Appendix S9). We estimated beta diversity across gardens by calculating Sørensen dissimilarity and partitioning it into turnover and nestedness components, using R package 'betapart' (v.1.5.2; Baselga and Orme, 2012). The Sørensen dissimilarity index describes the extent to which different sites (i.e. gardens) share species (perfect similarity = 0; perfect dissimilarity = 1).

The native versus non-native status of flowering plants was determined using the online plant atlas PLANTATT (Hill et al., 2004) and plant life form was determined using Brickell (2016), with each taxon categorised as a herbaceous plant, tree, shrub or woody climber. We grouped plants into those with 'generalised' or 'specialised' flower structures according to the accessibility of the nectar provided for pollinators. Generalised flowers have an open structure with nectar accessible to all short- and long-tongued insects (e.g. *Bellis perennis*). Specialised flowers in contrast offer nectar rewards that cannot be accessed by all pollinators. In most cases this is due to a long corolla tube which requires a long tongue (e.g. *Lamium album*) and in others a physical obstacle which requires sufficient force to manipulate (e.g. *Lotus corniculatus*). Although this dichotomy is necessarily simplistic, categories were decided from a combination of corolla measurements and observations of pollinator visits.

3. Results

In total, we recorded over two million floral units (2,061,703) belonging to 636 plant taxa in 98 families in the 59 surveyed gardens. Garden area ranged from 31.3 m^2 to 407.7 m^2, with a mean of 156.4 m^2 (±12.7 SE) and a combined area of 0.92 ha. Taxa with empirical values of nectar sugar accounted for 91.9% of the total supply and conclusions drawn from subsequent statistical analyses were unchanged if taxa assigned modelled nectar values were excluded.

3.1. Magnitude of the nectar supply through the year

Total annual (March-October) nectar sugar production per garden varied from 2.3 g to 1661.9 g (mean 395.5 g ±45.2 SE). The distribution of annual nectar supply was positively skewed, with the top 13 gardens (22%) accounting for 51% of the total nectar sugar (Fig. 1a). Gardens produced a mean of 3.2 g (±2.7 SE) of nectar sugar per square metre across the sampling period (range 0.03 g to 10.80 g). A generalised additive mixed model described a significantly non-linear trend in nectar supply through the year (GAMM: $F_{6,6} = 16.72$; $p < 0.001$), with a predicted peak of 05 July and periods of lower supply in early spring (March) and from late summer into autumn (August-October; Fig. 1b). There was a significant positive correlation between nectar sugar production and median household income (GAMM: $t = 2.87$; $p = 0.004$), but not between nectar sugar production and garden area (GAMM: $t = 0.92$; $p = 0.358$). Together, day of the year, income and garden area explained 13.2% of the variation in nectar sugar production. The temporal pattern of nectar supply varied among individual gardens, with 22 (37%) peaking outside of May-July and at least one garden peaking in each month. The mean monthly nectar sugar production per garden varied by a factor of two across the year (from 2.2 g in July to 1.1 g in October).

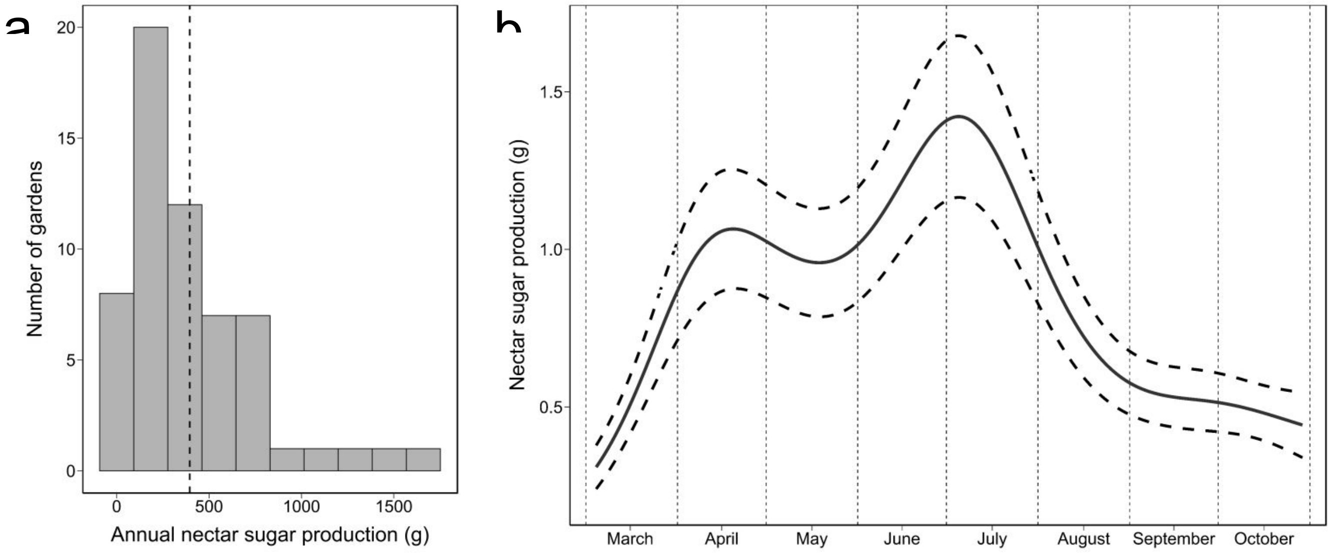

Figure 1. Spatial and temporal patterns in the magnitude of the nectar supply. (**a**) A histogram of annual (March-October) nectar sugar production per garden, with the mean (396 g) indicated by a dashed line. (**b**) Nectar sugar production per garden plotted through the sampling year, showing the prediction (using median values of household income and garden area) from a generalised additive mixed model (solid line) and boundaries one SE above and below the prediction (dashed lines).

3.2 Temporal stability of the nectar supply

There was a significant negative correlation between flowering plant richness in gardens and the coefficient of variation in monthly nectar sugar production (Linear model: $F_{1,57} = 24.67$; $R^2 = 0.302$; $p < 0.001$; Fig. 2a), hence gardens with richer floras tended to have a more stable supply of nectar through the year. Our simulations showed the more gardens a pollinator can visit, the more stable the overall supply of nectar through time (Fig. 2b). The coefficient of variation in nectar supply among months rapidly declines with an increasing number of gardens, with mean CV across iterations halving between one and seven gardens (Fig. 2b). Thus, complementarity among many gardens in residential areas smooths temporal variability in their combined nectar supply.

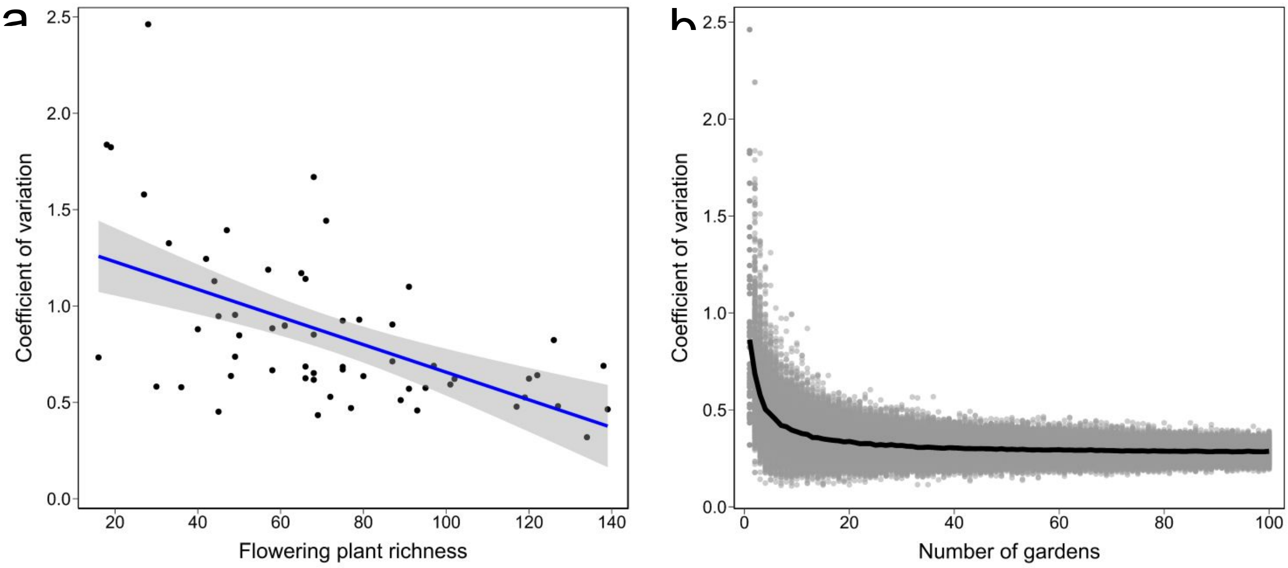

Figure 2. Patterns of temporal stability in the nectar supply. (**a**) The relationship between flowering plant richness and the coefficient of variation in monthly nectar sugar production (linear regression line in blue and shaded area covering one SE around the prediction). (**b**) The simulated relationship between the number of gardens and the coefficient of variation in their aggregated monthly nectar sugar production. Grey points represent iterations of our simulation and the mean line across iterations is shown in black.

3.3. Diversity and composition of the nectar supply

A generalised additive mixed model described a significantly non-linear trend in flowering plant richness through the year (GAMM: $F_{2,2}$ = 317.92; p < 0.001), with a predicted peak of 07 July and periods of lower richness in spring (March-May) and autumn (September-October; Fig. 3). Neither median household income (GAMM: t = 1.58; p = 0.115) nor garden area (GAMM: t = 1.92; p = 0.056) correlated significantly with flowering plant richness. The temporal pattern of flowering plant richness was relatively consistent, with 50 of the 59 gardens peaking in the summer (June-August) and none peaking in March or October. Beta diversity was very high (Sørensen dissimilarity 0.96) and driven by turnover among gardens rather than nestedness (turnover component 98%). Thus, gardens tended to share a very low proportion of their taxa and the floral composition of low richness gardens was not generally a subset of that in higher richness gardens. This was reflected in the incidence frequencies of taxa, with only 20 taxa (3.1% of the total) recorded in at least half of gardens (Appendix S10) and 203 taxa (31.9% of the total) only found in a single garden. Half of the total nectar supply was provided by 13 taxa, three quarters by 43 taxa and 95% by 154 taxa (Appendix S11).

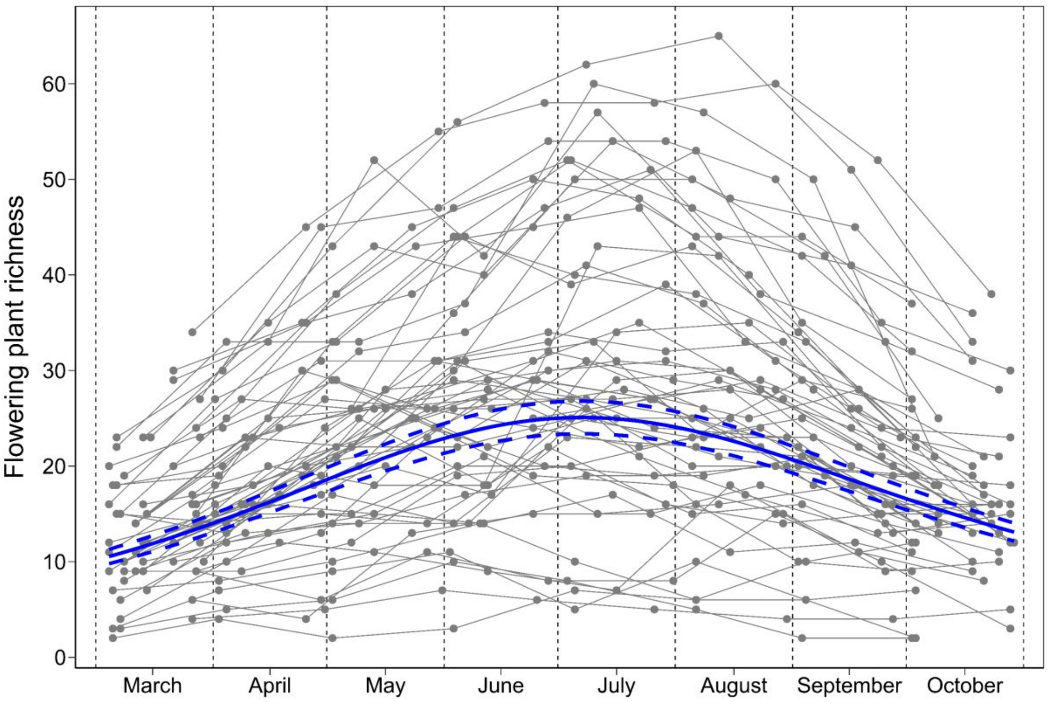

Figure 3. Flowering plant richness plotted for each garden through the sampling year (with lines joining points for individual gardens), showing the prediction (using median values of household income and garden area) from a generalised additive mixed model (solid blue line) and boundaries one SE above and below the prediction (dashed blue lines).

The composition of plant species underpinning nectar sugar production varied greatly through the year, reflecting different flowering periods among taxa (Fig. 4; Appendix S11). *Pieris* species provided the most nectar of any single taxon in March (31.0%) and April (26.1%) while *Fuchsia magellanica* was dominant from July to October (32.3-52.1%). Non-native taxa contributed 90.5% of total nectar sugar production, a proportion which remained relatively consistent through the year (Appendix S12). Shrubs produced 57.5% of nectar (more in spring and autumn; Appendix S12), herbaceous plants 33.5% and the contributions of woody climbers (6.2%) and trees (2.7%) were lower. Around two thirds (66.4%) of nectar was provided by flowers with a specialised structure, with just one third (33.6%) accessible to all pollinators. This pattern changed through time, with specialised flowers providing 73.9-82.6% of nectar in July-October (Appendix S12).

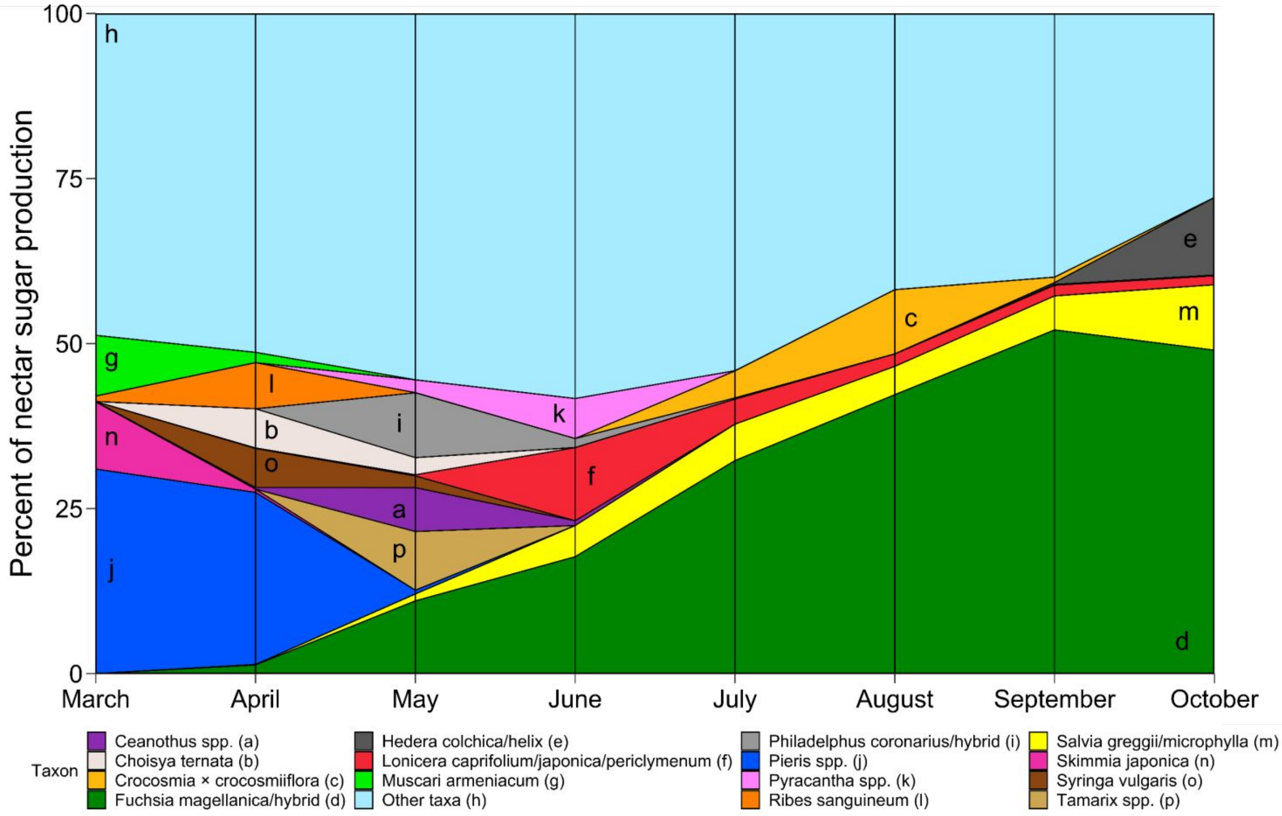

Figure 4. The contribution of plant taxa to monthly nectar sugar production plotted through the year, with the percentage indicated by the height of a coloured polygon. The 15 displayed taxa provided >5% of nectar sugar in at least one month, with the remainder included in the 'Other taxa' category.

4. Discussion

Garden nectar production peaked in mid-summer, but individual gardens differed markedly in both the magnitude of their nectar supply and its temporal pattern. Most of this variation was not explained by our model, indicating the importance of additional factors in determining nectar among gardens. The finding that garden size did not correlate significantly with nectar sugar production suggests that the quality of the garden habitat, driven by individual management decisions, is of primary importance. Nectar production was more stable through time in gardens with greater flowering plant richness and, at larger spatial scales temporal stability in the nectar supply rapidly emerges if pollinators forage across multiple gardens. In what follows we first consider the limitations of our work and then discuss our results in the context of urban pollinator conservation.

4.1 Limitations

There are two main limitations to our study of nectar supply in residential gardens. First, insect pollinators require additional resources to nectar sugar alone, which can include pollen, extrafloral nectar and honeydew, nest sites, prey items and foodplants for larvae (Wäckers et al., 2007). Given nectar sugar mass and total pollen volume both correlate with floral abundance (Hicks et al., 2016), the broad patterns we observe in nectar supply are likely to reflect those of pollen production. Currently, there is insufficient published pollen data to have included it in this study. Nevertheless, nectar sugar is a general energy source required by the vast majority of adult pollinators so it provides a common currency through which to compare the floral resource value of habitats (e.g. Baude et al., 2016; Timberlake et al., 2019). Second, we only surveyed gardens in a single city (Bristol, UK) in a single year (2019). Residential gardens cover 28% of Bristol by area (Baldock et al., 2019), putting it within the range seen for cities worldwide (e.g. 16% in Stockholm, Sweden; Colding et al., 2006 and 36% in Dunedin, New Zealand; Mathieu et al., 2007). In addition, there was no significant difference in the nectar sugar production of urban land uses between Bristol and three other UK cities (Tew et al., 2021), but there is no equivalent data for non-UK cities to make comparisons. Both mean annual temperature and total rainfall for Bristol in 2019 were typical of those in the past decade (Met Office, 2020), so we expect the patterns we observed in 2019 will be representative of those in other years. While the precise shape of the seasonal nectar supply curve and the contributions of specific plant taxa will differ in other cities and years, the general findings of extreme variability and turnover among single gardens but temporal stability across multiple gardens are very likely to apply in other cities because the principle that gardens comprise many small habitat patches which differ independently in their management remains true wherever they are located.

4.2 Nectar supply in gardens

There was substantial variation in the magnitude of nectar production among individual gardens (the scale at which management decisions are made). In our sample, the highest-nectar garden produced more than 700 times more sugar than the lowest-nectar garden during our survey period, but we found that garden size did not correlate significantly with nectar sugar production, which emphasises the importance of management decisions for nectar supply rather than total area *per se*. The highest-nectar gardens tended to be in more affluent regions (four of the top five nectar producing gardens were in income band 1) and contained ornamental flower borders, while the lowest-nectar gardens were likely to be in regions of lower income (four of the bottom five in income band 3) and typically lacked flower-rich borders. There was no clear negative role of hard surfaces like decking and paving in place of lawns because we observed that herbaceous plants and shrubs in pots or peripheral borders were usually the major nectar source rather than flower-rich lawns. Our study shows that it is not necessary for a gardener to have a large garden to provide pollinators with a large supply of nectar because it is how they choose to garden which is most important. However, a lack of gardener knowledge of which species are nectar rich could lead to suboptimal outcomes for pollinators even where the necessary motivation exists (Lindemann-Matthies et al., 2021).

Nectar production peaked in mid-summer, when UK pollinator abundance is also highest (Balfour et al., 2018), but patterns among individual gardens were idiosyncratic with at least one garden peaking in each month from March to October. It was common for a single flowering plant taxon (often a tree or shrub) to provide the majority of a garden's nectar sugar in a particular month, contributing to the variability in temporal patterns within and among gardens. Because each garden is managed by a single individual or group of individuals, temporal patterns of nectar supply vary among gardens in a relatively independent fashion. As a result, extreme temporal variation in nectar production tends to average out when summed across many gardens, resulting in an overall supply that is more stable through time, an example of the portfolio effect (Schindler et al., 2015). Across our 59 surveyed gardens, the mean monthly nectar sugar production only varied by a factor of two through the sampling year. This contrasts with patterns in rural farmland, where temporal peaks may be more than ten times as great as troughs in nectar supply (Timberlake et al., 2019). Because urban gardens are present at such a high density, the portfolio effect smooths temporal variability in their aggregated supply at a scale relevant to foraging pollinators. Hence, unless there are strong barriers limiting dispersal in urban areas, pollinators foraging in residential regions of towns and cities have access to a much more stable and continuous supply of nectar through the year than those in rural farmland.

The flowering plant richness of residential gardens is extremely high; we recorded 636 taxa from 98 families flowering in less than one hectare of land. This phenomenal richness (which is higher than in semi-natural habitats; e.g. Vessby et al., 2002) is driven by extreme turnover in species composition among gardens (Loram et al., 2008a). Individual gardens tend to have relatively distinct floras (only 3% of taxa were recorded in half the gardens) because gardeners have a wide variety of (native and non-native) species to choose from when planting and their active management (e.g. 'weeding') prevents plants being outcompeted (Loram et al., 2008a). The value of gardens as a habitat type is an emergent property, resulting from many small patches of land being managed independently, emphasising the importance of understanding landscape context for biodiversity conservation in urban areas (Goddard et al., 2010). Being mobile, insect pollinators have the potential to take advantage of the nectar supplied by gardens despite their patchy distribution in fragmented urban landscapes, but differences in diet, larval requirements, dispersal capability and nesting behaviour among taxa will affect the composition of pollinator communities that can be supported (Seitz et al., 2020; Wenzel et al., 2020).

4.3 Management recommendations

Shrubs, climbers and trees provided two-thirds of all nectar as their physical structure results in a three-dimensional arrangement of flowers, allowing a large number to be produced within a relatively small area of land. Ornamental shrubs, climbers and trees with nectar-rich flowers are therefore a space-efficient way to boost the garden nectar supply during their flowering periods. Gardens with higher flowering plant richness provide a more stable supply of nectar sugar through time, but by actively selecting nectar-rich species with complementary phenological profiles gardeners can achieve this result more efficiently with respect to cost and space (Table 1). An additional consideration when planting for pollinators is flower structure, which determines the accessibility of floral resources to different insects (e.g. Stang et al., 2006). From July to October 74-83% of nectar sugar was supplied by flowers that are not accessible to all pollinators (especially *Fuchsia magellanica*, *Lonicera* and *Salvia* species, which have long corolla tubes), so we recommend prioritising the planting of taxa which produce relatively open flowers in late summer and autumn to ensure sufficient food for short-tongued solitary bees and Diptera (Table 1).

Table 1. Recommended plants for different seasonal periods in UK gardens. Listed plants are nectar rich, attractive to flower-visiting insects and easily acquired by gardeners. Taxa are described as native ('N') or non-native alien ('A') and as having a generalised ('G') or specialised ('S') flower structure (or including members of both categories). Gardeners should avoid invasive plants, which can escape from gardens and spread extensively in rural habitats.

Seasonal period	Recommended plants	Native status	Flower structure
Early spring (March)	*Helleborus* spp.	N or A	S
	Pieris spp.	A	S
	Pulmonaria spp.	N or A	S
	Salix spp. (willow)	N or A	G
	Skimmia japonica	A	G
Mid to late spring (April-May)	*Aquilegia vulgaris*	N	S
	Ceanothus spp.	A	G
	Malus spp. (apple)	N or A	G
	Prunus avium (cherry)	N	G
	Ribes spp. (currants)	N or A	G or S
Early to mid summer (June-July)	*Campanula* spp. (bellflower)	N or A	G
	Geranium spp. (cranesbill)	N or A	G or S
	Lavandula spp.	A	S
	Lonicera periclymenum (honeysuckle)	N	S
	Pyracantha coccinea (firethorn)	A	G
Late summer to autumn (August-October)	*Echinacea purpurea* (purple coneflower)	A	G
	Hedera helix (ivy)	N	G
	Origanum vulgare	N	G
	Sedum spp.	N or A	G
	Verbena bonariensis	A	S

4.4 Conclusions

Our study demonstrates that urban residential gardens differ markedly in the magnitude and temporal pattern of nectar supply, but bigger gardens are not necessarily better for feeding pollinators. Instead, the management decisions made by individuals are particularly important, with gardeners able to control habitat quality if not quantity. By visiting multiple gardens which differ independently in plant species composition, pollinators have the potential to access a diverse and continuous supply of nectar in urban landscapes.

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Authors' contributions

N.E.T., J.M. and K.C.R.B. conceived the ideas and designed the methodology; N.E.T. collected the data; N.E.T. and I.P.V. analysed the data; N.E.T., J.M. and K.C.R.B. led the writing of the manuscript, with I.P.V. and S.B. contributing critically to the drafts; J.M., K.C.R.B., I.P.V. and S.B. acquired funding. All authors gave final approval for publication.

Data availability statement

Data will be archived in the Dryad Digital Repository.

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Supplementary Information for:

‘Turnover in floral composition explains species diversity and temporal stability in the nectar supply of urban residential gardens’

Contents

Appendix S1. Survey regions

Table S1: The six regions in Bristol in which we surveyed residential gardens. Data on number of households and income for Output Areas from Baldock et al. (2019).

Region name	Output Area code	Number of households	Median household income	Income band	Number of gardens surveyed
Hanham	00HDPG0014	110	£41,307.50	3	12
Horfield	00HBPJ0003	116	£28,676.50	2	10
Knowle	00HBPL0035	123	£19,149.00	1	7
Montpelier	00HBNM0037	104	£25,357.00	2	13
Southmead	00HBPS0009	105	£21,215.00	1	5
Westbury Park	00HBPG0010	101	£44,992.00	3	12

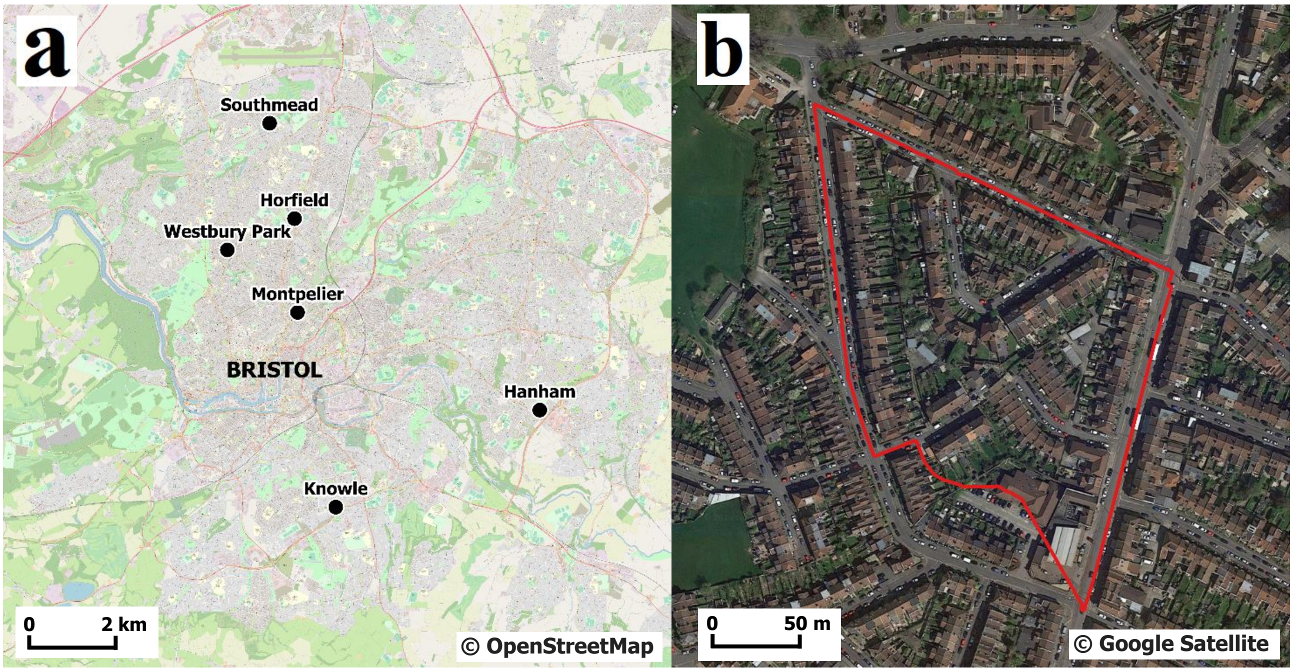

Figure S1. (**a**) A map showing the locations of the six regions of Bristol in which residential gardens were surveyed. (**b**) Example of a single Output Area (Horfield region), bounded by a red line.

Appendix S2. Method for obtaining permission to access gardens

To gain permission to survey residential gardens we posted a flyer advertising the project (Figure S2) through every letterbox in the six designated regions (21-24 January 2019) and subsequently visited households to ask for access to additional gardens (04-06 February 2019) to reach a desired sample size of approximately ten gardens per region. As far as possible we tried to minimise bias in responses by visiting all properties and ensuring that residents were aware of our interest in surveying gardens of all types, irrespective of size or its perceived habitat quality for pollinators.

Figure S2. The flyer posted through letterboxes used to advertise the project to members of the public and gain permission to sample their gardens.

Appendix S3. Validation of stratified sampling method for surveying gardens

Out of the 59 gardens we obtained permission to survey, 12 were in income band (IB) 1, 23 in IB2 and 24 in IB3 (Table S2). A truly representative selection would have contained equal numbers of gardens in each income band. To test the impact of this imbalance in our sampling methods on our major conclusions we re-ran some of our analyses on subsets of the data which contained equal numbers of gardens in each income band. For each of 20 subsets we included the 12 gardens in IB1 and randomly selected 12 gardens for inclusion from each of IB2 and IB3, giving a balanced selection with 36 of our 59 gardens included (12 in each IB). We report the results of re-running our analyses on these 20 subsets in Table S2.

Table S2: A comparison of results obtained by analysing our complete dataset (59 gardens) with results obtained by analysing 20 subsets of our data in which the number of sampled gardens in each income band was balanced.

Result being compared	Complete dataset (59 gardens)	20 subsets (36 gardens in each)
Mean annual (March-October) nectar sugar production per garden (g)	395.55	Mean: 370.47 Range: 307.18 – 417.33
Temporal peak in nectar sugar production (GAMM prediction)	05 July	Modal day: 06 July Range: 04 July – 11 July
P-value for effect of median household income on nectar sugar production	0.0043	Mean: 0.0135 Range: 0.0003 – 0.0377
P-value for effect of garden area on nectar sugar production	0.3580	Mean: 0.6774 Range: 0.3599 – 0.9470

The results in Table S2 show that our main conclusions about spatial and temporal variation in the nectar supply of urban gardens are unaffected by the imbalance in our sampling method. In a completely balanced design we estimate mean annual nectar sugar production to be around 6% lower, the temporal peak in nectar supply remains in early July, the effect of median household income remains significant and the effect of garden area remains non-significant.

Appendix S4. Floral unit definitions

Table S3. The definition of a floral unit for all plant taxa in this study.

Floral unit definition	Plant taxa
Single flower	All Acanthaceae, all Aizoaceae, *Alstroemeria* spp., all Amaranthaceae, all Amaryllidaceae, *Angelonia angustifolia*, *Anigozanthos* spp., all Apocynaceae, all Asparagaceae, all Asphodelaceae, *Aucuba japonica*, *Begonia* spp., all Berberidaceae, all Bignoniaceae, all Boraginaceae, *Bougainvillea* spp., all Brassicaceae (apart from *Lobularia maritima*), all Buxaceae, *Camellia japonica*, all Campanulaceae, *Canna* spp., all Caprifoliaceae (apart from *Sambucus nigra*), all Caryophyllaceae, all Cistaceae, all Convolvulaceae, *Corokia* × *virgata*, *Cotinus coggygria*, all Crassulaceae, all Cucurbitaceae, *Cyclamen* spp., *Daphne odora*, all Ericaceae (apart from *Calluna vulgaris*), *Escallonia rubra/hybrid*, *Euonymus* spp., all Fabaceae (apart from *Acacia dealbata*, *Medicago* spp. and *Trifolium* spp.), all Geraniaceae, *Grevillea rosmarinifolia*, all Grossulariaceae, *Hedera colchica/helix*, *Hemerocallis* spp., *Houttuynia cordata*, all Hydrangeaceae, *Hypericum* spp., *Ilex aquifolium*, *Impatiens* spp., all Iridaceae, all Lamiaceae (apart from *Lavandula* spp.), all Lardizabalaceae, *Laurus nobilis*, *Leptospermum scoparium*, all Liliaceae, *Limnanthes douglasii*, *Linum* spp., all Magnoliaceae, all Malvaceae, *Mercurialis perennis*, *Myrtus communis*, *Nymphaea* spp., all Oleaceae (apart from *Syringa* spp.), all Onagraceae, all Oxalidaceae, *Paeonia* spp., all Papaveraceae, *Passiflora caerulea*, *Paulownia* tomentosa, all Pittosporaceae, all Plumbaginaceae, all Polemoniaceae, *Polygala myrtifolia*, all Polygonaceae, all Primulaceae, all Ranunculaceae, *Rhodohypoxis* spp., all Rosaceae (apart from *Spiraea* spp.), all Rubiaceae, all Rutaceae, *Sagittaria sagittifolia*, all Sapindaceae, all Saxifragaceae, *Scaevola aemula*, all Scrophulariaceae (apart from *Buddleja davidii* and *Hebe* spp.), all Solanaceae, *Tropaeolum majus*, all Urticaceae, all Verbenaceae, *Viola* spp., all Vitaceae.
Part of panicle	*Spiraea* spp.
Secondary umbel	All Apiaceae
Single branch of capitula	*Solidago canadensis*
Single capitulum	All Asteraceae (apart from *Solidago canadensis*), all Dipsacaceae
Single catkin	*Salix* spp.
Single compound cyme	*Centranthus ruber*
Single corymb	*Cornus spp., Lobularia maritima, Sambucus nigra*
Single cyme	*Euphorbia* spp.
Single panicle	*Buddleja davidii*, *Syringa* spp.
Single raceme	*Acacia dealbata, Callistemon spp., Calluna vulgaris, Gunnera manicata*, *Hebe* spp., *Medicago* spp., *Tamarix* spp., *Trifolium* spp.
Single spadix	All Araceae
Single spike	*Lavandula* spp., *Plantago lanceolata*
Single thyrse	*Ceanothus* spp.

Appendix S5. Assigning nectar production values to plant taxa

Out of the 444 plant taxa assigned empirical values, we identified 73 to the level of a genus and the remaining 371 to a species, species aggregate or hybrid (hereafter referred to as species). For taxa only identified to genus level, 69 were assigned a nectar value derived from a single species in the genus and 4 were assigned a value obtained by averaging across multiple congeners. For the taxa identified to species level, 237 were assigned nectar values from the corresponding species and 134 were assigned values from a congener given that conspecific flowers were not available for sampling. This proxy method was only used if the two species shared similar floral morphologies and was deemed preferable to predictive modelling in these cases. Baude et al. (2016; Supplementary Table 11) was the source of nectar production data for 158 taxa, Hicks et al. (2016; S1 Table) for 66 taxa and Timberlake et al. (2019; Table S2) for 4 taxa. For 47 taxa, data from Baude et al. (2016) and Hicks et al. (2016) were combined by averaging (using a mean weighted by the number of flowers sampled) to increase the number of flowers and sampling sites contributing to the taxon-level mean nectar production value. To scale from flower to floral unit level, counts of flowers per floral unit were either collected in the field in this study, obtained from Baude et al. (unpublished data) or in one case (*Aethusa cynapium*), the floral units were counted in photographs. Nectar sugar values for Asteraceae in Hicks et al. (2016) were already given at the floral unit scale.

Appendix S6. Locations of nectar sampling.

Table S4. The locations of sites used for sampling nectar in the field in this study.

Sampling location	Address
Ashley Down allotment	Ashgrove Avenue, Bristol (51.481 N, 2.578 W)
Brackenwood Plant and Garden Centre	Pill Road, Bristol (51.467 N, 2.662 W)
Didcot town (road verges and borders)	Didcot, Oxfordshire (51.610 N, 1.239 W)
RHS Garden Wisley	Wisley Lane, Woking, Surrey (51.314 N, 0.474 W)
Royal Fort Gardens	Tyndall Avenue, Bristol (51.458 N, 2.602 W)
Speldhurst village (a private garden)	Ferbies Road, Speldhurst, Kent (51.148 N, 0.216 E)
University of Bristol Botanic Garden	Stoke Park Road, Bristol (51.478 N, 2.626 W)
University of Bristol halls of residence	Parrys Lane, Bristol (51.478 N, 2.623 W)

Appendix S7. Estimating nectar production by predictive modelling

We analysed variation in $\log_{10}(x+1)$ nectar sugar production (µg of sugars per floral unit per 24 hours) for the empirically measured taxa using a linear model. Prior to running this model, we excluded 126 of the original 444 taxa assigned empirical nectar sugar production values (leaving 318) due to their source nectar data being duplicated. Where multiple taxa were assigned nectar sugar production values from the same source species (e.g. both *Achillea millefolium* and *A. ptarmica* were assigned the nectar sugar production value of *A. millefolium*; Appendix S5) we only included one of the taxa in the model to avoid artificially inflating the degrees of freedom. Four traits were included as explanatory variables within the linear model. 'Plant family' contained 25 classes that were either taxonomic families or higher clades. If a family was represented by four or fewer taxa in the empirical dataset then it was replaced by a higher clade (ANA/magnoliids, asterids, eudicots, monocots or rosids) where possible following Baude et al. (2016). 'Floral unit type' contained two classes that were (1) single flower or (2) collection of flowers, depending on the floral unit definition (Supporting Information S2). 'Flower shape' contained five classes based upon the Müller flower classification system. Flower shape definitions for most taxa were extracted using the package 'TR8' (v.0.9.22; Bocci, 2015) in R v.4.0.3 (R Core Team, 2020), which downloaded the trait data from the BiolFlor database (Klotz et al., 2002). The five classes were: (1) open nectar (for flowers with open nectaries); (2) partly-hidden nectar (for flowers with partly-hidden nectaries); (3) hidden nectar (for flowers with completely hidden nectaries); (4) pollen, wind and trap flowers (for flowers where pollen is the major reward, flowers which are predominantly wind pollinated or flowers which trap insect pollinators rather than rewarding them with floral resources); (5) hymenopteran or lepidopteran flowers (for flowers recorded as being predominantly pollinated by Hymenoptera or Lepidoptera). When the flower shape was not documented in the BiolFlor database, closely related and morphologically similar species were used as proxies. 'Floral unit size' contained five size classes depending on the diameter of the floral unit (across the front of the floral unit, where a pollinator would land). The five classes were: (1) very small (diameter ≤ 5 mm); small (5 mm < diameter ≤ 15 mm); medium (15 mm < diameter ≤ 30 mm); large (30 mm < diameter ≤ 60 mm); very large: (diameter > 60 mm). Size class data were obtained from unpublished measurements in the field in this study, from Baude et al. (unpublished data) or from species descriptions in books and online resources.

Appendix S8. Validation of predictive modelling approach

To check the validity of the predictive modelling approach we used to model values for the 192 ‘unsurveyed’ taxa we adopted a repeated ‘leave-one-out’ approach on the 317 taxa for which we had empirical values of nectar sugar production (*Magnolia stellata* was excluded from the original 318 because it is the only member of its ‘Plant family’). We excluded a single taxon, fitted the linear model on the remaining 316 taxa and used the estimates from this model to predict the nectar sugar production value of the excluded taxon, and repeated this approach for each of the 317 taxa. Subsequently, we applied a major axis linear regression from ‘smatr’ package (v.3.4-8; Warton et al., 2012) to assess the relationship between the $\log_{10}(x+1)$ nectar sugar production (µg of sugars per floral unit per day) of predicted and empirical values for each taxon. There was a strong positive correlation between predicted and empirical values of nectar sugar production ($N = 317$; $R^2_{adj} = 0.464$; $p < 0.001$; Figure S3). The slope of the regression line is 0.681 (95% CI 0.603; 0.766) and y-intercept is 0.708 (95% CI 0.516; 0.900), suggesting a slight but not strong tendency for the model to underpredict nectar sugar production values.

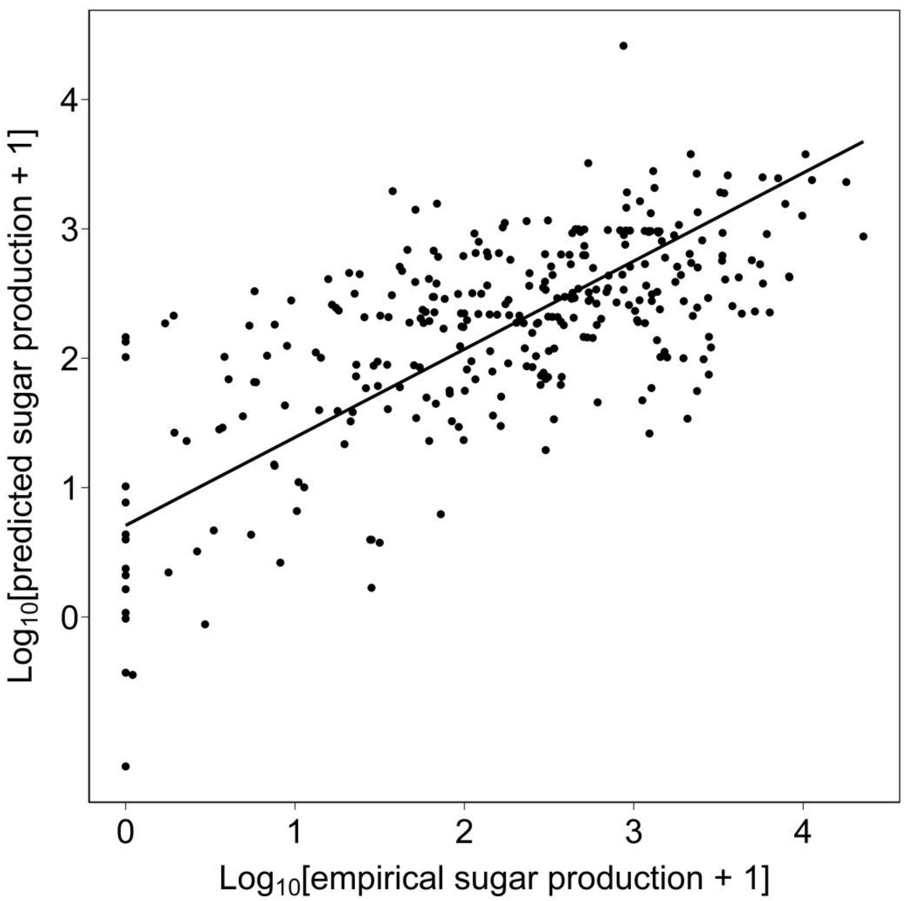

Figure S3. The relationship between the $\log_{10}(x+1)$ daily nectar sugar production (µg of sugars per floral unit per 24 hours) of predicted and empirical values for each taxon. The fitted line from a major axis linear regression is shown.

Appendix S9. Selection of generalised additive mixed models

Table S5. A comparison of candidate generalised additive mixed models for analysing nectar sugar production. The chosen model (k=7) is shown in bold and delta AIC shows the difference in AIC value between candidate models and this top ranking model.

Candidate model	Degree of smoothing	AIC	Delta AIC
gamm(nectar ~ s(day, fx=T, k=5) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	5	1403.66	15.12
gamm(nectar ~ s(day, fx=T, k=6) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	6	1394.62	6.07
gamm(nectar ~ s(day, fx=T, k=7) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	**7**	**1388.55**	**0**
gamm(nectar ~ s(day, fx=T, k=8) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	8	1390.16	1.61
gamm(nectar ~ s(day, fx=T, k=9) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	9	1388.71	0.16
gamm(nectar ~ s(day, fx=T, k=10) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	10	1390.65	2.10
gamm(nectar ~ s(day, fx=T, k=11) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	11	1392.02	3.48

Table S6. A comparison of candidate generalised additive mixed models for analysing plant taxon richness. The chosen model (k=3) is shown in bold and delta AIC shows the difference in AIC value between candidate models and this top ranking model.

Candidate model	Degree of smoothing	AIC	Delta AIC
gamm(richness ~ s(day, fx=T, k=3) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	**3**	**133.00**	**0**
gamm(richness ~ s(day, fx=T, k=4) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	4	135.02	2.02
gamm(richness ~ s(day, fx=T, k=5) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	5	133.10	0.10
gamm(richness ~ s(day, fx=T, k=6) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	6	133.62	0.62
gamm(richness ~ s(day, fx=T, k=7) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	7	135.62	2.62
gamm(richness ~ s(day, fx=T, k=8) + area + income, random = list(Garden_code = ~1), family = Gamma(link = log), method = 'REML')	8	137.11	4.11

Appendix S10. Most common flowering plant taxa

Table S7. The 20 plant taxa recording flowering in at least half of the 59 surveyed gardens. The native status of each taxon is indicated by the letter 'N' (native) or 'A' (non-native alien).

Plant taxon	Number of gardens	Percentage of gardens	Native status
Euphorbia peplus	53	89.8	A
Rosa spp.	50	84.7	A
Taraxacum agg.	47	79.7	N
Epilobium ciliatum/montanum	44	74.6	N
Cardamine flexuosa/hirsuta	43	72.9	N
Geum urbanum	41	69.5	N
Narcissus spp. (small flower cultivar)	40	67.8	A
Pelargonium spp.	40	67.8	A
Geranium robertianum	39	66.1	N
Clematis spp. (ornamental)	38	64.4	A
Hyacinthoides non-scripta/hispanica	37	62.7	N
Cyclamen spp.	35	59.3	A
Fuchsia magellanica/hybrid	33	55.9	A
Cymbalaria muralis	32	54.2	A
Muscari armeniacum	32	54.2	A
Sonchus oleraceus	32	54.2	N
Circaea lutetiana	31	52.5	N
Lonicera caprifolium/japonica/periclymenum	31	52.5	A
Primula spp. (*Polyanthus*)	31	52.5	A
Senecio vulgaris	30	50.8	N

Appendix S11. Plant taxon composition of the garden nectar supply

Table S8. The 10 plant taxa with the greatest contribution to overall monthly nectar supply across the surveyed 59 gardens. An asterisk (*) indicates a plant taxon's nectar production was estimated at the floral unit level by predictive modelling, all other taxa have empirically measured values. The native status of each taxon is indicated by the letter 'N' (native) or 'A' (non-native alien).

Plant taxon	Percentage of monthly nectar	Native status	Month
Pieris spp.	30.99	A	March
Skimmia japonica	10.17	A	March
Muscari armeniacum	9.21	A	March
Camellia japonica	4.97	A	March
Erica carnea	4.74	A	March
Prunus laurocerasus	4.40	A	March
Prunus spp. (ornamental)	4.23	A	March
Salix spp.	3.83	N	March
Helleborus × hybridus	3.25	A	March
Bergenia cordifolia	2.91	A	March
Other taxa (131)	21.29		March
Pieris spp.	26.07	A	April
Ribes sanguineum	6.99	A	April
Choisya ternata	5.93	A	April
Syringa vulgaris	5.91	A	April
Wisteria spp.	4.83	A	April
Prunus spp. (ornamental)	4.16	A	April
Amelanchier spp.*	4.10	A	April
Taraxacum agg.	3.03	N	April
Camellia japonica	2.92	A	April
Prunus laurocerasus	2.91	A	April
Other taxa (245)	33.14		April
Fuchsia magellanica/hybrid	11.02	A	May
Philadelphus coronarius/hybrid	9.82	A	May
Tamarix spp.*	8.89	A	May
Ceanothus spp.	6.65	A	May
Erysimum linifolium	4.48	A	May
Weigela florida	4.11	A	May
Cotoneaster spp. (red flowers)	3.21	A	May
*Cordyline australis**	3.08	A	May
Wisteria spp.	2.64	A	May
Choisya ternata	2.59	A	May
Other taxa (302)	43.50		May
Fuchsia magellanica/hybrid	17.71	A	June
Lonicera caprifolium/japonica/periclymenum	11.08	A	June
Pyracantha spp.	6.06	A	June
Salvia greggii/microphylla	4.72	A	June
Campanula portenschlagiana	4.12	A	June
Campanula poscharskyana	3.93	A	June
Penstemon barbatus	3.55	A	June
Erysimum linifolium	3.23	A	June
Bellis perennis	2.55	N	June
*Erigeron karvinskianus**	1.97	A	June
Other taxa (319)	41.07		June

Fuchsia magellanica/hybrid	32.27	A	July
Salvia greggii/*microphylla*	5.51	A	July
Crocosmia × *crocosmiiflora*	4.09	A	July
Lonicera caprifolium/*japonica*/*periclymenum*	3.79	A	July
Penstemon barbatus	3.59	A	July
Lavandula angustifolia	2.42	A	July
Buddleja davidii	2.34	A	July
Nicotiana spp.	2.00	A	July
Linaria purpurea	1.96	A	July
Senecio jacobaea	1.95	N	July
Other taxa (374)	40.06		July
Fuchsia magellanica/hybrid	42.25	A	August
Crocosmia × *crocosmiiflora*	9.72	A	August
Salvia greggii/*microphylla*	4.28	A	August
Penstemon barbatus	3.49	A	August
Nicotiana spp.	2.26	A	August
Dahlia spp.	2.22	A	August
Buddleja davidii	2.07	A	August
Lonicera caprifolium/*japonica*/*periclymenum*	1.89	A	August
Lavandula angustifolia	1.84	A	August
*Erigeron karvinskianus**	1.63	A	August
Other taxa (328)	28.36		August
Fuchsia magellanica/hybrid	52.07	A	September
Salvia greggii/*microphylla*	5.15	A	September
Sedum spectabile/*telephium*	3.75	N	September
Dahlia spp.	3.53	A	September
Penstemon barbatus	3.03	A	September
Nicotiana spp.	2.46	A	September
Buddleja davidii	2.32	A	September
Aster spp.	1.94	A	September
*Erigeron karvinskianus**	1.82	A	September
Erysimum linifolium	1.72	A	September
Other taxa (285)	22.21		September
Fuchsia magellanica/hybrid	49.00	A	October
Hedera colchica/*helix*	11.75	N	October
Salvia greggii/*microphylla*	9.91	A	October
Dahlia spp.	3.11	A	October
Penstemon barbatus	3.00	A	October
Salvia × *hybrida*	2.04	A	October
*Erigeron karvinskianus**	1.70	A	October
Aster spp.	1.55	A	October
Chrysanthemum spp.*	1.44	A	October
Sedum spectabile/*telephium*	1.39	N	October
Other taxa (237)	15.12		October

Table S9. The 43 plant taxa which cumulatively provide 75% of the total nectar supply across all gardens. An asterisk (*) indicates a plant taxon's nectar production was estimated at the floral unit level by predictive modelling, all other taxa have empirically measured values. The native status of each taxon is indicated by the letter 'N' (native) or 'A' (non-native alien); the plant life form by the letter 'H' (herbaceous), 'T' (tree), 'S' (shrub) or 'C' (woody climber) and flower structure by the letter 'G' (generalised) or 'S' (specialised).

Plant taxon	Percentage of total nectar	Native status	Life form	Flower structure
Fuchsia magellanica/hybrid	23.29	A	S	S
Pieris spp.	6.94	A	S	S
Salvia greggii/*microphylla*	3.56	A	S	S
Lonicera caprifolium/*japonica*/*periclymenum*	2.79	A	C	S
Erysimum linifolium	2.23	A	H	S
Penstemon barbatus	2.03	A	H	S
Crocosmia × crocosmiiflora	1.83	A	H	S
Philadelphus coronarius/hybrid	1.79	A	S	G
Tamarix spp.*	1.75	A	S	G
*Erigeron karvinskianus**	1.29	A	H	G
Choisya ternata	1.28	A	S	G
Pyracantha spp.	1.21	A	S	G
Ceanothus spp.	1.20	A	S	G
Muscari armeniacum	1.16	A	H	S
Syringa vulgaris	1.12	A	S	S
Wisteria spp.	1.12	A	C	S
Skimmia japonica	1.10	A	S	G
Ribes sanguineum	1.08	A	S	S
Prunus spp. (ornamental)	1.04	A	T	G
Nicotiana spp.	1.03	A	H	S
Hedera colchica/*helix*	1.02	N	C	G
Dahlia spp.	1.00	A	H	G
Camellia japonica	0.97	A	S	G
Campanula portenschlagiana	0.93	A	H	G
Prunus laurocerasus	0.90	A	S	G
Campanula poscharskyana	0.87	A	H	G
Buddleja davidii	0.85	A	S	S
Erica carnea	0.81	A	S	S
Taraxacum agg.	0.78	N	H	G
Lavandula angustifolia	0.77	A	S	S
Bellis perennis	0.76	N	H	G
Weigela florida	0.70	A	S	S
Linaria purpurea	0.69	A	H	S
*Cordyline australis**	0.65	A	S	G
Jasminum officinale	0.65	A	C	S
Amelanchier spp.*	0.58	A	T	G
Cotoneaster spp. (red flowers)	0.57	A	S	G
Rhododendron spp. (large flower cultivar)	0.53	A	S	S
Heuchera spp.	0.50	A	H	G
Aquilegia vulgaris/hybrid	0.48	N	H	S
Euonymus spp.	0.46	A	S	G
Sedum spectabile/*telephium*	0.45	N	H	G
Centaurea montana	0.44	A	H	G
Other taxa (606)	24.81			

Appendix S12. Plant trait composition of the garden nectar supply

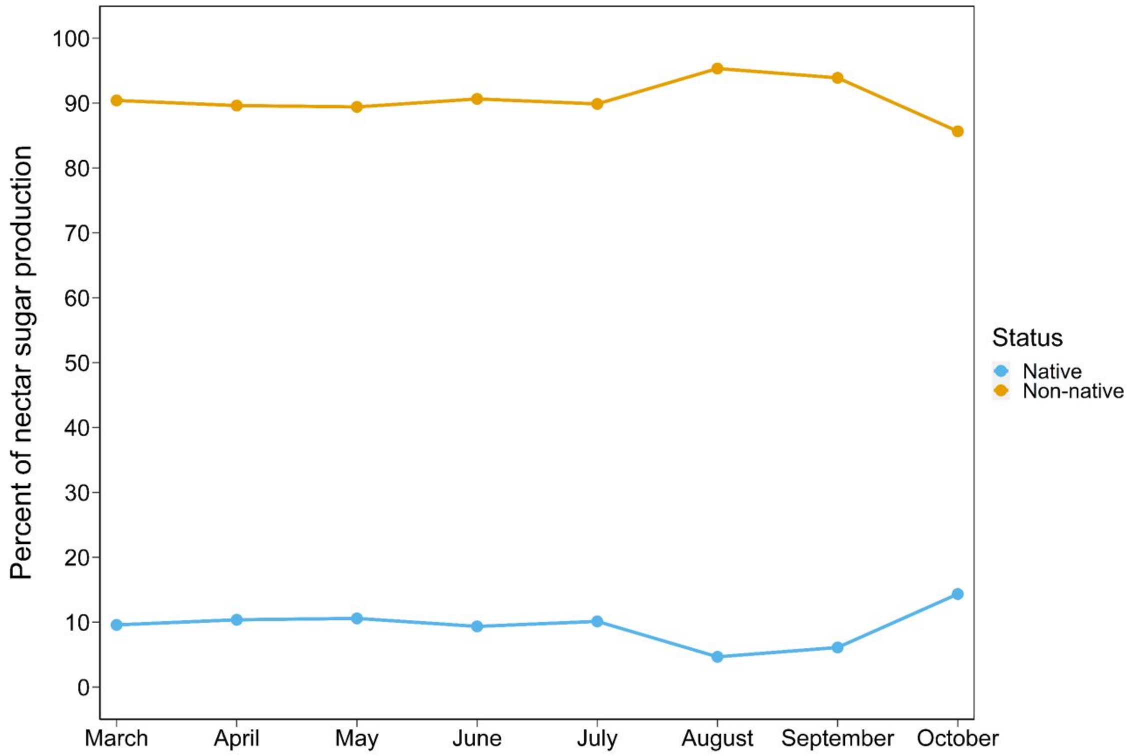

Figure S4. The percentage of the total nectar supply of all gardens in each month produced by native and non-native plant taxa.

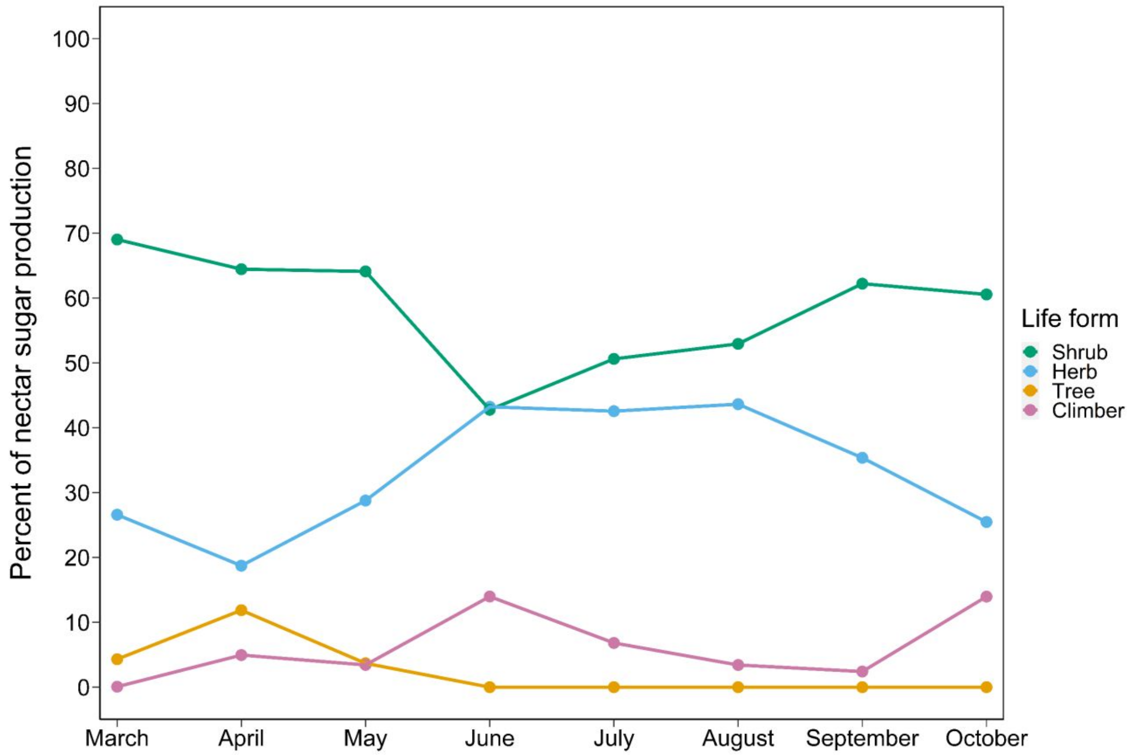

Figure S5. The percentage of the total nectar supply of all gardens in each month produced by shrubs, herbaceous plants (herbs), trees, and woody climbers (climbers).

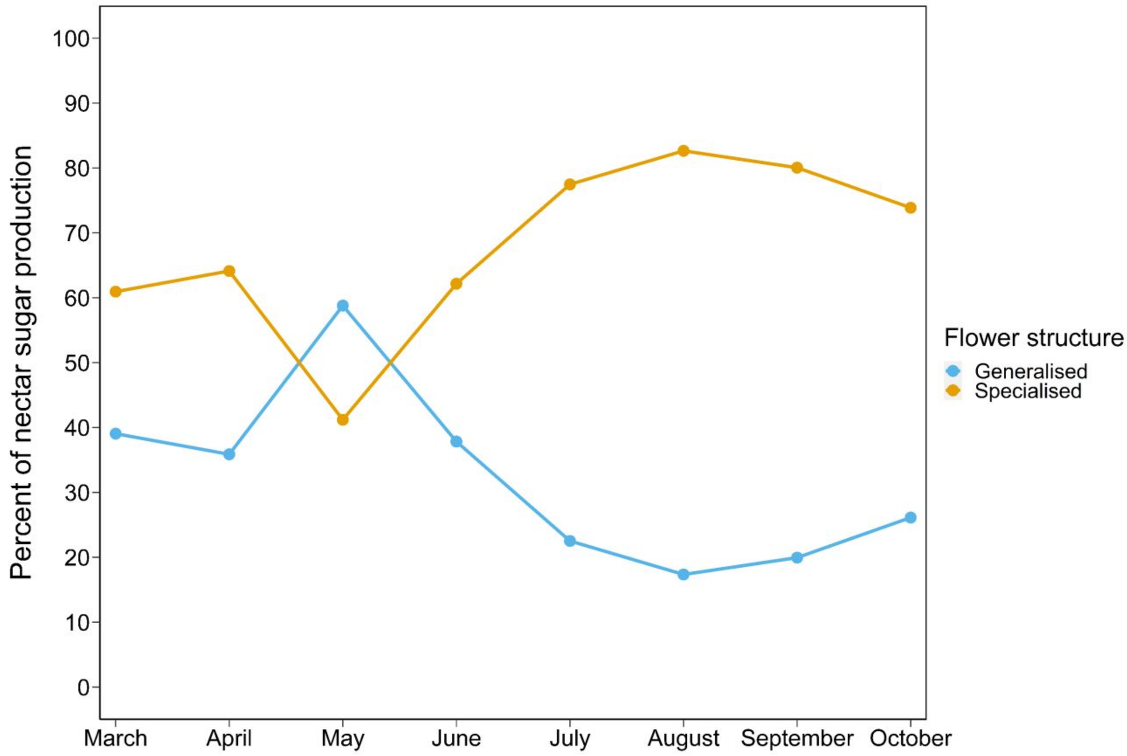

Figure S6. The percentage of the total nectar supply of all gardens in each month produced by flowers with a generalised or specialised structure.

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