Co-benefits from tree planting in a typical English agricultural landscape: comparing the relative effectiveness of hedgerows, agroforestry and woodland creation for improving crop pollination services

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Co-benefits from tree planting in a typical English agricultural landscape: Comparing the relative effectiveness of hedgerows, agroforestry and woodland creation for improving crop pollination services

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ABSTRACT

Land use policy in England is encouraging tree planting on farms to meet decarbonisation targets. This could be delivered through woodland creation, hedgerow planting or agroforestry. All three approaches could provide co-benefits for wild bee populations and crop pollination services, by increasing nesting and floral resources, but their relative effectiveness has not been studied at a landscape scale. We simulated six tree planting scenarios and used a validated process-based model to predict their effect on bumblebee abundance and pollination service to two common mass-flowering crops (oilseed rape and field beans) in a representative 10x10km agricultural landscape in England, UK. Two levels of planting intensity were studied: one representing the tree cover that would be achieved by 2035 if the 2020 woodland creation rate continues and another reflecting UK Government ambitions (threefold increase in planting rate). Hedgerow planting and woodland were predicted to give the biggest increase bumblebee abundance. Silvoarable agroforestry using fruit trees or willow was predicted, on average, to give the biggest increase in crop pollination service. However, the magnitude of increase was highly variable and hedgerow creation (which is more dispersed across the landscape) provided a more consistent increase in crop pollination services. Agroforestry with poplar (which offers less floral resource) and woodland creation (which concentrates tree planting in fewer locations) were only effective at enhancing landscape-level crop pollination at high planting intensity. Future land management policy should promote fruit tree and willow-based agroforestry as multifunctional tree planting measures in arable contexts, whilst continuing to encourage hedgerow planting and woodland creation for their role in promoting abundance and diversity of pollinators. Hedgerow planting may be needed alongside agroforestry to help stabilise pollination service through a crop rotation cycle.

1. Introduction

Wild bees significantly contribute to the pollination, and thus yield, of oilseed rape (*Brassica napus;* hereafter OSR) and field beans (*Vicia faba*) (Hutchinson et al., 2021), two of the most economically important UK arable mass-flowering crops. Wild bee population sizes are limited by access to forage resources (Roulston and Goodell, 2011) and nest availability (Carrié et al., 2018; Steffan-Dewenter and Schiele, 2008). There is evidence of widespread declines in wild bee populations in Great Britain between 1980 and 2013 (Powney et al., 2019) echoing global trends of decline (IPBES, 2016). This can impact food security where floral visitation is insufficient to achieve optimal yield in pollinator-dependent crops (Garratt et al., 2014a; Holland et al., 2020). Land use change, is a major contributor to pollinator declines; in particular, the intensification of UK agriculture during the 20th Century has led to simplification of farmed landscapes, significantly reducing resource availability for bees (Ollerton et al., 2014; Potts et al., 2016).

In the 21st Century, England's farmed landscapes are set to undergo further significant land-use changes, this time in response to an increased policy focus on tree planting. England had approximately 1310,000 ha or 10.0% woodland cover by total land area in 2020 (Forest Research, 2020) making it one of the least wooded countries in Europe (FAO, 2020). There are a further 560,000 ha of trees outside woodland, which includes 193,000 ha of trees in groups or lines (Brewer et al.,

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2017). 2340 ha of woodland was planted in 2020 (Forest Research, 2020) but national ambitions are to increase tree planting rates in England at least three-fold by 2024 (UK Government, 2021) to reach a level of tree cover by 2035 that would meet policy objectives set out by the Committee on Climate Change (the UK's independent climate change advisory body) in the UK's 6th Carbon Budget (Committee on Climate Change, 2020). Much of this planting will need to occur on land currently in agricultural use, and so will be delivered through England's proposed Environmental Land Management (ELM) scheme (Defra, 2022). This is a package of incentive measures that will provide economic support in the form of grants and management payments to landholders who enter agreements to deliver 'public goods'. It will replace England's existing broad agri-environment schemes such as Countryside Stewardship and bespoke grant schemes such as the England Woodland Creation Offer.

There are three main ways by which tree planting interventions can be incorporated in agri-environment schemes. Two of these (conventional woodland creation, hedgerow planting) are already part of existing voluntary schemes. A third, agroforestry, is being trialled as a potential ELM measure (Defra, 2021). In an arable context, agroforestry typically means silvoarable 'alley cropping' where commercially grown trees and crops occupy rows in the same field (Burgess, 2019). Commonly planted trees in these systems include orchard fruit trees such as apple and cherry (as an additional agricultural crop) as well as willow and poplar grown in short rotation coppice (SRC) as energy crops. Silvoarable agroforestry is relatively rare in the UK to date (0.05% of arable area), but is more common in the rest of Europe (0.41% of arable area) (den Herder et al., 2017). There are no explicit government targets for hedgerow planting or agroforestry but the UK Committee on Climate Change also recommends a 20% increase in hedgerow cover and 10% of agricultural land to be in agroforestry systems (including silvopasture) by 2035 (Committee on Climate Change, 2020).

Crucially, the trees used in these interventions can provide both nesting and floral resources to wild bees (Bentrup et al., 2019; Crowther et al., 2014; Hall et al., 2019; Stanley and Stout, 2013), especially in early spring when alternative foraging resource is scarce (Timberlake et al., 2019). Hence, tree planting done at scale has the potential to increase wild bee abundance, indirectly enhancing pollination services to nearby arable crops (Donkersley, 2019; Mola et al., 2021). Evidence from field- and farm-scale analyses has demonstrated a link between the presence of trees in woodlands, hedgerow and agroforestry systems and increases in bee abundance and crop visitation (Bailey et al., 2014; Berkley et al., 2018; Varah et al., 2020). However, no landscape-scale analysis has yet been carried out. Understanding how these interventions compare, in terms of their relative impact on pollinator abundance and crop pollination services at landscape scale, would help policymakers determine which types of tree planting interventions to prioritise in forthcoming schemes. This will enable such schemes to deliver multiple benefits – ecological, economic and food security - more efficiently, as well as carbon storage via the trees themselves.

Conducting such a landscape-level analysis for England requires a modelling approach due to the long timescales for fieldwork involving tree planting and the spatial sensitivity of pollination services. The process based model *poll4pop* (Gardner et al., 2020; Häussler et al., 2017) simulates how bees (central-place foragers) move around the landscape to nest, forage and reproduce, building on earlier attempts to capture habitat complementarity and foraging movements (Lonsdorf et al., 2009; Olsson et al., 2015). *Poll4pop* has already been used at landscape scale, demonstrating that current English agri-environment schemes have likely increased bumblebee abundance nationally and increased pollination services to mass flowering crops in select geographic locations (Image et al., 2022). A follow-on study examined to what extent the existing tree-planting interventions within these schemes contributed to the pollination service enhancement and found their effect was negligible, due to the low uptake of these interventions to date in areas containing mass-flowering crops (Image et al., in Press.).

Here, we examined the potential impacts on bee abundance and crop pollination services of future tree planting interventions with increased levels of uptake. We chose a representative English landscape containing mass-flowering crops and generated uptake scenarios for one woodland creation, two hedgerow planting and three silvoarable agroforestry interventions with tree cover equivalent to continuing tree planting at current rates until 2035. We then applied the *poll4pop* model to each tree planting scenario and a baseline landscape scenario, using Analysis of Variance (ANOVA) and post-hoc tests to determine differences between the predicted bumblebee abundance and crop pollination service in each scenario. We then repeated the analysis with trebled tree planting rates to examine how an increase in planting intensity to match government ambition would change the relative effectiveness of these interventions. We conclude with recommendations for maximising pollination co-benefits from tree planting activities.

2. Materials and methods

2.1. Selection of study area

We chose a 10 km^2 study area (computationally feasible for the number of simulations required) with a 5 km surrounding buffer zone (removed after the bee population simulations to eliminate edge effects) which was representative of typical conditions where mass-flowering crops are grown, and tree planting would be feasible in England. This was achieved by selecting an existing 10 km^2 Ordnance Survey grid tile that best satisfied the following conditions:

1. At least 10% of the tile and a surrounding 5 km buffer zone should be 'lower risk' land unlikely to face planning constraints for woodland creation (Forestry Commission, 2021), where low risk land is assumed to be arable or improved grassland with an Agricultural Land Classification of Grade 3, 4 or 5 that is not on peat soils (MAFF, 1988).
2. Area of "non-scheme resource" (suburban parks/gardens, commercial orchards, and semi-natural habitat outside existing AES management) within the tile is as close as possible to the mean (8.1%) of all the OS 10 km^2 tiles (plus 5 km buffer) that contain some OSR and/or field beans, since Image et al. (2021) showed that the impact of interventions on visitation rate depends on amount of non-scheme habitat resources.
3. Area of higher quality AES interventions (hedgerow/woodland edge management, floral margins, grass margins, fallow plots, traditional orchards) within the tile is as close as possible to the mean (1.2%) of all the OS 10 km^2 tiles (plus 5 km buffer) containing some OSR and/or field beans (for similar reasons to condition 2).
4. Percentage cover of OSR and percentage cover of field bean in the tile are above the mean values (6.0% and 1.6%, respectively) for all the 10 km^2 tiles containing some OSR and/or field beans, since the crop cover distribution is skewed by the large number of tiles that contain only negligible amounts of these crops (see Figure. S1 in Supplementary Material)
5. Not a coastal tile, to ensure interventions can be located within 5 km of any point in the tile.

The selection process chose tile 'SK86', which is in the East Midlands region of England (Fig. 1) and has 91.2% of low-risk land. 7.5% of the tile area is OSR and 2.2% is field beans. Of the area of the tile and its surrounding buffer, 8.0% is covered by non-scheme resource and 1.2% is covered by higher quality AES features. Full land cover details are provided in the Supplementary Material (Figs. S2 and S3).

2.2. Pollinator model description

We used the process-based model *poll4pop* (Gardner et al., 2020; Häussler et al., 2017), which predicts seasonal spatially-explicit

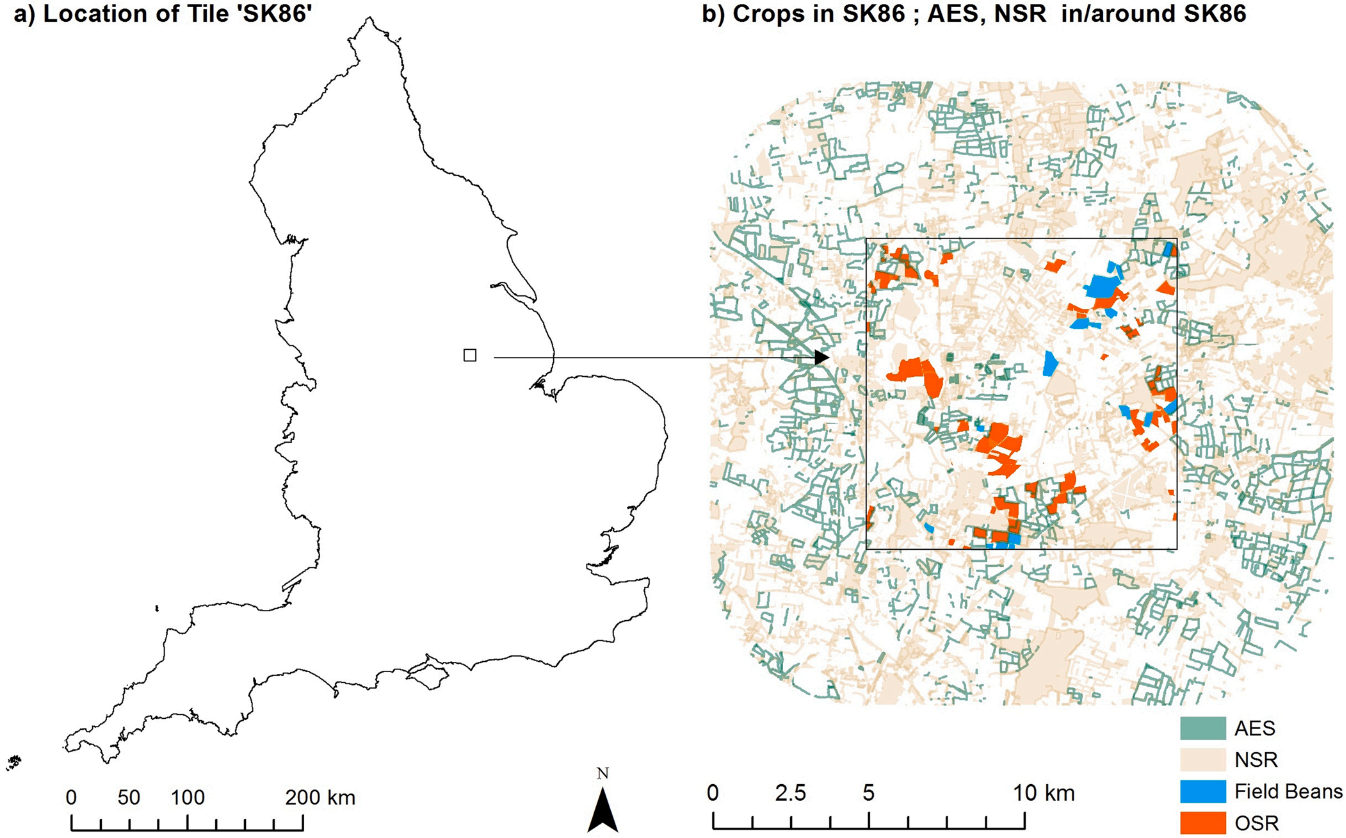

Fig. 1. a) Location of study tile (SK86) in England; b) Location of OSR and Field Beans within the tile and location of higher-value agri-environment scheme (AES) features and non-scheme resource (NSR; suburban parks/gardens, commercial orchards, and semi-natural habitat outside existing AES management) in the tile and within surrounding 5 km buffer. See Section 2.1 for definition of higher-value AES and NSR. See Image et al. (2022) for spatial data sources. See Figs. S2 and S3 for full land cover maps.

abundance and floral visitation rates for central-place foraging pollinators within a given rasterised landscape, incorporating fine-scale features such as hedgerows and grass margins. The model simulates optimal foraging of bees around their nests and population growth to calculate within-year production of workers for social bees and yearly population size for all bees (see Häussler et al., 2017 for a detailed description) and can be run for a particular species or for a group of species ('guild') that have common attributes. The model requires: a land cover map, floral cover parameters for each land cover class in each season, floral and nesting attractiveness (i.e., foraging and nesting quality from the perspective of the modelled species/guild) for each land cover class, maximum nest density and mean foraging and dispersal range for the species/guild, and a set of parameters determining nest productivity, i.e. number of new (workers and) reproductive females produced, as a function of forage resources gathered.

The model was parameterised and validated for England by Image et al. (2022) for four wild bee guilds (ground-nesting bumblebees, ground-nesting solitary bees, tree-nesting bumblebees, and cavity-nesting solitary bees), taking guild-specific parameters from Gardner et al. (2020). These parameters consisted of literature estimates, plus nesting and floral attractiveness and floral cover scores derived from expert opinion, which were slightly readjusted to better incorporate seasonal changes in crop flowering, and to capture additional land classes used by Image et al. (2022) but not included in the original Gardner et al. (2020) parameterisation (see Image et al., 2022 for details). Using this parameterisation, the model outputs spatially-explicit predictions for the following seasons: early spring (early/mid-March – late April/early May), late spring (late April/early May – early/mid-June) and summer (early/mid-June – early/mid-August).

In this study, we use the model parameterisations for bumblebees only. Ground-nesting bumblebees are already known to be more important pollinators of OSR and field beans than solitary bees (Garratt et al., 2014b; Stanley et al., 2013). Less is known about the relative importance of tree-nesting bumblebees in OSR or field bean pollination, but as they are known to be visitors of both crops (Hutchinson et al., 2021), their population is increasing in the UK (Huml et al., 2021) and they are likely to benefit from increased tree cover (Crowther et al., 2014), we also include them in this analysis.

2.3. Baseline scenario

Image et al. (2022) simulated bee abundance and visitation rates for two landcover scenarios for England: one in which AES-supported management in the year 2016 was present (*AES_Present*) and an alternative in which AES-supported management was absent (*AES_Absent*). The English AES schemes included were *Countryside Stewardship* (CS) and *Environmental Stewardship* (ES), though field margin and hedgerow features claimed by landholders as Ecological Focus Areas (EFA) under Common Agricultural Policy 'Greening' requirements (Rural Payments Agency, 2018) were also treated as AES. Locations of AES features were obtained from UK Rural Payments' Agency datasets and land cover maps (at 25 m^2 resolution) for these two landcover scenarios were developed as set out in Image et al. (2022).

We took the *AES_Present* scenario from Image et al. (2022) as our baseline landcover scenario. For each guild, we extracted a) the seasonal floral visitation rates for every 25 m^2 cell of the baseline landcover scenario, b) the total seasonal visitation rates summed across all cells of the baseline landcover scenario, c) the total visitation rate to OSR cells within the baseline landcover scenario, and d) the total visitation rate to field bean cells within the baseline landcover scenario. Where cells contain edge features, the crop visitation rate was adjusted *pro rata* to match the proportion of crop resource and its floral resource value (floral attractiveness * floral cover) relative to the edge features. These visitation rate predictions for the *AES_Present* scenario were then divided by the equivalent visitation rate predictions for the *AES_Absent* scenario to convert them into relative units, i.e. the visitation rate expressed as a fraction of the visitation rate without any of the current AES interventions present. This converts the *poll4pop* outputs (which are in arbitrary units) onto a meaningful scale to facilitate comparison between scenarios and guilds. An equivalent procedure was used to extract, sum and convert the spatially explicit nest density, worker productivity and nest productivity predictions from the baseline landcover scenario (*AES_Present*) into relative units (i.e. expressed as a fraction of the predictions obtained from the *AES_Absent* scenario).

The uncertainty in the baseline landcover scenario predictions was calculated, as in Image et al. (2022), by running 100 simulations where nesting attractiveness, floral attractiveness and floral cover score for each land class were drawn from a beta distribution representing the variation in individual expert opinion scores for these parameters, i.e., each simulation uses a unique input parameter set. This generates a distribution for the predicted quantities that incorporates this uncertainty in underlying input parameters.

2.4. Tree planting scenarios

We defined a set of six tree planting scenarios (Table 1) covering the three main mechanisms by which additional trees can be planted in farmland contexts (Fig. 2).

The two *Hedgerow planting* scenarios introduced new hedgerows along available arable or improved grassland field boundaries (i.e. any such boundaries currently without an existing hedgerow). These new hedgerows were either randomly distributed or clustered. In the clustered scenario, new hedgerows were preferentially located in specific areas within the landscape of between 100 ha to 700 ha representing farm and potential farm cluster boundaries. This was intended to represent a more realistic distribution of intervention uptake where: some farms are more pre-disposed to AES participation (Arnott et al., 2019), decision-making is often influenced by neighbouring farms behaviour (Marconi et al., 2015) and, policymaking is encouraging farmers to co-operate to achieve environmental outcomes (Prager, 2022). Actual farm boundary information is not publicly available in England, so the areas chosen for preferential location were selected randomly using an algorithm (see Supplementary Material Section 1 for details and Fig. S4 for a map output showing example spatial distributions).

Table 1
Tree-planting scenarios.

Scenario		Summary of allocation process
Hedgerow	Distributed	New hedgerows placed along **any** existing arable or improved grassland boundaries lacking woody linear features until linear target reached.
Hedgerow	Clustered	New hedgerows placed along existing arable or improved grassland boundaries lacking woody linear features, with **preferential allocation to farm / farm-cluster sized (~100 to ~700 ha) spatial zones** until linear target reached.
Agroforestry	Fruit Trees	Crop + (orchard) **fruit trees** aligned north-south in ratio 80%/20% replaces crop in **any** cereal, OSR or field bean parcel until area target reached.
Agroforestry	Poplar	Crop + **poplar** (*Populus spp.*) trees aligned north-south in ratio 80%/20% replaces crop in **any** cereal, OSR or field bean parcel until area target reached.
Agroforestry	Willow	Crop + **willow** (*Salix spp.*) trees aligned north-south in ratio 80%/20% replaces crop in **any** cereal, OSR or field bean parcel until area target reached.
Woodland		Woodland (86% broadleaf, 14% conifer) in contiguous blocks not exceeding 20 ha replaces randomly chosen eligible arable or improved grassland parcels (or parts thereof if parcel area>20 ha), until area target is reached.

The *Agroforestry* scenarios consisted of silvoarable alley cropping with 20% trees / 80% crop aligned north-south. We defined three scenarios for three different trees commonly used in agroforestry systems – fruit trees (e.g., apple), poplar (*Populus* spp.), and willow (*Salix* spp.) – since each offer different floral and nesting resource levels for bees. In practice, the tree rows in a typical silvoarable system would be 1 tree-width wide plus 2–4 m to accommodate tree-related machinery and at least twice the tree-height apart from adjacent rows or wide enough for crop-related machinery (Burgess, 2019), i.e. tree rows approx. 10 m wide and 40 m apart for poplar, 7 m / 30 m for willow and 5 m / 25 m for fruit trees. However, to ensure the new trees would be reflected in the resolution of the land cover map, we set the tree and crop rows to have widths of 30 m and 120 m respectively for all three scenarios. Agroforestry interventions were permitted to occur in any cereal, OSR and field bean fields.

The *Woodland creation* scenario introduced new woodland features of ~20 ha with an 86% broadleaf and 14% conifer mix, consistent with the typical woodland creation project between 2015 and 2020 in England (Forest Research, 2020). Woodland creation interventions were only permitted to occur on arable and improved grassland parcels of Grade 3 agricultural land or poorer (MAFF, 1988), but avoiding peat soils. These are locations which would be expected to be lower risk for woodland creation under Environmental Impact Assessment guidance (Forestry Commission, 2021). This does not completely replicate the lower risk exclusion criteria but was a necessary proxy as neither the exclusion layer itself nor the complete set of contributing datasets were publicly available.

2.5. Tree planting intensity

For each scenario, we applied two different levels of tree planting intensity, determined with reference to current woodland planting rates and UK government ambitions. A top-down target was chosen because tree-planting targets for the study area itself were not available and the scenarios were intended to represent conditions for a typical mass-flowering crop landscape. We chose a single area target between scenarios to enable consistent comparison, and this was chosen with respect to woodland planting because this scenario has explicit government targets for England specifically.

For the low planting intensity, we used the 2016 England woodland area (1305,280 M ha; Forest Research, 2020) and applied a constant woodland creation rate equivalent to the 2020 England woodland creation rate (2340 ha yr^{-1}; Forest Research, 2020) to calculate the resulting level of tree cover in 2035. For the high planting intensity, we repeated this calculation with an increased tree planting rate of 7000 ha yr^{-1}, which represents a threefold increase consistent with the minimum desired rate by the end of 2024 set out in the England Trees Action Plan (UK Government, 2021). The year 2035 was chosen as this is the reference year for the UK's sixth Carbon Budget, in which tree planting is a key component (Committee on Climate Change, 2020). The lower intensity is equivalent to a 3.4% increase in tree cover nationally (relative to 2016) and the higher intensity is equivalent to a 10.2% increase.

Applying these percentage increases to the 2016 area of woodland already in tile SK86 and its 5 km buffer zone (2223 ha) gives an increase in woodland cover of 76 ha for the low planting intensity and 228 ha for the high planting intensity. We used these values as the area targets for woodland creation and for the tree component of the agroforestry systems. For hedgerows, linear targets (304 km, 912 km) were determined from the area target by assuming a typical hedgerow is 2.5 m wide,

Fig. 2. Images of different types of tree planting used in farmland contexts. Hedgerow planting © Paul Franks (cc-by-sa/2.0); Agroforestry © Rafael Pompa – used with permission; Woodland creation © Eirian Evans (cc-by-sa/2.0).

consistent with the width assumptions for conventionally managed hedgerows used in Image et al. (2022).

2.6. Simulations

We generated 100 alternative land cover realisations for each tree-planting scenario and planting intensity using a land allocation algorithm that modified the land cover in the baseline scenario, according to the rules given in Table S2 (see SM for further details). Tree planting interventions were added to both the study area and 5 km surrounding buffer zone (to ensure that every part of the study area would be equally likely to benefit from a randomly allocated intervention) until the appropriate area target was reached.

For each land cover realisation, the *poll4pop* model was then run to predict the resulting bee abundance and visitation rates, assuming all interventions were in their mature state. 100 runs of the model were done for each scenario, where each land cover realisation (i.e., spatial pattern of interventions) was combined with one of the *poll4pop* parameter sets used to run the baseline scenario to create a unique pattern-parameter set. The visitation rate predicted for each was divided by the visitation rate predicted for the *AES_Absent* scenario (run with the same parameter set) to produce a distribution of relative visitation rates for each scenario that incorporates uncertainty from both input parameters and random placement of interventions. Although there were theoretically 10,000 possible pattern-parameter combinations (100 land cover realisations x 100 input parameter sets), we randomly selected only 100 unique pattern-parameter sets to avoid introducing pseudoreplication (through using the same parameter or land cover realisation more than once).

The same procedure was applied to the other *poll4pop* outputs to obtain the corresponding predicted distributions of nest density, worker productivity and nest productivity, also in relative units (i.e., expressed as a fraction of the predictions obtained from the *AES_Absent* scenario), for each tree planting scenario. This provided both bee abundance and visitation rate predictions for each simulation that were comparable to those obtained for the baseline scenario.

2.7. Comparing effectiveness of tree-planting scenarios at different intensities

2.7.1. Landscape-level

We ran ANOVAs with post-hoc Tukey tests to determine whether there were significant differences in bee abundance between tree-planting scenarios and the baseline scenario at landscape level. For each of the 100 low intensity planting simulations, we calculated the total predicted relative nest densities (R), queen production (Q) and worker production per season (W) for each guild across all raster grid cells in our 10 km^2 study area and treated each tree planting scenario and baseline as a separate group within the ANOVA. The same analysis was repeated with data from the high intensity tree planting simulations. We also carried out an equivalent analysis to compare the scenarios' effects on total relative visitation rate (V) to OSR and field beans.

2.7.2. Field-level

We selected a land cover realisation for each scenario whose effect on relative OSR and field bean visitation was closest to the mean of all land cover realisations for that scenario (as calculated with input parameters held at their mean values). The same land cover realisation was used to set the alley locations for all agroforestry scenarios, in order to facilitate comparison. We then mapped the visitation rate for that tree planning scenario divided by the visitation rate for the baseline scenario (i.e. $V_{Scenario} / V_{Baseline}$). The resulting maps were then visually examined to understand the typical field-scale spatial distribution of visitation rate change across the study area (with respect to the baseline scenario) for each tree planting scenario.

3. Results

3.1. Landscape-level

3.1.1. Nest density

The hedgerow scenarios significantly increased nest density for ground-nesting bumblebees, compared to the baseline scenario, at both low and high planting intensities. In contrast, fruit tree agroforestry and woodland only significantly increased ground-nesting bumblebee nest density at the high planting intensity (Fig. 3a; Table S2, S4), while the other agroforestry scenarios showed no significant increase above the baseline. The hedgerow scenarios also showed significantly higher predicted nest density for this guild compared to poplar and willow agroforestry at low planting intensity, and significantly outperformed all other scenarios at high planting intensity (Fig. 2a). Fruit tree agroforestry and woodland scenarios only showed significantly higher nest density than poplar and willow agroforestry for ground-nesting bumblebees at high planting intensity.

For tree-nesting bumblebees, woodland creation and fruit tree agroforestry were the only scenarios that significantly increased nest density above the baseline at both low and high planting intensity (Fig. 3b; Tables S3, S5). High planting intensity was required for the hedgerow scenarios to significantly increase nest density for this guild above the baseline. Woodland also showed significantly higher tree-nesting bumblebee nest density than all other scenarios, at both planting intensities. Fruit tree agroforestry showed significantly higher tree-nesting bumblebee nest density than poplar and willow at both planting intensities, but only significantly outperformed the hedgerow scenarios at high planting intensity (Fig. 2b). Likewise, the hedgerow scenarios only significantly increased nest density above the poplar and willow agroforestry scenarios at high planting intensity.

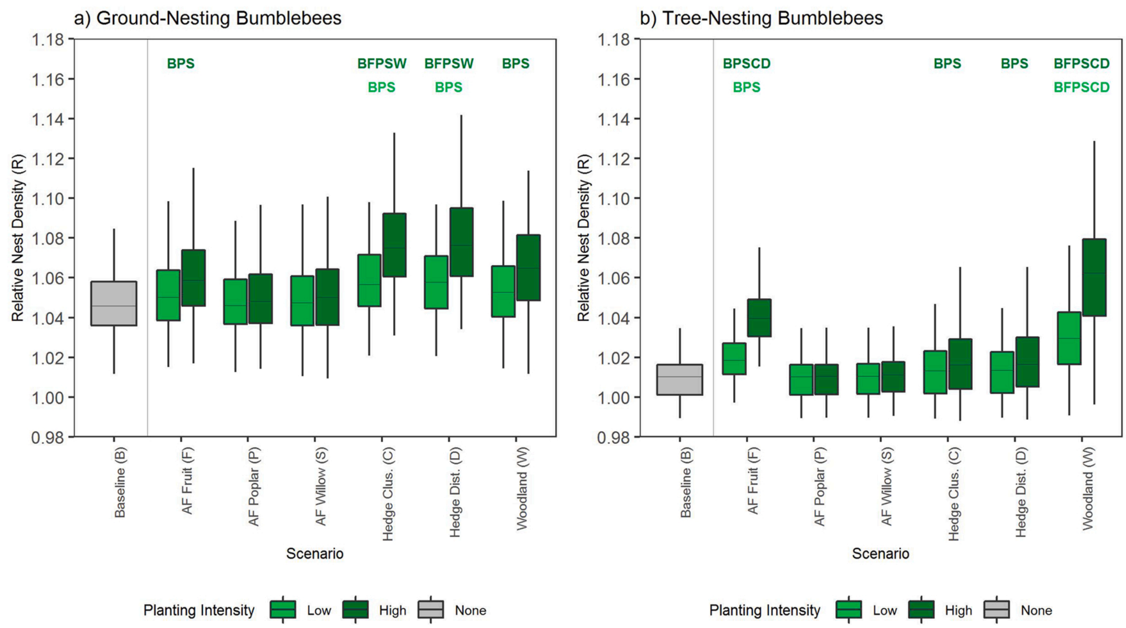

Fig. 3. Box plots showing relative **nest density** (R – total number of nests as a fraction of the number predicted with no AES interventions or tree planting present) for the baseline scenario (2016 AES features only; grey) and the tree planting scenarios (2016 AES features plus additional tree cover; green). Low planting intensity (light green) represents 3.4% increase in tree cover, equivalent to maintaining current tree-planting rates to 2035. High planting intensity (dark green) represents 10.2% increase in tree cover, equivalent to a trebled rate over the same period that matches UK Government targets. Letters above each scenario's boxplot indicate mean value significantly greater (Tukey Test) than other scenario(s) at the same intensity level (or baseline) where: B = Baseline, F = AF Fruit, P = AF Poplar, S = AF Willow, C = Hedge Clus, D = Hedge Dist, W = Woodland.

3.1.2. Queen production

All scenarios, except for poplar agroforestry, significantly increased ground-nesting bumblebee queen production (i.e., number of new reproductive females produced at the end of the active season) above the baseline at high planting intensity (Fig. 4a; Table S9). At low planting intensity, only the hedgerow scenarios significantly increased ground-nesting bumblebee queen production above the baseline (Fig. 4a; Table S7). The hedgerow scenarios also showed significantly higher queen production than poplar agroforestry for this guild at low planting intensity. At high intensity, the distributed hedgerow scenario significantly outperformed all other scenarios and the clustered hedgerow scenario all but fruit tree agroforestry (Fig. 3a, Table S9). Fruit tree and

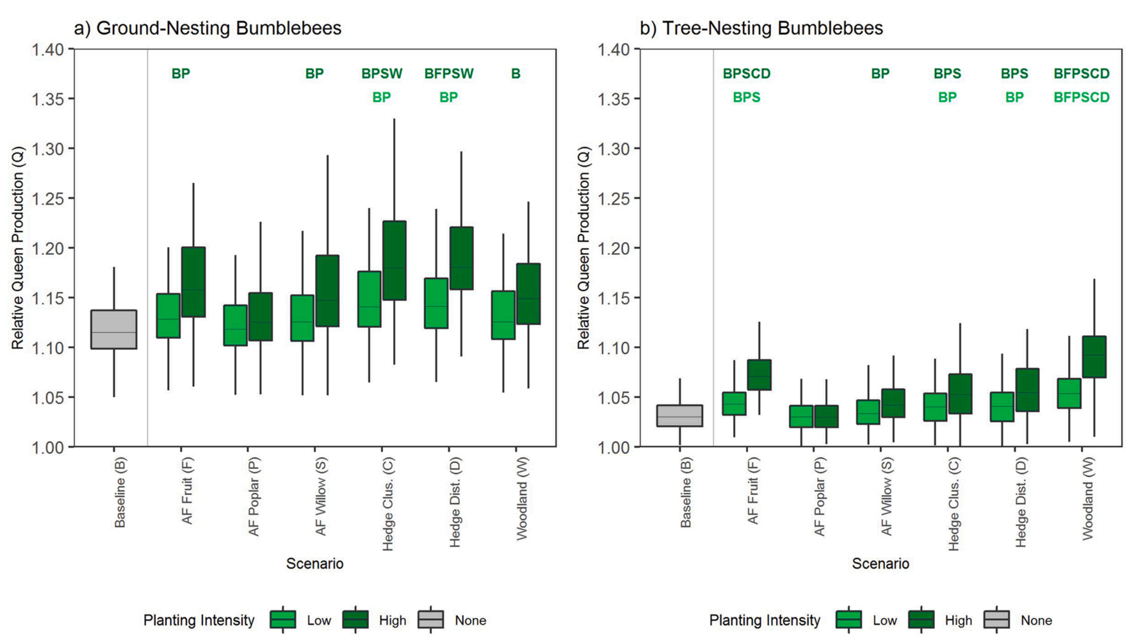

Fig. 4. Box plots showing relative **queen production** (Q – total number of new reproductive females as a fraction of the number predicted with no AES interventions or tree planting present) for the baseline scenario (2016 AES features only; grey) and the tree planting scenarios (2016 AES features plus additional tree cover; green). Low planting intensity (light green) represents 3.4% increase in tree cover, equivalent to maintaining current tree-planting rates to 2035. High planting intensity (dark green) represents 10.2% increase in tree cover, equivalent to a trebled rate over the same period that matches UK Government targets. Letters above each scenario's boxplot indicate mean value significantly greater (Tukey Test) than other scenario(s) at the same intensity level (or baseline) where: B = Baseline, F = AF Fruit, P = AF Poplar, S = AF Willow, C = Hedge Clus, D = Hedge Dist, W = Woodland.

willow agroforestry also showed significantly higher ground-nesting bumblebee queen production at high planting intensity compared to poplar agroforestry.

For tree-nesting bumblebees, queen production was significantly greater than the baseline for woodland, fruit tree agroforestry and hedgerow scenarios at both low and high planting intensities, whilst willow agroforestry only achieved this at high planting intensity (Fig. 4b; Table S8, S10). Woodland creation showed significantly higher tree-nesting bumblebee queen production than all other scenarios at both low and high planting intensity. Fruit tree agroforestry showed significantly higher tree-nesting bumblebee queen production than the other agroforestry scenarios, and also outperformed hedgerows at high planting intensity. The two hedgerow scenarios significantly outperformed poplar agroforestry at both planting intensities and also willow agroforestry at high planting intensity, while tree-nesting bumblebee queen production under willow agroforestry was only greater than poplar agroforestry at high planting intensity (Fig. 3b, Table S10).

3.1.3. Worker production

For ground-nesting bumblebees, fruit tree agroforestry, willow agroforestry and the hedgerow scenarios significantly increased worker production above the baseline at both low and high planting intensity (Fig. 4a, c; Tables S12-S13, S16-S17). Woodland creation required high planting intensity to significantly increase worker production above baseline for this guild, whilst poplar agroforestry only significantly

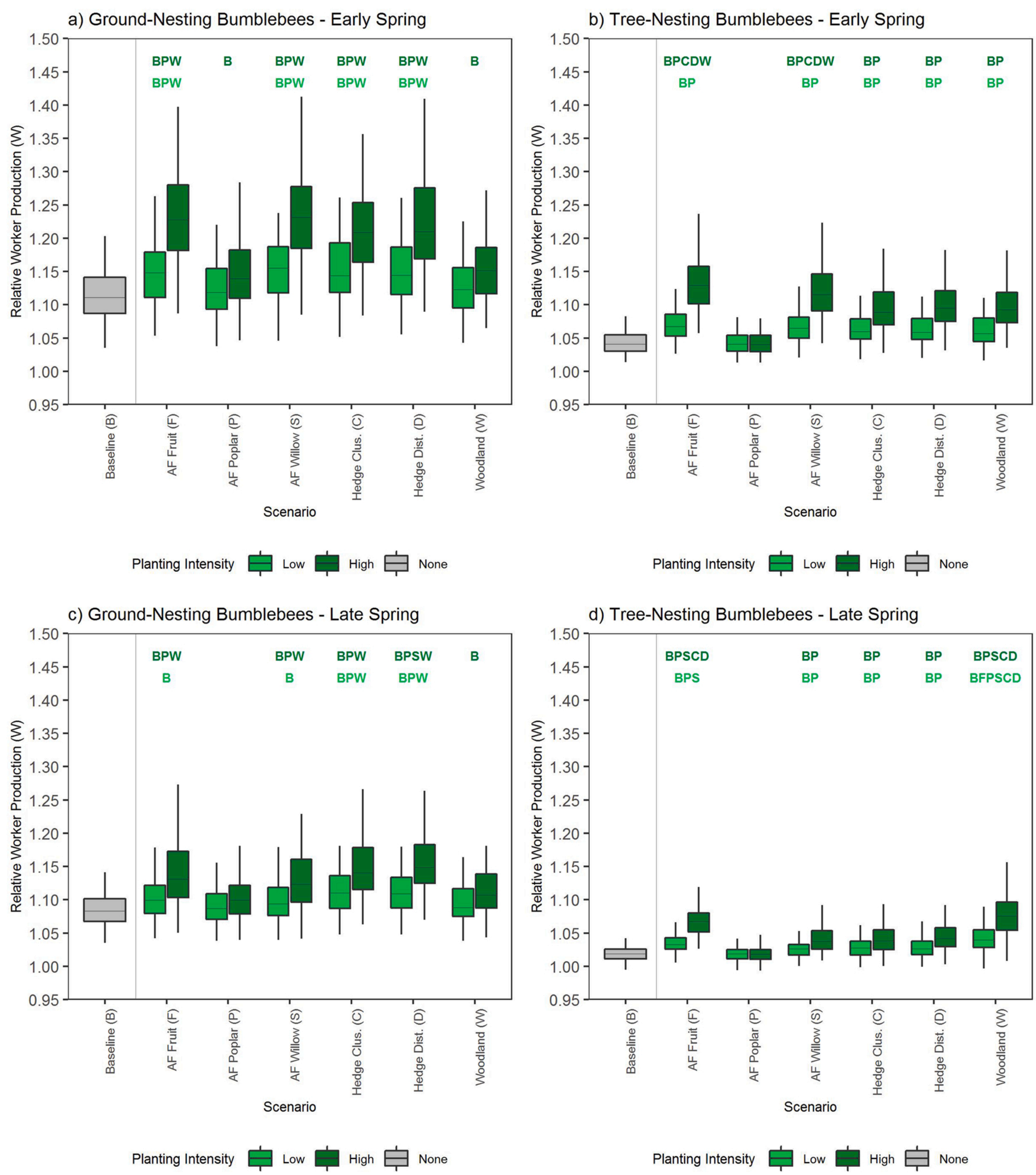

Fig. 5. Box plots showing relative **worker production** per season (W – total number of new worker bees produced as a fraction of the number produced with no AES interventions or tree planting present) for the baseline scenario (2016 AES features only; grey) and the tree planting scenarios (2016 AES features plus additional tree cover; green). Low planting intensity (light green) represents 3.4% increase in tree cover, equivalent to maintaining current tree-planting rates to 2035. High planting intensity (dark green) represents 10.2% increase in tree cover, equivalent to a trebled rate over the same period that matches UK Government targets. Letters above each scenario's boxplot indicate mean value significantly greater (Tukey Test) than other scenario(s) at the same intensity level (or baseline) where: B = Baseline, F = AF Fruit, P = AF Poplar, S = AF Willow, C = Hedge Clus, D = Hedge Dist, W = Woodland.

increased worker production in early spring and again only under high planting intensity. The fruit tree agroforestry, willow agroforestry and hedgerow scenarios generally showed significantly higher ground-nesting bumblebee worker production than the poplar agroforestry and woodland creation scenarios, except in late spring when there was no significant difference between the agroforestry scenarios (Fig. 4a, c).

For tree-nesting bumblebees, all scenarios, except for poplar agroforestry (at both planting intensities), resulted in significantly higher relative worker production than the baseline (Fig. 4b, d; Tables S14-S15, S18-19). In early spring, fruit tree and willow agroforestry also showed significantly higher tree-nesting bumblebee worker production compared to hedgerow and woodland scenarios at high planting intensity. In late spring, fruit tree agroforestry showed significantly higher tree-nesting bumblebee worker production than willow agroforestry at both planting intensities and significantly higher than the hedgerow scenarios at high intensity, while the woodland scenario significantly outperformed all other scenarios at low planting intensity and all except fruit-tree agroforestry at high intensity (Fig. 4b, d).

3.1.4. Crop visitation

OSR visitation by ground-nesting bumblebees was significantly higher than the baseline in all scenarios under high planting intensity, while only fruit tree agroforestry, willow agroforestry and the hedgerow scenarios produced significant increases above baseline at low planting intensity (Fig. 5a). Field bean visitation by ground-nesting bumblebees was significantly higher than the baseline in all scenarios, except

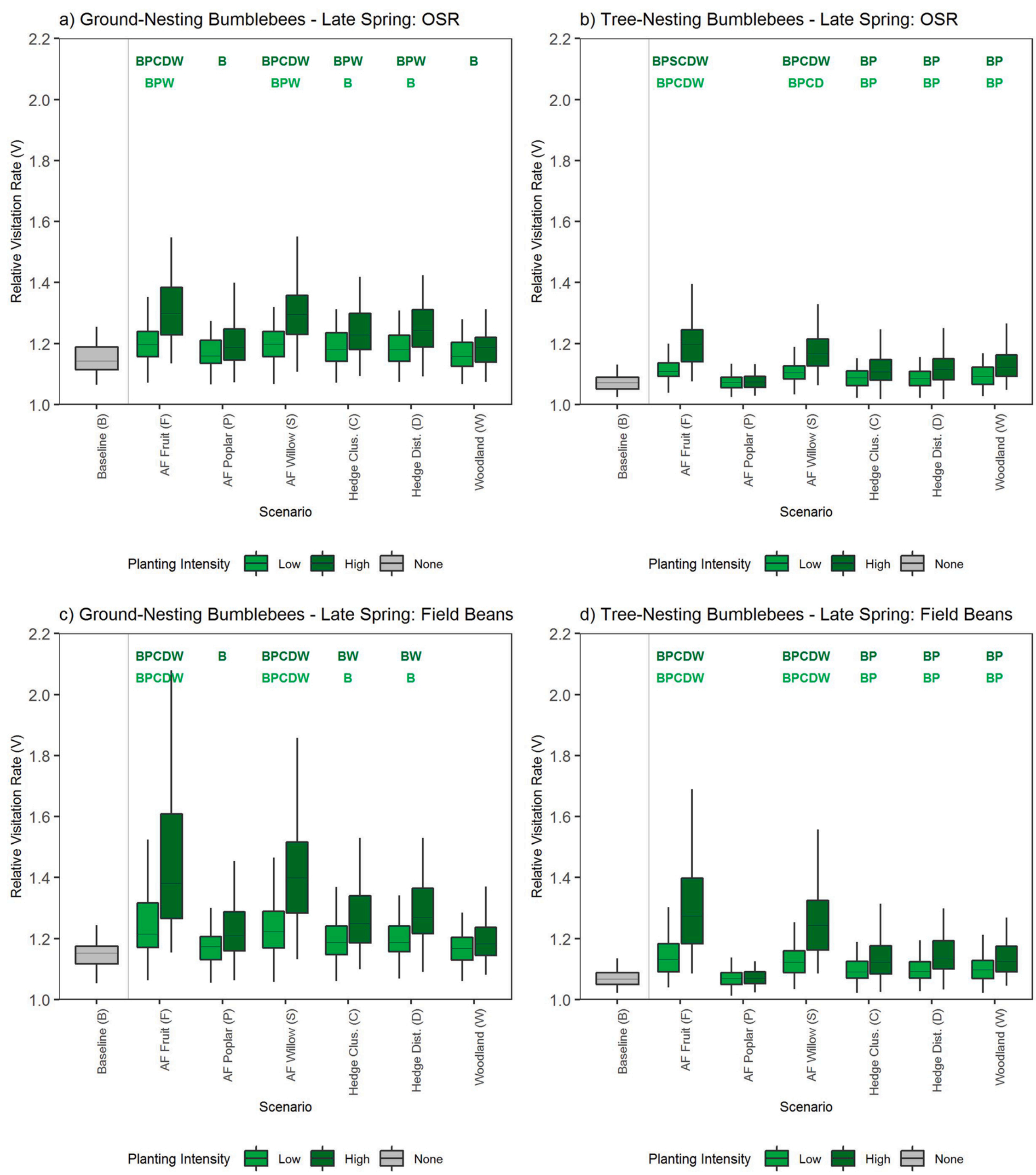

Fig. 6. Box plots showing relative **visitation rate** (V – total number of visits as a fraction of the visitation with no AES interventions or tree planting present) to **OSR** and **field beans** during late spring (peak flowering) for the baseline scenario (2016 AES features only; grey) and the tree planting scenarios (2016 AES features plus additional tree cover; green). Low planting intensity (light green) represents 3.4% increase in tree cover, equivalent to maintaining current tree-planting rates to 2035. High planting intensity (dark green) represents 10.2% increase in tree cover, equivalent to a trebled rate over the same period that matches UK Government targets. Letters above each scenario's boxplot indicate mean value significantly greater (Tukey Test) than other scenario(s) where: B = Baseline, F = AF_Fruit, P = AF_Poplar, S = AF_Willow, C = Hedgerow_Clus, D = Hedgerow_Dist, W = Woodland.

woodland, under high planting intensity. Again, the fruit agroforestry, willow agroforestry and hedgerow scenarios showing significant increases above baseline at low planting intensity (Fig. 5c). The fruit tree and willow agroforestry scenarios generally produced significantly higher ground-nesting bumblebee visitation rates to both crops than all the other scenarios (Fig. 5a, c), while the hedgerow scenarios significantly outperformed woodland for crop pollination service provision at high planting intensity.

Tree-nesting bumblebee visitation to OSR and field bean was significantly greater than baseline at both planting intensities in all scenarios, except for poplar agroforestry (Fig. 6b, c; Tables S23-S24, S27-S28). The fruit tree and willow agroforestry scenarios generally produced significantly higher tree-nesting bumblebee visitation rates to both crops than the other scenarios, while poplar agroforestry was significantly outperformed by all other scenarios (Fig. 5b, d).

It should be noted that the simulations for fruit tree and willow agroforestry showed much larger variance in their predicted crop visitation rate than the other scenarios. This was especially the case for field beans, where the interquartile range for these scenarios was ~1.5–2 times that of the other scenarios (Fig. 5c, d).

3.2. Field-level

3.2.1. Ground-nesting bumblebees

Fig. 6 shows how the change in ground-nesting bumblebee Late Spring visitation rate (relative to the baseline scenario) is distributed across the study area for each low intensity tree planting scenario. In the distributed hedgerow scenario, there are moderate (2–6%) visitation rate increases spread across a wide area (Fig. 6a). In the clustered hedgerow scenario, the change in visitation rate is more unevenly distributed across the study area; there are larger increases (>10%) concentrated in areas where the hedgerow clustering is most dense, with less than 2% increase across much of the rest of the study area (Fig. 7b). In both scenarios, cells receiving > 20% increase correspond to those where the hedgerow features themselves are located.

In the fruit and willow agroforestry scenarios (Fig. 6c and e), the change in ground-nesting bumblebee Late Spring visitation rate shows a similar spatial distribution to the clustered hedgerow scenario, but a greater number of cells around the intervention locations receive high (>10%) changes in visitation rate. This is due to the additional tree cover in these scenarios being even more spatially concentrated than the additional tree cover in the clustered hedgerow scenario. Cells receiving > 20% increase in visitation are those where alleys of agroforestry trees have replaced cereals. Where these alleys replace OSR or field beans, there is a visitation rate decrease as they provide less floral resource than mass flowering arable crops in late spring. The poplar agroforestry scenario shows the same pattern but with much lower magnitude changes, as poplar only provides very limited resources for bumblebees in our parameterisation (Fig. 6d).

The woodland creation scenario produces a very large visitation rate increase within the new woodland itself, with spill-over effects extending out to a radius of ~5 km (Fig. 6 f). However, this most spatially concentrated method of delivering additional tree cover means that at low planting intensity there is only one woodland patch in or close to the study area, resulting in no change in bumblebee visitation beyond this 5 km radius.

Fig. 7 shows the much more extensive (and higher magnitude) changes in ground-nesting bumblebee Late Spring visitation rate achieved across all scenarios when high intensity tree planting is applied. Increases in relative visitation of over 10% now cover more than half the study area in the fruit and willow agroforestry scenarios (Fig. 7c & e) and nearly half the study area in the two hedgerow scenarios (Fig. 7a & b). These areas of larger increase also occur across more of the study area in the woodland creation and agroforestry-poplar scenario but still 'miss' much of the mass-flowering crop area (Fig. 7d & f).

3.2.2. Tree-nesting bumblebees

Figs. S5 and S6 show how the change in tree-nesting bumblebee Late Spring visitation rate (relative to the baseline scenario) is distributed across the study area for the low and high tree planting scenarios, respectively. The spatial distribution of visitation rate change for tree-nesting bumblebees is similar to that of the ground-nesting bumblebees (cf. Figs. 6 and S5; 7 and S6). The main difference, compared to the ground-nesting bumblebee distribution, is that the magnitude of the change for tree-nesting bumblebees is smaller in the hedgerow, willow agroforestry and poplar agroforestry scenarios and larger in the woodland creation scenario.

4. Discussion

We modelled the effect of different tree planting interventions on bumblebee abundance and pollination service to mass-flowering arable crops in a representative English arable landscape. We tested six tree planting scenarios (distributed hedgerow planting, clustered hedgerow planting, fruit tree agroforestry, poplar agroforestry, willow agroforestry, woodland creation) at two levels of intensity: one where the area of tree cover added to the landscape corresponds to the 2035 level of tree cover that would be achieved if the 2020 tree planting rate continues and a higher level corresponding to the 2035 level of tree cover that would be achieved if the UK Government's trebled tree planting target rates were implemented.

4.1. Hedgerow planting

Hedgerows provide attractive floral resources for both bumblebee guilds across all seasons (Kovács-Hostyánszki et al., 2013), but are only an important nesting habitat for ground-nesting bumblebees – tree-nesters usually require taller more mature trees (Crowther et al., 2014), which may occur only sporadically in hedgerows. Consequently, when planted at low intensity, hedgerows deliver significant relative increases in worker and queen production for both guilds, but only significantly increase the number of ground-nesting bumblebee nests. Worker production in early spring is a function of both nesting density and early spring floral resource availability, explaining the greater relative worker production for ground-nesting bumblebees than tree-nesters in the hedgerow scenarios.

Workers produced in early-spring forage in late spring and are thus the main visitors to mass-flowering crops (Garratt et al., 2014b; Stanley et al., 2013). The increase in relative visitation to OSR and field beans is therefore more pronounced for ground-nesting bumblebees than tree-nesting bumblebees. The significant increase in relative visitation predicted by both guilds to these crops also suggests that the location of the new hedgerows is sufficiently close to OSR and field beans parcels for the workers to reach the crops with minimal floral competition, as observed empirically (Sutter et al., 2018). In our simulations we assume that the hedgerows created will be managed as per standard hedgerow management practice. In reality, once the hedgerows have reached maturity, there would be the potential to manage them more sensitively to maximise floral and nesting resource provision. This can be achieved by avoiding overly frequent cutting (increases quantity of flowers and reduces disturbance) while ensuring they maintain a robust structure (Staley et al., 2012). If hedgerows created in the simulations received this additional management, then the abundance and crop pollination service provided are likely to increase further (Image et al., in Press), possibly even to levels offered by agroforestry.

We used a consistent area target for planting across all scenarios to facilitate a fair comparison, so our hedgerow targets were 304 km and 912 km. There is no explicit target for hedgerows in the England Tree Action Plan but the 6th Carbon Budget recommends extending their coverage by 20% by 2035 relative to current rates (Committee on Climate Change, 2020), which would represent a 357 km increase if applied *pro rata* to the study area and its buffer. This roughly

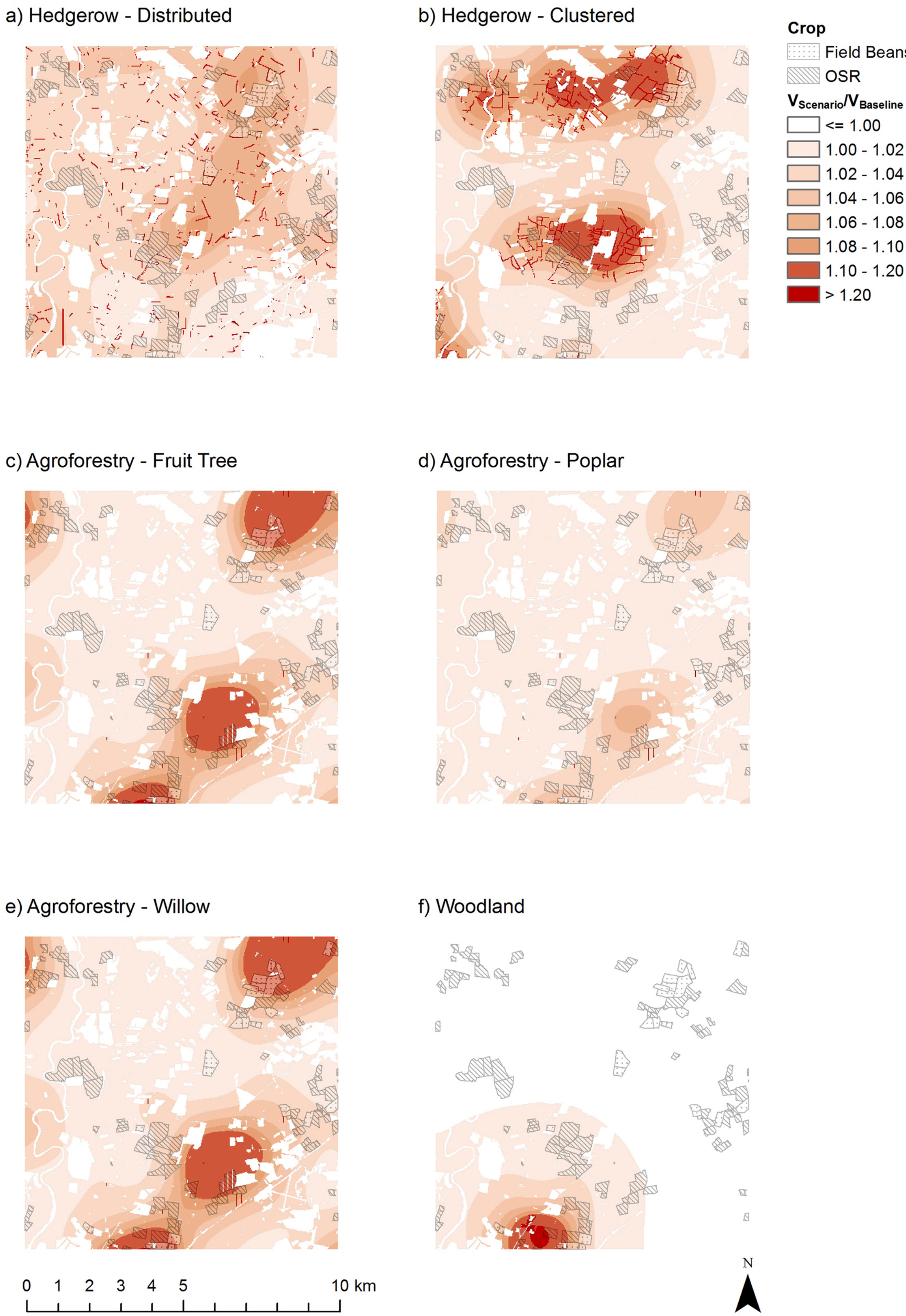

Fig. 7. Typical spatial distributions for the change in relative **ground-nesting bumblebee Late Spring visitation rate** for each tree planting scenario, expressed as a fraction of the baseline scenario visitation rate ($V_{Scenario}$ / $V_{Baseline}$), where the additional tree cover corresponds to the **low planting intensity** scenarios. Visitation rate maps correspond to the land cover realisation whose effect on relative OSR and field bean visitation was closest to the mean of all land cover realisations for that scenario. Hashed and dotted polygons indicate the locations of OSR and field bean fields.

corresponds to our low intensity planting scenario, suggesting that if this 20% recommendation were achieved there would be a significant co-benefit to pollinators and crop-pollination service.

Clustering hedgerows into defined geographical areas to represent uneven levels of farm uptake resulted in higher visitation rate increases to crops within or near to those areas (Fig. 7, Fig. 8). However, when those increases were averaged across multiple realisations of uptake pattern there was no significant difference in the mean landscape-level increase in pollination service compared to the randomly distributed uptake pattern (Fig. 6). This is probably because, even in the clustered scenario, the hedgerow resource is still sufficiently distributed across the study area compared to more compact methods of tree planting (e.g. woodland creation). This has implications for policy because it suggests that spatial targeting of hedgerow planting for landscape-level pollination service benefits is not important as long as a sufficient quantity (and quality) of hedgerow is delivered.

A limitation of our simulations is that we have not included crop rotation, as information on crop cover was available for one year only. In reality, once a hedgerow uptake pattern has been determined, there may be greater inter-annual variation in pollination service in the clustered scenario, as crop rotation moves mass-flowering crop fields away from / closer to pollinator habitat clusters over successive years (Andersson et al., 2014). Evidence from another simulated uptake study, using the same bee model, suggests that hedgerows can actually help stabilise pollination service over the crop rotation cycle (Gardner et al., 2021). At farm scale, targeting hedgerow planting around those fields that are likely to be used for pollinator-dependent crops at some point during the rotation would therefore be beneficial for promoting local-level pollination service benefits.

4.2. Agroforestry

There are clear differences between the three agroforestry scenarios in terms of their impact on bumblebee abundance, which reflect the relative qualities of the poplar, willow, or fruit trees as resource for bumblebees (see Image et al., 2022 - Suppl. Mat.). Poplar is not thought to be attractive nesting habitat for either guild, and is only thought to be of limited floral value to ground-nesting bumblebees (Gardner et al., 2020) and thus had little effect on nest density or queen production for bumblebees. However, it could still be a useful floral resource to ground-nesting bumblebee queens in early spring if provided at scale (particularly so if other early spring floral resources are scarce), as demonstrated by the significant increase in worker production for that season under high intensity planting.

Willow is a more attractive floral resource (thus enhancing early worker production for both guilds and enhancing queen production at higher planting intensity) but is still insufficient as a nesting resource to enhance nest density. This is consistent with empirical work that has observed increased bumblebee visitation in the immediate vicinity of SRC willow, but not at a distance (Berkley et al., 2018). In our simulations, fruit tree agroforestry was assigned the same parameters as orchards, i.e., a similar level of floral resource quality to willow but greater nesting potential, especially for tree-nesting bumblebees. The fruit tree scenario was therefore able to significantly increase nest density for tree-nesting bumblebees and worker / queen production levels for both guilds. However, it may be that agroforestry systems do not meet the expected habitat provision of intact orchards and may require additional flower-strips and/or peripheral hedgerow features to deliver an equivalently high quality bumblebee habitat (Gervais et al., 2021; McKerchar et al., 2020). In practice, whether fruit-tree based agroforestry offers this level of resource quality may therefore depend on management and farmers' willingness to adopt such management (Graves et al., 2017; Nalepa et al., 2020).

The fruit tree and willow agroforestry scenarios also showed significantly higher relative crop visitation compared to the other scenarios, even more so than hedgerow planting and despite the hedgerow scenarios producing similar relative increases in worker numbers. This is due to the configuration of tree planting in agroforestry. Trees are only located within arable fields, which may include fields of OSR or field beans (see Fig. 7 and Figure 8Figure 8). The increased worker population therefore has less distance to travel to reach those crops in late spring when foraging and so agroforestry has a greater pollination service effect than hedgerows, which are located only around the field margins. This is especially true for field beans, which are a more scarce crop in the landscape and whose level of pollination service is thus more sensitive to the location of intervention (Image et al., in Press.). The benefits of the fruit tree scenario may extend beyond the effect on mass-flowering arable crop pollination because fruit trees themselves are pollinator-dependent. Mass-flowering arable crops (and other nearby semi-natural habitat) could in turn enhance pollination of the (earlier flowering) fruit-trees, by providing complementary year-round floral resources for bumblebees, relative to monoculture systems (Proesmans et al., 2019; Staton et al., 2022).

However, the extent to which mass-flowering arable crop visitation is enhanced varies much more over the 100 runs in fruit tree and willow agroforestry scenarios compared to the hedgerow or woodland scenarios (compare the range of box plots in Fig. 6). Each run has a different spatial configuration of tree alleys, resulting in some runs where the configuration is very efficient at enhancing mass-flowering crop visitation, up to a doubling of visitation rate across the study area when tree alleys and mass-flowering arable crops are co-located in the same fields, and others where there is less co-location, and the enhancement levels are lower. Our simulations only consider one year of cropping and not a full crop rotation cycle. As fields cycle through cereals, OSR and field beans, the location of the mass-flowering crops will change but the trees will stay fixed and so the efficacy of a given agroforestry scheme on crop pollination will vary year-to-year (of an order similar to that demonstrated in our simulations where the arable cropping pattern remains fixed and the alley locations are shifted). Spatially optimal configurations of intervention will therefore depend on long-term planning within the landscape (Faichnie et al., 2021). Given hedgerows' greater potential for supporting bumblebee abundance, combining agroforestry with hedgerow planting may generate optimal spatial configurations that promote consistent pollination services through the crop rotation cycle (Eeraerts et al., 2021; Martins et al., 2018). Indeed coppiced hedgerows also have the potential to act as productive agroforestry systems (Smith et al., 2021).

4.3. Woodland

Mature woodland is valuable nesting habitat for both guilds (Crowther et al., 2014; O'Connor et al., 2017), and, as expected, there was a significant increase in nesting density in the woodland creation scenario, especially for tree-nesting bumblebees. Woodland flora are also attractive foraging resources for both guilds (Crowther et al., 2014; Kämper et al., 2016), but the expert scores are relatively more attractive to tree-nesting bumblebees than ground-nesters (see Image et al., 2022 - Suppl. Mat.). Hence, the higher planting intensity was required to achieve significant increases in worker or queen production for the ground-nesting guilds, whereas the lower intensity tree-planting was sufficient for the tree-nesting bumblebees. Some of this benefit arises from the additional woodland edge habitat created, which was included in the simulated landscape, and whose parameterisation reflects the importance of this habitat as a resource, especially to ground-nesting bumblebees (Rivers-Moore et al., 2020).

Woodland creation typically occurs in contiguous blocks and most grant schemes available in England require at least 1 – 5 ha (Forestry Commission, 2022) in total to make a viable project. Our scenario used a consistent size of ~20 ha, which is close to the mean value of recent projects and consequently, habitat creation is very spatially clustered. Even though populations of late spring foraging worker bees increased, this was only of benefit to mass-flowering crop parcels located close to

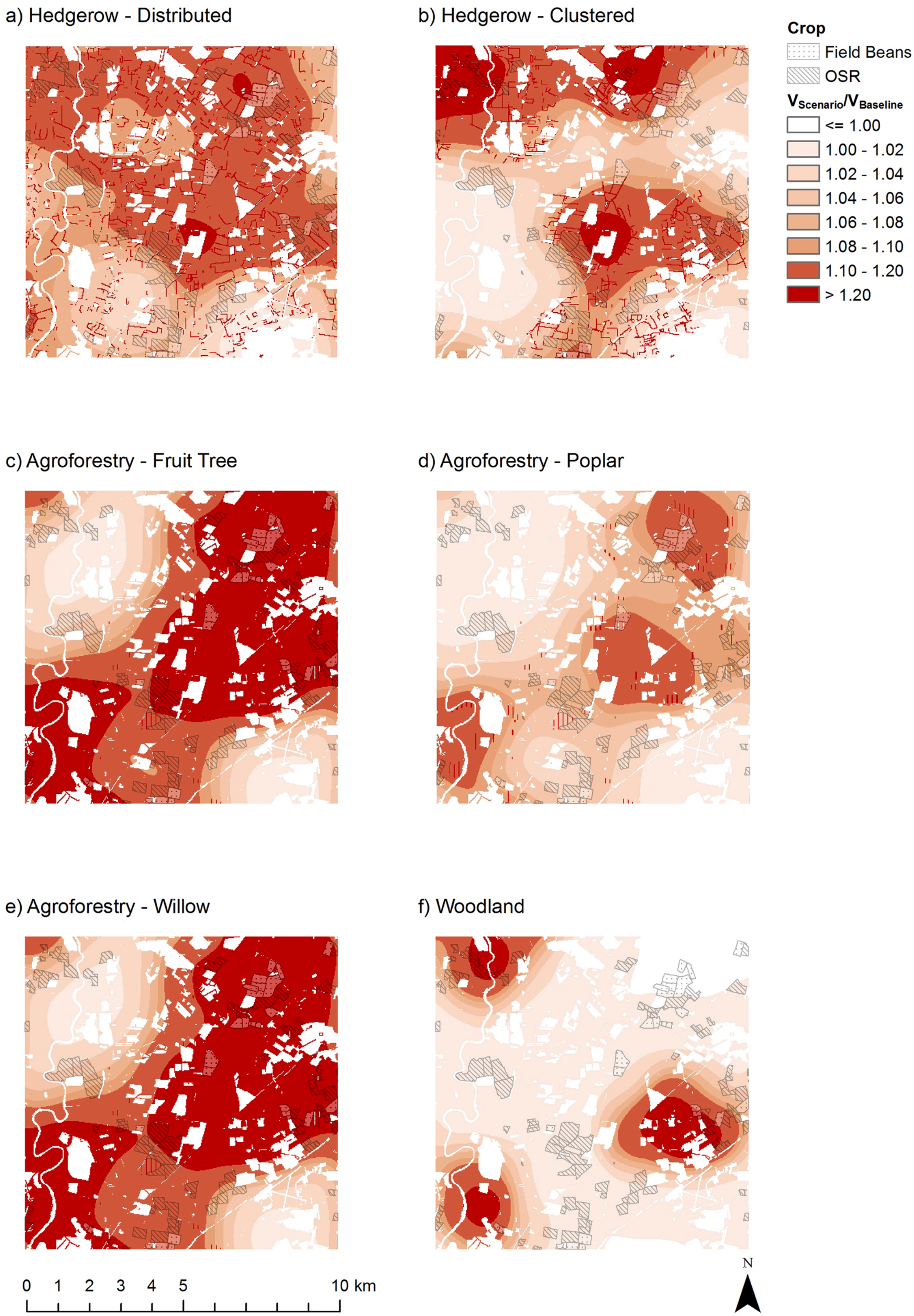

Fig. 8. Typical spatial distributions for the change in relative **ground-nesting bumblebee Late Spring visitation rate** for each tree planting scenario, expressed as a fraction of the baseline scenario visitation rate ($V_{Scenario}$ / $V_{Baseline}$), where the additional tree cover corresponds to the **high planting intensity** scenarios. Visitation rate maps correspond to the land cover realisation whose effect on relative OSR and field bean visitation was closest to the mean of all land cover realisations for that scenario. Hashed and dotted polygons indicate the locations of OSR and field bean fields.

the new woodlands, which was insufficient to significantly enhance ground-nesting bumblebee crop pollination on average for the entire landscape.

Woodland creation was sufficient to significantly increase crop pollination services from tree-nesting bumblebees because the population increase was greater than ground-nesting bumblebees, but the high spatial clustering of the effect means the level of benefit realised in any given year is likely to vary with crop rotation. If we had used a smaller woodland size, but kept the same total area target, we may have achieved a greater increase in crop pollination service, because mean distance between crop and woodland would have been reduced (Joshi et al., 2016). This implies woodland creation schemes with smaller woodland plot sizes and an even distribution of woodland features throughout the landscape would be preferable, if crop pollination service co-benefits are desired. Smaller woodland plot size would also increase the proportion of woodland edge habitat, so increasing the patch's attractiveness to ground-nesting guilds and potentially supporting a wider range of pollinators (Bailey et al., 2014).

A further caveat is that our simulations used a parameterisation that did not explicitly account for habitat maturity. Created woodland in the UK can take between 80 and 160 years to reach this state (Fuentes-Montemayor et al., 2022), whilst for hedgerows and agroforestry systems, mature would mean 10–20 years post-establishment (Burgess, 2019; Smith et al., 2021). Due to its long relative maturity time, woodland creation would therefore need to be supported by agroforestry and hedgerow planting to deliver benefits to pollinators and pollination services within the next 30 years.

5. Conclusions

We tested six tree-planting scenarios informed by the UK Government's current tree planting ambitions. All of the tested scenarios provided some co-benefits for bumblebee abundance and mass-flowering crop pollination service, although there were clear differences in the magnitude and spatial distribution of these benefits at different scales. Based on our findings, we recommend the design/implementation of England's current ambitious tree planting policy could maximise pollinator and pollination service co-benefits in the following ways:

1) Extending existing hedgerow networks would be the most effective way to support bumblebee abundance generally and for ensuring widespread crop pollination service increases for mass-flowering arable crops under crop rotation. Spatial targeting is less important for these interventions, as long as the quantity of uptake is sufficient.
2) Fruit tree and willow-based agroforestry systems can potentially deliver very large increases in mass-flowering arable crop pollination service as a co-benefit. To ensure a consistent enhancement over time, tree alleys need to be close to mass-flowering arable crops throughout the whole rotation cycle. Where this is not possible, these agroforestry systems could be combined with hedgerow planting to deliver the greatest benefits.
3) Poplar-based agroforestry (which offers fewer resources for bees in our parameterisation) requires higher planting intensities to deliver lower bee abundance and crop pollination service benefits than other systems. The need for crop pollination services should therefore be considered when selecting tree species in agroforestry systems in order to make the most efficient use of land.
4) Woodland creation plots need to be more widely distributed across the landscape to achieve consistent crop pollination service enhancement, even at higher planting intensity. This means that woodland plot size may need to be smaller and/or woodland creation combined with other types of farm tree planting, and this would also help to benefit a wider range of bee species beyond just the specialist tree-nesters.

Data availability

Process-based pollinator model freely available to download at https://github.com/image ma/poll4pop_python (https://doi.org/10.5281/zenodo.5680076). The datasets used to generate the land cover maps and the paramaters used to populate the model are described in Image et al. (2022). N.b. we do state this in the method text and figures.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2022.106497.

References

Andersson, G.K.S., Ekroos, J., Stjernman, M., Rundlöf, M., Smith, H.G., 2014. Effects of farming intensity, crop rotation and landscape heterogeneity on field bean pollination. Agric. Ecosyst. Environ. 184, 145–148. https://doi.org/10.1016/j.agee.2013.12.002.

Arnott, D., Chadwick, D., Harris, I., Koj, A., Jones, D.L., 2019. What can management option uptake tell us about ecosystem services delivery through agri-environment schemes. Land Use Policy 81, 194–208. https://doi.org/10.1016/j.landusepol.2018.10.039.

Bailey, S., Requier, F., Nusillard, B., Roberts, S.P.M., Potts, S.G., Bouget, C., 2014. Distance from forest edge affects bee pollinators in oilseed rape fields. Ecol. Evol. 4, 370–380. https://doi.org/10.1002/ece3.924.

Bentrup, G., Hopwood, J., Adamson, N.L., Vaughan, M., 2019. Temperate agroforestry systems and insect pollinators: A review. Forests 10, 14–16. https://doi.org/10.3390/f10110981.

Berkley, N.A.J., Hanley, M.E., Boden, R., Owen, R.S., Holmes, J.H., Critchley, R.D., Carroll, K., Sawyer, D.G.M., Parmesan, C., 2018. Influence of bioenergy crops on pollinator activity varies with crop type and distance. GCB Bioenergy 10, 960–971. https://doi.org/10.1111/gcbb.12565.

Brewer, A., Ditchburn, B., Cross, D., WHitton, E., Ward, A., 2017. Tree Cover Outside Woodland in Great Britain - Summary Report. Forestry Commission,, Edinburgh.

Burgess, P., 2019. Silvoarable. In: Raskin, B., Osborn, S. (Eds.), The Agroforestry Handbook: Agroforestry for the UK. Soil Association, Bristol, UK, pp. 61–80.

Carrié, R., Lopes, M., Ouin, A., Andrieu, E., 2018. Bee diversity in crop fields is influenced by remotely-sensed nesting resources in surrounding permanent grasslands. Ecol. Indic. 90, 606–614. https://doi.org/10.1016/j.ecolind.2018.03.054.

Committee on Climate Change, 2020, Policies for the Sixth Carbon Budget and Net Zero.

Crowther, L.P., Hein, P.L., Bourke, A.F.G., 2014. Habitat and forage associations of a naturally colonising insect pollinator, the Tree Bumblebee Bombus hypnorum. PLoS One 9, e107568. https://doi.org/10.1371/journal.pone.0107568.

Defra, 2021, Tests and Trials Evidence Report. Schemes for environmental land management [WWW Document]. URL ⟨https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/999402/elm-tt-june21.pdf⟩ (accessed 4.8.22).

Defra, 2022, Environmental Land Management Scheme - overview [WWW Document]. URL ⟨https://www.gov.uk/government/publications/environmental-land-management-schemes-overview/environmental-land-management-scheme-overview⟩ (accessed 8.4.22).

Donkersley, P., 2019. Trees for bees. Agric. Ecosyst. Environ. 270–271, 79–83. https://doi.org/10.1016/j.agee.2018.10.024.

Eeraerts, M., Van Den Berge, S., Proesmans, W., Verheyen, K., Smagghe, G., Meeus, I., 2021. Fruit orchards and woody semi-natural habitat provide complementary resources for pollinators in agricultural landscapes. Landsc. Ecol. 36, 1377–1390. https://doi.org/10.1007/s10980-021-01220-y.

Faichnie, R., Breeze, T.D., Senapathi, D., Garratt, M.P.D., Potts, S.G., 2021. Scales matter: Maximising the effectiveness of interventions for pollinators and pollination. Adv. Ecol. Res 64, 105–147. https://doi.org/10.1016/bs.aecr.2020.11.003.

FAO, 2020, Global Forest Resources Assessment 2020 - Key findings. Rome. ⟨https://doi.org/10.4060/ca8753en⟩.

Forest Research, 2020, Forestry Statistics 2020. Forest Research, Edinburgh.

Forestry Commission, 2021, Environmental Impact Assessments for woodland [WWW Document]. URL ⟨https://www.gov.uk/guidance/environmental-impact-assessments-for-woodland⟩ (accessed 1.10.22).

Forestry Commission, 2022, Woodland grants and incentives overview table [WWW Document]. URL ⟨https://www.gov.uk/government/publications/woodland-grants-and-incentives-overview-table⟩ (accessed 6.6.22).

Fuentes-Montemayor, E., Park, K.J., Cordts, K., Watts, K., 2022. The long-term development of temperate woodland creation sites: from tree saplings to mature woodlands. Forestry 95, 28–37. https://doi.org/10.1093/forestry/cpab027.

Gardner, E., Breeze, T.D., Clough, Y., Smith, H.G., Baldock, K.C.R., Campbell, A., Garratt, M.P.D., Gillespie, M.A.K., Kunin, W.E., McKerchar, M., Memmott, J., Potts, S.G., Senapathi, D., Stone, G.N., Wäckers, F., Westbury, D.B., Wilby, A., Oliver, T.H., 2020. Reliably predicting pollinator abundance: Challenges of calibrating process-based ecological models. Methods Ecol. Evol. 2020, 1673–1689. https://doi.org/10.1111/2041-210X.13483.

Gardner, E., Breeze, T.D., Clough, Y., Smith, H.G., Baldock, K.C.R., Campbell, A., Garratt, M.P.D., Gillespie, M.A.K., Kunin, W.E., McKerchar, M., Potts, S.G., Senapathi, D., Stone, G.N., Wäckers, F., Westbury, D.B., Wilby, A., Oliver, T.H., 2021. Field boundary features can stabilise bee populations and the pollination of mass-flowering crops in rotational systems. J. Appl. Ecol. 58, 2287–2304. https://doi.org/10.1111/1365-2664.13948.

Garratt, M.P.D., Breeze, T.D., Jenner, N., Polce, C., Biesmeijer, J.C., Potts, S.G., 2014a. Avoiding a bad apple: Insect pollination enhances fruit quality and economic value. Agric. Ecosyst. Environ. 184, 34–40. https://doi.org/10.1016/j.agee.2013.10.032.

Garratt, M.P.D., Coston, D.J., Truslove, C.L., Lappage, M.G., Polce, C., Dean, R., Biesmeijer, J.C., Potts, S.G., 2014b. The identity of crop pollinators helps target conservation for improved ecosystem services. Biol. Conserv. 169, 128–135. https://doi.org/10.1016/j.biocon.2013.11.001.

Gervais, A., Bélisle, M., Mazerolle, M.J., Fournier, V., 2021. Landscape enhancements in apple orchards: Higher bumble bee queen species richness, but no effect on apple quality. Insects 12. https://doi.org/10.3390/insects12050421.

Graves, A.R., Burgess, P.J., Liagre, F., Dupraz, C., 2017. Farmer perception of benefits, constraints and opportunities for silvoarable systems: Preliminary insights from Bedfordshire, England. Outlook Agric. 46, 74–83. https://doi.org/10.1177/0030727017691173.

Hall, M.A., Nimmo, D.G., Cunningham, S.A., Walker, K., Bennett, A.F., 2019. The response of wild bees to tree cover and rural land use is mediated by species' traits. Biol. Conserv. 231, 1–12. https://doi.org/10.1016/j.biocon.2018.12.032.

Häussler, J., Sahlin, U., Baey, C., Smith, H.G., Clough, Y., 2017. Pollinator population size and pollination ecosystem service responses to enhancing floral and nesting resources. Ecol. Evol. 7, 1898–1908. https://doi.org/10.1002/ece3.2765.

den Herder, M., Moreno, G., Mosquera-Losada, R.M., Palma, J.H.N., Sidiropoulou, A., Santiago Freijanes, J.J., Crous-Duran, J., Paulo, J.A., Tomé, M., Pantera, A., Papanastasis, V.P., Mantzanas, K., Pachana, P., Papadopoulos, A., Plieninger, T., Burgess, P.J., 2017. Current extent and stratification of agroforestry in the European Union. Agric. Ecosyst. Environ. 241, 121–132. https://doi.org/10.1016/j.agee.2017.03.005.

Holland, J.M., Sutter, L., Albrecht, M., Jeanneret, P., Pfister, S.C., Schirmel, J., Entling, M.H., Kaasik, R., Kovacs, G., Veromann, E., Bartual, A.M., Marini, S., Moonen, A.-C., Szalai, M., Helsen, H., Winkler, K., Lof, M.E., van der Werf, W., McHugh, N.M., Smith, B.M., Wallis, D.W., Cresswell, J.E., 2020. Moderate pollination limitation in some entomophilous crops of Europe. Agric. Ecosyst. Environ. 302, 107002 https://doi.org/10.1016/j.agee.2020.107002.

Huml, J.V., Ellis, J.S., Lloyd, K., Benefer, C.M., Kiernan, M., Brown, M.J.F., Knight, M.E., 2021. Bucking the trend of pollinator decline: the population genetics of a range expanding bumblebee. Evol. Ecol. 35, 413–442. https://doi.org/10.1007/s10682-021-10111-2.

Hutchinson, L.A., Oliver, T.H., Breeze, T.D., Bailes, E.J., Brünjes, L., Campbell, A.J., Erhardt, A., de Groot, G.A., Földesi, R., García, D., Goulson, D., Hainaut, H., Hambäck, P.A., Holzschuh, A., Jauker, F., Klatt, B.K., Klein, A.M., Kleijn, D., Kovács-Hostyánszki, A., Krimmer, E., McKerchar, M., Miñarro, M., Phillips, B.B., Potts, S.G., Pufal, G., Radzevičiūtė, R., Roberts, S.P.M., Samnegård, U., Schulze, J., Shaw, R.F., Tscharntke, T., Vereecken, N.J., Westbury, D.B., Westphal, C., Wietzke, A., Woodcock, B.A., Garratt, M.P.D., 2021. Using ecological and field survey data to establish a national list of the wild bee pollinators of crops. Agric. Ecosyst. Environ. 315, 107447 https://doi.org/10.1016/j.agee.2021.107447.

Image, M., Gardner, E., Clough, Y., Kunin, W.E., Potts, S.G., Smith, H.G., Stone, G.N., Westbury, D.B., Breeze, T.D., n.d. Which interventions contribute most to the net effect of England's agri-environment schemes on pollination services? (In Press). Landsc. Ecol.https://doi.org/10.1007/s10980-022-01559-w.

Image, M., Gardner, E., Clough, Y., Smith, H.G., Baldock, K.C.R., Campbell, A., Garratt, M., Gillespie, M.A.K., Kunin, W.E., McKerchar, M., Memmott, J., Potts, S.G., Senapathi, D., Stone, G.N., Wackers, F., Westbury, D.B., Wilby, A., Oliver, T.H., Breeze, T.D., 2022. Does agri-environment scheme participation in England increase pollinator populations and crop pollination services. Agric. Ecosyst. Environ. 325, 107755 https://doi.org/10.1016/j.agee.2021.107755.

IPBES, 2016, Summary for policymakers of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. Bonn, Germany.

Joshi, N.K., Otieno, M., Rajotte, E.G., Fleischer, S.J., Biddinger, D.J., 2016. Proximity to woodland and landscape structure drives pollinator visitation in apple orchard ecosystem. Front. Ecol. Evol. 4, 1–9. https://doi.org/10.3389/fevo.2016.00038.

Kämper, W., Werner, P.K., Hilpert, A., Westphal, C., Blüthgen, N., Eltz, T., Leonhardt, S. D., 2016. How landscape, pollen intake and pollen quality affect colony growth in Bombus terrestris. Landsc. Ecol. 31, 2245–2258. https://doi.org/10.1007/s10980-016-0395-5.

Kovács-Hostyánszki, A., Haenke, S., Batáry, P., Jauker, B., Báldi, A., Tscharntke, T., Holzschuh, A., 2013. Contrasting effects of mass-flowering crops on bee pollination of hedge plants at different spatial and temporal scales. Ecol. Appl. 23, 1938–1946. https://doi.org/10.1890/12-2012.1.

Lonsdorf, E., Kremen, C., Ricketts, T., Winfree, R., Williams, N., Greenleaf, S., 2009. Modelling pollination services across agricultural landscapes. Ann. Bot. 103, 1589–1600. https://doi.org/10.1093/aob/mcp069.

MAFF, 1988, Ministry of Agriculture, Fisheries and Food Agricultural Land Classification of England and Wales.

Marconi, V., Raggi, M., Viaggi, D., 2015. Assessing the impact of RDP agri-environment measures on the use of nitrogen-based mineral fertilizers through spatial econometrics: The case study of Emilia-Romagna (Italy. Ecol. Indic. 59, 27–40. https://doi.org/10.1016/j.ecolind.2015.02.037.

Martins, K.T., Albert, C.H., Lechowicz, M.J., Gonzalez, A., 2018. Complementary crops and landscape features sustain wild bee communities. Ecol. Appl. 28, 1093–1105. https://doi.org/10.1002/eap.1713.

McKerchar, M., Potts, S.G., Fountain, M.T., Garratt, M.P.D., Westbury, D.B., 2020. The potential for wildflower interventions to enhance natural enemies and pollinators in commercial apple orchards is limited by other management practices. Agric. Ecosyst. Environ. 301, 107034 https://doi.org/10.1016/j.agee.2020.107034.

Mola, J.M., Hemberger, J., Kochanski, J., Richardson, L.L., Pearse, I.S., 2021. The importance of forests in bumble bee biology and conservation. Bioscience 71, 1234–1248. https://doi.org/10.1093/biosci/biab121.

Nalepa, R.A., Epstein, G., Pittman, J., Colla, S.R., 2020. Perceptions of wild bees and farm characteristics associated with the uptake of pollinator-supporting land management practices among Canadian apple growers. Renew. Agric. Food Syst. 36, 334–343. https://doi.org/10.1017/S1742170520000344.

O'Connor, S., Park, K.J., Goulson, D., 2017. Location of bumblebee nests is predicted by counts of nest-searching queens. Ecol. Entomol. 42, 731–736. https://doi.org/10.1111/een.12440.

Ollerton, J., Erenler, H., Edwards, M., Crockett, R., 2014. Extinctions of aculeate pollinators and the role of large-scale agricultural changes. Science 346 (6215), 1360–1362. https://doi.org/10.1126/science.1257259.

Olsson, O., Bolin, A., Smith, H.G., Lonsdorf, E.V., 2015. Modeling pollinating bee visitation rates in heterogeneous landscapes from foraging theory. Ecol. Modell. 316, 133–143. https://doi.org/10.1016/j.ecolmodel.2015.08.009.

Potts, S.G., Imperatriz-Fonseca, V., Ngo, H.T., Aizen, M.A., Biesmeijer, J.C., Breeze, T.D., Dicks, L.V., Garibaldi, L.A., Hill, R., Settele, J., Vanbergen, A.J., 2016. Safeguarding pollinators and their values to human well-being. Nature 540, 220–229. https://doi.org/10.1038/nature20588.

Powney, G.D., Carvell, C., Edwards, M., Morris, R.K.A., Roy, H.E., Woodcock, B.A., Isaac, N.J.B., 2019. Widespread losses of pollinating insects in Britain. Nat. Commun. 10, 1–6. https://doi.org/10.1038/s41467-019-08974-9.

Prager, K., 2022. Land Use Policy Implementing policy interventions to support farmer cooperation for environmental benefits. Land Use Policy 119, 106182. https://doi.org/10.1016/j.landusepol.2022.106182.

Proesmans, W., Smagghe, G., Meeus, I., Bonte, D., Verheyen, K., 2019. The effect of mass-flowering orchards and semi-natural habitat on bumblebee colony performance. Landsc. Ecol. 34, 1033–1044. https://doi.org/10.1007/s10980-019-00836-5.

Rivers-Moore, J., Andrieu, E., Vialatte, A., Ouin, A., 2020. Wooded semi-natural habitats complement permanent grasslands in supporting wild bee diversity in agricultural landscapes. Insects 11, 1–21. https://doi.org/10.3390/insects11110812.

Roulston, T.H., Goodell, K., 2011. The role of resources and risks in regulating wild bee populations. Annu. Rev. Entomol. 56, 293–312. https://doi.org/10.1146/annurev-ento-120709-144802.

Rural Payments Agency, 2018, Greening workbook for the Basic Payment Scheme in England. Version 1.0 [WWW Document]. URL www.gov.uk/rpa/bps2018 (accessed 3.6.20).

Smith, J., Westaway, S., Mullender, S., Giannitsopoulos, M., Graves, A., 2021. Making hedgerows pay their way: the economics of harvesting field boundary hedges for bioenergy. Agrofor. Syst. 9. https://doi.org/10.1007/s10457-021-00631-9.

Staley, J.T., Sparks, T.H., Croxton, P.J., Baldock, K.C.R., Heard, M.S., Hulmes, S., Hulmes, L., Peyton, J., Amy, S.R., Pywell, R.F., 2012. Long-term effects of hedgerow management policies on resource provision for wildlife. Biol. Conserv. 145, 24–29. https://doi.org/10.1016/j.biocon.2011.09.006.

Stanley, D.A., Stout, J.C., 2013. Quantifying the impacts of bioenergy crops on pollinating insect abundance and diversity: A field-scale evaluation reveals taxon-specific responses. J. Appl. Ecol. 50, 335–344. https://doi.org/10.1111/1365-2664.12060.

Stanley, D.A., Gunning, D., Stout, J.C., 2013. Pollinators and pollination of oilseed rape crops (Brassica napus L.) in Ireland: Ecological and economic incentives for pollinator conservation. J. Insect Conserv. 17, 1181–1189. https://doi.org/10.1007/s10841-013-9599-z.

Staton, T., Breeze, T.D., Walters, R.J., Smith, J., Girling, R.D., 2022. Productivity, biodiversity trade-offs, and farm income in an agroforestry versus an arable system. Ecol. Econ. 191, 107214 https://doi.org/10.1016/j.ecolecon.2021.107214.

Steffan-Dewenter, I., Schiele, S., 2008. Do resources or natural enemies drive bee population dynamics in fragmented habitats? Ecology 89, 1375–1387. https://doi.org/10.1890/06-1323.1.

Sutter, L., Albrecht, M., Jeanneret, P., 2018. Landscape greening and local creation of wildflower strips and hedgerows promote multiple ecosystem services. J. Appl. Ecol. 55, 612–620. https://doi.org/10.1111/1365-2664.12977.

Timberlake, T.P., Vaughan, I.P., Memmott, J., 2019. Phenology of farmland floral resources reveals seasonal gaps in nectar availability for bumblebees. J. Appl. Ecol. 56, 1585–1596. https://doi.org/10.1111/1365-2664.13403.

UK Government, 2021, The England Trees Action Plan 2021–2024 [WWW Document]. URL ⟨https://www.gov.uk/government/publications/england-trees-action-plan-2021-to-2024⟩ (accessed 3.31.22).

Varah, A., Jones, H., Smith, J., Potts, S.G., 2020. Agriculture, Ecosystems and Environment Temperate agroforestry systems provide greater pollination service than monoculture. Agric. Ecosyst. Environ. 301, 107031 https://doi.org/10.1016/j.agee.2020.107031.