University of Reading

The impact of agri-environment schemes on pollination services in England

Submitted for the Degree of Doctor of Philosophy

Centre for Agri-Environmental Research, School of Agriculture Policy and Development

Michael Image

August 2022

University of Reading

Declaration

I confirm that that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Michael Image

August 2022

Contributions to co-authored papers

- Chapter 2 was co-authored with Emma Gardner, Yann Clough, Henrik Smith, Katherine Baldock, Alistair Campbell, Mike Garratt, Mark Gillespie, William Kunin, Megan McKerchar, Jane Memmott, Simon Potts, Deepa Senapathi, Graham Stone, Felix Wackers, Duncan Westbury, Andrew Wilby, Tom Oliver and Tom Breeze. I conceived the ideas, carried out the research and wrote the manuscript. Emma Gardner and Tom Breeze contributed to conceptual development and manuscript revisions. Yann Clough and Emma Gardner provided the *poll4pop* model and parameters which I adapted and applied to this context. All other authors provided comments on the manuscripts or datasets used for model validation. I estimate my contribution to be 90%.

- Chapter 3 was co-authored with Emma Gardner, Yann Clough, William Kunin, Simon Potts, Henrik Smith, Graham Stone, Duncan Westbury and Tom Breeze. I conceived the ideas, carried out the research and wrote the manuscript. Tom Breeze, Emma Gardner, Graham Stone and Henrik Smith contributed to conceptual development and manuscript revisions. Yann Clough and Emma Gardner provided the poll4pop model and parameters which I adapted and applied to this context. All other authors provided comments on the manuscripts. I estimate my contribution to be 90%.

- Chapter 4 was co-authored with Emma Gardner and Tom Breeze. I conceived the ideas, carried out the research and wrote the manuscript. Emma Gardner and Tom Breeze contributed to conceptual development and manuscript revisions. I estimate my contribution to be 90%.

Acknowledgements

First of all, I would like to express my gratitude to my two supervisors, Tom Breeze and Emma Gardner. They have provided great technical and moral support throughout the process and have enabled me to develop new skillsets in areas such as pollinator ecology, computer programming, academic writing and communications which were fundamental to completing this thesis. They have also helped refine my loosely formed ideas into a consistent body of research and have made me feel included and welcome in the academic community. I have enjoyed our many discussions over the past few years and hope this thesis lays the foundation for future collaboration!

Completion of this work would also not have been possible without the support of the wider network of academics in the 'Modelling Landscapes for Resilient Pollination Services' grant funded by the Global Food Security 'Food Resilience Programme' including Yann Clough, Henrik Smith, Katherine Baldock, Alistair Campbell, Mike Garratt, Mark Gillespie, William Kunin, Megan McKerchar, Jane Memmott, Simon Potts, Deepa Senapathi, Graham Stone, Felix Wackers, Duncan Westbury, Andrew Wilby and Tom Oliver. I would also like to thank the University of Reading for supporting my tuition fees through a Wilkie Calvert co-supported PhD studentship grant.

Many other University of Reading have supported me throughout a journey of almost six years and deserve acknowledgement, including: Elizabeth Robinson for her support as my initial supervisor; Giuseppe Nocella for being an understanding and supportive monitor,; Martin Lukac for chairing my Confirmation of Registration and for providing useful technical information for Chapter 4; Sarah Duddigan for useful advice on the overall PhD process; Yiorgos Gadanakis for taking an interest in my work, and giving me the opportunity to communicate with students; Giacomo Zanello and Garth Holloway for technical support during the early stages of my PhD; Karen Garrod and Aidan Dowling for excellent administrative support. Many thanks also to my fellow students who have provided moral and practical support during the PhD journey, in particular Cath Jackson, Caroline Harkness, Gilka Da Silva, Kaan Alkan, Nick Buck and Caitlin Lewis.

I have completed this PhD on a part-time basis whilst working 20 hours a week, initially at ADAS and subsequently at Atkins. I would like to thank Susan Twining, John Elliott, Liz Lewis-Reddy, Monica Barker and Jo Nicholls for being understanding and supportive line managers over the years, and I am also grateful for all the encouragement and interest I have received from colleagues especially Fiona Tweedie, Kath Behrendt, Jon Nicholls, Dave Gasca and Emma Everard. I would also like to thank Helen Davies for inspiring me to apply for a PhD in the first place!

Finally, I would like to thank my wife Jo and sons Tom and Charlie for their love, support and patience throughout my time as a PhD student. It has been worth the wait!

Abstract

Agri-environment schemes fund landholders to manage land to achieve environmental objectives and other public goods. Previous research has shown that individual scheme interventions can boost wild pollinator populations locally. However, the effect of an entire scheme at a national scale has never previously been assessed.

The location of every intervention implemented in England during 2016 was mapped and schemes' predicted impact on bee abundance and pollination services was modelled using a validated, process-based spatial model (*poll4pop*), which simulates foraging and population dynamics. The study considered four wild bee guilds (incorporating bumblebees and solitary bees) and their visitation rates to four pollinator-dependent crops (oilseed rape, field beans, orchard fruit and strawberries). The modelling predicted that the scheme significantly increased ground-nesting (but not tree/cavity-nesting) bee populations nationally. There were no significant increases in crop visitation at national scale, but some locally significant increases in ground-nesting bumblebee visitation to oilseed rape and field beans were predicted.

Linear regression at 10 km scale was used to determine which interventions were driving increased oilseed rape and field bean visitation and found that hedgerow/woodland edge management dominated, due to high resource quality. Floral margins were estimated to provide more limited benefit, due to later resource phenology and low uptake. Fallow also had a strong effect, despite lower relative resource quality, implying effective placement with respect to crops.

Finally, the effect of additional tree-planting interventions (hedgerows, agroforestry, and woodland) on bumblebee abundance and crop visitation (oilseed rape, field beans) was studied. This showed that hedgerow planting would deliver the greatest increase in bumblebee abundance, whereas fruit or willow agroforestry would increase crop visitation the most, due to higher co-location.

Based on these findings, recommendations are set out for design of future schemes to help deliver greater and more resilient crop pollination services in arable landscapes.

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1 General Introduction

1.1 Pollinators and pollination services

Pollination by animals is a critical ecosystem function that supports reproduction in an estimated 87.5% of flowering plant species worldwide and underpins the yields of over three quarters of the world's leading food crops (Ollerton *et al.*, 2011; Klein *et al.*, 2007). Global demand for insect pollinated crops is increasing: the 2006 relative contribution to overall crop yields is almost double the 1961 value, whilst the absolute volume of pollinator dependent outputs has increased threefold over the same period (Aizen and Harder, 2009). Pollinator-dependent crops are also of greater importance than simply their contribution to overall production because they include fruit, vegetable, seed, nut and oil plants that are primary sources of nutrients essential for human health (Eilers *et al.*, 2011). Pollination also directly contributes to other supply chains, such as biofuels and fibres. Pollinators also underpin the life cycle of wild plants and trees, and so support a wide range of benefits which humans derive from the natural environment such as recreation and visual amenity.

In England, the most important pollinator-dependent crops from a food production perspective are oilseed rape, field beans, orchard fruit (apples, pears, and plums) and soft fruit (mainly strawberries). Oilseed rape (OSR) and field beans have the largest area of pollinator-dependent crop (Figure 1.1a, b), representing on average around 15.9% and 3.2% respectively of all crop cover over the five-year period from 2012-2016 (DEFRA, 2018). Orchards (0.6%) and soft fruit (0.2%) represent a much smaller land area (Figure 1.1c, d), but have economic significance due to their higher financial returns per hectare. Annual production (at UK level) for each was on average £519m and £143m over the same time frame (DEFRA, 2017a), representing 5.7% and 1.6% of total crop production respectively (DEFRA, 2017b). In line with the global shift mentioned above, the UK has also increased its demand for pollinator dependent crops in the past three decades (Breeze *et al.*, 2011).

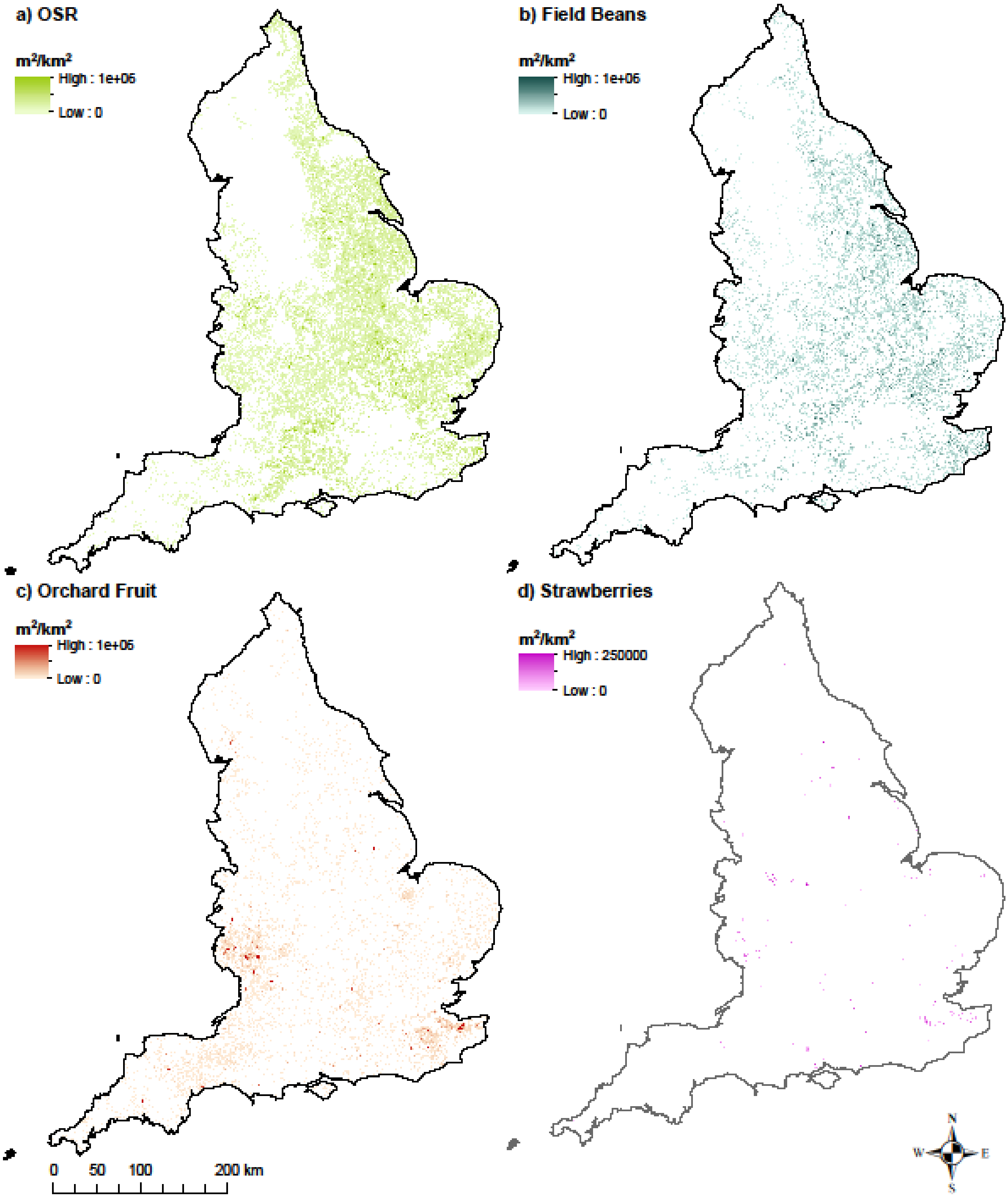

Figure 1.1: Distribution and intensity of crop cover in England for 2016 for a) OSR, b) Field Beans, c) Orchard fruit, and d) Strawberries (not in polytunnels). Data: Rural Payments Agency (LPIS Parcels 2016, BPS Claims 2016, Crop Map of England 2016), Ordnance Survey Master Map (Orchards). See Table A1.2 for source detail.

A range of animals are responsible for pollination. In the tropics, butterflies, moths, birds, bats, and midges are primary pollinators of key crops, whilst in temperate zones the role is mainly performed by bees and flies, particularly hoverflies (Klein *et al.*, 2007). In the UK, the majority of pollination is carried out by wild bumblebees, solitary bees and hoverflies (Garibaldi *et al.*, 2013; Vanbergen *et al.*, 2014; Hutchinson *et al.*, 2021). The managed Western honeybee (*Apis mellifera*) contributes to less than a third of pollination services to UK agriculture (Breeze *et al.*, 2011), whilst managed colonies of Buff-tailed bumblebees (*Bombus terrestris*) are only used in enclosed soft-fruit systems (DEFRA, 2014a; Chandler *et al.*, 2019).

Bumblebees (genus *Bombus*) are mostly eusocial, meaning that they live in colonies with division of labour by caste and gender, and there are 24 species in the UK. In a typical cycle, a mated female (queen) emerges from hibernation in early spring and searches for a nesting site. She forages by herself initially for nectar (sugar) and pollen (protein) to feed herself and her brood of sterile daughters (workers). By late spring the workers emerge and take over the role of foraging, bringing in more resources to sustain and grow the colony into the summer. A typical nest will produce a few hundred workers but this depends on species, resource availability and other factors (Goulson *et al.*, 2002). The queen then produces fertile male and female offspring which leave the nest and mate. The old queen, workers and males die whilst the new queen hibernates continuing the cycle to the next year. For convenience and to reflect the modelling approach used, in this study bumblebees are split into two 'guilds' which are species groupings with common functional traits (in this case nesting preferences): ground-nesters, which make their nests in the ground or in long grass (Table 1.1a), and those which nest above-ground in holes in trees or man-made structures (tree-nesters - Table 1.1b). The six cleptoparasitic bumblebee species ('cuckoos') which occupy or take over the nests of other species are not considered in this study.

The remaining wild bee species (>200 in the UK) are predominantly solitary, meaning that mated females provision for their own growing young rather than producing workers for this purpose. When the next generation hatch, they mate and establish new nests to continue the cycle. Again, in this study they are divided into two guilds: bees that nest in subterranean chambers (ground-nesters – Table 1.1c) and bees that nest aerially in natural and man-made above-ground cavities (cavity-nesters - Table 1.1d), though the distinction is not always clear-cut in practice. Some species in the *Halictus* and *Lassioglossum* genera display a primitive form of eusociality (Schwarz *et al.*, 2007) which can vary geographically even within the same species (Davison and Field, 2018). Flight periods vary between species with some active mainly in spring (e.g. Mason bees – *Osmia* spp.) and others mainly in summer (e.g. Leafcutter bees *Megachile* spp.). Some Mining bees are active in spring only (e.g. *Andrena clarkella* – Clarke's Mining Bee) whilst others such as *Andrena flavipes* (Yellow-legged Mining Bee) are bivoltine, completing a spring and then a summer generation within the same year.

Table 1.1: Descriptions of the four wild bee guilds in this study. Cleptoparasitic species are not considered. Images are from Steven Falk's Flickr library[1] and are used with permission. Abundance, distribution and richness information from BWARS (2012) *and Falk* (2015).

Guild	Notes
Ground-Nesting Bumblebee  *Bombus terrestris*	17 of the 18 eusocial bumblebee species in Britain prefer nest sites that are underground or amongst dense vegetation. Four are geographically widespread and common: *Bombus terrestris* (Buff-tailed Bumblebee)*, B. hortorum* (Garden Bumblebee), *B. lapidarius* (Red-tailed Bumblebee), *B. pascuorum* (Common Carder Bee) and *B. pratorum* (Early Bumblebee). Some are geographically constrained but locally abundant (e.g. *Bombus jonellus* – Heath Bumblebee). Some are now geographically constrained and rare (e.g. *B. sylvarum* – Shrill Carder Bee).
Tree-Nesting Bumblebee  *Bombus hypnorum*	The Tree Bumblebee (*B. hypnorum*) is a eusocial bumblebee that makes use of holes in trees to nest (hence the name) but is actually a more general aerial nester, sometimes occupying man-made cavities (e.g., abandoned bird boxes, house eaves). Arrived in England in 2001, now widespread and common across England and Wales and also established in Scotland. Other eusocial bumblebee species will also occasionally nest aerially.
Ground-Nesting Solitary Bee  *Andrena cineraria* Ashy mining bee	Nests are generally located in dry, south-facing locations and have a single entrance tunnel which branch off into side passages and cells. Genera include: Mining Bees (*Andrena* - 67 species), Plasterer Bees (*Colletes* – 9 species), Shaggy Bees (*Panurgus* – 2 species), End-banded Furrow Bees (*Halictus* – 7 species), Base-banded Furrow Bees (*Lassioglossum* – 13 species), Bristle-headed Bees (*Rophites* – 1 species), Short-faced Bees (*Douforia* – 2 species), Blunthorn Bess (*Melitta* – 4 species), Oil-collecting Bees (*Macropis* – 1 species), Pantaloon Bees (*Dasypoda* – 1 species), Flower Bees (*Anthophora* – 2 species), Long-horned Bees (*Eucera* - 1 species). Abundance and distribution varies considerably across genera and species – see Falk (2015) for information at species level.
Cavity-Nesting Solitary Bee  *Megachile willughbiellla* Willughby's Leafcutter Bee	Nests are above-ground cavities which can include hollow stems, holes in walls, trees or dead wood, snail shells, and purpose built 'bee hotels'. Genera include Leafcutter and Mud Bees (*Megachile* – 7 species)– pictured), Wool Carder Bees (*Anthidium* - 1 species), Yellow-face Bees (*Hyleaus* – 12 species), Resin Bees (*Heriades* – 1 species), Scissor Bees (Chelastoma – 2 species), Mason Bees (*Osmia* – 11 species), Lesser Masons (Hoplitis – 1 species), Flower Bees (*Anthophora* – 3 species), Small Carpenter Bees (*Ceratina* – 1 species), Large Carpenter Bees (*Xylocopa* - 1 species). Abundance and distribution varies considerably across genera and species – see Falk (2015) for information at species level.

[1] http://www.flickr.com/photos/63075200@N07/collections/

Dispersal range (the distance between the birth nest of a reproductive female and the nest that she establishes in the next cycle) can be a few km for bumblebees (Lepais *et al.*, 2010) but is typically less than 1 km for solitary bees which have smaller body size (Franzén *et al.*, 2009; Warzecha *et al.*, 2016). Bees also vary in their foraging range by species (Zurbuchen *et al.*, 2010), with bumblebees typically foraging within approximately 450 - 750 metres of the nest (Knight *et al.*, 2005). Solitary bees tend to have shorter foraging ranges of 150 – 600 m, again linked to their smaller body size (Gathmann and Tscharntke, 2002).

Bees have different foraging preferences for flowers depending on guild and species (Gresty *et al.*, 2018; Crowther *et al.*, 2014; Wood and Roberts, 2017; Kleijn and Raemakers, 2008). Most British bees obtain forage from a variety of flower types and colour, but some have more specialised preferences. These specialisms reflect a variety of factors such as having the right morphology (body shape, tongue length) to access pollen and nectar from certain flowers, and the relationship between active period, nest site location, flower availability and quantity of flower rewards (Woodcock *et al.*, 2013; Rotchés-Ribalta *et al.*, 2018; Knopper *et al.*, 2016; Ogilvie and Forrest, 2017). Bumblebees tend to be more generalist as they have a longer active period so need a greater variety of resources to sustain themselves, and their wider foraging and dispersal ranges enables them to access a wider variety of flowers (Hagbery and Nieh, 2012). Solitary bees tend to be more specialist due to their more constrained active period (Schenk *et al.*, 2018) and their shorter foraging and dispersal ranges (Gathmann and Tscharntke, 2002).

1.2 Pollinator declines, consequences and the policy response

There is considerable evidence that populations of wild bees are declining in Europe, North America and potentially also other global regions (Potts *et al.*, 2016). Great Britain's wild bees experienced widespread decline between 1980 and 2013 (Powney *et al.*, 2019; Vanbergen *et al.*, 2014) especially in rarer species with more specialist forage and nesting requirements. The declines are attributed to a range of interacting factors including:

- Loss or damage to foraging and nesting habitat resources to more intensive agricultural or other land use, including the expansion of monocultures, which can reduce the availability of forage resources through the year (Ollerton *et al.*, 2014);
- Direct toxicity from certain pesticides, including chronic sub-lethal effects (Whitehorn *et al.*, 2012; Siviter *et al.*, 2021);
- Competition from alien and managed species (Goulson and Sparrow, 2009; Iwasaki and Hogendoorn, 2022);

- Pests and pathogens (Graystock *et al.*, 2014);
- Phenological mismatch between bee emergency and flower availability due to climate change (Slominski and Burkle, 2021; Reeves *et al.*, 2022).

These pressures impact some bee species more than others (Winfree *et al.*, 2011), but the decline in species richness, even if overall abundance were maintained is also a concern for pollination services to crops and wild plants as it reduces the system's resilience to other factors such as land use and climate change (Burkle *et al.*, 2013).

From a crop pollination perspective if the population of wild bees were to fall below certain thresholds, then this would have negative implications for crop yields (Garratt *et al.*, 2013; Mashilingi *et al.*, 2021). If the declines became too acute, then farmers might have to replace animal-pollinated crops with wind pollinated crops, with potential economic and food security implications (Bauer and Wing, 2010). Increasing the number of managed honeybees could be one policy option to mitigate pollinator declines. There has been some increase in the number of managed hives but this follows decades of decline and does not appear to be sufficient in volume or geographic targeting to compensate for the declines in wild pollinator numbers (Aizen and Harder, 2009; Breeze, Vaissière, *et al.*, 2014). Even still, this is not a complete solution: managed honeybees are themselves vulnerable to outbreaks of pests and pathogens, and are sub-optimal pollinators for some crops (Garratt, Coston, *et al.*, 2014).

To avoid potential food security, nutrient deficiency and wider socioeconomic issues ensuing from a collapse in wild pollinator abundance and diversity, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has highlighted the following potential policy responses:

- Ecological intensification by supporting appropriate farm practices to support pollinators;
- Strengthening diversification of farm systems to improve resilience;
- Investment in ecological infrastructure to support pollinator nesting and foraging resources;
- Promote better understanding of pollinator importance to farms and society;
- Link people and pollinators through collaborative, cross-sector approaches

In England, the National Pollinator Strategy pre-dates the IPBES recommendations but has a similar five-point approach, with a common theme and desired outcome being to expand food, shelter and nesting sites in the form of semi-natural habitat across the country, and especially on farmland (DEFRA, 2014a). Arable farms are of particular focus as, where long term historic data exists for bees, areas of England that have shown an expansion in arable cover over the past 80 years show greater declines in pollinator species richness than areas that have not (Senapathi *et al.*, 2015). Farmers have therefore been advised to provide flower rich areas throughout spring, summer and autumn, as well as providing hedgerow, bank and other edge features suitable for nesting or hibernation (Campaign for the Farmed Environment, 2014; FERA, 2014).

1.3 Agri-Environment Schemes (AES)

1.3.1 What are Agri-Environment Schemes

Providing habitat for wildlife on farms means taking land out of direct production (i.e., for crops, fodder, or grazing) and replacing it with economically non-productive land, so reducing the potential economic return from the land. Agri-environment schemes (AES) overcome this hurdle by providing multi-year contractual agreements (usually with governments) where landholders receive financial incentives to manage land in ways that improve the natural environment and deliver benefits to society. In the UK, the scope of these schemes is very broad and covers a range of interventions that either create, restore, or manage some aspect of non-crop land cover which includes hedgerows, field margins, fallow areas, flower-rich leys, low-input grassland, as well as semi-natural grassland, moorland, wetland, and woodland.

1.3.2 AES in England to 2020

In England, AES emerged from a series of national initiatives[2] as well as key reforms[3] to the EU's Common Agricultural Policy (CAP) that acknowledged the environmental impact of previous decades of agricultural intensification and the need for increasingly focussed action (Natural England, 2012). Schemes have evolved in breadth and sophistication over the past two decades in response to policy needs and learning from evaluation. Earlier schemes (*Environmental Sensitive Areas, Countryside Stewardship Scheme*) active until 2005 focussed on wildlife conservation with mixed success (Kleijn and Sutherland, 2003). These were replaced by *Environmental Stewardship* (ES) in 2006, which had a broader geographic and environmental ambition. ES also had a two-tier structure with an entry-level scheme (ELS) and a higher-level scheme (HLS) differentiated in terms of difficulty of management requirements (Natural England, 2013).

At EU level, criticism of national schemes over environmental effectiveness, monitoring and value for money (Kleijn and Sutherland, 2003; Batáry *et al.*, 2015; European Court of Auditors, 2011) has led to

[2] The Broads Grazing Marshes Conservation Scheme of 1985 in Norfolk was the first recognisable AES in England. Its success led to the introduction Environmentally Sensitive Area (ESA) schemes in 1987/88 across 10 designated areas.

[3] The 1992 MacSharry reform made the application of AES a compulsory requirement for Member States. Subsequent reforms (Agenda 2000, CAP Reform 2003, CAP Health Check 2008, CAP Reform 2013) have added further emphasis and specification to scheme design.

an increase in the suite and sophistication of prescriptions to target certain species, habitat, and environmental contexts. Scheme operators have also introduced spatial stratification and selection processes for AES so that priority is given to geographic areas with key environmental assets and to those farms best suited to achieving the desired objectives.

The current scheme for England, *Countryside Stewardship* (CS) has been active since 2014 and comprises a diverse range of 262 interventions with a budget of around £3 billion (DEFRA, 2014b). This includes funding for multi-year legacy agreements still active the legacy ES scheme. CS has a Higher Tier and a Mid-Tier (Natural England, 2018b). The former is targeted at designated features such as Sites of Special Scientific Interest (SSSI) and Priority Habitats or Species under the UK Biodiversity Action Plan and is only relevant to certain farms in specific areas where these can occur. The latter is open to all qualifying farms on an annual basis (budget-depending), but the scheme operator Natural England (NE) applies a scoring mechanism aligned to local environmental priorities meaning that contracts are more likely to be secured by farms if they address these issues. The specific priorities vary by locality, but generally target priority or other habitats/species in decline, watercourses/bodies falling short of Water Framework Directive (WFD) standards, and historic environment or landscape features needing additional protection.

Interventions within the CS and ES schemes are arranged into sets of management options or capital grants with common land applicability or common environmental objective. Certain interventions are explicitly targeted at pollinators. For example, AB1 – Nectar flower mix / EF4 – Nectar flower mixture, AB8 – Flower-rich margins and plots and AB16 – Autumn sown bumblebird mix create temporary features in arable context that are sown with flowers intended to provide attractive foraging resource for wild bees. NE has also introduced a set of non-selective ‘bundle offers’ in the 2018 Mid-Tier for each of the main farming types in England (arable, lowland grazing, upland grazing, mixed farming) and the arable bundle contains pollinator-relevant management interventions (Natural England, 2018a). However, any intervention which results in an increase in the quality or quantity of nesting or foraging resource relative to the land cover in the absence of the intervention is potentially of value to bees. Since less intensively managed agricultural land is generally higher in floral resource quality / quantity (Potts *et al.*, 2009) and is generally more attractive nesting habitat (Goulson *et al.*, 2010), the majority of interventions are potentially valuable to wild bees even if they do not explicitly target them.

The 2013 CAP reform also introduced a “Greening” requirement whereby certain simple habitat actions have become a condition to receive full funding under the Basic Payment Scheme (BPS). For arable farmers this meant maintaining at least 5% of their eligible land as Ecological Focus Areas (EFA); these are semi-natural habitat features such as fallow land, buffer strips, field margins, hedges, and lines of trees (Rural Payments Agency, 2018). Unlike CS or ES, these management requirements were mandatory, unless farmers choose to forgo the full BPS payment; so greening payments had commonalities with AES and can also provide potential pollinator habitat.

To conceptualise the full range of AES and EFA interventions, it is useful to categorise them into groups based on the target habitat and whether the objective is creation or maintenance (Table 1.2). Fallow, field margins and flower-rich leys are all comprised of interventions that create temporary non-cropped features within arable landscapes. They vary depending on whether crops are replaced with sown grass (grass margins, leys), sown floral mixes (floral margins) or if the area is allowed to re-vegetate more naturally (fallow – though some fallow mixes are sown). Other interventions involve the creation of semi-natural habitat in place of arable or improved grassland. This new habitat could be grassland, heathland, scrub, woodland, or wetland. Hedgerow and woodland edge management involve specific management requirements that result in hedgerows and woodland edges becoming neither too overgrown nor cut too frequently. The final category – semi-natural habitat management – covers a wide range of interventions which largely maintain the habitat's current status and avoid degradation, and so produce a smaller change in nesting and floral resources than interventions that convert one land-use to another.

Table 1.2: Categorisation of AES interventions

AES Category	Broad Description	Example interventions
Fallow	Allow parts of or all of an arable field to go fallow	Unharvested cereal headland, Skylark plots, Sown legume fallow, fallow buffer strip.
Floral Margin	Create a flower-rich margin or plot within a field	Nectar flower mix, Flower-rich margins and plots, Autumn-sown bumblebird mix
Grass Margin	Create a grass margin or plot within a field (floral richness not enhanced by sowing with wildflowers)	Buffer strips, beetle banks, riparian margins, in-field grass strips, field corner management
Hedgerow/Woodland Edge	Create or manage hedgerows and woodland edges (woody linear features)	Hedgerow management, management of woodland edges
Flower-rich Ley	Manage a field as a herb or legume-rich ley	Legume and herb-rich swards, multi-species ley
Semi-natural Habitat Management	Maintain existing semi-natural habitat	Permanent grassland with low inputs, management of rush pastures, ditch management, management of species rich grassland
Grassland/Heath Creation	Create grassland (low-input or species-rich) or lowland heath from other land use	Creation of grassland from target features, arable reversion to unfertilised grassland, creation of species-rich semi-natural grassland, creation of lowland heathland
Scrub/Wood Creation	Create scrub, successional areas, wood pasture or woodland from other land use	Creation of woodland (and maintenance payments), creation of wood pasture, creation of successional areas and scrub
Traditional Orchard Creation	Create traditional orchards from other land use	Creation of traditional orchards
Wetland/Coast Creation	Create wetland or coastal habitats from other land use	Creation of reedbed, creation of wet grassland, restoration of coastal saltmarsh

1.3.3 Trees in English AES

Scheme provision for tree planting and management is more complex. Prior to CS, AES in England had typically only funded planting of individual trees (including fruit trees) or hedgerows on farms. Support for hedgerow planting and restoration emerged as a response to a ~50% decline in hedgerow cover between the 1950's and the 1990's (Robinson and Sutherland, 2002). AES also funded creation of traditional orchards, which are small groups of low-density fruit / nut trees on permanent grassland and are geographically constrained to sites with or near to existing or historic traditional orchards. Woodland creation had been funded through a series of Forestry Commission run grant schemes outside AES which had helped increase woodland cover from 5.8% in 1947 to 10.0% in 2015 (Aldhous, 1997; Forestry Commission, 2016). The final scheme was the English Woodland Grant Scheme (EWGS) which opened in 2005. Annual maintenance payments to cover income forgone from agriculture were provided by a Farm Woodland Premium Scheme. Applications for new grants and maintenance payments were then moved to the CS scheme when that opened in 2015.

Despite the availability of the EWGS and its predecessors, woodland cover in England is one of lowest in Europe (FAO, 2020). To a certain extent, this is due to the very low starting cover in the mid-20th century, but it also reflects cultural, economic, and practical barriers to woodland creation on farms (Lawrence and Dandy, 2014; Staddon *et al.*, 2021). Most farmers also consider their primary purpose to be food production rather than provision of forest products, often reflecting generations of family tradition and culture (Watkins *et al.*, 1996; Duesberg *et al.*, 2013). Conifers require around 40 years before they can be harvested as softwoods and broadleaved trees can take up to 150 years before they are ready to produce hardwoods. As such, woodland creation is often viewed by farmers as a permanent land use change whose economic benefits will not be realised in their lifetime (Lawrence and Dandy, 2014). Moreover, although farmers who create woodland through grant schemes are still allowed to claim BPS funding during the lifetime of the grant support (10 – 15 years), once this ends the land is deemed to be permanent woodland and is no longer eligible. This has also been a disincentive to take up woodland creation as farmers choosing to do so then face a long time period between end of grant support and timber harvest where the land will potentially generate no income (Schleyer and Plieninger, 2011). Converting farmland to woodland also requires considerable administrative barriers such as planning permission and Environmental Impact Assessment. As such, the majority of woodland in England is managed by specialist foresters. 'Farm woodland' accounted for only ~0.35 M ha in England in 2015, or 27% of the national woodland cover, though this had increased to ~ 0.39 M ha (30%) by 2020 (Forest Research, 2021).

Another mechanism to introduce trees onto farmland includes planting willow or poplar for short rotation coppice (SRC) or short rotation forestry (SRF), which are fast-growing high-density plantation systems that produce wood or woodchip, primarily for bioenergy purposes. An Energy Crops Scheme active from 2000 – 2013 provided support for farmers establishing SRC but this was not strictly an agri-environment scheme as the objectives were only indirectly environmental. It was not taken forward into CS.

Agroforestry systems, where commercially grown trees occupy the same fields as crops or pastures, are also mechanisms by which trees can be planted on farms. Agroforestry systems are relatively common in continental Europe, but adoption rates in the UK are low with only 3.3% of land under this system (den Herder *et al.*, 2017). Low uptake reflects a range of factors including farmer knowledge, perceived conflicts with other agricultural activities, economic concerns, and an uncertain policy environment (Tosh and Westaway, 2021). To date, there has never been explicit support for agroforestry within English AES.

1.3.4 English AES beyond 2020

Following the UK's departure from the EU, the UK Government announced a new 25 Year Environmental Plan (HM Government, 2018) that would see the CAP replaced with an Environmental Land Management Scheme (ELMS) where land managers only receive payments for provision of public goods (i.e. non-excludable and non-rivalrous benefits to society such as carbon sequestration, flood risk management etc.). As such, the BPS (which provides only area-based income support) will be phased out by 2024; greening payments already ended in 2021. ELMS will have three tiers with an entry-level Sustainable Farming Incentive (SFI) sitting below Local Nature Recovery (LNR) and Landscape Recovery (LR). The CS scheme remains open, and many agreements (including some legacy ES) have been extended until ELMS goes live. Woodland creation incentives were moved to a separate England Woodland Creation offer, but eventually will be part of ELMS. At the time of writing, the details of each tier are still being defined. The implications of research conducted in this thesis for the ELMS scheme is discussed later in Section 5.3.1.

1.4 Effectiveness of Agri-Environment interventions for supporting pollinator populations

There is a reasonable evidence base for the effectiveness of agri-environment interventions on wild bee species richness and abundance at field/farm-scale.

1.4.1 Floral / grass margins, fallow, and floral-rich leys

Sown flower patches are known to increase provision of suitable resources and thus reduce foraging distance (Carvell, Jordan, *et al.*, 2011). Studies also demonstrate that these features improve bumblebee abundance and diversity (Carvell, Osborne, *et al.*, 2011; Carvell *et al.*, 2015; Scheper *et al.*, 2015) and that they can help bumblebee colonies to disperse in otherwise intensive arable landscapes (Dreier *et al.*, 2014). These effects are dependent on the area of features: increases in abundance and diversity were only significant when 8% of usable cropped land was removed from production as compared to a 3% removal scenario typical of ELS agreements (Pywell *et al.*, 2015a). However, sown floral features only increase the populations of a limited set of solitary bee species (Wood *et al.*, 2017), likely because there is insufficient floral diversity in the mixes sown (Wood *et al.*, 2015; Gresty *et al.*, 2018).

Unsown margins do not achieve as high a floral abundance or diversity as sown features but there is some evidence they can increase bumblebee abundance and diversity if they are sufficiently wide (Cole *et al.*, 2015). Fallow features, where land is left uncropped for a season or longer, will also not reach the same level of floral quality as wildflower sown margins, but could still support wild bee populations under the right management conditions (Ouvrard and Jacquemart, 2018). Reduced disturbance and the presence of suitable nesting habitat (tall grass, hollow stems, bare ground) may also make these features more attractive nesting habitat than fields growing crops or improved grassland.

A ley is created when arable land is converted to grassland or to a grass/legume mix for at least one growing season, but not permanently (no longer than five years). This helps manage weeds such as blackgrass and improves soil fertility (Bliss, 2018). Certain AES interventions in CS and ES enhance the quality of leys by specifying a more florally-rich sowing mix, which is likely to be of value to wild bees and other pollinators (Woodcock *et al.*, 2015). Red clover (often included in mixes) in particular has been shown to support bumblebee abundance (Rundlöf *et al.*, 2014).

1.4.2 Hedgerows and woodland edge management

Hedgerows are an important habitat for wild bees but the extent to which they support populations depends on what trees they contain and how they are managed (Garratt et al., 2017). Native hedge plants such as blackthorn (*Prunus spinosa*) and hawthorn (*Crataegus monogyna*) flower early in the year when other resources are scarce. Similarly, hedgerows containing ivy (*Hedera helix*) will provide floral resources in early autumn – another key floral resource gap (Timberlake *et al.*, 2021). Well-managed hedgerows will also have an un-cut buffer zone between the crop and the trees that will support vegetation flowering at other times of the year. Hedgerows can also provide a range of nesting habitats for ground-nesting species (Sardiñas *et al.*, 2016). The edges of woodlands have a different vegetation structure, and thus ecological value, to their interiors, typically receiving greater light and solar heat and supporting smaller, shrubbier trees and more ground flora. This means they are more likely to provide floral resources for bees and suitable nesting habitat for ground-nesting bees (Fry and Sarlöv-Herlin, 1997).

Whilst hedgerows and woodland edges outside of AES can also be of value to wild bees, they can either be overmanaged (reducing floral cover) or under-managed (compromising structural quality). AES managed hedgerow features are cut at a specific frequency that maintains structural integrity without compromising floral cover (Staley *et al.*, 2012). Woodland edge AES management creates a wide buffer zone where agricultural management is ceased and a scrub / grass mosaic is allowed to develop, but succession to woodland is prevented by annual cutting and thus creates similar habitat to a well-managed hedgerow.

1.4.3 Semi-natural habitat management and creation

Aside from hedgerows and woodland edges, many AES interventions seek to maintain or improve the quality of existing semi-natural habitat on farms. The focus of interventions is often on grassland or moorland / heathland which are semi-productive systems that rely on grazing animals or cutting of vegetation to prevent succession to scrub and/or woodland. Interventions such as 'Permanent grassland with (very) low-input' which prevent intensification of grassland and 'Maintenance of moorland' / 'Restoration of moorland' which set out a grazing and stocking regime for upland areas are some of the most popular scheme interventions by land area (see Table A1.4). Such interventions have the potential to be valuable to wild bees because they promote floral diversity and abundance whilst maintaining suitable nesting habitat for certain guilds (Sexton and Emery, 2020; Redpath *et al.*, 2010). In practice, the management regimes often result in only very subtle changes in vegetation structure, meaning that the benefit to wild bees is minimal (Berg *et al.*, 2019).

Some AES interventions make more substantial changes to agricultural landscapes by creating semi-natural habitats from arable land or improved grassland. The target habitat could be semi-natural grassland, moorland or heathland, wetland, coastal habitat, depending on the landscape context and suitability. Such land use change will also alter the floral and nesting quality of the land, though the extent to which individual bee species and guilds benefit depends on their particular needs (Vaudo *et al.*, 2015).

1.4.4 Tree planting

Willow (*Salix* spp.) and fruit trees are commonly deployed as the tree component of agroforestry systems and these are especially valuable to wild bees because they flower early in the year, often where there is limited alternative foraging resource (Bentrup *et al.*, 2019). The understory of trees in orchard systems provides a continuous floral resource for wild bees (Rosa García and Miñarro, 2014), which might also apply to fruit tree agroforestry. Indeed, empirical evidence has found that wild bees are more abundant in areas where agroforestry systems have been adopted (Berkley *et al.*, 2018; Varah *et al.*, 2020) and where more woodland is present (Bailey *et al.*, 2014).

Mature woodland is also valuable to wild bees, most obviously for *Bombus hypnorum* which is a specialist tree-nester (Crowther *et al.*, 2014). Woodland also offers ample opportunities to for underground cavities and other sites used by ground-nesters (Mola *et al.*, 2021). A wider range of floral resources are provided not just by the trees themselves, but by understory vegetation, especially in more open areas such as glades and rides (Donkersley, 2019), whose creation are a focus of many woodland management operations. The value of hedgerows is already discussed in Section 1.4.2.

1.5 Effectiveness of agri-environment interventions for supporting pollination services in England

The relationship between AES interventions and wild bee crop pollination services is more complex. For an intervention to increase the pollination service to a given crop it must increase the population of bees within foraging distance of the crop during the season when the crop is in flower, but not offset this by offering more attractive floral resources with the same phenology. Landscape context also plays a role, with interventions placed in a resource poor areas likely to be more effective than those located in richer areas (Tscharntke *et al.*, 2012; Scheper *et al.*, 2013). As a result, a recent meta-analysis on the effectiveness of common interventions, such as floral margins and hedgerows, reveals uncertainty about their effect on crop pollination service (Albrecht *et al.*, 2020).

In an English arable landscape, floral margins can have a positive effect on OSR and field bean yield across the entire field, but only when they have been established for at least four years (Pywell *et al.*, 2015a). The timeframe may reflect the amount of time needed for interventions to reach sufficient floral quality. A study of OSR visitation in a similar Swiss landscape found an increase in crop visitation with floral margins and hedgerow but not an increase in yield, suggesting perhaps that the landscape resource quality was already sufficient to achieve optimum pollination (Sutter *et al.*, 2018). Positive relationships have also been demonstrated between agroforestry systems (especially those involving early flowering trees such as willow) and pollination of later flowering crops such as oilseed rape (Stanley *et al.*, 2013; Varah *et al.*, 2020).

Floral visitation has also shown to be higher where wildflower strips are sown adjacent to strawberry fields in Scotland (Feltham *et al.*, 2015) and similar effects have been seen a US context for blueberries (Blaauw and Isaacs, 2014). However, a Swiss study on wildflower strips' effect on strawberry yields found only an effect in the area immediately adjacent to the field with no overall effect across the whole field (Ganser *et al.*, 2018). This may have reflected the shorter study timeframe (2 years) and richer landscape context (arable-grass-forest mosaic vs. homogeneous arable). It could also reflect the fact that the study measured pollination service as change in yield rather than change in visitation. Floral visitation by wild bees to English orchards (which are early flowering) and fruit yield is not affected by the addition of wildflower strips (McKerchar *et al.*, 2020). Although another study by Campbell *et al.* (2017) did find some evidence of increased wild bee floral visitation to apple orchards though this might be potentially a confounding effect of plant protection products and variability between cultivars and years.

1.6 Modelling pollinators and pollination services

All the effects outlined above have been studied at field or farm scale. However, schemes operate at regional or national level and can cover vast areas. Understanding the effectiveness of schemes at these scales requires modelling techniques that build on the results of empirical studies and incorporate information on where interventions have been implemented. Three types of modelling have been applied to the study of pollinators and pollination services. Habitat-based models simply assign a value to a land cover type or transition, (e.g. representing its assumed habitat value for supporting pollinators), which is then applied to all land cover of that type within the study area. Process-based models represent the mechanics of biological systems (e.g. wild bee life cycles and foraging within landscapes) as a set of mathematical functions and algorithms that usually represent population-level processes (Buck-Sorlin, 2013). Agent-based models simulate the behaviour and decisions of individual entities (e.g. individual bees foraging paths, nesting choices) within their environment (Wang and Deisboeck, 2013).

1.6.1 Habitat-based

Habitat-based models assign values to different habitat which represents the potential for that habitat to support pollinators (and thus indirectly represent potential for pollination service). Where these values are assigned to different interventions, which vary in their area of uptake, they can be used to predict the impact of schemes at larger spatial scales. In earlier efforts, values were assigned by expert opinion and are therefore ordinal. Breeze *et al*. (2014) scored ES interventions on a 0 – 5 scale for their benefit to pollinators with certainty weighting and combined the values with actual area of uptake and costs to determine which interventions were most ecologically- and cost-effective for pollinators considering their uptake. FERA (2012) assigned scores to interventions to reflect their potential contribution to supporting pollination service and multiplied by area of uptake within a $5km^2$ grid to produce a map of predicted crop pollination service delivery across England. The Environmental Benefits from Nature (EBN) tool (Smith *et al.*, 2021) uses a 0 – 10 score for pollination service assigned to different habitat types (amongst 17 other ecosystem services). The tool was developed more for use in land-use planning rather than agri-environmental measures, and so only captures certain interventions such as habitat creation and floral margins but does allow for the time to reach target condition, rather than assuming that interventions are immediately effective.

The main advantage of these models is that they are relatively easy to construct and operate and allow for rapid assessments to be made of scheme effectiveness. However, they have some key limitations.

Firstly, they attempt to generalise value to pollinators and contribution to pollination services to one number representing all pollinators and all pollinator dependent crops whilst, in reality, pollination is provided by a range of species, each of which have different floral, nesting, foraging range, dispersal range and population growth dynamics across the year. Secondly, they do not take into consideration key spatial and temporal factors. Interventions could be highly effective in boosting pollinator populations but may have limited effect on pollination services if those pollinators cannot reach crops that require the service, or if the floral resources provided compete for pollinators with those crops. Moreover, the effect of an intervention will be moderated by its landscape context: high quality interventions placed in areas already well serviced by pollinators may potentially be less effective than low quality interventions placed in areas with high potential demand. Finally, because they do not indicate where the additional pollination service is delivered it is not possible to disentangle the service to crops from the service to wild plants. By missing these subtleties, habitat-based approaches could provide misleading policy advice.

Other attempts have used landscape context to formulate a more robust 'score'. Staley et al. (2018) surveyed CS interventions and assigned them a score based on percentage cover of forbs, grasses, plants in intervention specification, diversity, vegetation height and structure, and other variables specific to the intervention. These were then combined with area of uptake within a 1 km^2 (local) and a 3 km^2 (landscape) area and compared to observed bumblebee abundance. They found a positive and significant relationship between bumblebee abundance and uptake at the 1 km^2 but not at the 3 km^2 level, and also showed that the effect of interventions at the local level was greater where uptake at the wider scales was lower, further demonstrating the importance of landscape context. However, this study is not publicly available.

1.6.2 Process-based

The first established process-based model for pollinators and pollination services was developed by Lonsdorf *et al*. (2009). The model takes a map of land cover and translates it into a map of nesting suitability. A map of floral resource provision is also calculated from the land cover map based on the landcovers' floral quality and seasonality but decaying exponentially with distance from the nesting map to reflects the species foraging range. The floral and nesting values are then multiplied to produce a map showing predicted relative abundance of pollinators (in their nests). Pollination services are then calculated by working out the distance weighted proportion of those pollinators that are foraging in a map of crops, again assuming the average foraging distance of the species. Lonsdorf *et al*. populated the parameters using expert opinion and validated against observed abundances and pollination services in three locations (Costa Rica, California, New Jersey / Pennsylvania). Their model was able to predict these to a reasonable degree in homogeneous landscapes (e.g. coffee plantations in Costa Rica) but was not as effective in more heterogenous landscapes (e.g. arable + remnant woodland landscapes in New Jersey and Pennsylvania).

The model was enhanced by Olsson *et al.* (2015) by incorporating preferential selection of foraging resources so that bees (central-place foragers) will potentially travel further to collect resources if they are sufficiently attractive allowing for travel 'cost', rather than having a fixed foraging kernel irrespective of resource quality. They also used the model to demonstrate that interventions which offered competing floral resource but no net increase in nesting resource might actually decrease pollination service by attracting bees away from the target crop.

Häussler *et al.* (2017) have further built on the model by incorporating other aspects of wild bees' life cycle including preferential selection of nesting resources, maximum nest density, and parameters for the dispersal range of reproductive females when they seek a new nest site. This version of the model also incorporates population growth and eusocial dynamics for bumblebees (queens foraging initially followed by workers in subsequent seasons). It was parameterised and then applied to examine the effect of introducing grass and floral margins into a digitised version of a real landscape containing OSR. Both interventions were predicted to enhance pollinator abundance and early season pollination service (including to OSR) with floral margins predicted be three times more effective than grass margins, reflecting their enhanced floral resource value. The Häussler model, now called *poll4pop*, has subsequently been adapted to a UK context, parameterised for over 30 land cover types based on an expert opinion survey, and its predicted visitation rates validated against observed relative abundances of four pollinator guilds (ground-nesting bumblebees, tree-nesting bumblebees, ground-nesting solitary bees and cavity-nesting solitary bees) measured in pollinator dependent crops (OSR, field beans and orchard fruit) semi-natural and urban habitats across over 200 survey sites (Gardner *et al.*, 2020).

The main disadvantages of these models are that they are more computationally expensive, especially if applied at very large scale, and require technical expertise to operate as well as considerable data input to be able to run on realistic landscapes. The Gardner et al. iteration has been validated against field data, but it still relies on expert opinion (although they did show this was preferable to calibrating habitat preference scores against the observational data due to the level of observational biases embedded in the survey datasets). Although *poll4pop* has intra-year temporal sensitivity (two seasons in Häussler *et al.* (2017); three in Gardner *et al*. 2020) this is still quite coarse given the variability in flowering windows. Nevertheless, the Lonsdorf version model has been incorporated into the InVEST natural capital mapping tool as its pollination component (Lonsdorf *et al.*, 2011). As a result it has become widely used in used in academia to evaluate effects of actual and prospective interventions (Groff *et al.*, 2016; Grafius *et al.*, 2016; Davis *et al.*, 2017; Cong *et al.*, 2014; Desaegher *et al.*, 2021).

1.6.3 Agent based

Agent or individual based models (ABM, IBM) simulate the behaviour of individual bees rather than generalising their behaviour to that of an entire colony or nest. The earliest application of an ABM for bees made predictions for solitary bee visitation to alfalfa in the US, though this was with a managed species and so did not need to consider nesting and alternative foraging resource availability (Strickler and Vinson, 2000). More recent examples (e.g. EcoSimInGrid) use reinforcement learning to inform a foraging algorithm determining foraging decisions of a population of pollinators within a matrix of grid cells containing plants of different species (Qu *et al.*, 2013).

Bumble-BEEHAVE (Becher *et al.*, 2018) also simulates the behaviour of individual bumblebees within a colony on a day-by-day basis throughout the year including explicit functions to link worker and new queen production to pollen and nectar inputs by weight and volume, and bee foraging efficiency based on size. The bees forage on floral resources which are provided as 'patches' with a specified location and area relative to the nesting locations. These patches require a flowering period, quantity of pollen and nectar production. This allows for inter- and intra-specific competition for resources to be considered (which has only begun to be explored in *poll4pop*) and also allow for external anthropogenic stressors such as sub-lethal pesticide effects to be modelled, as is the case with the SimBee model (Gegear *et al.*, 2021).

Although ABM / IBM have the potential to be more accurate than process-based models, they are extremely computationally expensive because every decision of every bee needs to be modelled, making them general unsuitable for large-scale pollinator simulations. The performance time of Bumble-BEEHAVE is not discussed in the paper but the reported simulation time of EcoSimInGrid using 2013 technology was several minutes for a landscape of 400 * 400 cells containing 1600 pollinators, though this may reflect that this model also considers individual plant life cycle as well as that of pollinators. They also often have even higher data input requirements than process-based models because quantitative information is required about nectar and pollen requirements of bumblebee colonies and the production levels of the floral resources within the land cover map.

1.7 Aims and Structure of the thesis

1.7.1 Summary of knowledge gaps

Although there have been numerous studies on the effectiveness of selected interventions at field or farm scale, there have been few attempts to study entire schemes at larger scale. Where this has occurred (e.g. FERA, 2012), they have relied on habitat-based models that do not take into consideration spatial factors such as foraging / nesting dispersal range and landscape context, or temporal factors such as the phenology of crops, semi-natural features, and bees. As such, there is a knowledge gap in understanding how effective *entire* AES are at enhancing wild bee populations and the crop pollination services that the wild bees provide. Interventions are usually studied in isolation and not collectively as part of whole schemes, there is also a knowledge gap in terms of how effective interventions are in the context of their actual uptake within schemes. Interventions that may be considered of relatively low value to bees could in fact be highly effective if they are typically taken up close to pollinator-dependent crops (and vice versa) or by many farmers. Environmental priorities are changing, with a stronger emphasis on tree-planting on farms to increase carbon sequestration. This offers the potential for enhancement of crop pollination services as a co-benefit, but the relative contribution of different tree-planting approaches has not been evaluated. Finally, when these knowledge gaps are addressed, there is a need to synthesise the findings to be able to inform the development of the next generation of AES, and especially the ELMS scheme.

1.7.2 Aims

The parameterisation of the *poll4pop* model by Gardner et al. to Great Britain makes it possible for the first time to apply a spatially explicit process-based model to investigate these knowledge gaps in England. This study is intended to leverage this development to:

- Determine to what extent the AES scheme(s) implemented in England in 2016 have affected populations of wild bees and their pollination services to OSR, field beans, orchard fruit and soft fruit (strawberries/raspberries not in polytunnels[4]).
- Uncover the relative contribution of different AES interventions within those schemes to wild bee pollination services and what factors (intervention quality, quantity, placement) determine that contribution.
- Predict which tree-planting interventions at current tree-planting rates, if added to existing AES uptake, would have the greatest contribution to supporting wild bee populations and their pollination service, and how that would change at more ambitious planting rates.
- Make recommendations for future schemes.

1.7.3 Approach and Structure

The remainder of thesis is structured into three chapters representing distinct research studies carried out to achieve the first three aims and a final chapter which synthesises the findings.

[4] For convenience this is abbreviated to 'strawberries' for the remainder of the thesis.

Chapter 2 studies the entire population of English AES interventions active for a given calendar year (2016) and uses the *poll4pop* model to predict whether AES have had a significant impact in increasing wild bee pollinator abundance and crop pollination services at a national scale for four wild bee guilds and four pollinator dependent crops. This involved building a high-resolution land cover map for England for the study year 2016, including the AES features present, and an alternative scenario for this map where these features were absent, parameterising and validating the additional AES features classes against observed data provided by Gardner et al. (2020). The year 2016 was chosen as it was the year for which accurate crop cover and AES data was made available by the RPA. The *poll4pop* model was run for both scenarios, taking into consideration uncertainty associated with the habitat attractiveness and floral cover parameters to determine the extent to which the AES interventions present during that year had affected wild bee populations for the four bee guilds (ground-nesting bumblebees, tree-nesting bumblebees, ground-nesting solitary bees and cavity-nesting solitary bees) and four pollinator dependent crops (OSR, field beans, orchard fruit and strawberries) at both national and fine scale.

Chapter 3 examines the predictions of the first paper and uses linear regression to determine the extent to which different interventions within the scheme (categorised as in Table 1.2) have contributed toward its overall effect, focusing on the pollination service provided by bumblebees to mass-flowering crops and non-cropped areas. This analysis takes into consideration interactions between interventions and prior landscape context and considers whether the effects of interventions relate to their respective resource quality, quantity (area) of uptake, or placement within the landscape.

Chapter 4 then predicts the relative enhancement of crop pollination service of bumblebees to mass-flowering crops (OSR, field beans) that would be achieved by including different tree-planting interventions (woodland, agroforestry, hedgerow planting) at two levels of planting intensity in a sample landscape. a sample landscape was chosen to simulate the effect of introducing different tree-planting interventions at different planting intensities on wild bee populations and crop pollination services.

Finally, Chapter 5 summarises the key findings of the three preceding chapters and discusses their implications for future AES scheme design in England. Supplementary Material to Chapters 2, 3, and 4 is provided in a set of Appendices (1, 2, and 3). Although Chapters 2 – 4 had their own reference lists upon publication/submission, for convenience a single table of references is provided covering all 5 chapters and the appendices. A schematic showing the with inputs, methods, results and analyses and relationship between Chapters 2, 3 and 4 is presented in Figure 1.2.

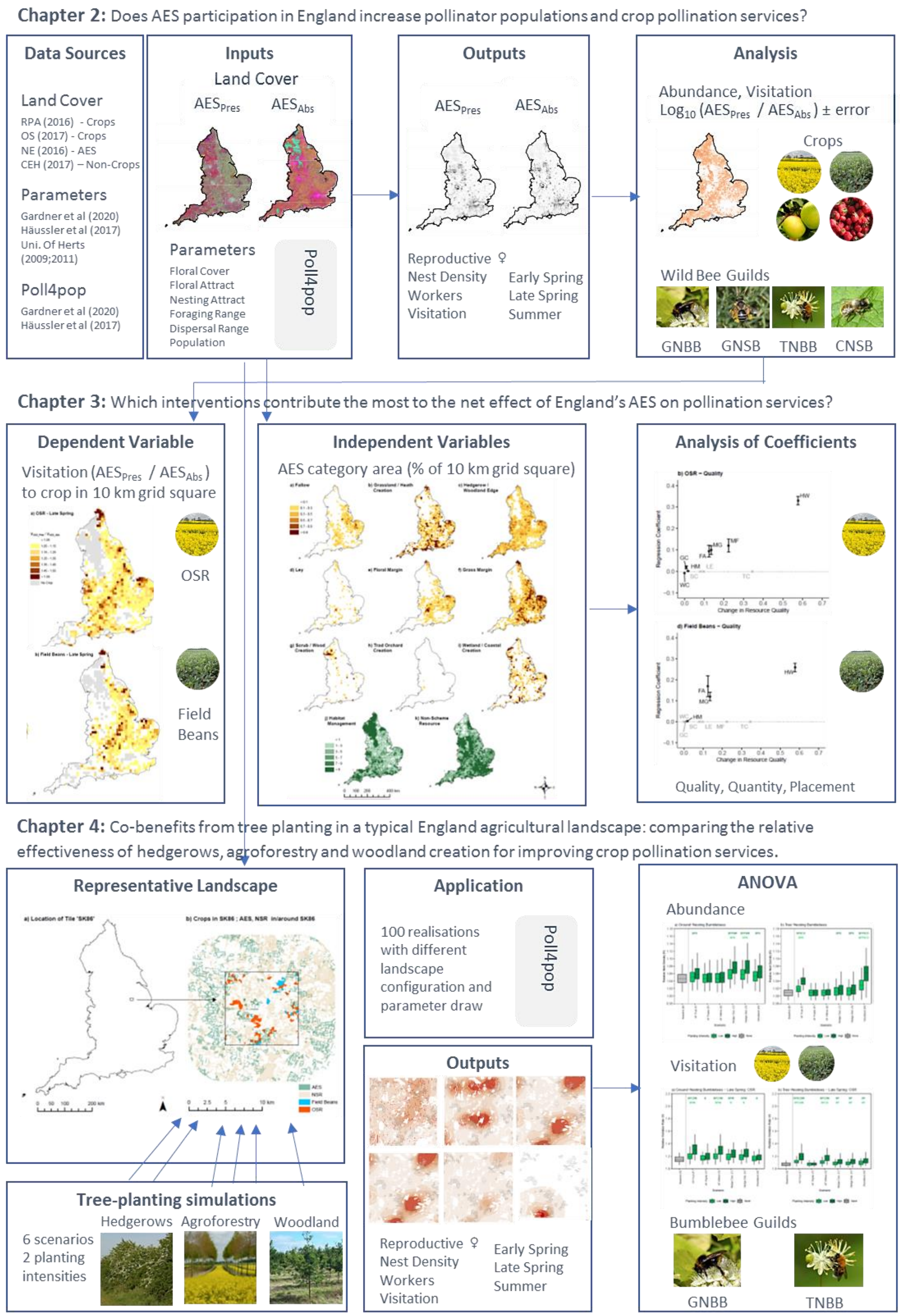

Figure 1.2: Schematic with inputs, methods, results and analyses and relationship between Chapters 2, 3 and 4

2 Does agri-environment scheme participation in England increase pollinator populations and crop pollination services?

Abstract

Agri-environment schemes are programmes where landholders enter into voluntary agreements (typically with governments) to manage agricultural land for environmental protection and nature conservation objectives. Previous work at local scale has shown that these features can provide additional floral and nesting resources to support wild pollinators, which may indirectly increase floral visitation to nearby crops. However, the effect of entire schemes on this important ecosystem service has never previously been studied at national scale. Focusing on four wild pollinator guilds (ground-nesting bumblebees, tree-nesting bumblebees, ground-nesting solitary bees, and cavity-nesting solitary bees), we used a state-of-the-art, process-based spatial model to examine the relationship between participation in agri-environment schemes across England during 2016 and the predicted abundances of these guilds and their visitation rates to four pollinator dependent crops (oilseed rape, field beans, orchard fruit and strawberries).

Our modelling predicts that significant increases in national populations of ground-nesting bumblebees and ground-nesting solitary bees have occurred in response to the schemes. Lack of significant population increases for other guilds likely reflects specialist nesting resource requirements not well-catered for in schemes. We do not predict statistically significant increases in visitation to pollinator-dependent crops at national level as a result of scheme interventions but do predict some localised areas of significant increase in bumblebee visitation to crops flowering in late spring. Lack of any significant change in visitation to crops which flower outside this season is likely due to a combination of low provision of nesting resource relative to floral resource by scheme interventions and low overall participation in more intensively farmed landscapes.

We recommend future schemes place greater importance on nesting resource provision alongside floral resource provision, better cater for the needs of specialised species and promote more contiguous patches of semi-natural habitat to better support solitary bee visitation.

This chapter is published by Agriculture Ecosystems and Environment as:

Image, M., Gardner, E., … Breeze, T. D. (2022). Does agri-environment scheme participation in England increase pollinator populations and crop pollination services? *Agriculture, Ecosystems & Environment* 325, 107755. doi: 10.1016/j.agee.2021.107755. *The terms 'nest productivity' used in the original article has been replaced by 'queen production' to be consistent with Chapter 4.*

2.1 Introduction

Animal pollinators support reproduction in an estimated 87.5% of flowering plant species worldwide, including over three quarters of the world's leading food crops (Klein *et al.*, 2007; Ollerton *et al.*, 2011). In England, the most important pollinator-dependent crops are oilseed rape (*Brassica napus;* hereafter OSR), field beans (*Vicia faba*), orchard fruit (apples, pears, and plums) and soft fruit (mainly strawberries and raspberries) (Breeze *et al.*, 2020; DEFRA, 2017b). Pollination of these crops is mainly carried out by wild, unmanaged pollinators – principally bumblebees and solitary bees (Blitzer *et al.*, 2016; Garratt, Coston, *et al.*, 2014; Hutchinson *et al.*, 2021; Klatt *et al.*, 2013). There is evidence of widespread declines in wild bee populations in Great Britain between 1980 and 2013 (Powney *et al.*, 2019) echoing a global trend of decline (IPBES, 2016). This can impact food security where floral visitation is insufficient to achieve optimal yield in pollinator-dependent crops (Garratt, Breeze, *et al.*, 2014; Holland *et al.*, 2020). Even where this risk is not imminent, declining wild bee abundance and diversity can leave areas vulnerable to future shocks in bee populations or instability of other ecosystem services (Hutchinson *et al.*, 2021; Senapathi *et al.*, 2015).

Land use change, particularly the simplification of landscapes through intensified agriculture, is a major driver of pollinator decline (Ollerton *et al.*, 2014; Potts *et al.*, 2016) as the proportion of land used for crops and improved grassland increases at the expense of 'semi-natural habitat' such as hay meadows, fallow land, leys and hedgerows (Firbank *et al.*, 2008; Ridding *et al.*, 2020). Relative to crops and improved grassland, semi-natural habitat provides better quality nesting habitat (Lye *et al.*, 2009) and provides floral resources on which pollinators can forage when managed crops are not in flower (Michael P.D. Garratt *et al.*, 2017; Kovács-Hostyánszki *et al.*, 2017; Timberlake *et al.*, 2019). Addressing wild bee declines and associated risks to ecosystem services therefore typically involves creating, restoring, or at least maintaining semi-natural habitat (Bommarco *et al.*, 2013).

Agri-environment schemes (AES) are programmes where landholders enter into voluntary agreements (typically with governments) to manage agricultural land for environmental protection and nature conservation objectives (Dicks *et al.*, 2016). In England, the main AES are *Countryside Stewardship* (CS) scheme (active since 2015) and the previous *Environmental Stewardship* (ES). In both schemes, landholders choose from a selection of over 200 multi-year management options and capital items with associated payment rates per option, based on costs and income forgone for loss of agricultural production.

Many options serve a broad environmental purpose aligned to the farming system such as hedgerow management, grass margins and low-input grassland. Others are specifically designed to restore or maintain habitats such as semi-natural grassland, moorland, and woodland, while capital items provide funding for one-off activities such as hedge planting. Where these options and items increase the quality and quantity of nesting and/or floral resources in a landscape, they can be valuable to pollinators depending on species' preferences (Vaudo *et al.*, 2015). Some CS options have been explicitly designed to provide floral resources for wild bees and other pollinators in arable farms, (e.g., AB1 – Nectar flower mix, and AB16 – Autumn sown bumblebird mix) and its 'Wild Pollinator and Farm Wildlife Package' encourages farmers to bundle these with options that may provide nesting resources (e.g., hedgerows and field corner management).

Several studies demonstrate that these AES features can boost wild bee species richness and abundance at field and farm scale (Balfour *et al.*, 2015; Heard *et al.*, 2012; Scheper *et al.*, 2015). The relationship between AES and crop pollination services is more complex and less well understood. A relationship between provision of AES features in agricultural landscapes and crop pollination services has been demonstrated empirically at farm and field scale (Blaauw and Isaacs, 2014; Morandin *et al.*, 2016; Nicholson *et al.*, 2017; Pywell *et al.*, 2015a) but, due to different bees foraging ranges and preferences (Kennedy *et al.*, 2013) this is not consistent across feature type (Albrecht *et al.*, 2020).

However, AES feature effectiveness at local scale does not necessarily translate into whole-scheme effectiveness at national scale. Schemes are not mandatory and even where farmers do participate, the choice of options implemented may not necessarily be the most effective at supporting wild bees due implementation cost influencing option choice (Austin *et al.*, 2015). Since empirical approaches are unfeasible at national scale, detailed modelling that incorporates how bees move around the landscape to nest, forage and reproduce is needed to estimate the impact of AES on pollination service. The process-based pollinator model developed by Lonsdorf *et al*. (2009) and later developments of it (Häussler *et al.*, 2017; Olsson *et al.*, 2015) have this capability and have already been applied at regional scale to examine the impact of interventions (Cong *et al.*, 2014; Davis *et al.*, 2017; Häussler *et al.*, 2017) while the latest state-of-the-art version ('poll4pop') has recently been validated in Great Britain for four wild bee guilds (Gardner *et al.*, 2020).

This study integrates spatially explicit data from multiple sources to generate the most detailed and realistic map yet of AES, crop, and non-crop features across England for the year 2016. It then applies the fully validated poll4pop model to this landscape to predict wild bee abundance and the level of crop and non-crop pollination service provided. By comparing the pollinator model's predictions including and excluding AES management, we estimate the schemes' current effectiveness at promoting wild bee abundance and pollination services at national scale. The study provides an assessment of participation in schemes as a whole, including the effects of options that may not explicitly target pollinators but still have an effect through changing the quantity/quality of resources.

Based on the findings, recommendations are made to increase the effectiveness and direct/incentivise participation in future AES.

2.2 Methodology

All modelling/data processing was carried out in ArcGIS 10.7 (ESRI, 2019) and Python 2.7 / 3.5. The Poll4pop model source code was transcribed from R (R Core Team, 2018) to Python to facilitate integration with ArcGIS and improve processing times.

2.2.1 Model Description

Poll4pop (Gardner *et al.*, 2020; Häussler *et al.*, 2017) is a process-based model that predicts seasonal spatially explicit abundance and floral visitation rates for central-place foraging pollinators in a given landscape including fine-scale features such as hedgerows and grass margins. It can be parameterised for a particular species or for a species grouping ('guild') with common attributes. A brief overview of the model is given as follows, but for a more detailed description see Häussler *et al*. (2017).

The model requires a land cover raster detailing the land class assigned to each cell as well as a rasterised map showing the area of 'edge' land classes (features smaller than the cell resolution – 25m^2 in our case) within each cell. Each land class has a score representing the amount of floral resource provided during a given season (floral cover), the attractiveness of that floral resource to the guild (floral attractiveness; representing its nutritional quality), and its attractiveness as a nesting resource to that guild (nesting attractiveness). Floral cover and floral attractiveness are multiplied to generate a floral resource raster by season. Where a cell contains edge features, these are assigned an area based on the length of that feature in the cell and a width parameter for that edge type (see Table A1.3 and Table A1.4). The non-edge feature area is adjusted down accordingly. The cell's cover and attractiveness parameters are then calculated as the area-weighted sum of the parameters for the edge and non-edge features in the cell.

Nests are initially allocated to cells according to a Poisson distribution around the expected number per cell predicted from the nesting attractiveness raster and input maximum nest density. For every season during which the guild is active, foragers from each cell containing nests gather floral resources from cells within a distance-and floral-resource-weighted Gaussian kernel surrounding that cell. The size of the kernel is determined by a guild specific mean foraging distance parameter (β_f). The visitation rate to a given cell (per season) within the kernel is the product of its distance and floral resource weights. The total visitation rate to a given cell for that season (V_s) is the sum of all the visitation from all the nests whose kernels cover that cell.

For solitary guilds, the foragers are reproductive females, but for social guilds the reproductive females (queens) are replaced by foraging workers after the first season. For solitary guilds, the number of new reproductive females produced by a cell (Q) depends on the amount of resource gathered during the active period and a lognormal growth function with median, steepness, and maximum parameters specific to that guild. For social guilds, the number of workers produced by a cell (W_s) at the end of a season is determined by the amount of the resources gathered and a similar lognormal growth function specific to that guild. In the final active season for social guilds the resources are used to produce new reproductive females.

At the end of the final active season, new reproductive females disperse to cells within a distance- and nesting-attractiveness-weighted Gaussian kernel. The size of the kernel is determined by a guild specific mean nesting distance parameter (β_n). The number of nests in a given cell (R) in the following year is the sum of the nesting dispersal from all the kernels that cover that cell, subject to the maximum nest density parameter. The modelling process is repeated using these nests until the total number of nests in the landscape converges (<1% change between runs).

The model therefore outputs, per guild, three measures of abundance and a measure of visitation as rasters at the same resolution as the input rasters:

- Number of nests in a given cell (R).
- Number of workers produced at the end of a given season by the nests in a given cell and thus available to forage in the next season (W_s) – social bees only.
- Number of new reproductive females produced at the end of the final active season by the nests in a given cell (Q).
- Flower visitation rate in a cell for a given season (V_s).

We note that these predicted visitation rates do not include visitation by other non-modelled pollinators, that crop yield ultimately depends non-linearly on this visitation rate and that the relationship between our predicted visitation rates and the rate required for optimum pollination of any given crop is still uncertain (see Discussion). Nonetheless, by simulating foraging and population processes, the model represents the best tool currently available for assessing how fine-scale changes in habitat provision/configuration may influence bee abundance and visitation rates at landscape-scale.

2.2.2 Model Parameterisation and Validation

Gardner *et al.* (2020) - hereafter G2020 – parameterised and validated the poll4pop model in Great Britain for four guilds: ground-nesting bumblebees, ground-nesting solitary bees, tree-nesting bumblebees, and cavity-nesting solitary bees. We took guild specific parameters for foraging and dispersal distance, population growth and maximum nest density directly from G2020 and Häussler *et al*. (2017).

G2020 used 33 land classes and derived their (guild-specific) floral attractiveness and nesting attractiveness parameters and floral cover parameters across three seasons (spring, summer, autumn) via an expert opinion survey (Table A1.7 - Table A1.11 in Appendix 1). We adopt their values and derive additional attractiveness and floral cover parameters for our extended range of land cover as described in section 2.2.3.1 below.

We also readjust the seasonal definitions for floral cover to represent 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) to better capture differences in flowering windows for mass-flowering arable crops (generally late spring flowering) and orchards (generally early spring flowering) relative to floral resources created by AES features (flowering across spring). Our early and late spring floral cover parameters relate to the original spring G2020 parameters as follows:

- OSR, Linseed/flax, Peas, Field beans, Strawberries/raspberries not in polytunnels, Other berries: the G2020 floral cover parameter for spring was allocated 90% to late spring and 10% to early spring.
- Orchards: the G2020 floral cover parameter was allocated 90% to early spring and 10% floral to late spring.
- All other land classes: the G2020 floral cover parameter was allocated 50% to early spring and 50% to late spring.

The 90/10 allocation was used rather than 100/0 since late spring flowering crops will have some inflorescence in Early Spring (see e.g. AHDB (2020b) for OSR), whilst some orchard cultivars flower into late spring.

We repeated the validation process carried out by G2020 to confirm that our extended parameter set, and new seasonal definitions still produce model predictions that agree with observed pollinator abundances (see Appendix 1.6).

2.2.3 AES Present and AES Absent Scenarios

In order to make predictions for pollinator abundances and visitation rates with, and in the absence of, current AES management, we generated land cover and edge input rasters at 25m^2 resolution for two scenarios: '*AES_Present*' representing the scenario where the AES management was present, and '*AES_Absent*' representing the scenario where AES management was absent. The year 2016 was chosen because it was the most recent to have agricultural, non-agricultural and AES spatial data at sufficient resolution. A brief overview of the process is given in the following section, with a detailed description provided in Appendix 1.2.

2.2.3.1 Source landcover data

Land cover and edge feature information were sourced to represent as closely as possible the coverage of non-agricultural land, crops and permanent grassland, and land under agri-environment scheme (AES) option management for England during the year 2016. We included a 5km buffer zone into Scotland and Wales to eliminate edge effects based on the largest mean dispersal distance parameter (1km for bumblebee nesting).

Agricultural land cover for England came from 2016 Basic Payment Scheme (BPS) claims data identifying the type and area of crop, grassland or other eligible feature and was assigned to the corresponding polygon from the Land Parcel Information System (LPIS). Orchard polygons were sourced from the Ordnance Survey Master Map Orchards layer (MMOrch; Ordnance Survey, 2017).

Land outside LPIS and MMOrch was classified according to land cover information from the CEH Landcover Map 2015 (LCM; Rowland *et al*., 2017). Two additional data sources - Crop Map of England 2016 (CROME; Rural Payments Agency, 2019) and OpenStreetMap (OSM; OpenStreetMap contributors, 2017) - were used to determine land class where there was inconsistency between the LCM, LPIS and BPS datasets: i.e. where LCM indicated 'Arable or Horticulture' but there was no corresponding LPIS polygon, or where there was a LPIS polygon with no corresponding BPS claim (see Appendix 1.2 for more detail.)

Two English AES schemes had active agreements during 2016: the current Countryside Stewardship (CS) scheme (open since 2015) and Environmental Stewardship (ES), the legacy scheme open to applications prior to 2015. We sourced AES features from both schemes' datasets (CS: Natural England, 2018a) (ES: Natural England, 2018b) selecting only options with agreements active during 2016. Features that would not impact on habitat quality for bees (e.g. water troughs, archaeological site management) or whose management impact was outside the seasonal scope of the model (e.g. winter cover actions) were removed. A full list of excluded options is provided in Table A1.5 of Appendix 1.

ES and CS datasets only provide a LPIS reference and the length or area of feature. So, we implemented a process to split up LPIS parcel polygons into smaller components representing the individual AES features and the remainder of the parcel (See Appendix 1.3). Where the AES option type was too small to be resolved at 25m^2 cell resolution in the subsequent raster conversion, we used an analogous process to create polylines (e.g. at the polygon boundary) appropriate to the option.

Buffer strips and hedgerow features in BPS claims relate to Environmental Focus Areas (EFA) under Common Agricultural Policy 'Greening' requirements (Rural Payments Agency, 2018). These were assumed equivalent to the simplest buffer strip creation and hedgerow maintenance options in ES and were converted to appropriate length polylines at the parcel boundary, avoiding duplication with equivalent AES features. Other hedgerow features were created from the CEH Woody Linear Features Framework (WLF: Scholefield *et al.*, 2016) and a woodland edge polyline layer was created at the boundaries of contiguous LCM woodland features.

2.2.3.2 Parameterising changes in land cover habitat quality

Our combined source data included 28 non-agricultural land cover types, 128 agricultural land cover types and 364 AES land cover types. Below we detail how we align these with the 33 land classes already parameterised by G2020 for use in the poll4pop model and how intermediate parameters are derived where required to represent the more subtle changes generated by AES management. Full details are Appendix 1.4.

Land in AES was assigned an *AES_Present* land class and an AES_Absent land class with reference to Defra Reports BD2302 (University of Hertfordshire, 2009) as refined in BD5007 (University of Hertfordshire, 2011); – hereafter, BD2302/5007). These reports describe the expected land cover resulting from the option (used to generate *AES_Present*) and the absence of management (used to generated *AES_Absent*). Assignment of *AES_Present* and *AES_Absent* land classes to CS options was made using an 'Equivalency Table' provided by Natural England (the scheme developer) that links these options to their ES equivalents (Natural England, 2018 *pers. comm*). Option descriptions provided in scheme manuals (Natural England, 2018c; 2013) were used where required.

For some options, the descriptions in both the *AES_Present* and *AES_Absent* scenarios could be matched directly to G2020 land classes. For example, land under the CS option LH3 (Creation of heathland from arable or improved grassland) was mapped to "Moorland" in *AES_Present* and an arable crop type or improved grassland in *AES_Absent* as appropriate. These options received the attractiveness and floral cover scores for those land classes in each respective scenario. For other options, the G2020 land classes were not sufficient to match the description given in one or both of the scenarios. G2020 only has land classes for intensively managed land (agricultural crops, improved grassland / meadow) or broad habitats (unimproved grassland / meadow, moorland, wetland, woodland) while the BD2302/5007 descriptions reflect more subtle transitions in land cover. To capture these distinctions, new land classes (e.g. semi-improved grassland, degraded moorland, etc.) were created by blending existing G2020 land classes to approximate the description given in BD2302/BD5007. The attractiveness and floral cover parameters for these blended land classes were set to the weighted average of the parameters from their constituent G2020 land classes. When hedgerows, ditches and woodland edges are not in AES, they are assumed to still be present with the same associated parameter values, but their width is halved in the *AES_Absent* scenario to model the reduced management.

Land not in AES was assigned the same land cover class as G2020 with the exception of semi-natural grassland categories in LCM (acid grassland, neutral grassland, calcareous grassland) which were assigned to a semi-improved grassland category rather than an unimproved grassland category as per the LCM metadata (CEH, 2017). As this land was outside AES in both scenarios, the classification was the same in *AES_Present* and *AES_Absent*. The final parameter values used for all land classes, the weighting rules for new land classes, and the guild-specific parameters are shown in Appendix 1.5.

2.2.3.3 Assessment of change in abundance and visitation rates

The model was run to generate abundance and visitation rate predictions for each guild in each season for the *AES_Present* and *AES_Absent* scenarios, respectively. For solitary bees (active during only one season) we simulated spring-flying and summer-flying populations separately, where spring-flying populations used the cumulative resources from both Early and Late Spring.

The change in predicted visitation rate V for season s (V_s) due to the presence of AES management at cell level was assessed by calculating the log ratio between the predicted visitation rates in the two scenarios ($log_{10}(V_{s\_AES\_Present}/V_{s\_AES\_Absent})$). The ratios are logged to ensure that reductions in visitation rate have the same magnitude as proportionally equivalent increases. Cells with identical visitation rates in both scenarios will therefore have a value of 0, while +1 represents a tenfold increase in visitation rate in the presence of AES features and -1 a tenfold decrease. The same log ratio approach was applied to calculate the predicted change in new reproductive production (Q), new nest production (R), and new worker production per season (W_s).

To estimate the uncertainty in the log ratio caused by uncertainty in the underlying parameter values, 100 simulations were run where the nesting attractiveness, floral attractiveness and floral cover score for each land class were drawn from a beta distribution ($B(a, b)$) with mean ($\mu = a / (a + b)$) and variance ($\sigma^2 = \mu(1 - \mu) / (a + b + 1)$) equal to the mean and variance of the G2020 expert opinion scores for that parameter. A beta distribution was used as the scores are bounded and, since $B(a, b)$ is only defined on the interval (0,1), the randomly drawn scores are rescaled to the appropriate scale for that parameter. For new blended land classes, where the mean value was generated by averaging the scores of two existing classes, the variances were calculated using error propagation (Hughes and Hase, 2010). Draws for land classes were constrained as described in Appendix 1.5 to prevent instances that unreasonably exceeded the range of expert opinion.

The significance of the change in visitation rate with respect to the uncertainty in underlying habitat quality parameters was assessed by calculating the standard deviation of the 100 simulations of the log ratio visitation rate and then measuring how many standard deviations a given cell or region's log ratio visitation rate was from the no change value of zero (the point at which the ratio would be 1:1). A log ratio more than 2 standard deviations away from zero was considered to show a significant change in visitation rate between *AES_Present* and *AES_Absent* scenarios. Locations where the log ratio was more than 3 standard deviations from zero were considered a highly significant difference. 2 standard deviations and 3 standard deviations are equivalent to probability thresholds of 0.05 and 0.01 respectively.

To examine the overall impact at national scale on different land resources such as pollinator-dependent crops and semi-natural habitat, the land classes are grouped into categories (Table 2.1). Detail of individual land class allocations to these categories is given in Table A1.1 of Appendix 1. The total impact of AES participation and its significance on a particular land category at national level is calculated for the log ratio of the sum of V_s, Q, R, and W_s across all cells in England within that category for *AES_Present* and *AES_Absent* respectively.

Table 2.1: Land Categories

Land Category	Description
Oilseed Rape (OSR)	Pollinator-dependent crop
Field Beans	Pollinator-dependent crop
Strawberries	Pollinator-dependent crop; includes all open-grown strawberries (i.e., excluding those grown in polytunnels) and Raspberries
Orchards	Pollinator-dependent crop
Other Crops	Any other crop not listed above
Improved Grassland	
Semi-natural Habitat	This covers all land that is not a classified as crop, improved grassland, suburban or urban. It therefore includes hedgerows, ditches, grass/flower margins, fallow areas, grass/legume leys, semi-natural grassland, moorland, heathland, wetland, woodland, and coastal habitats.
Suburban	Suburban areas (areas with a mixture of buildings and gardens), parks
Urban	Built-up areas with little vegetation, e.g. city centres & industrial estates, Also includes other null value land cover such as open water and rock
All Land	All land classes listed above

2.2.4 Exemplar Area

To illustrate the fine-scale effects predicted by our $25m^2$ resolution simulations at farm-scale, we selected an exemplar area in western England to present alongside the national maps. This area was chosen because it is one of the few areas in England to grow all four pollinator-dependent crops and it represents a heterogeneous landscape incorporating a variety of agri-environment interventions.

2.3 Results

2.3.1 Area and distribution of crops and land under AES

The pollinator-dependent crops OSR (621,014 ha) and field beans (189,332 ha) were grown across much of lowland England during 2016, while orchard fruit (39,335 ha) and strawberries (2,914 ha) were concentrated in certain areas of south-east and western England (Figure 2.1a; Figure A1.13a – b; Figure A1.14a-b. Otherwise, England's agricultural area was dominated by other crops (not pollinator-dependent) and improved grassland. There was over 3.5M ha of semi-natural habitat of potential value to wild bees including hedgerows, ditches, grass/flower margins, heathland, and woodland. ~1.5M ha of this was under AES management (Figure A1.15a) but the rest was outside the CS and ES schemes (Figure A1.15b). Suburban parks and gardens (highly valuable pollinator habitat) covered ~1.0M ha.

Only 108,237 ha (~7% of the AES area) involved the creation of semi-natural habitat at the expense of crops or improved grassland (Figure 2.1b). The remaining area comprised options that aim to maintain, restore, or enhance *pre-existing* semi-natural habitat. AES participation rates and type of option applied are also linked to land use intensity. Much of the upland area (generally farmed extensively) was in AES and there were many field-scale features. In arable regions (generally farmed intensively) the participation rates were lower, mostly consisting of linear features with some small and dispersed field-scale options. Participation rates were lower in the orchard fruit and strawberry growing areas relative to areas where only OSR and field beans were cultivated (compare exemplar area patterns in c, d of Figure A1.13, Figure A1.14 and Figure A1.15.

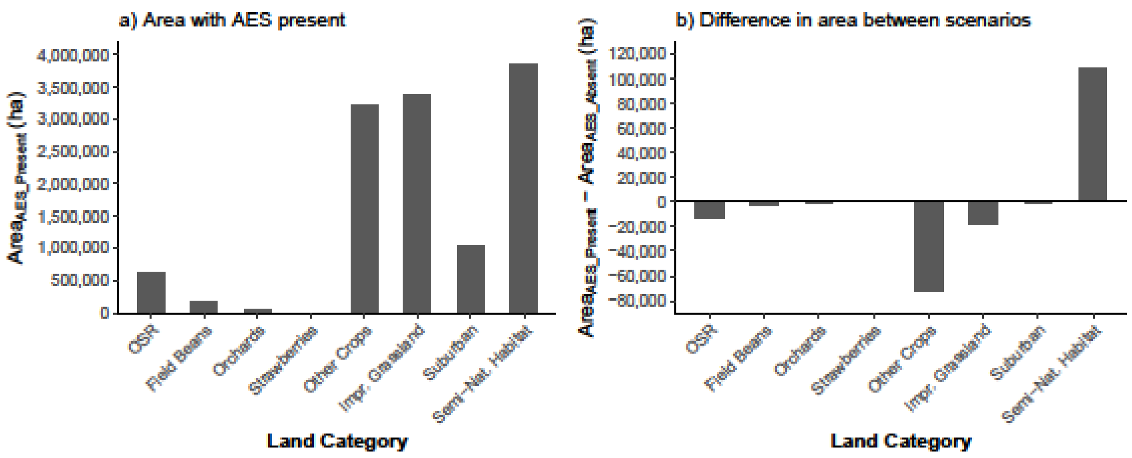

Figure 2.1: a) Total area by land category in England for 2016 when Agri-environment scheme (AES) features are present - AES_Present scenario; b) Area change (ha) between scenarios with AES feature present (AES_Present) and absent (AES_Absent) in each land category. The Urban land category is excluded as it is parameterised with no resource value.

2.3.2 Impact of AES participation on pollinator abundance at national level

Queen productivity (number of new reproductive females produced per cell) is predicted to be significantly higher for ground-nesting guilds when AES management is present (Figure 2.2 – 'All land') with relative increases of 10.4% for ground-nesting bumblebees and 15.4% / 7.8% for spring-active / summer-active ground-nesting solitary bees.

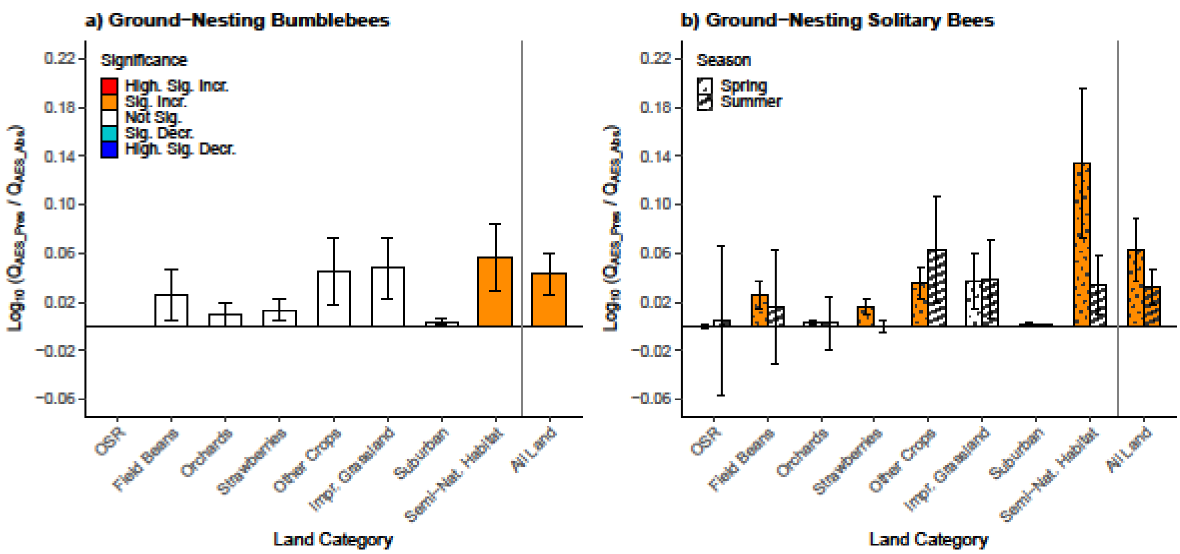

Figure 2.2: Predicted impact of Agri-environment schemes (AES) on queen production (Q; production of new reproductive females per 25m2) nationally to all land categories and subdivided by land category for (a) ground-nesting bumblebees and b) ground-nesting solitary bees (separated by active season). The impact is measured as the log of the ratio between the scenarios with AES features present and absent. Significance thresholds are number of standard deviations that the log ratio is above (increase) or below (decrease) zero: value >=|3| is highly significant, |2| <= value <|3| is significant. See Figure A1.1 for other guilds.

Nest density is also predicted to be significantly higher for ground-nesting guilds when AES management is present (Figure 2.3, 'All land') with increases of 4.6% for ground-nesting bumblebees and 16.2% for spring-active ground-nesting solitary bees. The predicted increase in nest density for summer-active ground-nesting solitary bees is not significant. Semi-natural habitat shows the largest and consistently significant nest density increases (6.6% and 36.9% for the above-mentioned guilds respectively) across the land categories and this drives the change in the 'All land' category. Significant nest density increases in crop and improved grassland categories for ground-nesting solitary bees are relatively small (2.8% – 9.0%) while no significant overall increase is predicted for tree-nesting bumblebees or cavity-nesting solitary bees (Figure A1.2).

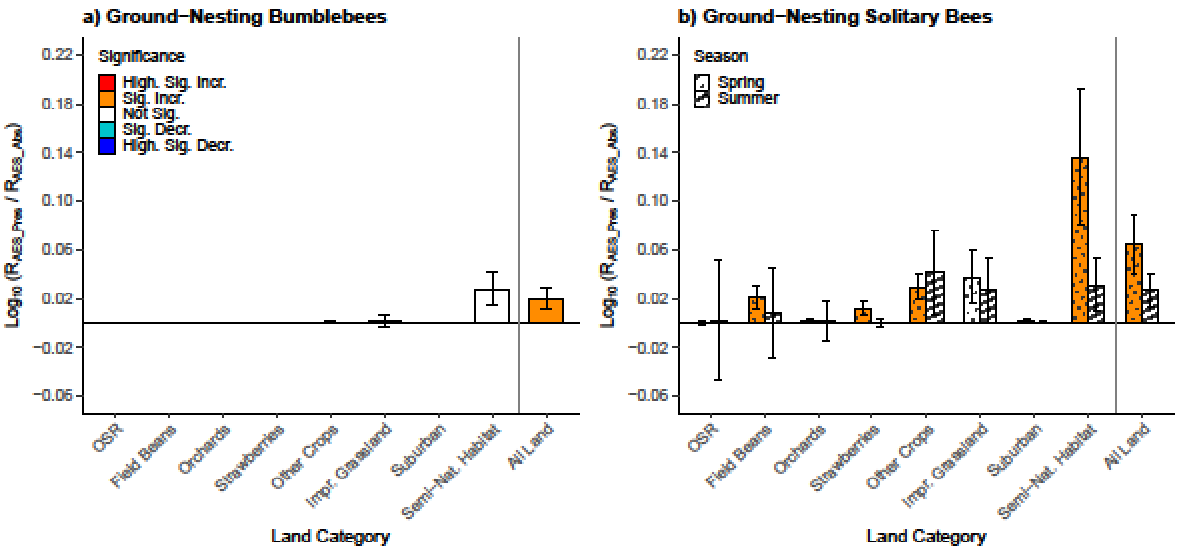

Figure 2.3: Predicted impact of Agri-environment schemes (AES) on nest density (R; nests per 25m2 cell) nationally to all land classes and subdivided by land category for (a) ground-nesting bumblebees and b) ground-nesting solitary bees (separated by active season). The impact is measured as the log of the ratio between the scenarios with AES features present and absent. Significance thresholds are number of standard deviations that the log ratio is above (increase) or below (decrease) zero: value >=|3| is highly significant, |2| <= value <|3| is significant. See Figure A1.2 for other guilds.

AES management is also predicted to have a significant overall positive impact on ground-nesting bumblebee worker production in late spring (increase of 8.15%; Figure 2.4b - 'All Land') although semi-natural habitat is the only land category to show a significant increase (11.5% equivalent). Overall increases in worker production are predicted for early spring but these are not significant given current uncertainties, the exception being a small but significant predicted increase in the worker population for nests in orchards during early spring (2.5% equivalent). No significant overall change in tree-nesting bumblebee worker production is predicted, though the results do show a similar significant increase for orchards in early spring (Figure A1.3).

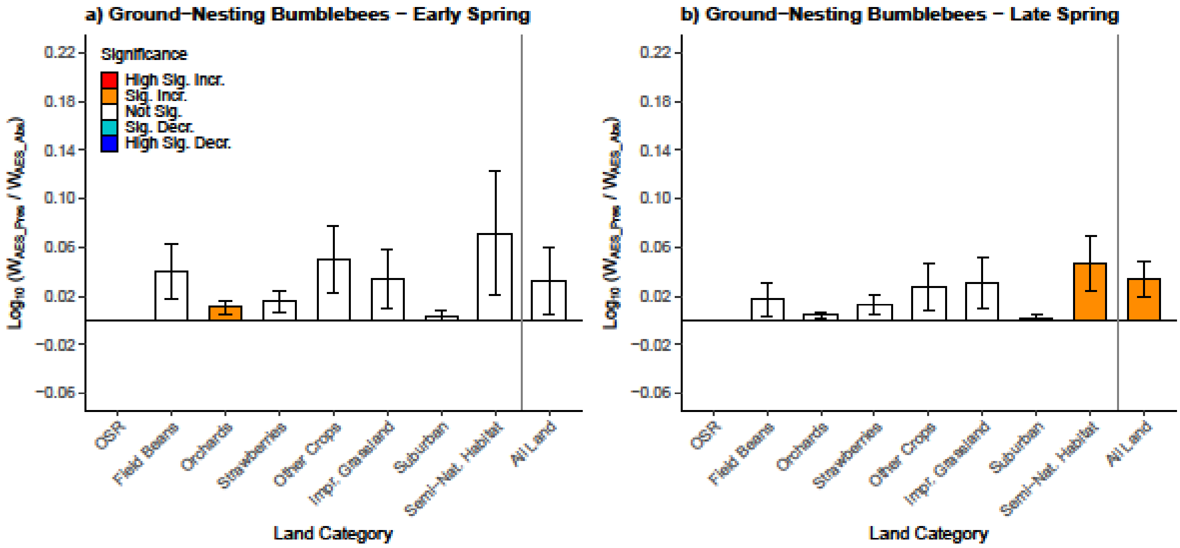

Figure 2.4: Predicted impact of Agri-environment schemes on ground-nesting bumblebee worker production (W; workers produced per 25m2 cell) nationally to all land classes and subdivided by land category for (a) Early Spring and (b) Late Spring. The impact is measured as the log ratio between the scenarios with AES feature present and absent. Significance thresholds are number of standard deviations that the log ratio is above (increase) or below (decrease) zero: value >=|3| is highly significant, |2| <= value <|3| is significant. Early spring: early/mid-March – late April/early May. Late spring: late April/early May - early/mid-June. See Figure A1.3 for tree-nesting bumblebees.

2.3.3 Impact of AES participation on floral visitation rate at national level

The model predicts significantly higher floral visitation overall (across all land categories) in Early Spring and Summer for ground-nesting bumblebees (+4.6% and +8.2% respectively; Figure 2.5) and in Early and Late Spring for ground-nesting solitary bees (+16.2% both seasons). Visitation to semi-natural habitat is also predicted to be significantly higher for these guilds in those seasons. Predicted increases for tree-nesting bumblebees and cavity-nesting solitary bees are not significant overall or for semi-natural habitat (see Figure A1.4).

Although the model predicts increased visitation rate to OSR and field beans during peak flowering (Late Spring) due to AES management, this increase is only significant for the case of ground-nesting solitary bees to field beans where visitation rises by 6.2% (Figure 2.5). An increase of similar scale and significance to field beans is also predicted for cavity-nesting solitary bees. The absolute change in both cases is not large and is from a low base (e.g. V_s in *AES_Absent* for field beans is 0.19 for ground-nesting solitary bees compared to 7.9 for ground-nesting bumblebees; Figure A1.9).

There are no significant changes to orchard or strawberry visitation at national-level, with the exception of tree-nesting bumblebees where the model predicts a small but significant decrease in visitation in Early Spring (-2.2%; Figure A1.4). Tree-nesting bumblebees are also predicted to show reduced visitation to OSR, Field Beans in Early Spring (-4.5% in both cases) in the presence of AES features. This is not a flowering season for these crops, so the change is relative to a very low absolute visitation rate (V_s in *AES_Absent* is 0.12 and 0.03 for OSR and field beans, respectively).

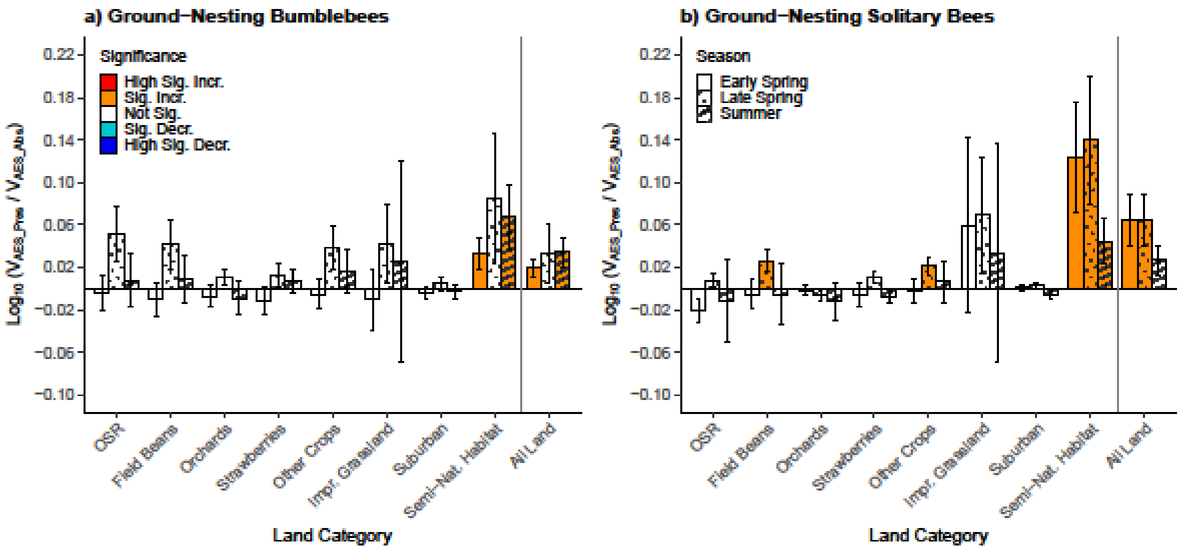

Figure 2.5: Predicted impact of Agri-environment schemes (AES) on floral visitation rate (V; visits per 25m2 cell) nationally to all land classes and subdivided by land category for (a) ground-nesting bumblebees and b) ground-nesting solitary bees in each season. The impact is measured as the log ratio between the scenarios with AES feature present and absent. Significance thresholds are number of standard deviations that the log ratio is above (increase) or below (decrease) zero: value >=|3| is highly significant, |2| <= value <|3| is significant. Early spring: early/mid-March – late April/early May. Late spring: late April/early May - early/mid-June. Summer: early/mid-June – early/mid-September. See Figure A1.4 for other guilds.

2.3.4 Impact of AES participation on floral visitation rate at cell-level

Despite a lack of significant changes at national-level, Figure 2.7 shows that significant increases are predicted in localised areas for both ground-nesting guilds in late spring. Closer inspection of their distribution within the exemplar area (Figure 2.7c-d) shows significant increases occurring for cells which correspond to AES management locations. There are also localised areas of significant increase covering a defined neighbourhood around these locations, whose extent is related to bee foraging range. These neighbourhoods are typically narrow for solitary bees (approx. 250-500m radius) and are usually isolated, whilst the neighbourhoods of significant bumblebee visitation increase extend to a wider radius (approx. 1-2km) and often merge with each other. The scale of increase in late spring is generally 0.1 to 2-fold in the neighbourhood and 2 to 10-fold within the AES cells. The effect is less evident in other seasons (see Figure 2.6 for early spring and Figure A1.16 for summer).

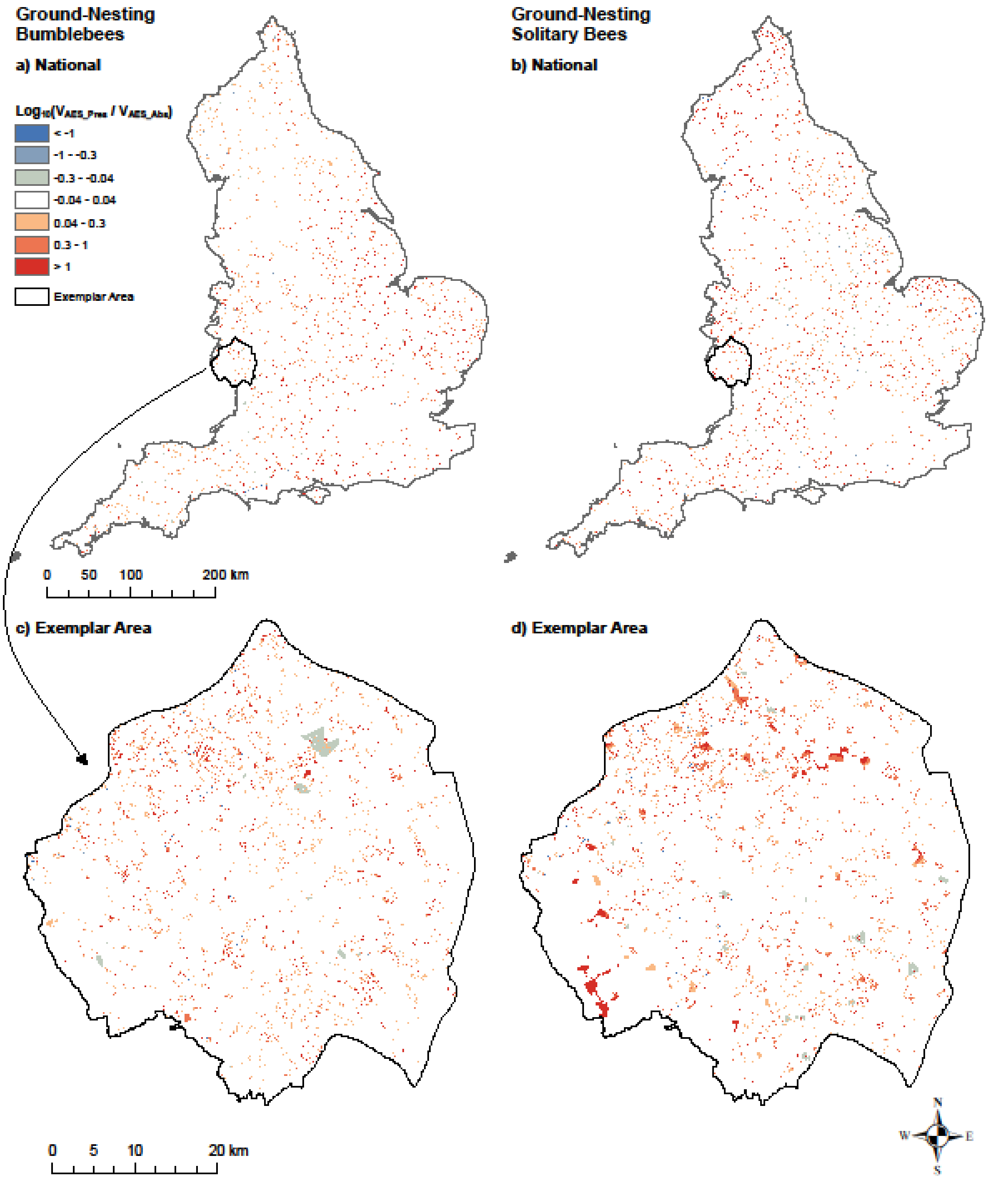

Figure 2.6: Impact of Agri-environment schemes on floral visitation rate (V) for ground-nesting guilds in England for early spring 2016 at cell-level nationally (a, b) and within an exemplar area (c, d) in western England. The impact is shown as the log of the ratio of V (visitation/25m2) between the scenarios with AES feature present and absent. Only cells with significant change are shown - where the log ratio is at least 2 standard deviations from zero. Early spring: early/mid-March – late April/early May. See Figure A1.17 for other guilds.

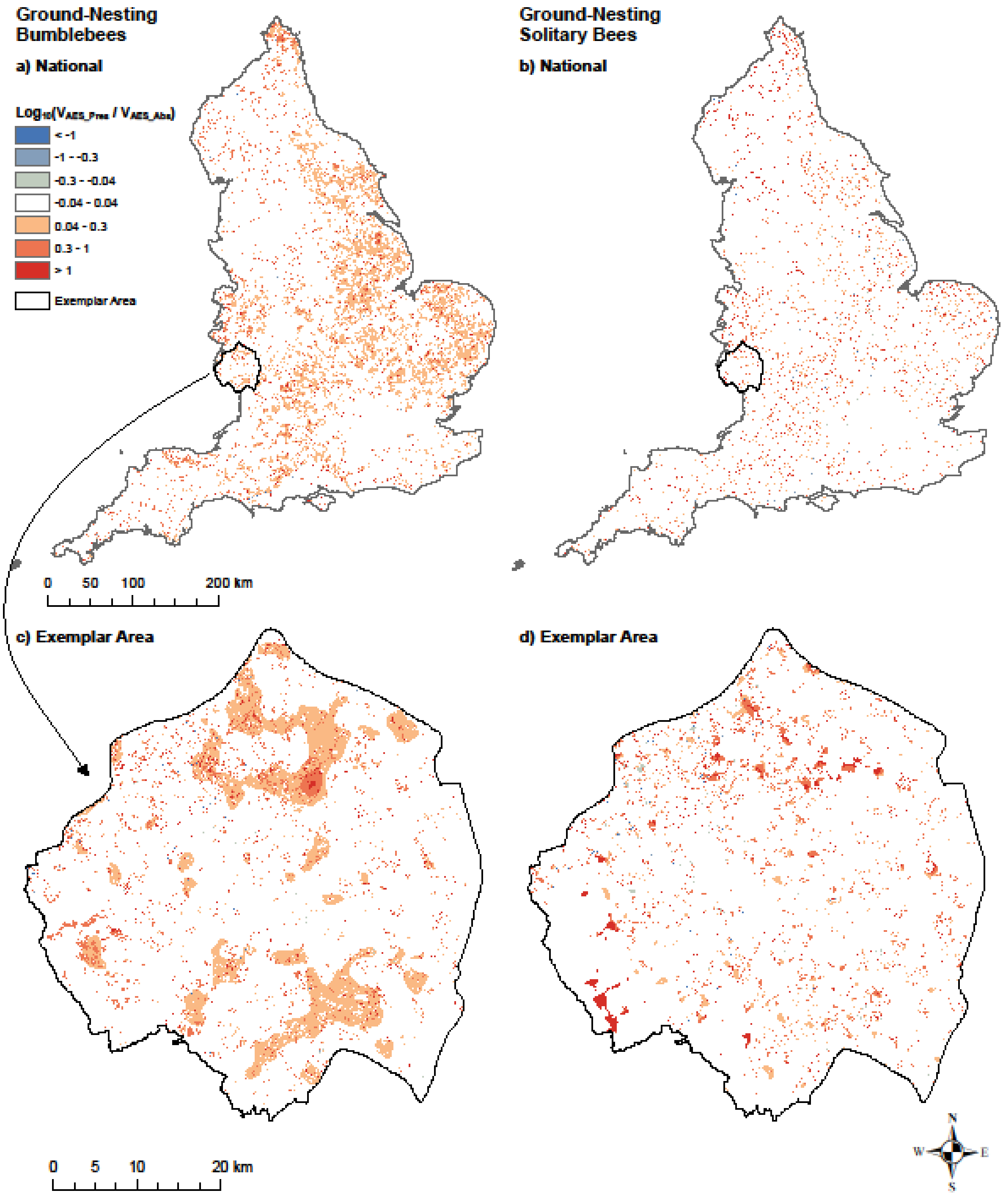

Figure 2.7: Impact of Agri-environment schemes on floral visitation rate (V) for ground-nesting guilds for late spring 2016 at cell-level nationally (a, b) and within an exemplar area (c, d) in western England. The impact is shown as the log of the ratio of V (visitation/25m2) between the scenarios with AES feature present and absent. Only cells with significant change are shown - where the log ratio is at least 2 standard deviations from zero. Late spring: late April/early May - early/mid-June. See Figure A1.18 for other guilds.

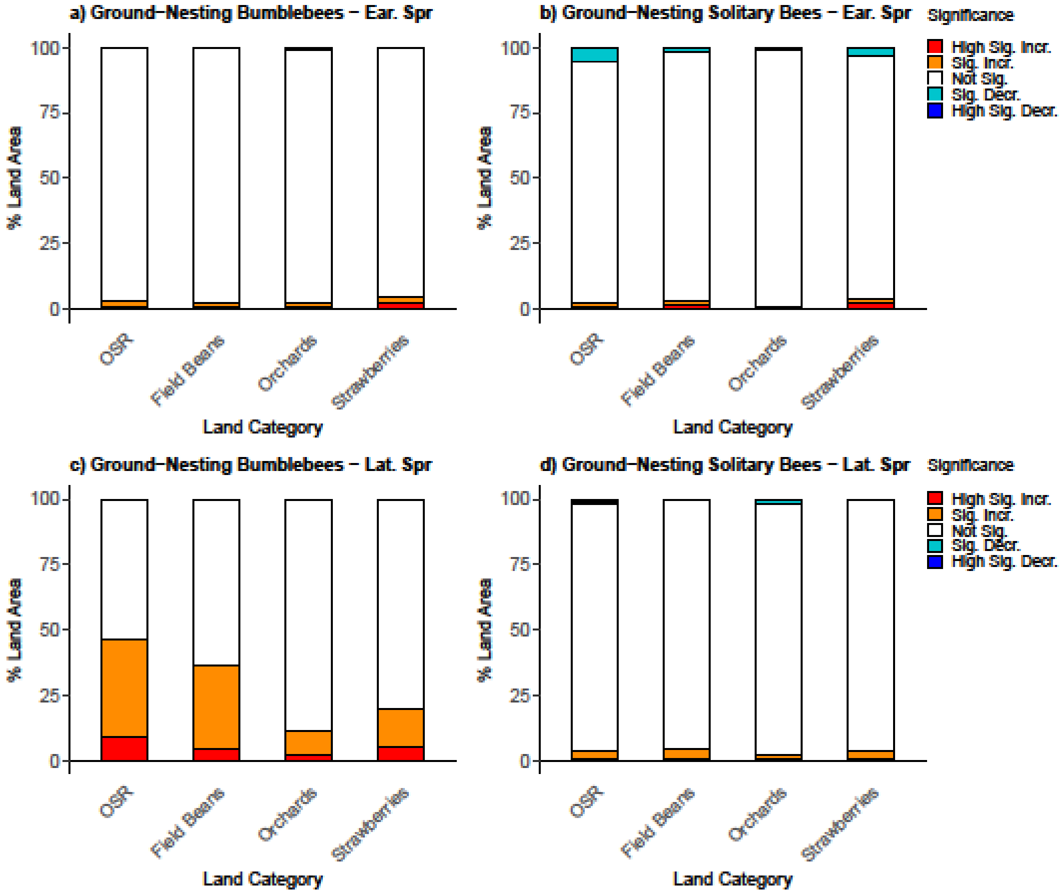

Figure 2.8: Percentage of cropland area within significance thresholds for predicted impact of Agri-environment schemes (AES) on floral visitation rate (V; visits per 25m2 cell) for ground-nesting guilds in early (a, b) and late (c, d) spring. The impact is measured as the log ratio between the scenarios with AES feature present and absent. Significance thresholds are number of standard deviations that the log ratio is above (increase) or below (decrease) zero: value >=|3| is highly significant, |2| <= value <|3| is significant. Early spring: early/mid-March - late April/early May; Late spring: late April/early May - early/mid-June. See Figure A1.11 for other guilds.

The presence of a neighbourhood effect has implications for crop pollination services where pollinator-dependent crops form part of this neighbourhood. 46.4% of the national OSR cropping area and 36.1% of the national field bean cropping area is predicted to experience a significant or highly significant increase in ground-nesting bumblebee visitation during what is the peak flowering season for these crops (Figure 2.8c). 11.5% of the orchard resource is also predicted to benefit from increased late spring ground-nesting bumblebee visitation but this will only be beneficial if those orchards are growing late flowering cultivars. 20% of strawberry cells also experience a significant or highly significant ground-nesting bumblebee visitation increase in Late Spring.

By contrast less than 5% of the resource for any of the pollinator-dependent crops are predicted to receive significantly increased ground-nesting solitary bee visitation during this season (Figure 2.8d). There is very little neighbourhood effect for pollinator-dependent crops in Early Spring (Figure 2.8a, b). This is peak flowering season for orchard fruit and only 0.9% and 2.3% of orchard cells are predicted to experience a significant or highly significant increase for ground-nesting bumblebee and ground-nesting solitary bee visitation. Likewise, very few cells are predicted to receive significantly more bee visitation in Summer (Figure A1.16).

Tree-nesting bumblebees show similar trends to the ground-nesting bumblebees, although fewer cells are predicted to receive significantly more visitation (for OSR and Field Beans in Late Spring those proportions are 26.1% and 20.3%, respectively; Figure A1.11), while the percentage of cropland with significant changes in cavity-nesting solitary bees visitation is similar to that for ground-nesting solitary bees.

2.4 Discussion

This study applied a validated spatially explicit process-based model (*poll4pop*) to examine changes in pollinator abundance and pollination service provision due to uptake of agri-environment scheme (AES) options across the whole of England for the year 2016. The model was used to compare bee visitation rates across four guilds in a scenario where the agri-environment features and/or management were present (*AES_Present*) with an alternative scenario where these were absent (*AES_Absent*).

The predictions suggest that participation in AES increased bee abundances, but these increases were only significant nationally for ground-nesting guilds. No significant increase is predicted for tree-nesting bumblebee and cavity-nesting solitary bee populations. We also predict significantly increased floral visitation rates nationally by ground-nesting guilds but only consistently within the semi-natural habitat enhanced by AES management. On average, visitation to pollinator dependent crops did not significantly increase nationally, but our simulations suggest some significant localised increases in visitation to late-spring flowering crops (predominantly OSR and field beans) by bumblebees. We do not predict enhanced crop visitation in other seasons from any guild.

2.4.1 Impact of AES on pollinator abundance

Predicted significant increases in queen production, nest density, and the number of workers for ground nesting guilds align with results of fieldwork in England demonstrating a significant relationship between observed bee abundances and presence of AES management (Crowther and Gilbert, 2020; Wood *et al.*, 2015). The lack of predicted significant increases in the national-level abundance outputs for tree-nesting bumblebees or cavity-nesting solitary bees may be because few AES options provide or increase the quality of their preferred nesting habitat (Crowther *et al.*, 2014; Gresty *et al.*, 2018), as reflected in the expert opinion parameters assigned to these guilds for key AES options (e.g., flower rich margins, semi-improved/unimproved grassland, fallow, hedgerow – see Table A1.8 and Table A1.10). The greater benefits of AES to spring-active, rather than summer active, ground nesting solitary bees is likely due to the early season boost in floral resources when there is less alternative floral provision from land outside schemes (Scheper *et al.*, 2015).

Interestingly, our modelling suggests that the significant increases in queen production for ground-nesting bumblebees, induced by AES participation, are not matched by significant increases in nest density. This suggests the increased foraging resources provided by AES participation support larger pollinator populations during the active season, but this is not being met with a corresponding increase in the availability of nesting resources for new queens. AES schemes have focused on boosting bee abundances through floral resource provision (Dicks *et al.*, 2015), however our predictions suggest schemes should pay increased attention to nesting resource availability (Requier and Leonhardt, 2020).

Predicted increases in abundance (number of new reproductive females) are predominantly associated with semi-natural habitats, which are typically of higher floral and nesting quality under AES participation. We do also predict an increase in solitary bee nest abundance in some crop fields (Figure 2.2b, Figure A1.2b), although abundance in these areas still remains low compared to semi-natural habitats (Figure A1.6b, d). The experts who provided the model's habitat scores assigned some limited solitary bee nesting value to certain crop types (Table A1.9 and Table A1.10), assumed to represent nesting opportunities in bare but untilled margins/tramlines, etc. The predicted increase in in-crop nests therefore likely reflects the fact that solitary bee reproductive females produced within adjacent AES features face limited availability of their preferred nesting habitat, due to their limited dispersal range (βn = 100m vs 1000m for bumblebees) and the relatively low semi-natural habitat coverage in arable areas (Figure A1.15).

2.4.2 Impact of AES on pollination services

The simulations predict significant and often large (2 to 10-fold) increases in visitation at cells under AES management (where floral and nesting values have generally increased relative to their value in *AES_Absent*). There is also a significant but generally smaller "neighbourhood effect" representing 0.1 to 2-fold changes in predicted visitation to surrounding cells outside AES management, where resource value is otherwise unchanged. The magnitude and direction of this neighbourhood effect depends on the guild and season. Where foraging is done by reproductive females (i.e. solitary bees in all seasons and bumblebees in early spring), increased neighbourhood visitation only occurs if the nesting density has increased sufficiently to offset the relative increase in floral value within the AES cell (Zamorano *et al.*, 2020). Otherwise, there will be no change or even potentially sink effects where foragers are drawn away from neighbouring cells (see Figure A1.17 for tree-nesting bumblebees in early spring). For bumblebees in later seasons, workers do the foraging so floral resource increases support higher worker production rates and thus higher neighbourhood foraging rates without the need for increases in nest density (Riedinger *et al.*, 2014).

The neighbourhood effect extends over a larger area for ground-nesting bumblebees compared to ground-nesting solitary bees due to their larger foraging and dispersal ranges (β_f = 530m vs 191m; β_n = 1000m vs 100m). This enables bumblebee populations to forage and disperse more widely, especially in more fragmented landscapes (Cranmer *et al.*, 2012), so extending their neighbourhood effect. To encourage more solitary bee visitation into crops, schemes would need to provide larger, contiguous habitat features that better account for their limited dispersal range (Martínez-Núñez *et al.*, 2020; Woodcock *et al.*, 2013). In so doing, schemes would also help increase the diversity of pollinators provided thus increasing the resilience of the service.

A contributing factor towards the lack of a significant change in national visitation from ground-nesting bumblebees in late spring (despite significant changes in other seasons) could be the much larger variance in predictions for this guild for this season. This is driven by high uncertainty in the change in floral resource value for the 14,830 ha of semi-natural habitat in *AES_Present* where AES features have replaced (late-spring-flowering) OSR or field beans in *AES_Absent* (Figure 2.1).

2.4.3 Effect on OSR and field beans

At national scale, 46% of OSR and 36% of field bean area receive increased visitation from ground nesting bumblebees (key pollinators of both crops; Hutchinson *et al.*, 2021) due to the presence of AES. Flowering OSR and field beans are attractive resources relative to the surrounding landscape (Kovács-Hostyánszki *et al.*, 2013), so additional bees supported by AES are then attracted to this resource. Even a small increase in semi-natural habitat area due to AES can increase populations which would otherwise be constrained by the relatively low floral quality of mass-flowering crops at other times of the year (Holzschuh *et al.*, 2016; Riedinger *et al.*, 2015). In areas where OSR and field bean visitation is not predicted to increase, this may reflect insufficient cover or placement of higher quality AES in general (Krimmer *et al.*, 2019) uptake of AES land classes with higher resource parameter uncertainty (e.g. semi-natural grassland), or nesting limitation (see above) which can constrain the scale of the neighbourhood effect.

AES are predicted to have less impact on mass-flowering crop visitation by solitary bees. Only field beans, where solitary bees are not a common pollinator (Garratt, Coston, *et al.*, 2014; Hutchinson *et al.*, 2021; Nayak *et al.*, 2015) show any significant change. This is again due to the shorter foraging and dispersal ranges of solitary bees, with much of the increased visitation stemming from greater nesting within the field bean cells themselves and the apparently substantial fractional change simply due to the very low level of solitary bee visitation predicted to this crop in both scenarios. By contrast, OSR is an attractive floral resource to solitary bees (Knopper *et al.*, 2016), but to promote increased visitation by these guilds, AES management would need to be better distributed to enable these short-range foragers to reach a greater proportion of the crop.

2.4.4 Effect on orchard fruit and strawberries

At national scale, there was no significant increase in visitation to orchard or strawberry cells due to AES during their peak flowering seasons (early spring and summer, respectively). Both crops are predominantly located in areas of England that have relatively low AES participation (Figure A1.13, Figure A1.14). Field studies elsewhere in Europe have found significantly lower populations of wild bees in the vicinity of commercial orchards (Eeraerts *et al.*, 2017; Marini *et al.*, 2012). This was attributed to lack of habitat diversity, suggesting that greater targeting of AES towards orchards would be beneficial for visitation, especially in more intensive agricultural landscapes (Holzschuh *et al.*, 2012). Landscape fragmentation and simplification around strawberry crops is also associated with lower wild bee abundance and lower crop visitation rates (Bukovinszky *et al.*, 2017; Castle *et al.*, 2019; Connelly *et al.*, 2015).

However, when wildflower strips have been experimentally introduced to orchards, no significant impact on pollination service is observed (Campbell *et al.*, 2017; McKerchar *et al.*, 2020). Placing wildflower strips alongside strawberries can increase visitation to the crop (Feltham *et al.*, 2015), though the visitation is not always consistent across the field (Ganser *et al.*, 2018). Meanwhile, manually increasing the population of bees through *in situ* nest provision does increase pollination of both crops (Bosch *et al.*, 2006; Horth and Campbell, 2018).

Early spring orchard visitation is dependent on reproductive females, and we do not predict nest density increases in orchards (Figure 2.3). Although workers are available to forage on strawberry crops, their peak flowering season (summer) coincides with that of many AES interventions, potentially causing competition for pollinators. Significant increases in visitation to both these crops will therefore only be achieved if AES provide a large increase in nest density (which increases the absolute number of foragers) relative to the increase in floral value provided (which decreases the relative attractiveness of the crop). Scheme design may also need to change to increase the financial incentive available to fruit growers as current AES payment rates may not cover the income foregone in more productive agricultural areas where these crops are grown (Lastra-Bravo *et al.*, 2015).

2.4.5 Caveats

Although the *poll4pop* model is sophisticated, it currently has limited temporal resolution (three seasons) and does not allow for mortality during 'hunger gaps' at the start/end of the active period (Jachuła *et al.*, 2021). Some AES hedgerow options may provide floral resources in early-March (due to tree/shrub flowering) and again in autumn via flowering ivy (*Hedera helix*), while options promoting legume and herb-rich swards may also provide important late resources such as red clover (*Trifolium pratense*). Wild bees in English landscapes are highly dependent on these resources at these critical points for survival of reproductive females (Timberlake *et al.*, 2019). We may therefore have underestimated the value of some AES options due to the relatively coarse temporal resolution of our model.

Our application of the model generalised wild bees into four guilds, but this may overstate the value of AES to bee species. For ground-nesting solitary bees in particular, field data suggests AES only provide beneficial floral resources for a minority of common species (Wood *et al.*, 2017). We also note that an increase in visitation rate for one guild alone does not necessarily mean an increase in pollination service if the level of pollination service in the absence of the intervention is already sufficient to achieve optimal pollination, less pollinator-dependent crop varieties are grown or there are other limiting factors (Garratt *et al.*, 2018). Further work is needed to link model visitation rates to yield in order to examine the impact of schemes on pollination service deficits.

Our study has sought to predict the extent to which participation in AES at scheme level, given current uptake patterns, has changed wild bee guild abundances and flower visitation rates. The geographic variation in magnitude and significance of the effect will depend on the type, quantity, quality (relative resource value-add) and placement of the AES resource with respect to crops or other areas of interest. The relative importance of these factors and the relative importance of individual interventions in driving these predicted scheme-level changes will be investigated in forthcoming work.

2.5 Conclusions and Recommendations for Policy

This study has demonstrated how a sophisticated process-based model (poll4pop) can be used in conjunction with detailed landcover data to examine the effectiveness of entire agri-environment schemes (AES) at supporting bee populations and the ecosystem services they provide. Our results also demonstrate the potential of this approach to inform selection and targeting of AES incentives to enhance these outcomes.

Our modelling predicts that the pattern of AES participation in 2016 was effective in boosting ground-nesting bee populations compared to a scenario without these features. However, tree-nesting and cavity-nesting bee populations nationally were not predicted to benefit from AES participation. Furthermore, current AES participation was not predicted to significantly increase visitation to pollinator-dependent crops at national level. Significant localised increases were predicted only for late-spring flowering crops (OSR and field beans), and these were delivered by bumblebees. Motivated by our predictions we summarise below our recommendations for future AES design in England:

- **Floral resource provision**. Our predictions for ground-nesting bee populations align with monitoring data suggesting a slowing of the decline in recent years for generalist bee species due to AES (Powney *et al.*, 2019) and with estimates that a 2% land allocation to floral cover options within AES would provide sufficient resource for common wild bee species (Dicks *et al.*, 2015). Schemes should therefore continue to incentivise floral resource provision.

- **Nesting resource provision**. We identified nest site limitation as preventing populations from fully benefiting from the increased floral resource provided by AES features and as a contributing factor in our prediction for lack of significant national increase in crop visitation. Schemes should enhance the uptake and sophistication of options that provide nesting resources, especially in orchard- and strawberry-growing regions. Interspersing larger, more contiguous patches of semi-natural habitat within arable areas may also better support short-range solitary bee populations and their pollination services.

- **Resource diversity**. Tree-nesting and cavity nesting bee species have habitat requirements that are not well-catered for in current AES (Crowther *et al.*, 2014; Gresty *et al.*, 2018). To increase populations of these guilds, schemes should increase the range of interventions that provide specialist nesting and floral resources. Although more bespoke and locally specific features may be required to support some species, AES could support these guilds generically through options that create/manage hedgerows, trees, and scrub (in potentially good alignment with current carbon sequestration goals that also favour such options; Summers *et al.* (2021)).

3 Which interventions contribute most the net effect of England's agri-environment schemes on pollination services?

Abstract

Agri-environment schemes support land management interventions that benefit biodiversity, environmental objectives, and other public goods. Process-based model simulations suggest the English scheme, as implemented in 2016, increased wild bee pollination services to pollinator-dependent crops and non-crop areas in a geographically heterogeneous manner.

We investigated which interventions drove the scheme-wide predicted pollination service increase to oilseed rape, field beans and non-cropped areas. We determined whether the relative contribution of each intervention was related to floral and/or nesting resource quality of the intervention, area of uptake, or placement in the landscape.

We categorised interventions into functional groups and used linear regression to determine the relationship between predicted visitation rate increase and each category's area within a 10 km2 grid square. We compared the magnitude of the regression coefficients to measures of resource quality, area of uptake nationally, and placement to infer the factors underpinning this relationship.

Hedgerow/woodland edge management had the largest positive effect on pollination service change, due to high resource quality. Fallow areas were also strong drivers, despite lower resource quality, implying effective placement. Floral margins had limited benefit due to later resource phenology. Interventions had stronger effects where there was less pre-existing semi-natural habitat.

Future schemes could support greater and more resilient pollination service in arable landscapes by promoting hedgerow/woodland edge management and fallow interventions. Including early-flowering species and increasing uptake would improve the effect of floral margins. Spatial targeting of interventions should consider landscape context and pairing complimentary interventions to maximise whole-scheme effectiveness.

At the time of submission this chapter was in review by Landscape Ecology. Reviewers' comments had not yet been received:

Image, M., Gardner, E., … Breeze, T. D. (2022). Which interventions contribute most to the net effect of England's agri-environment schemes on pollination services?

3.1 Introduction

Agri-environment schemes (AES) provide economic support to landholders who enter into voluntary agreements (typically with governments) to manage land to benefit biodiversity, meet environmental objectives and deliver other public goods (Dicks *et al.*, 2016). Many schemes allow landholders to choose from a set of interventions based on suitability for the farming system, geographical context and the type of habitats already present on the farm. Current schemes in England offer a variety of interventions in the form of 'management options' that support the creation, restoration and/or management of habitat features such as hedgerows, field margins, fallow areas, flower-rich leys, low-input grassland, as well as semi-natural grassland, moorland, wetland, and woodland (Natural England, 2013; Natural England, 2018b). Agri-environmental schemes therefore reduce the amount of land being intensively managed and increase the quality and quantity of semi-natural habitat.

Wild bees (bumblebees and solitary bees) significantly contribute to pollination and thus, yield of oilseed rape (*Brassica napus;* hereafter OSR) and field beans (*Vicia faba*) (Hutchinson *et al.*, 2021), two economically important UK arable crops. Wild bees' population sizes are limited by access to forage resources (Roulston and Goodell, 2011) and also by nest availability (Carrié *et al.*, 2018; Steffan-Dewenter and Schiele, 2008). Objectives for AES interventions are not necessarily wild bee-specific, but many of them can provide important non-crop floral and nesting resources for wild bees, thus increasing individual reproductive output and overall population sizes. This has been demonstrated empirically for specific AES interventions including floral margins (Carvell *et al.*, 2015), hedgerows (Timberlake *et al.*, 2019) and grassland management (Berg *et al.*, 2019), as well as for AES interventions more generally (Crowther and Gilbert, 2020). Field and farm scale analyses have shown that by increasing populations of wild bees, AES can indirectly contribute to increased crop visitation (Morandin *et al*., 2016; Pywell *et al.*, 2015). Moreover, by supporting pollination of wild flowers AES also contribute to wider integrity of ecosystem-level pollination services (Senapathi *et al.*, 2015).

Understanding the impacts of agri-environment schemes on wild bee abundance and pollination service at larger spatial scales requires modelling that reflects how bees (central place foragers) move in the landscape to nest, forage and reproduce. The process based model poll4pop (Gardner *et al.*, 2020; Häussler et al., 2017) has this capability, by building on earlier attempts to capture landscape complementarity and foraging movements (Lonsdorf *et al.*, 2009; Olsson *et al.*, 2015). Image et al. (2022) (hereafter IM2022) used poll4pop to predict the national scale impact of 2016 AES participation on wild bee abundances and visitation rates to different land cover types in England. The model predicted that AES participation led to nationally significant increases in ground-nesting bumblebee and ground-nesting solitary bee abundances, and significant increases in visitation to non-crop plants. However, only 46% of the national OSR cropping area and 36% of the national field bean cropping area were predicted to experience significantly increased ground-nesting bumblebee visitation. For both crops, increases in ground-nesting solitary bee visitation were predicted for less than 5% of crop areas.

Although comprehensive, IM2022 only captured the effect of all AES interventions collectively. In practice, schemes are offered as sets of interventions where participants have flexibility as to the type, quantity and location of interventions implemented. Individual interventions differ in their floral and/or nesting value contributions (Cole *et al.*, 2020) but the effect of an individual intervention depends on its placement relative to pollinator-dependent crops as well as its quantity and quality (Albrecht *et al.*, 2020). The change in visitation achieved may also potentially depend on the interaction between intervention types: for example, an intervention that individually provides only good nesting resource, and an intervention that provides only a good floral resource may be more effective if co-located. The effect on pollination service may also be dependent on the quantity of pre-existing floral and/or nesting resource: if this is already high then the baseline pollination service may also be high so that the marginal effect of AES interventions will be low (Tscharntke *et al.*, 2005). Examining how different types of intervention have contributed to the overall predicted change in the context of their quality, quantity and placement could help to understand the uneven pattern of pollination service enhancement and inform which interventions or combinations to promote in future schemes.

Here, we grouped >350 individual AES options into categories according to habitat type and extent of land-use change and used regression analysis to determine the contribution of each group to the overall increase in visitation rate to OSR, field beans and non-cropped areas predicted by IM2022. A regression approach is used rather than repeating the IM2022 method for individual groups because it allows us to account for the interaction between different AES intervention groups and with existing semi-natural habitat. We then consider how intervention quality, quantity, and placement in the landscape influence these effects, enabling recommendations to be made for how future AES could better support pollination services.

3.2 Methods

3.2.1 Predicted change in visitation due to AES

Estimates of the predicted change in wild bee visitation in England due to AES participation were obtained from IM2022. We briefly outline below how these predictions were subsequently processed for use in the current study.

3.2.1.1 Pollinator model description

IM2022 used the process-based model poll4pop (Häussler *et al.*, 2017; Gardner *et al.*, 2020), which predicts seasonal spatially-explicit 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 IM2022 for an overview and 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 to the modelled species or 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 in terms of how many new (workers and) reproductive individuals are produced as a function of forage resources gathered.

The model was run 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 IM2022 augmented to allow for additional land classes and to incorporate seasonal adjustments related to crop flowering. Finally, the model was validated against observed bee abundance to demonstrate that model parameters correctly reproduced observed abundance trends across a range of landscapes.

3.2.1.2 AES feature mapping

IM2022 simulated two landcover scenarios for England in the year 2016: one in which AES supported management 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 the two scenarios were developed as set out in IM2022. Allocation of AES management options to land cover classes in *AES_Present* and *AES_Absent* was made with reference to Defra Reports BD2302 (University of Hertfordshire, 2009), BD5007 (University of Hertfordshire, 2011) or intervention descriptions (Natural England, 2018b; Natural England, 2018e).

3.2.1.3 Calculating change in visitation due to AES

IM2022 predicted floral visitation rates for each guild for three 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) under both scenarios for every 25 m^2 cell in England. In the present study, we aggregated these past results to 10 km level (Ordnance Survey tiles) to allow an efficient scale for further analysis whilst still capturing geographic differences in crop and AES intervention type coverage. We would also expect enhanced model fit at our 10km resolution relative to 25m2 cells, due to reduced edge effects from neighbouring tiles.

We identified the OSR cells (see Figure 3.1, Figure 3.2 for their location) and took the 25 m^2 cell-level floral visitation (by guild) predictions to those cells during late spring, when OSR is pollinated. We then aggregated these values to the 10 km tile level and divided by the number of cells to generate the average visitation rate (Figure 3.2a). Where cells contained edge features, the crop visitation rate was adjusted *pro rata* to the proportion of crop resource and its floral resource value (floral attractiveness * floral cover) relative to the edge features. The visitation rate for the *AES_Present* scenario was divided by the visitation rate for the *AES_Absent* scenario to generate the visitation ratio, which was the dependent variable reflecting the change in visitation to OSR. We did the same calculation for field beans (Figure 3.1b, Figure 3.2b), again for late spring when beans are pollinated. A similar process was followed for non-cropped land cover, but the visitation rates were summed across all three seasons (Figure 3.1c, Figure 3.2c). Non-cropped land included all semi-natural habitat, improved grassland (including grass leys), and suburban parks/gardens. As with IM2022, for each tile we also calculated uncertainty 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, to generate a standard deviation for the visitation change ratio at 10 km tile level.

Although we ran the analyses for all four wild bee guilds, here we have focused on ground-nesting bumblebees as this was the only guild showing a widespread and significant response in OSR and field bean visitation rates due to AES management in IM2022. Results for the other three guilds are provided in the Supplementary Material (Appendix 2).

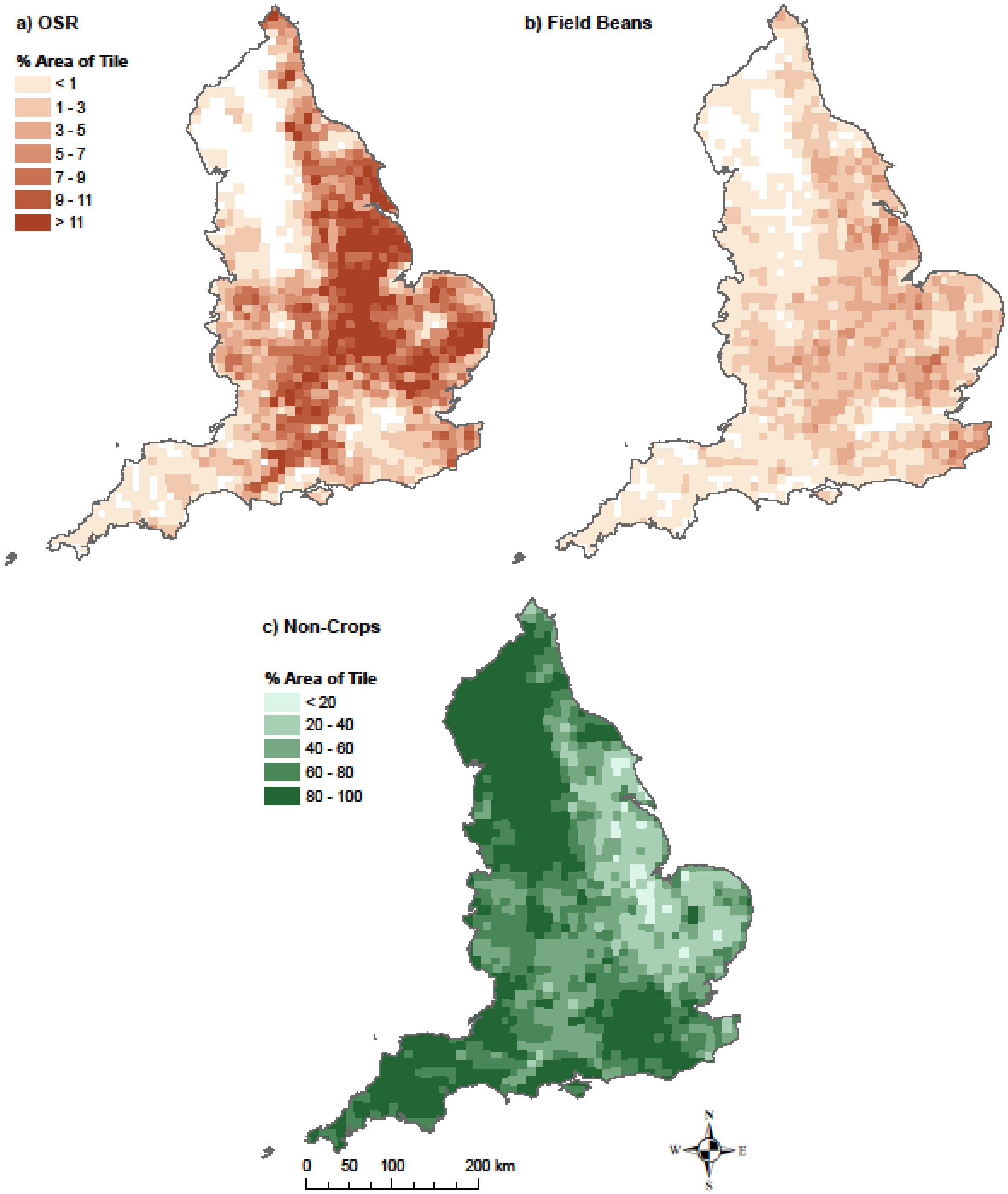

Figure 3.1: Coverage of a) OSR, b) Field Beans and c) Non-Crop land cover by 10 km tile for England in 2016. Non-crop means all land classes that are not arable crops

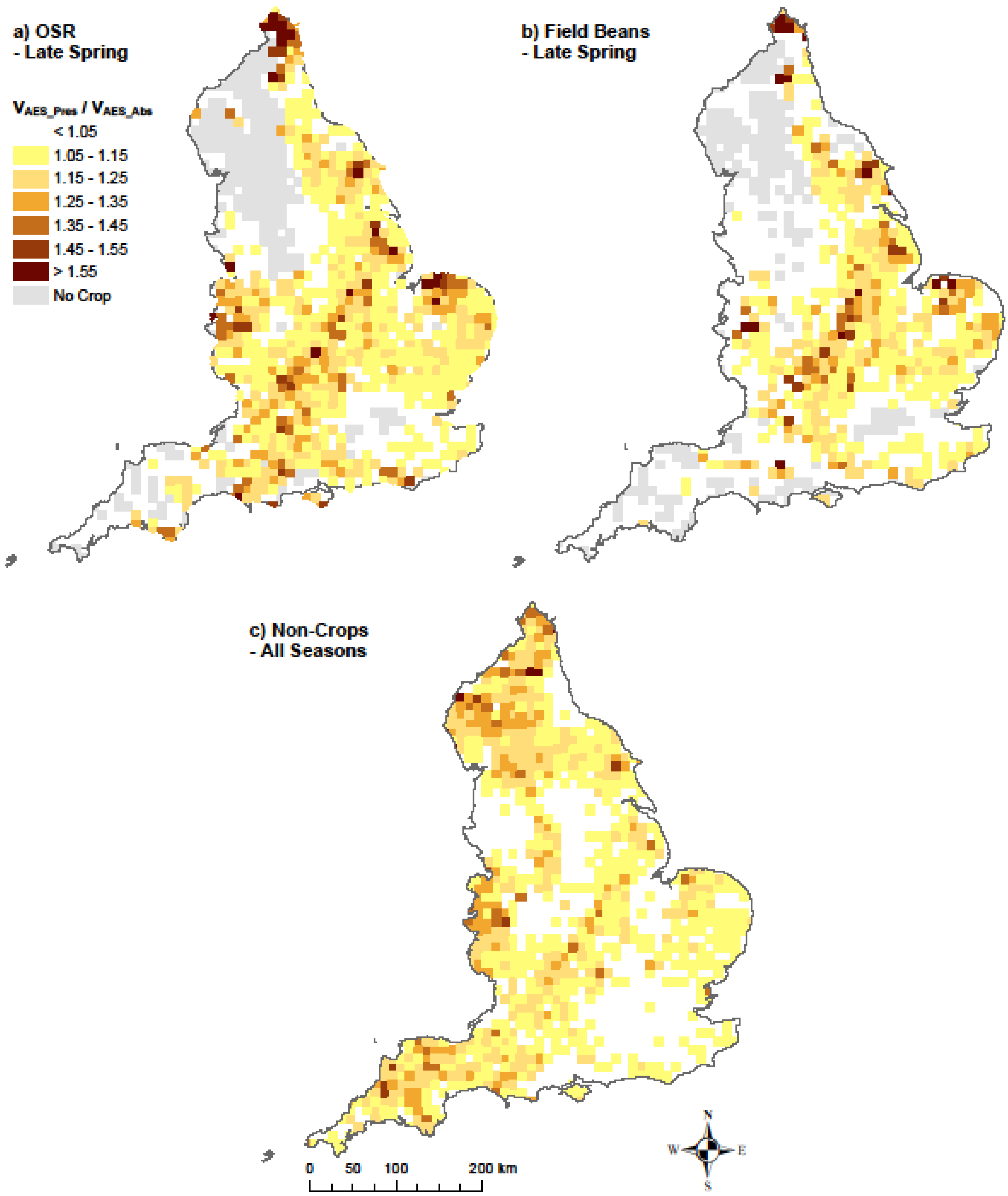

Figure 3.2: Impact of AES on ground-nesting bumblebee visitation by 10 km tile for England in 2016 to a) OSR (in late spring), b) Field Beans (in late spring), and c) Non-cropped areas (all seasons combined) as measured by the ratio of visitation in a scenario where AES management is present (AES_Present) to a scenario where it is absent (AES_Absent). Tiles with < 1% crop coverage (excluded from the regression analysis) are shown in grey

3.2.2 Classification of AES into categories

The IM2022 dataset contained 364 distinct AES management options (interventions) derived from CS, ES and EFA datasets. Each had an effect on floral and nesting resource quality, determined by the change in its land class allocation (and associated parameterisation) in the AES_Present and

AES_Absent scenarios. We grouped management options into ten categories (Table 3.1) based on the type of habitat feature and management objective (category allocations of all 364 interventions are shown in Supplementary Table S1). This removed redundancy and collinearity where several interventions had identical or similar qualitative effects and were likely to be taken up in similar geographies. Considering broad categories rather than specific interventions also made the results more transferable and generalisable to future schemes and other countries.

Table 3.1: Agri-environment scheme (AES) intervention categories, acronyms used for convenience in other tables/figures and broad descriptions of what intervention types in each group involve. For full details of allocation of individual scheme management options (intervention) to group see Supplementary Material (Table A2.1)

AES Category	Acronym	Broad Description
Fallow	FA	Allow parts of or all of an arable field to go fallow
Floral Margin	MF	Create a flower-rich margin or plot within a field
Grass Margin	MG	Create a grass margin or plot within a field (floral richness not enhanced by sowing with wildflowers)
Hedgerow/Woodland Edge	HW	Create or manage hedgerows and woodland edges (woody linear features)
Flower-rich Ley	LE	Manage a field as a herb or legume-rich ley
Semi-natural Habitat Management	HM	Maintain existing semi-natural habitat with limited change in nesting or floral resource quality
Grassland/Heath Creation	GC	Create grassland (low-input or species-rich) or lowland heath from other land use
Scrub/Wood Creation	SC	Create scrub, successional areas, wood pasture or woodland from other land use
Traditional Orchard Creation	TC	Create traditional orchards from other land use
Wetland/Coast Creation	WC	Create wetland or coastal habitats from other land use

The quantity of each AES category varied geographically (Figure 3.3a-j). The categories also exhibited different changes in nesting and floral resource quality change with respect to the *AES_Absent* scenario (Figure 3.4). Field margin options requiring landholders to sow with flowers (floral margin) had greater floral attractiveness than those which are sown with grasses only (grass margins), but the latter provided more attractive nesting habitat (Figure 3.4; Table A2.1). We also separated interventions that change land use from crops or improved grassland to semi-natural habitat (creation) from those that maintain or restore existing semi-natural habitat (habitat management), as the latter typically imply a smaller change in resources in our parameterisation (Figure 3.4). We grouped grassland and heathland creation into a common category as overall resource change is similar for our guild-level analysis. Likewise, we grouped woody linear feature management (hedgerows, woodland edge) into a single category, but we separated traditional orchards from other tree creation options (scrub, woodland, wood pasture) as they have distinct floral and nesting resource values.

We chose to categorise interventions by change in early spring floral resource, rather than change in aggregate or other season floral resource, because empirical evidence suggests that wild bee populations are more sensitive to floral resource provision in early spring (Timberlake *et al.*, 2019). Moreover, IM2022 predictions showed evidence of nesting resource limitation on crop visitation rate and predicted that mass flowering crop visitation by ground-nesting bumblebee workers in late spring is strongly dependent on the resources available to the early-spring-foraging queens who produce these workers.

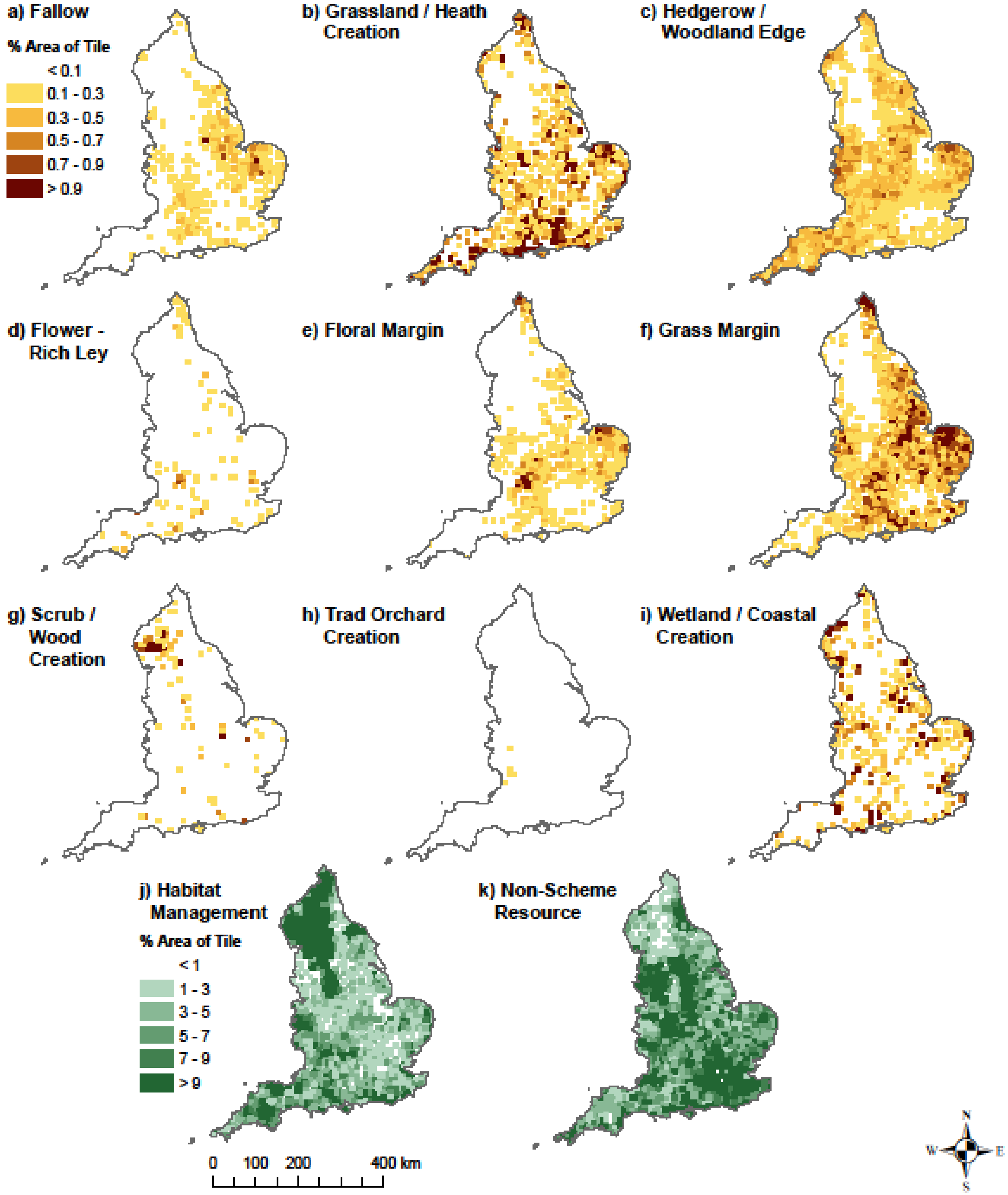

Figure 3.3: Quantity of each AES category (a – j) and non-scheme resource (k) per 10 km tile for England in 2016. Non-scheme resource includes all habitat of value to wild bees outside AES management including

suburban parks/gardens, most commercial orchards and semi-natural habitat not entered into an eligible AES management option (mainly woodland)

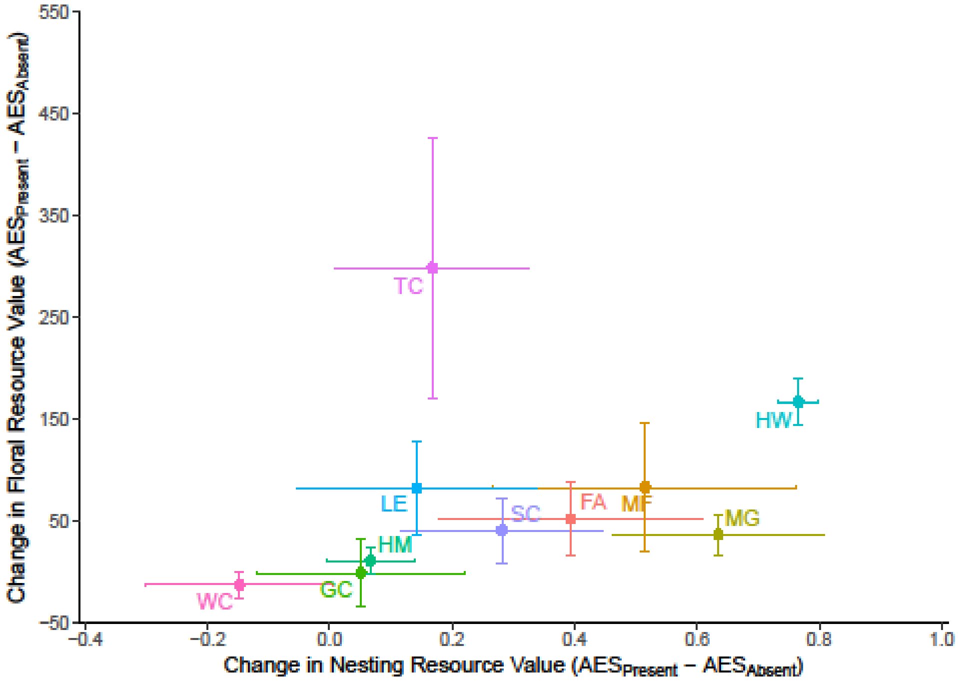

Figure 3.4: Change in ground-nesting bumblebee mean nesting resource value and in mean early spring floral resource value for each agri-environment scheme (AES) category between scenario with AES management (AES_present) and with AES management (AES_absent). Values are weighted by the national proportion of land area taken up by each component for the reference year (2016). Horizontal and vertical bars represent the standard deviation of the mean nesting and floral resource value respectively, also area weighted and incorporating error propagation (Hughes and Hase, 2010). *Categories are FA: Fallow, MF: Floral Margin, MG: Grass Margin, GC: Grassland / Heath Creation, HM: Semi-natural Habitat Management, HW: Hedgerow / Woodland Edge Management, LE: Flower-rich Ley, SC: Scrub / Wood Creation, TC: Traditional Orchard Creation, WC: Wetland / Coastal Habitat Creation*

3.2.3 Determining relative contribution of each AES category to predicted change in visitation

We assumed that change in visitation rates at a 10 km tile level would be determined by the quantity of each AES category in the tile. We determined the relative contribution of different AES categories to change in target crop visitation by stepwise backward Ordinary Least Squares (OLS) regression where the dependent variable was the visitation change ratio (change in visitation rate to target crop or non-crop land between *AES_Present* and *AES_Absent*) and the explanatory variables were the percentage cover of each AES category per 10 km tile (Table 3.2).

Because the dependent variable is a ratio of change in visitation, we also anticipated tiles with higher level of visitation in the *AES_Absent* scenario would be less responsive to area of AES. For this reason, we therefore included the proportion of “Non-Scheme Resource” in a tile as an interacting variable, where Non-Scheme Resource captured high resource quality land cover always outside the schemes in our study: this primarily covered suburban parks and gardens, woodland, and commercial orchards (Figure 3.3k). We allowed the area of semi-natural habitat management AES variable to interact with other categories for the same reason. To account for the possibility that co-location of complementary resources might have an effect on the visitation ratio above and beyond summed effect of each intervention alone, we also allowed the following commonly co-located variables to interact in the regression: fallow, hedgerow/woodland edge, floral margin, grass margin.

Table 3.2: Description of variables used in the regression analysis

Variable	Description
Dependent	
Visitation Ratio	Predicted average visitation to target cells within the tile in scenario where AES management is present / Predicted average visitation to target cells within the tile in scenario where AES management is absent
Explanatory	
Fallow (FA)	% area of tile in a fallow AES intervention
Grassland / Heath Creation (GC)	% area of tile in a grassland or heath creation AES intervention
Habitat Management (HM)	% area of tile in a semi-natural habitat management AES intervention
Hedgerow / Woodland Edge (HW)	% area of tile in a hedgerow or woodland edge AES intervention
Flower Rich Ley (LE)	% area of tile in a flower-rich ley AES intervention
Floral Margin (MF)	% area of tile in a flower-rich margin AES intervention
Grass Margin (MG)	% area of tile in a grass margin AES intervention
Scrub / Wood Creation (SC)	% area of tile in a scrub, woodland or wood pasture creation AES intervention
Trad. Orchard Creation (TC)	% area of tile in a traditional orchard creation AES intervention
Wetland / Coastal Creation (WC)	% area of tile in a wetland or coastal habitat creation AES intervention
Non-Scheme Resource (NSR)	% area of tile that contains potentially valuable habitat not in the schemes considered (primarily suburban parks and gardens, woodland and commercial orchards).
Interacting Variables	
FA – HW – MF – MG	Mutual 2-way interactions only
NSR	Interactions with all other explanatory variables
HM	Interactions with all other explanatory variables

Although there was a strong positive correlation between the percentage coverage of some AES categories (Figure 3.5), variance inflation factors for all categories were below 5.00 (Supplementary Material Section A2.6). When fitting, we weighted by the inverse of the standard deviation of the visitation ratio to account for uncertainty in the visitation rate change due to uncertainty in the poll4pop parameter inputs. A regression with the percentage of target crop in the tile as an interacting variable was also explored but this did not improve fit and so this variable was dropped.

3.2.4 Quality, quantity and placement. Identifying reasons for differing contribution of AES category

The regression coefficients produced for each AES category, where significant, indicate the change in relative visitation rate for a 1% increase in the area of that AES category in a 10 km tile. The size and direction of that coefficient is influenced by the change in nesting and floral resource provision per unit area for the AES category (quality) as well as the location of these interventions relative to the crop or non-crop areas being pollinated, and to other nesting and floral resources (placement). The total quantity of uptake (by area) of an intervention nationally, as well as quality and placement, affect the significance of each coefficient: categories that provide high resource value and/or are well located may not result in significant effects if uptake is too low.

To disentangle the effects of quantity and quality, we plotted the size and significance of each AES category's regression coefficient against its logged mean area of uptake per 10 km tile and against its change in resource quality. The change in resource quality of each AES category (Q_c) was calculated by normalising the per unit change in nesting resource ($N_c = N_{c(AES\_Pres)} – N_{c(AES\_Abs)}$) and per unit change in early spring floral resource ($F_c = F_{c(AES\_Pres)} – F_{c(AES\_Abs)}$) with respect to the minimum and maximum category values (N_{min}, N_{max},, F_{min} , F_{max}) (see Figure 3.4) and multiplying these values together (Equation 2). This multiplication approximated the process occurring in the poll4pop model.

$$Q_c = (N_c - N_{min})(N_{max} - N_{min}) * \ (F_c - F_{min})(F_{max} - F_{min}) \qquad \text{Equation.1}$$

The influence of placement was then inferred by considering the size and significance of the regression coefficient with respect to change in resource quality and the mean area of uptake, and by cross-referencing with the spatial correlations shown in Figure 3.3. An AES category whose coefficient is larger than might be expected for the change in resource quality may indicate one that is better located with respect to the crop or non-crop of interest. Whereas poor placement of an AES category may explain the lack of a significant effect despite having reasonable uptake and providing good quality resource. Significant interactions in the regression would also indicate whether the effect of an AES category was influenced by prior landscape context (i.e., availability of non-scheme resource) or co-location with other AES categories with different resource quality.

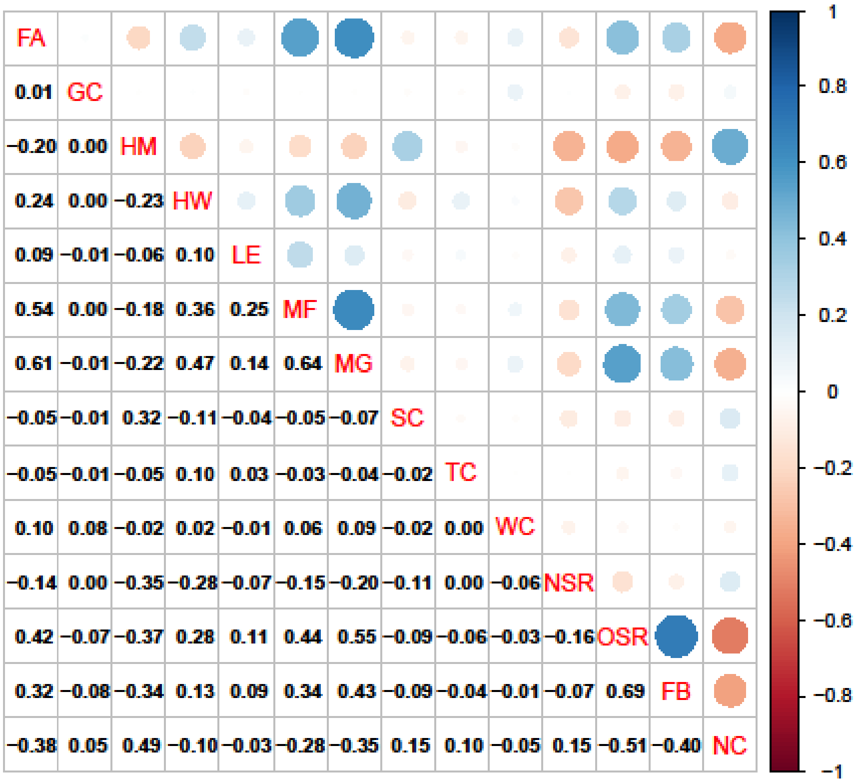

Figure 3.5: Correlation Matrix, % Area of Tile: Categories are FA: Fallow, MF: Floral Margin, MG: Grass Margin, GC: Grassland / Heath Creation, HM: Semi-natural Habitat Management, HW: Hedgerow / Woodland Edge Management, LE: Floral Ley, SC: Scrub / Wood Creation, TC: Traditional Orchard Creation, WC: Wetland / Coastal Habitat Creation, NSR: Non-Scheme Resource, OSR: Oilseed Rape, FB: Field Beans, NC: Non-Cropped Areas. Cells below the leading diagonal show correlation coefficients whilst cells above indicate the same information as colour code (blue = positive, red = negative) and shade / size (larger values are represented by larger discs with darker shades)

3.2.5 Tools

Data processing was carried out in Python 2.7 / 3.5 and R (R Core Team, 2018). Map outputs were produced in ArcGIS 10.7 (ESRI, 2019).

3.3 Results

3.3.1 Relative contribution of each AES category to predicted change in visitation.

Of the four bee guilds assessed, only ground nesting bumblebees showed widespread and significant increases in OSR and field bean visitation due to AES management at a national scale (IM2022). Hence, as noted above, we present below results for this guild only (for results for other guilds, see Supplementary Material; Table A2.3-5).

Table 3.3: Results (regression coefficients, standard errors) for linear regression for ground-nesting bumblebee Visitation Ratio (visitation per tile to target land class (season) with AES features present / visitation per tile to target land class (season) with AES features absent) to each of OSR (late spring), Field Beans (late spring) and non-crops (all seasons) as a function of percentage composition of different AES categories in landscape tiles (see Table 3.2 for definitions of all response and explanatory variables).

Variable	OSR	Field Beans	Non-Crop
(Intercept)	0.99 ± 0.01 ***	0.99 ± 0.01 ***	1.0E-4 ± 9E-5***
Fallow (FA)	0.09 ± 0.03 ***	0.17 ± 0.04 ***	
Grassland / Heath Creation (GC)	0.019 ± 0.007 **		-0.008 ± 0.001 ***
Habitat Management (HM)	0.0016 ± 0.0003 ***	0.0025 ± 0.0004 ***	0.0023 ± 0.0001 ***
Hedgerow / Woodland Edge (HW)	0.33 ± 0.02 ***	0.26 ± 0.02 ***	0.29 ± 0.01 ***
Flower-Rich Ley (LE)	-0.053 ± 0.034	-0.043 ± 0.039	0.08 ± 0.03 **
Floral Margin (MF)	0.12 ± 0.03 ***	0.008 ± 0.048	0.11 ± 0.03 ***
Grass Margin (MG)	0.10 ± 0.02 ***	0.12 ± 0.02 ***	-0.010 ± 0.006
Scrub / Wood Creation (SC)			0.03 ± 0.01 *
Trad. Orchard Creation (TC)			
Wetland / Coastal Creation (WC)	-0.0076 ± 0.0034 *	0.0025 ± 0.0049	-0.012 ± 0.002 ***
Non-Scheme Resource (NSR)	0.0006 ± 0.0002 ***	0.00042 ± 0.00001 **	0.0E-6 ± 2E-7
*GC * NSR*	-0.0006 ± 0.0002 **		
*HW * NSR*	-0.013 ± 0.001 ***	-0.0075 ± 0.0015 ***	-0.0100 ± 0.006 ***
*LE * NSR*			-0.0039 ± 0.0019 *
*MF * NSR*	-0.005 ± 0.002 *		-0.0033 ± 0.0013 **
*FA * HM*	0.012 ± 0.004 **		
*GC * HM*	-0.0008 ± 0.0004 *		
*HM * LE*	0.026 ± 0.005 ***	0.030 ± 0.007 ***	
*HM * MF*		0.009 ± 0.003 **	
*HM * MG*	0.0029 ± 0.0013 *		0.0034 ± 0.0006 ***
*HM * WC*		-0.00064 ± 0.00026 *	
*HW * MF*			-0.19 ± 0.05 ***
*FA * MG*	-0.14 ± 0.04 **	-0.18 ± 0.04 ***	
N	1189	1195	1496
R^2	0.73	0.68	0.74

*** *P* < 0.001; ** *P* < 0.01; * *P* < 0.05.

3.3.1.1 Crop visitation

There are significant positive relationships between the area of fallow, habitat management, hedgerow/woodland edge, and grass margin categories within a tile and the predicted change in visitation rate to both crops for ground-nesting bumblebees (Table 3.3). Of these four AES categories, hedgerows/woodland edge has the largest effect size: a 1% increase in cover between *AES_Present* and *AES_Absent* scenarios accounts for a 0.33 (± 0.02) and 0.26 (± 0.02) proportional increase in relative predicted visitation rate to OSR and field bean, respectively. Fallow cover has a stronger positive association with change in field bean visitation than change in OSR visitation (0.17 ± 0.04 vs 0.09 ± 0.03 increase in relative predicted visitation rate per 1% increase in area). Change in coverage of habitat management interventions has only a very weak positive relationship with the net change in relative predicted visitation rate (0.0016 ± 0.0003 (OSR), 0.0025 ± 0.0004 (field beans)).

Relationships between area of other AES categories in a tile and net change in relative predicted crop visitation rates are less consistent. The predicted change in relative OSR visitation rate is positively dependent on area of floral margin (+0.12 ± 0.03) and grassland/heath creation (+0.019 ± 0.007) but shows no relationship with scrub/woodland creation cover. In contrast, change in relative field bean visitation rate shows no significant relationship with the area of any of these categories. There is no significant relationship between cover of flower-rich ley or traditional orchard creation with change in relative predicted visitation rate to either crop. Wetland/coastal habitat creation has a slightly negative relationship (-0.0076 ± 0.0034) with change in OSR visitation but not field beans.

Examination of statistical interactions shows that increasing the area of non-scheme resource in a tile significantly weakens the positive relationship between area of certain AES categories (hedgerow/woodland edge, floral margins, grassland/heath creation) and predicted change in crop visitation rate (Table 3.3, Figure A2.4a-c, Figure A2.5a-c). The positive effect on crop relative visitation rate of increasing fallow coverage is enhanced when there is more semi-natural habitat management also present (Figure A2.4d, Figure A2.5d) in the tile but is diminished when there are larger areas of grass margin (Figure A2.4g, Figure A2.5f-g). The positive effect on crop relative visitation rate of increasing grassland/heath coverage is also enhanced when there is more semi-natural habitat management present. The positive effect of semi-natural habitat management on change in crop visitation is enhanced where floral ley, floral margin and grass margin cover is higher, but reduced where wetland / coastal habitat creation is higher.

3.3.1.2 Non-Crop Visitation

As with the crop visitation predictions, there was also a significant positive relationship between predicted relative non-crop visitation rate and the area of hedgerow / woodland edge (+0.29 ± 0.01). There were also significant, but weaker, positive relationships with area of floral margin (+0.11 ± 0.03), flower-rich ley (+0.08 ± 0.03), scrub / wood creation (+0.03 ± 0.01) and semi-natural habitat management (+0.0023 ± 0.0001) interventions, whilst increasing the cover of wetland creation (-0.01 ± 0.002) and grassland heath creation interventions (-0.008 ± 0.001) each have small but significant negative effects. Unlike mass flowering crops, there is no significant relationship between change in relative visitation rate and the quantity of fallow or grass margin interventions.

Again, the positive relationship between relative non-crop visitation rate and quantity of certain AES categories (hedgerow / woodland edge, floral margin, and flower-rich ley) is significantly weaker for higher areas of non-scheme resource (Table 3.3, Figure A2.6a-c). The positive effect of hedgerow / woodland edge is also reduced in the presence of greater areas of floral margin edge (HW*MF -0.19 ± 0.05). However, there is a positive interaction between area of grass margin and area of semi-natural habitat management (MG*HM +0.0034 ± 0.0006).

3.3.2 Quantity, quality, and placement: differing contribution to change in pollination service by AES category

Categories with lower quantity (area of uptake) nationally tend to be those which do not have a significant effect on the net change in visitation rate (Figure 3.6a, c, e), e.g. traditional orchard creation (both crops and non-crop) and flower-rich ley (both crops). Uptake quantity appears to be a more important factor in determining significance of effect on change in visitation to crops than non-crops (compare Figure 3.6a, c vs. e). Categories with greater resource added value (quality) such as grass margins, floral margins, hedgerow/woodland edge and fallow tend to have more positive marginal effects on net change in relative visitation rate (Figure 3.6b, d, f) across both crops and non-crops.

Placement effects were inferred for: fallow (much higher regression coefficient than interventions of similar quality and quantity indicating effective placement), grassland/heath creation and floral margins (significant positive effect for OSR and non-crop visitation but not for field beans inferring differential placement), grass margins (significant positive effect for OSR and field bean visitation but not for non-crops also inferring differential placement), flower rich ley and scrub/woodland creation (significant positive effect for non-crop visitation but not for either crop also inferring differential placement).

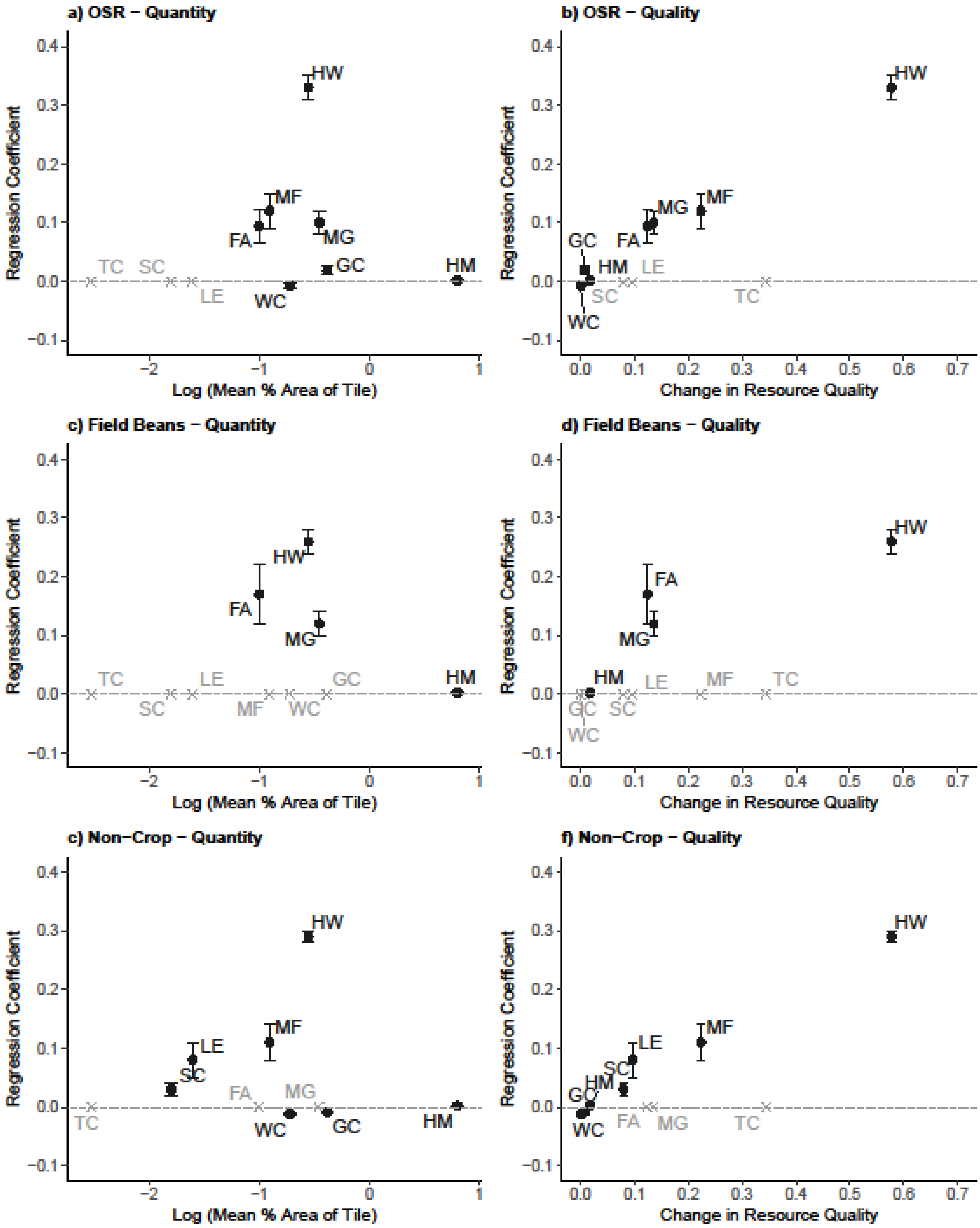

*Figure 3.6: Magnitude of regression coefficient (representing change in predicted ground-nesting bumblebee relative visitation rate between scenario with AES present and scenario with AES absent per unit area of intervention) as a function of national uptake quantity of AES category (measured as the log of the mean percentage intervention area per 10 km tile recorded in the year 2016) for OSR (a), Field Beans (c) and Non-Crop (e). Magnitude of regression coefficient as a function of quality of AES category (normalised change in nesting quality * normalised change in early spring floral quality) for OSR (b), Field Beans (d) and Non-Crop (f). Categories are FA: Fallow, MF: Floral Margin, MG: Grass Margin, GC: Grassland / Heath Creation, HM: Semi-natural Habitat Management, HW: Hedgerow / Woodland Edge Management, LE: Flower Rich Ley, SC: Scrub / Wood Creation, TC: Traditional Orchard Creation, WC: Wetland / Coastal Habitat Creation. Black points denote significant regression coefficients with standard errors. Crosses denote intervention categories with no significant regression coefficient*

3.4 Discussion

IM2022 (Image *et al.*, 2022) used a spatially explicit process-based model to simulate foraging and population processes of wild bees and predict the net change in bee visitation due to the suite of AES interventions under active management in England during 2016, compared to a land-use scenario where these interventions were absent. In this study, we used linear regression to determine which of the implemented AES interventions (aggregated by category) are driving the predicted changes in relative visitation to OSR, field beans and non-crop areas and why. We focussed our analysis on ground-nesting bumblebees as this was the only guild to show a widespread and significant response in OSR and field bean visitation rates due to AES management in IM2022.

In general, the AES categories with larger area of uptake are the ones with significant effects on change in ground-nesting bumblebee visitation. Of those, the ones that provide higher relative nesting and floral resource quality tend to have a greater effect on the net change in visitation. However, the results also reveal differences between AES categories in terms of significance and magnitude of their visitation effects across crop type and non-crops. These suggest placement effects, mutual interactions and other factors which also have important implications for scheme design.

3.4.1 Hedgerow and Woodland Edge Management

Our results suggest that the predicted increases in both mass-flowering crop *and* non-crop relative visitation due to the AES participation are strongly dependent on the area of hedgerow and woodland edge interventions in a tile. The magnitude of the increases predicted reflects empirical evidence (Bailey et al., 2014; Sutter et al., 2018) and is likely linked to the high resource quality. AES management provides greater nesting opportunity for ground-nesting bumblebees as well as greater early-spring floral resource, factors which are more critical for population growth than floral resource provision in late spring or summer seasons (Carvell *et al.*, 2017; Timberlake *et al.*, 2019). Whilst hedgerows and woodland edges outside of AES can also be of value to wild bees, they can either be overmanaged (reducing floral cover) or under-managed (compromising structural integrity). AES managed features are cut at a specific frequency that maintains structural integrity without compromising floral cover (Staley *et al.*, 2012). We approximated this effect in the model by allowing AES features to be twice the width of a feature outside the scheme, so our prediction does rest on the assumption that features under an AES regime effectively provide twice as much resource quality. However, visitation rate changes of this order are observed empirically (Byrne and delBarco-Trillo, 2019).

The consistency of the predicted net visitation rate change to both crops and non-crops is likely because these interventions have high uptake quantity across both arable and non-cropped areas (compare Figure 3.3c to Figure 3.2). They may also be providing ecological connectivity from resource-limited cropping areas to resource-rich existing semi-natural habitat features (Sullivan *et al.*, 2017). Maintaining this extent of hedgerow/woodland edge management in future schemes will therefore be important in supporting pollination services (Albrecht *et al.*, 2020). In principle, the beneficial effect could be enhanced by planting new hedgerows to further extend the hedgerow network, though it may take over five years for these to provide resources of equivalent quality to mature hedgerows (Kremen *et al.*, 2018).

3.4.2 Floral and Grass Margins

We predict that floral margins have positively affected the change in relative visitation to OSR and non-cropped areas due to overall AES participation but have not had a significant effect on relative field bean visitation. The magnitude of their effect on OSR and non-crops is much smaller than hedgerow/woodland edge but is consistent with a more limited resource quality (Figure 3.6). Although floral margins include wildflowers in their seed mix, the parameterisation in the model reflects that the species selected in schemes provide most floral resources in the summer season with very limited spring provision (Ouvrard *et al.*, 2018). The lack of significant effect on field beans suggests a placement factor where there are insufficient floral margin interventions near field bean parcels to result in a significant effect. This may simply be because the area covered by floral margins is not sufficiently high to enhance bee populations consistently across the landscape (Carvell *et al.*, 2015), so field beans (which are rarer in the landscape than OSR and non-crop features; Figure 3.1) are less likely to be co-located.

Our predictions suggest that grass margins have positively affected the change in relative visitation to OSR and field beans due to overall AES participation but have not had a significant effect on net non-crop visitation. The magnitude of their effect on crops is also consistent with their resource quality (Figure 3.6). Grass margins can still provide an important nesting resource for ground-nesting bumblebees but do not achieve the same floral resources as interventions explicitly sown with wildflowers (hence their lower parameterisation), and the species which establish will also tend to be summer flowering. However, they are a very popular intervention covering a large area (Figure 3.3f) which likely allows them to influence field bean visitation as the chance of co-location is high. Grass margins are negatively correlated with non-crops (-0.35; Figure 3.5), but placement is not a complete explanation for the lack of significant effect on non-crops as floral margins also have a negative correlation (-0.28). Low resource quality may also be a factor as visitation rates to non-crop in the *AES_Absent* scenario may be already high, so grass margins are unable to add sufficient additional visitation to be significant.

Grass margins are playing an important role in supporting the crop pollination services provided by the overall schemes and should continue to be incentivised. Floral margins are also valuable but could support more pollination of sparsely distributed crops if they were more abundant in the landscape. Another potential enhancement to the floral margin intervention would be to incorporate species in the sowing mix which come into flower before mass-flowering crops, such as primrose (*Primula vulgaris*), cowslip (*Primula veris*) and red campion (*Silene dioica*) (Nowakowski and Pywell, 2016). This would help sustain larger wild bee populations and further enhance pollination service. A similar effect could be achieved more generally by land users by tolerating some early-flowering perennial weeds such as dandelion (Hicks *et al.*, 2016) which has been identified as a strong predictor of pollinator abundance in urban habitats (Baldock *et al.*, 2019).

3.4.3 Fallow

Our results suggest that the predicted increases in visitation to both mass-flowering crops due to the AES participation are dependent on the area of fallow interventions in a tile. Fallow interventions have a similar net resource quality as grass margins in our parameterisation (Gardner *et al.*, 2020) and the magnitude of the effect on OSR is very similar. Like grass margins, fallow also has a strong negative correlation with non-crop areas (-0.35; Figure 3.5) so it is likely that the lack of significant effect on non-crops is driven by the same factors as those already discussed for grass margins. However, the effect of fallow on net field bean visitation is stronger than would be expected from resource quality alone even though area of fallow is more strongly correlated at tile level with area of OSR than area of field beans. This suggests that fallow interventions are being located more efficiently with respect to field bean parcels than other interventions though this may be an inadvertent consequence of landholder decision-making.

The fallow category comprises a range of interventions that create non-cropped areas within arable rotations, sometimes for specific biodiversity objectives (e.g., plots for ground-nesting birds) and our simulations support site-specific observational evidence that fallow options represent an important asset in the context of ecosystem service delivery by supporting crop pollination and farmland bird populations simultaneously (Ouvrard and Jacquemart, 2018). Temporary features such as fallow plots may be particularly valuable contributors to crop pollination in more intensive arable contexts where there is less land given up to longer-term or permanent semi-natural features like field margins or hedgerows. These interventions should continue to be promoted in future schemes.

3.4.4 Tree Planting

Scrub/woodland creation interventions (representing conventional woodland creation but also including successional habitat creation) do not have a significant effect on the net change in mass-flowering crop visitation rate due to overall AES participation but do have a small but significant positive effect on net non-crop visitation by ground-nesting bumblebees. The quanity of these interventions is very low in more intensively farmed areas (compare Figure 3.3g to Figure 3.2) so it is not surprising to see no significant crop effect. The magnitude of the non-crop effect is in line with the limited scale of increase in resource quality that scrub/woodland creation provides to this guild. However, this does not take into consideration the woodland edge effect (which is grouped with hedgerow) so woodland creation may be providing a greater service than our categorisation suggests.

Traditional orchard creation has no effect on either crop or non-crop net visitation, most likely because the quantity is very limited. This is a missed opportunity to significantly enhance pollination service because fruit trees have very high early spring visitation and so could potentially support higher wild bee populations whilst not competing with later flowering crops or habitats for bee visitation. Realistically, traditional orchards have geographical constraints and are unlikely to be taken up in more intensive arable areas. Instead, English AES could increase the quantity of fruit trees (and other early-flowering trees such as poplar) by promoting silvoarable agroforestry (e.g., alley cropping with fruit trees or poplar). This was not supported in the schemes studied but might be highly valuable due to early season floral resource quality and potential for co-location with mass flowering crops (Varah *et al., 2020)*. They also provide a range of other ecosystem services beyond pollination (Burton *et al*., 2018).

3.4.5 Other interventions

Semi-natural habitat management interventions are predicted to have a significant positive effect on net visitation to crops and non-crops due to overall AES participation, but the magnitude of the effect is very small. As the category name suggests the focus is on management rather than enhancement and as such they tend to only slightly increase resource quality (Berg *et al*., 2019), as reflected in our parameterisation. However, their high uptake means they are making small changes over a large area, and they often enhance the effects of other categories. For instance, nearby semi-natural habitat management supports the positive effects of higher value interventions (e.g. fallow, flower-rich ley, grass and floral margins; see interaction effects in Table 3.3).

Our simulations also suggest that grassland/heath creation interventions have a small but significant positive effect on net OSR and non-crop visitation but not on field beans (likely for similar reasons as suggested for floral margins). Again, the magnitude of effect is consistent with change in resource quality which is small in our parameterisation. This may be because only a small proportion of the interventions within this category are higher quality types like “Creation of species-rich grassland – GS8” (Table A2.1). These are potentially being diluted by “Restoration of Lowland Heath – HO2”, a popular ES management option with more limited overall floral resource change as it requires some scrub removal to promote heather regeneration. Moreover, our simulations focus on ground-nesting bumblebees and are at the guild level. As such, they do not capture the vital role that grassland/heath creation interventions (and related semi-natural habitat management, discussed above) can play in maintaining wild bee species richness (Rotchés-Ribalta *et al.*, 2018). As pollinator species richness can be as valuable as abundance to maintaining reliable pollination services (Woodcock *et al.*, 2019), these interventions should continuing to be supported.

Our simulations predict that flower-rich leys currently significantly influence net non-crop visitation but not crop visitation due to low uptake (Figure 3.3). They offer similar floral quality to floral margins, but this is also mainly expressed in the summer months when the clover and other forbs that are in the specified sowing mixes will flower. Their effect may also be smaller in magnitude relative to floral margins as they have a lower nesting quality (greater disturbance is expected). Nevertheless, if uptake were greater within arable rotations, they may potentially be able to contribute to mass-flowering crop visitation.

3.4.6 Targeting inventions at landscape-scale and farm-scale

Our simulations demonstrate significant landscape-scale negative interactions between the implemented AES interventions and area of non-scheme resource, implying interventions tend to be more effective in simplified landscapes where the baseline visitation rate is lower, consistent with theories of landscape moderation of ecological process (Tscharntke *et al.*, 2012; Tscharntke *et al.*, 2005). This suggests scheme designs should consider quantity of non-scheme resource and pre-existing habitat management to effectively target interventions at areas with limited pre-existing nesting or floral resources, if supporting wild and crop pollination services is a desired outcome.

Interactions between individual interventions are driven by nesting/foraging choices of our simulated bees at the farm scale. In arable areas with few grass margins, bees rely on fallow areas for nesting producing a positive relationship between fallow area and change in crop visitation rate in our simulations. Where there are more grass margins, bees preferentially use these for nesting due to their higher nesting resource value in our parameterisation (Figure 3.4), hence weakening this relationship with fallow area (interaction effect; Figure A2.4h, Figure A2.5e). A similar interaction effect occurs between floral margins (summer flowering) and hedgerows (early spring flowering) on non-crop visitation (Fig. S6e). This is likely due to the complementarity of their floral resources meaning bees nesting in close proximity to both features no longer need to access nearby non-crop areas (e.g. semi-natural habitats) for resources. These interactions emphasise the importance of landholders considering complementarity and current level/limitations in resource provision on their land when choosing suites of interventions in order to maximise benefits for food production and for nearby natural habitats.

3.5 Conclusions and Recommendations

Our study disentangles the contributions of different intervention types implemented within agri-environment schemes (AES) in England in 2016 to predicted impacts on ground-nesting bumblebee pollination services to OSR, field beans and the wider landscape. We find intervention categories with high uptake quantity and those offering high resource quality (specifically nesting and early spring resource provision) typically had most influence on the schemes' net effect on pollination services. We also show that placement matters for some interventions, with their location relative to crops, other AES interventions and pre-existing habitat influencing their effectiveness for supporting pollination services.

Based on our findings, we make the following recommendations for improving the design of future agri-environment schemes to better support wild and crop pollination services.

Promote hedgerow and woodland edge management: These interventions offer good nesting and floral resources (especially early in the year) and have a strong effect on pollination services to crops and non-crop areas alike, due to wide uptake and high landscape connectivity.

Include more early flowering species in floral margins and increasing their uptake in the landscape: Floral margins provide high floral resource in summer but little in early spring, so adding early flowering species may increase pollination service benefits. and greater uptake will better enable these valuable features to support pollination service to important but less frequently planted crops such as field beans.

Promote fallow interventions in intensively managed landscapes: Fallow features do not require long-term land use change so can be easily incorporated into rotations in intensive arable landscapes where baseline pollination service is lower. Our findings show they provide an efficient multifunctional asset, significantly supporting bees in addition to their more commonly bird-focused objectives.

Promote tree creation in arable landscapes: Our simulations already highlighted the potential pollination service benefits of linear/elongated management interventions. Increasing tree cover (especially hedgerows and agroforestry systems) can provide further nesting and early floral resource value.

Consider landscape context at different scales when targeting uptake: Current interventions are predicted to be more effective in landscapes with lower quantities of pre-existing habitat. At farm scale, our simulations indicate that encouraging co-location of interventions with complementary nesting and early spring floral resource quality is likely to increase their effectiveness.

4 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.

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.

At the time of submission this chapter was in review by Land Use Policy: Reviewers' comments had not yet been received:

Image, M., Gardner, E., & Breeze, T. D. (2022). 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.

4.1 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, Breeze, *et al.*, 2014; 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 1,310,000 ha or 10.0% woodland cover by land area in 2020 (Forest Research, 2020) making it one of the least wooded countries in Europe (FAO, 2020). There was a further 560,000 ha cover of trees outside woodland, which includes 193,000 ha of trees in groups or lines (Brewer *et al.*, 2017). 2,340 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 Environmental Land Management (ELM) scheme (Defra, 2022b). 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, 2021d). 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 (Crowther *et al.*, 2014; Hall *et al.*, 2019; Stanley and Stout, 2013; Bentrup *et al.*, 2019), 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.

4.2 Materials and Methods

4.2.1 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 we assume arable or improved grassland not on peat soils with an Agricultural Land Classification of Grade 3, 4 or 5 is low risk (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 3).

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 A3.1 in Supplementary Material)

5. Not a coastal tile, to ensure interventions can be located within 5 km of any point in the tile.

1101 tiles contained both OSR and field beans, of which 958 were not coastal (criterion 5). Of those 958, there were 283 which contained sufficient low-risk land (criterion 1) and whose % OSR and field bean cover exceeded their respective means (criterion 4). Of those, tile 'SK86' minimised the equally weighted sum of absolute difference from mean for criteria 2 and 3. SK86 is in the East Midlands of England (Figure 4.1) 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.

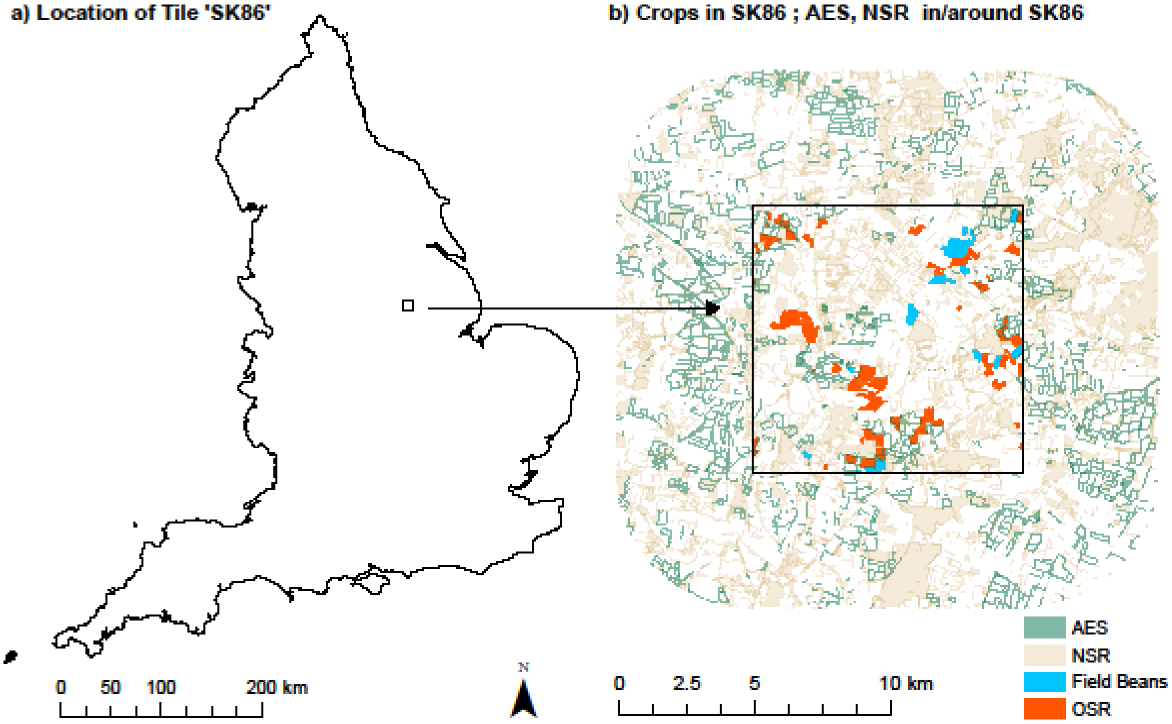

Figure 4.1: a) Location of study tile (SK86) in England; b) Location of OSR and Field Beans within the tile and location of higher-value agri-environment scheme (AES) features and non-scheme resource (NSR) in the tile and within surrounding 5 km buffer. See Section 4.2.1 for definition of higher-value AES and NSR.

4.2.2 Pollinator model description

We used the process-based model *poll4pop* (Häussler *et al.*, 2017; Gardner *et al.*, 2020), which predicts seasonal spatially-explicit 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 augmented to incorporate seasonal adjustments related to crop flowering and allow for additional land classes required 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 (Stanley *et al.*, 2013; Garratt, Coston, *et al.*, 2014). 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.

4.2.3 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 IM2022.

We took the *AES_Present* scenario from IM2022 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 IM2022, 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.

4.2.4 Tree planting scenarios

We defined a set of six tree planting scenarios (Table 4.1) covering the three main mechanisms by which additional trees can be planted in farmland contexts.

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 Appendix 3.1 for details and Figure A3.2 for a map output showing example spatial distributions).

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.

Table 4.1: 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>20ha), until area target is reached.

4.2.5 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 (1,305,280 M ha; Forest Research, 2020) and applied a constant woodland creation rate equivalent to the 2020 England woodland creation rate (2,340 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 7,000 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 (2,223 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, consistent with the width assumptions for conventionally managed hedgerows used in Image et al (2022).

4.2.6 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 4.1 (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.

4.2.7 Comparing effectiveness of tree-planting scenarios at different intensities

4.2.7.1 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.

4.2.7.2 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.

4.3 Results

4.3.1 Landscape-level

4.3.1.1 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 (Figure 4.2a; Table A3.2, A3.4), 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 (Figure 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 (Figure 4.2b; Table A3.3, A3.5). 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 (Figure 2b). Likewise, the hedgerow scenarios only significantly increased nest density above the poplar and willow agroforestry scenarios at high planting intensity.

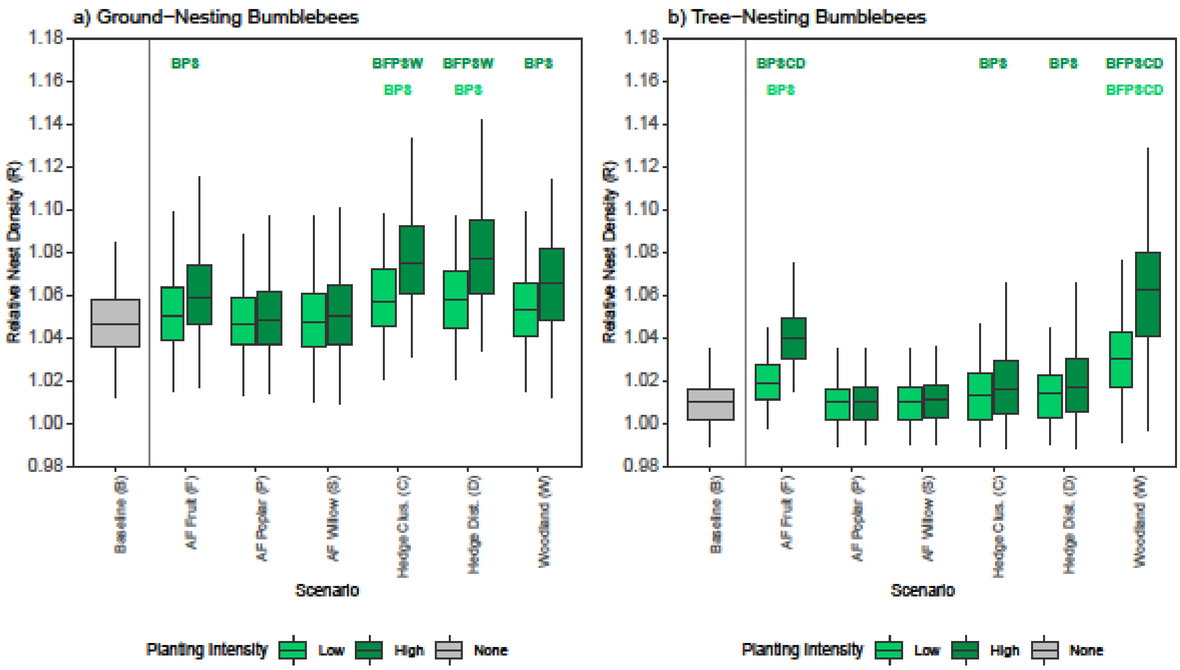

Figure 4.2: Box plots showing relative nest density (R – total number of nests as a fraction of the number predicted with no AES interventions or tree planting present) for the baseline scenario (2016 AES features only; grey) and the tree planting scenarios (2016 AES features plus additional tree cover; 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.

4.3.1.2 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 (Figure 4.3a; Table A3.9). At low planting intensity, only the hedgerow scenarios significantly increased ground-nesting bumblebee queen production above the baseline (Figure 4.3a; Table A3.7). 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 (Figure 4.3a;, Table A3.9). Fruit tree and 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 (Figure 4.3b; Table A3.8, A3.10).

Woodland creation showed significantly higher tree-nesting bumblebee queen production than all other scenario 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 (Figure 4.3b;, Table A3.10).

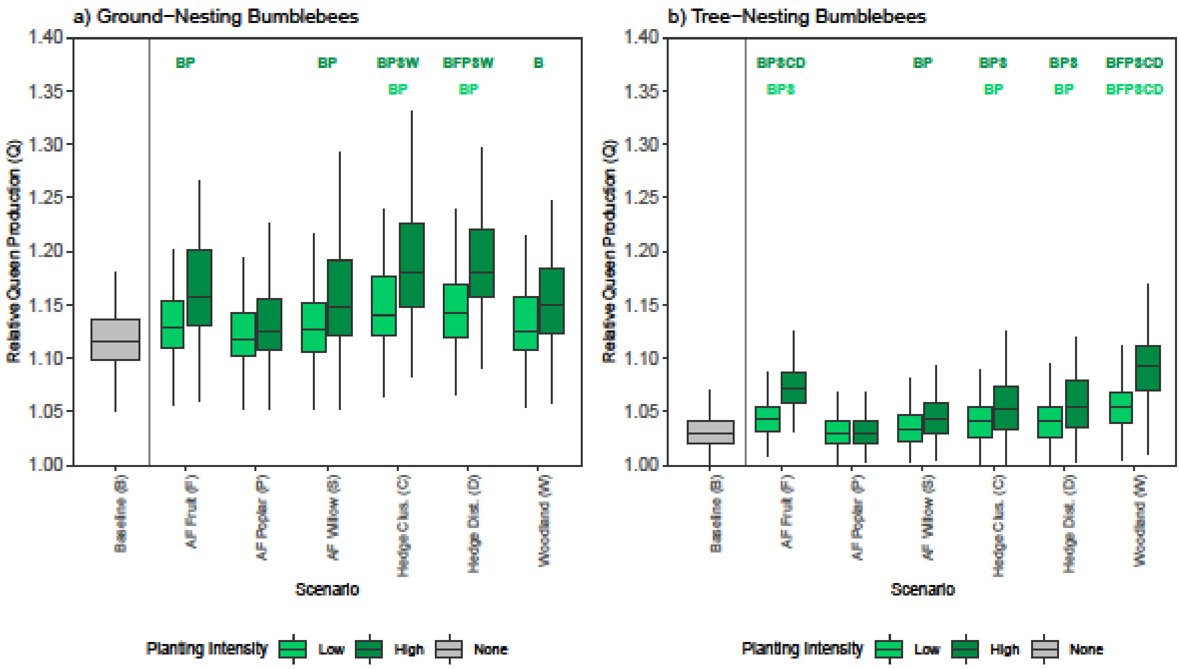

Figure 4.3: Box plots showing relative queen production (Q – total number of new reproductive females as a fraction of the number predicted with no AES interventions or tree planting present) for the baseline scenario (2016 AES features only; grey) and the tree planting scenarios (2016 AES features plus 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.

4.3.1.3 Worker production

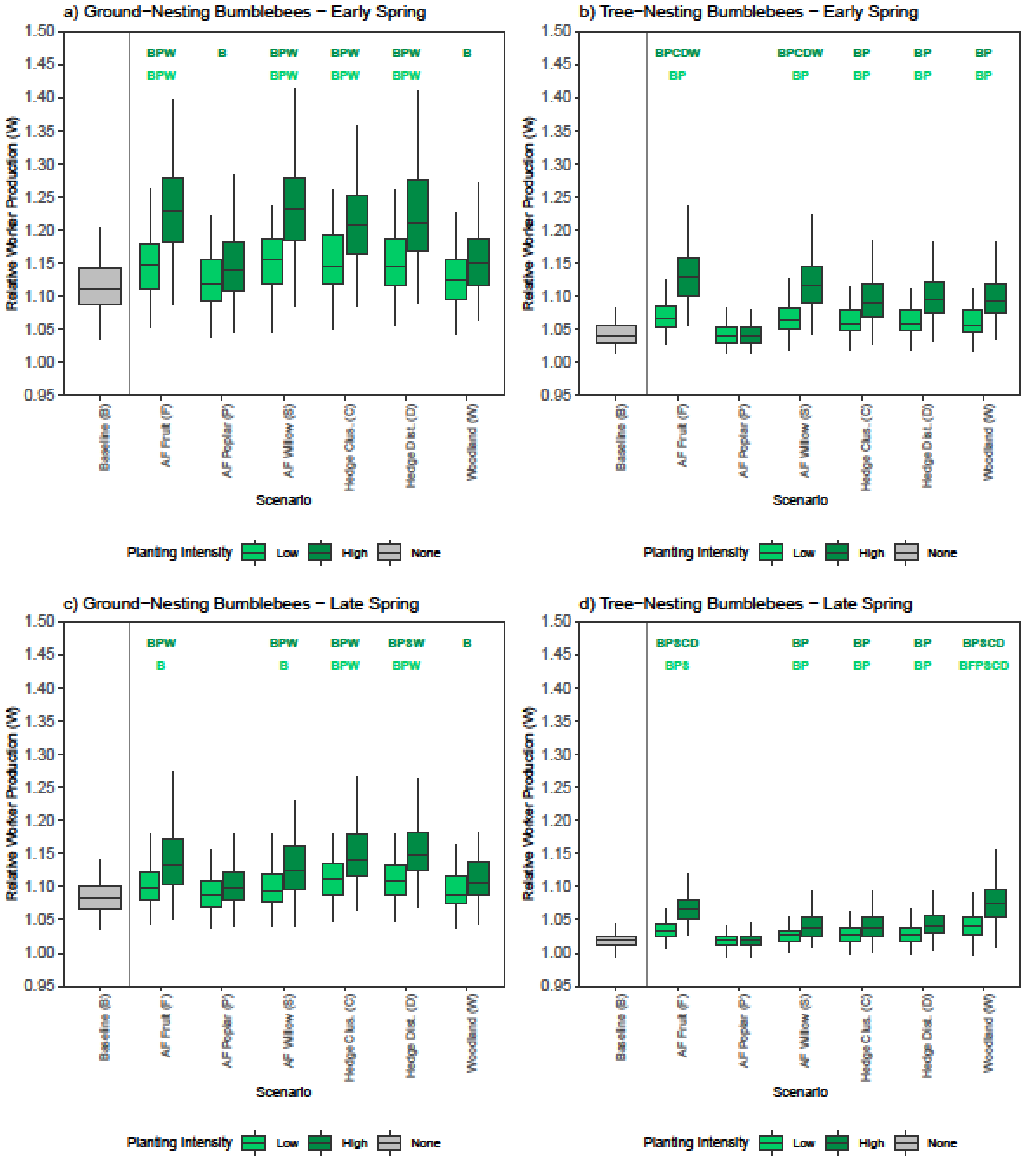

Figure 4.4: Box plots showing relative worker production per season (W – total number of new worker bees produced as a fraction of the number produced with no AES interventions or tree planting present) for the baseline scenario (2016 AES features only; grey) and the tree planting scenarios (2016 AES 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.

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 (Figure 4.4a, c; Table A3.12-13, A3.16-17). Woodland creation required high planting intensity to significantly increase worker production above baseline for this guild, whilst poplar agroforestry only significantly 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 (Figure 4.4a, c).

For tree-nesting bumblebees, the fruit tree and willow agroforestry scenarios, the hedgerow scenarios and the woodland scenario showed significantly higher relative worker production than the baseline and the poplar agroforestry scenario at both planting intensities (Figure 4.4b, d; Table A3.14-15, A3.18-19). In early spring, fruit tree and willow agroforestry also showed significantly higher tree-nesting bumblebee worker production than the 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 (Figure 4.4b, d).

4.3.1.4 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 (Figure 4.5a). Field bean visitation by ground-nesting bumblebees was significantly higher than the baseline in almost all scenarios (woodland being the exception) under high planting intensity, with again only the fruit agroforestry, willow agroforestry and hedgerow scenarios showing significant increases above baseline at low planting intensity (Figure 4.5c). The fruit tree and willow agroforestry scenarios generally produced significantly higher ground-nesting bumblebee visitation rates to both crops than all the other scenarios (Figure 4.5a, c), while the hedgerow scenarios significantly outperformed woodland for crop pollination service provision at high planting intensity.

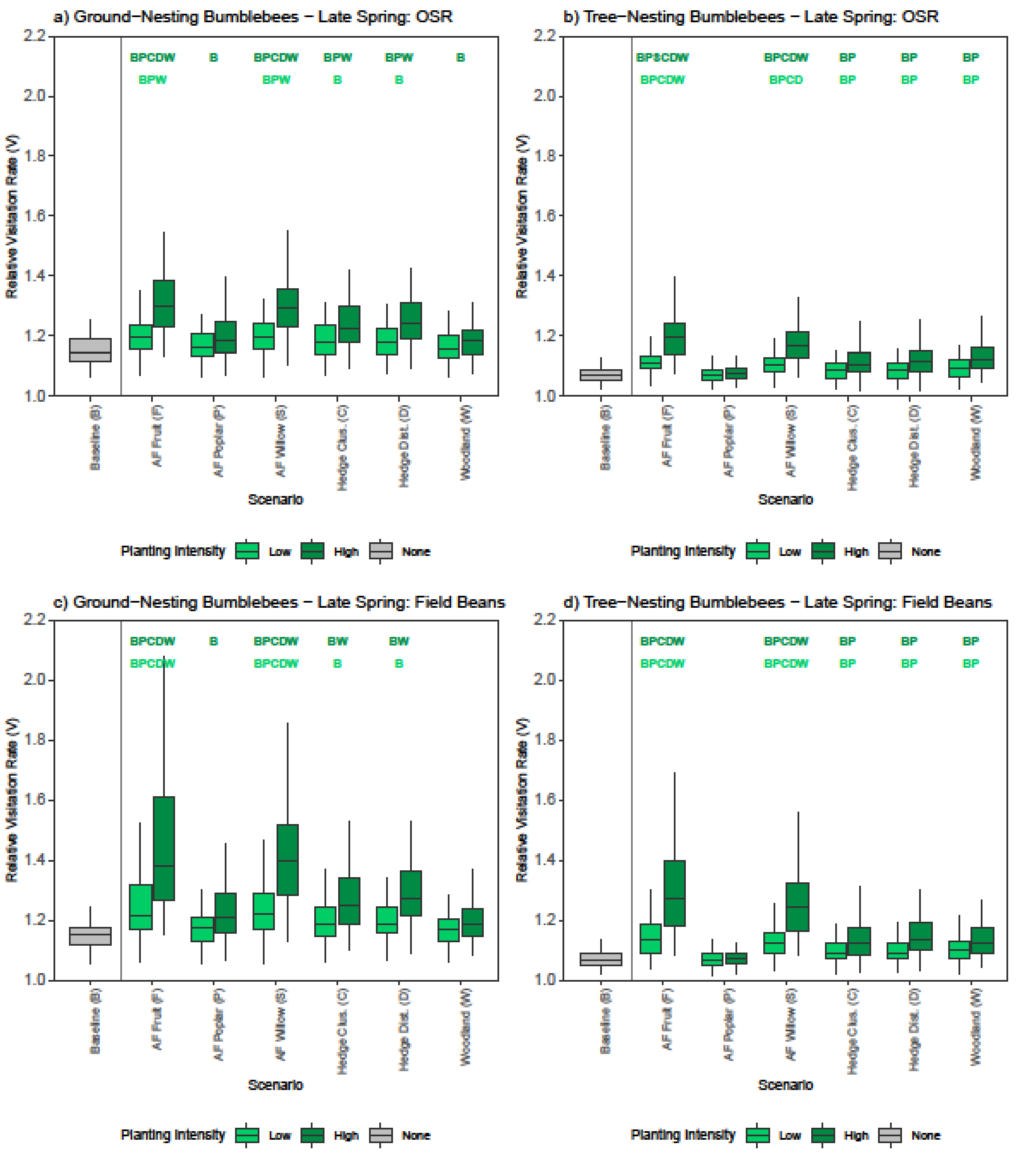

Figure 4.5: Box plots showing relative visitation rate (V – total number of visits as a fraction of the visitation with no AES interventions or tree planting present) to OSR and field beans during late spring (peak flowering) for the baseline scenario (2016 AES features only; grey) and the tree planting 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.

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 (Figure 4.5b, c; Table A3.23-24, A3.27-28). 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 (Figure 4.5b, 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 (Figure 4.5c, d).

4.3.2 Field-level

4.3.2.1 Ground-nesting bumblebees

Figure 4.6 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 (Figure 4.6a). 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 (Figure 4.6b). In both scenarios, cells receiving > 20% increase correspond to those where the hedgerow features themselves are located.

In the fruit and willow agroforestry scenarios (Figure 4.6c 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 correspond to 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 (Figure 4.6d).

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 (Figure 4.6f). However, this most spatially concentrated method of delivering additional tree cover means there is only one woodland patch in or close to the study area at low planting intensity, resulting in no change in bumblebee visitation beyond this 5 km radius.

Figure 4.7 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 (Figure 4.7 c & e) and nearly half the study area in the two hedgerow scenarios (Figure 4.7 a & 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 (Figure 4.7 d & f).

4.3.2.2 Tree-nesting bumblebees

Figures A3.1 and A3.2 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. Figure 4.5 and A3.3; Figure 4.6 and A3.4). 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.

Figure 4.6: 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 (VScenario / VBaseline), 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.

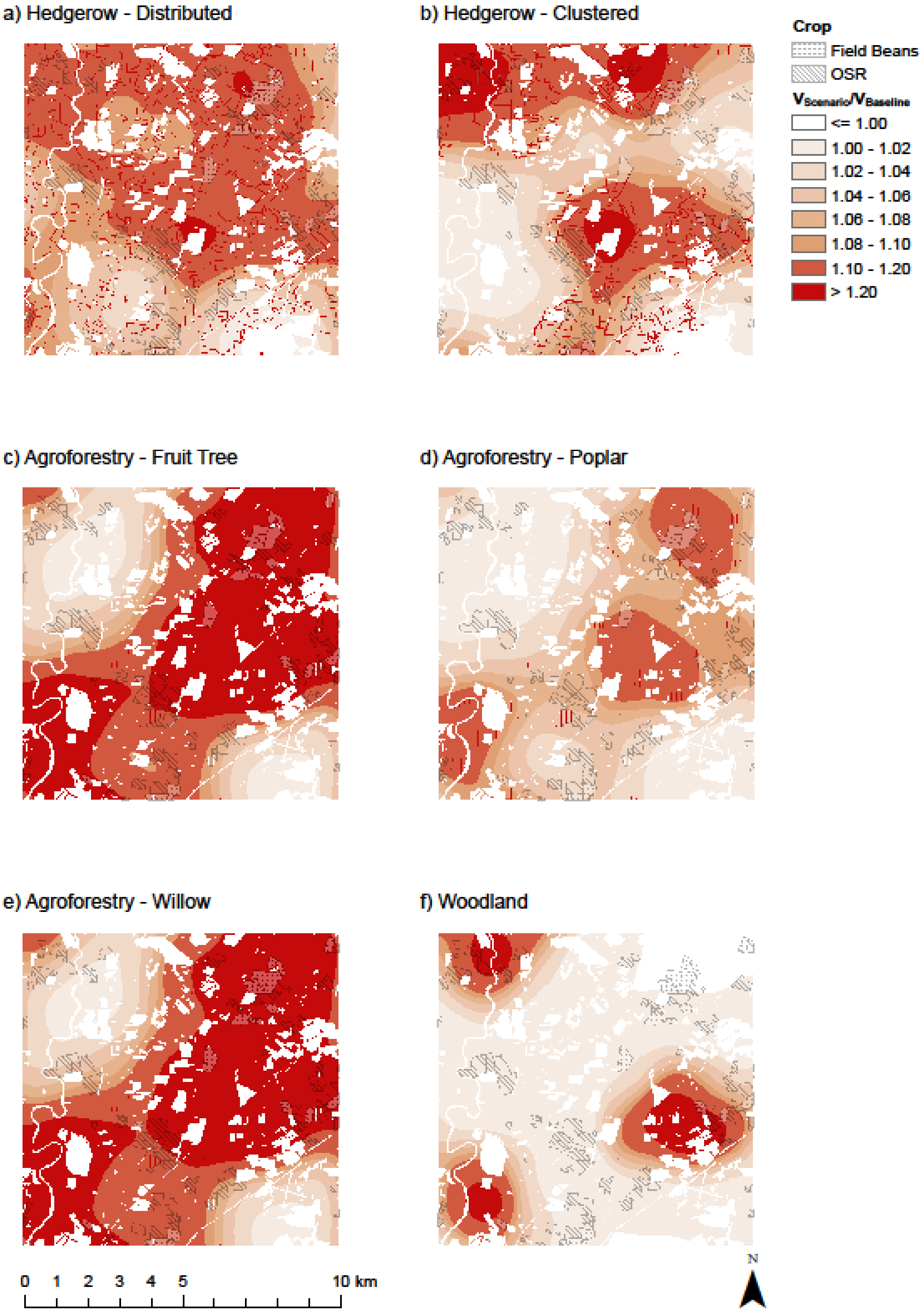

Figure 4.7. Typical spatial distributions for the change in relative ground-nesting bumblebee Late Spring visitation rate for each tree planting scenario, expressed as a fraction of the baseline scenario visitation rate (VScenario / VBaseline), where the additional tree cover corresponds to the high 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.

4.4 Discussion

We have 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.

4.4.1 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 (Stanley *et al.*, 2013; Garratt, Coston, *et al.*, 2014). 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 hedgerow 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 Review), 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 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 (Figure 4.6, Figure 4.7). However, when those increases are averaged across multiple realisations of uptake pattern there was no significant difference as compared to the randomly distributed uptake pattern (Figure 4.5). A limitation of our simulations is that we have not included crop rotation (as information on crop cover was available for one year only) so once an uptake pattern has been determined, there may be greater annual variation in pollination service in the clustered scenario as rotations move mass-flowering crop fields away from / closer to pollinator habitat clusters (Andersson *et al.*, 2014). However, we do not see much difference in the variance of visitation rate between the two scenarios when allowing for alternative spatial realisations and parameter uncertainty, suggesting that any temporal variation in pollination service due to crop rotation may only be minor. This is probably because, even in the clustered scenario, the hedgerow resource is sufficiently distributed across the study area. Indeed, evidence from another simulated uptake study using the same model points to a stabilisation effect of hedgerows on pollination service over the crop rotation cycle (Gardner *et al.*, 2021). This has implications for policy as it suggests that spatial targeting of hedgerow planting for pollination service is not important as long as a sufficient quantity (and quality) of hedgerow is delivered.

4.4.2 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 trees 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 (Nalepa *et al.*, 2020; Graves *et al.*, 2017).

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, sometimes even fields of OSR or field beans themselves (see Figure 4.6 and Figure 4.7). 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. The mass-flowering arable crops (and other nearby semi-natural habitat) can in turn enhance pollination of the (earlier flowering) fruit-trees, because the combination of these two crops offers a complementary year-round floral resource 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 Figure 4.5). 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 collocated 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, it may be sensible to combine agroforestry with hedgerow planting to 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 (Jo Smith *et al.*, 2021).

4.4.3 Woodland

Mature woodland is valuable nesting habitat for both guilds (O'Connor *et al.*, 2017; Crowther *et al.*, 2014), 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 (Kämper *et al.*, 2016; Crowther *et al.*, 2014), 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 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 the parameterisation for mature habitat. 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 (Jo Smith *et al.*, 2021; Burgess, 2019). 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.

4.5 Conclusions

All of the tested tree planting 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. Based on our findings, we make the following recommendations:

1) Extending the hedgerow network 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, a combination of these agroforestry systems and hedgerow planting may be a good compromise.

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 SRC 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 combined with other types of farm tree planting, both of which would help to benefit more bee species than just the specialist tree-nesters.

5 General Discussion

5.1 Overview

AES are programmes of interventions that manage land for the benefit of biodiversity, environmental objectives, and other public goods. Many such interventions are known to benefit wild bees and thus indirectly augment the pollination service that they provide, but the effects have only previous been studied at small spatial scale. This thesis is the first study to investigate the effect of schemes at a national scale, using England and the schemes active in 2016 as its reference point, critically analyse the importance of each option and model the benefits of possible new scheme options. Chapter 2 examined the effect of the schemes in their entirety on the abundance of four wild bee guilds and the pollination service they provide to four key crops. Chapter 3 determined the contribution of different categories of intervention to the main effects predicted in Chapter 2 and examined the reasons for differences in their contribution. Chapter 4 investigated how bee abundance and crop pollination are enhanced when different tree-planting interventions are added to the landscape. In this discussion chapter, the findings from each chapter are synthesised and recommendations derived to inform the design of future schemes. Limitations of the methodologies used are also discussed, highlighting opportunities for future research.

5.2 Synthesis of Findings

5.2.1 Does agri-environment scheme participation in England increase pollinator populations and crop pollination services?

Summary

- The impact of England's agri-environment schemes on wild bee populations was modelled at nationwide scale for the year 2016.
- The model predicts that only ground-nesting bee populations have increased nationally.
- Current schemes produce no significant increase in national crop pollination service.
- However, localised pollination service increases to late spring flowering crops were predicted.
- Lack of significant effect on other crops may reflect limited localised scheme uptake or that constituent interventions have limited effect on inter-year population growth.

The study described in Chapter 2 was a statistical comparison of the outputs of *poll4pop* (a spatially explicit process-based model) between a scenario with all the AES interventions present and a scenario where they were absent. It predicted that the pattern of AES participation in 2016 was effective in boosting ground-nesting bumblebee and ground-nesting solitary bee populations nationally but did not significantly affect tree-nesting and cavity-nesting bee populations. A similar analysis found no overall national-scale effect on the pollination service from to any of the four crops.

Examination of the fine scale maps revealed that less than 5% of the orchard or strawberry growing areas were predicted to receive significantly enhanced crop visitation by any guild during their peak flowering seasons (early spring and summer, respectively). However, 46.4% of the national OSR cropping area and 36.1% of the national field bean cropping area was predicted to experience a significant increase in ground-nesting bumblebee visitation in late spring. Enhancement of tree-nesting bumblebee visitation was less extensive but still reached 26.1% and 20.3% of the OSR and field bean area, respectively. Less than 5% of the area of these crops experienced significantly enhanced solitary bee visitation in this season.

The predictions suggest that schemes are supporting populations of ground-nesting guilds but are not supporting populations of aerial-nesting guilds (tree-nesting bumblebees and cavity-nesting solitary bees). The empirical literature comes to similar conclusions on cavity-nesting solitary bees (Gresty *et al.*, 2018), though the positive effect on ground-nesting solitary bees is likely to be limited to fewer species with more generalist forage requirements only (Wood *et al.*, 2017) and at an overall level solitary bee populations remain in decline (Powney *et al.*, 2019). Recent population increases in more generalist ground-nesting bumblebee species have also been attributed to AES (Powney *et al.*, 2019). The requirements of tree-nesting bumblebees are not met by the schemes assessed because woodland creation and other tree-planting interventions did not factor prominently.

Failure to predict consistent spillover into pollinator dependent crop fields is also consistent with fieldwork, which also finds inconsistent and context dependent effects (Albrecht *et al.*, 2020). Because schemes currently only support enhanced intra-year population growth within the simulations, it is not surprising that they are not predicted to affect orchard fruit pollination service, which relies on foraging from reproductive individuals in early spring. Another explanation could be that AES uptake itself is lower in areas growing orchard fruit, which would also explain why strawberry visitation did not significantly increase (the two crops have a similar geographic distribution). The lack of effect on strawberries (which flower from late spring into summer) could also be exacerbated by the scarcity of the crop in the landscape: it is less likely that interventions are sited close to a field hence they have less chance of being influenced by AES. Reasons for the geographic inconsistency in the OSR and field bean were then explored in Chapter 3.

5.2.2 Which interventions contribute most to the net effect of England's agri-environment schemes on pollination services?

Summary

- The relationship between the area of different intervention categories and predicted net visitation rate change was examined using linear regression modelling within 10 km grid cells.
- Hedgerow / woodland edge management had the strongest positive relationship.
- Floral margins, grass margins and fallow also make important contributions.
- The effectiveness of management contributions depended on their contribution to early season resources (hedgerows, woodland edge) or their placement within the landscape (fallow, grass margin).

In order to further understand the inconsistent pattern of bumblebee pollination service enhancement to OSR and field beans, Chapter 3 took the predictions of Chapter 2 (change in visitation due to AES participation), aggregated them to 10 km^2 grid square resolution and then regressed them against the percentage area uptake of different intervention categories within each square including interactions. The regression coefficients were examined in the context of resource quality (change in early spring floral value * change in nesting value) and total area of uptake nationally to elicit effects of intervention placement.

In general, results were consistent with prior expectations based on intervention resource quality, with area of the hedgerow / woodland edge management category (providing high quality resources) showing the strongest positive relationship with net change in visitation. The relationships was stronger where background cover of high-resource value non-scheme habitat was lower, consistent with theories of landscape ecology (Tscharntke *et al.*, 2005; Tscharntke *et al.*, 2012). There were some differences from this general trend for certain intervention – crop visitation relationships: floral margin area showed a positive relationship with OSR net visitation but not for field beans, whilst fallow areas (and to a lesser extent grass margins) had a stronger effect than expected based on resource quality alone, suggesting effective placement with respect to mass-flowering crops. Tree planting did not occur at sufficient scale within the scheme to make a significant contribution to the net response, despite the high resource-value potential of early-flowering types (e.g. traditional orchards). The weaker relationship between floral margins and net visitation vs. hedgerows/woodland edge is predicted by resource quality which values early spring flowering resource more than later season flowering. Floral margins also have lower uptake, meaning that they do not enhance populations consistently over space (Carvell *et al.*, 2015), so are less able to influence field bean parcels which are rarer in the landscape.

The varying geographical scheme effect on OSR and field bean pollination service predicted in Chapter 2 is therefore likely related to the pattern of uptake of higher quality early spring floral and nesting resource interventions such as hedgerow and woodland edge management. In landscapes with limited uptake of these interventions, the contribution to net pollination service is reliant on more moderate quality resources such as fallow and grass margins, though these can still make important contributions to mass-flowering crop pollination by virtue of being located close to the crops.

5.2.3 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.

Summary

- Different farmland tree-planting scenarios in a typical English arable landscape were modelled to determine effect on bumblebee abundance and crop visitation.
- Two planting intensities were evaluated: current planting rates and planting rates necessary to achieve government planting targets.
- Hedgerows and woodland produced the greatest increase in bumblebee abundance.
- Fruit tree and willow agroforestry produced the greatest increase in crop visitation.
- Hedgerows produced a smaller increase in crop visitation than agroforestry, but this was spread over a larger area.

A further conclusion from Chapter 3 was that tree-planting interventions have potential to be effective at enhancing bumblebee populations and crop pollination services if taken up at sufficient scale. UK land use policy now requires woodland creation rates to increase at least three-fold on current levels and the government’s climate change advisory body (Committee on Climate Change) has also recommended increasing hedgerow cover and adopting agroforestry at scale. Hence, in Chapter 4, a set of six equal area tree-planting scenarios covering hedgerow planting (one scenario spatially clustered and one more evenly distributed), silvoarable agroforestry (three scenarios using fruit trees, willow and poplar, respectively) and conventional woodland creation (one scenario) were developed and applied to a representative English arable landscape. Bee abundance and visitation to OSR and field beans were calculated using poll4pop for ground-nesting bumblebees and tree-nesting bumblebees for each scenario and for a baseline without additional tree planting and compared using

ANOVA and post-hoc tests at two levels of planting intensity reflecting current and policy ambition rates.

Hedgerow planting and woodland delivered the greatest predicted enhancements to bee abundance for ground-nesting and tree-nesting guilds, respectively. Silvoarable agroforestry using fruit trees or willow delivered the greatest mean enhancements to crop pollination service for both guilds, but these increases were more variable than those predicted for hedgerow creation. Agroforestry with poplar and woodland creation were only effective at enhancing crop pollination at high planting intensity. There was no difference between the clustered and distributed hedgerow scenario on any measure of abundance or crop visitation.

Differences between scenarios reflected both resource quality and placement in the landscape. Abundance was more sensitive to resource quality: hedgerow provides the highest resource quality for ground-nesting bumblebees and woodland for tree-nesting bumblebees. Crop visitation was sensitive to both resource quality (to enhance populations sufficiently but not compete with the crop during its flowering period) and placement (to be sufficiently close to nearby crops to produce a crop pollination service spillover effect). At the levels of intensity simulated, there was always enough hedgerow distributed across the landscape's field boundaries for some pollinator-dependent crops to experience a significant spillover, but within-field agroforestry interventions may be placed still closer to the target crops. Some agroforestry configurations could therefore be highly effective in a given year, but this would vary with crop rotation. Poplar offered insufficient resources to support enhanced populations, whilst woodland creation was predicted to be too geographically concentrated to affect a sufficient proportion of the mass-flowering crop area.

5.3 Implications for England's new Environmental Land Management Scheme (ELMS)

The thesis has predicted the effect of the current English AES scheme on pollinator abundance and pollination service to four key crops at national scale. It has determined the relative contribution of interventions within that scheme to two mass-flowering crops that experienced a net service increase. It has also examined the potential for different tree-planting interventions to enhance the level of pollination to those two crops. The findings have important implications for the development of the successor scheme (ELMS) which are explored in this section.

5.3.1 The Environmental Land Management Scheme (ELMS)

ELMS is three-tier scheme consisting of the Sustainable Farming Incentive (SFI), Local Nature Recovery (LNR) and Landscape Recovery that will gradually replace the previous CAP architecture (BPS + CS). The SFI began its pilot in 2021 and will be formally launched in 2022 as an 'entry-level' scheme focussed on common farmland features (e.g. soils, hedgerows, waterbodies, grassland etc.) and is intended to promote appropriate environmental management. The LNR will pay for more detailed, sophisticated actions intended to meet local environmental priorities. Landscape Recovery will pay for large-scale long-term projects which include landscape-scale tree planting, peatland restoration and 'rewilding'. LNR and Landscape Recovery will pilot in 2022. Unlike the CAP, entry to ELMS will be entirely voluntary even at the entry-level.

The SFI will consist of a set of 'standards' which govern how certain aspects of farms are managed. In the 2021 pilot there were eight standards covering: arable and horticultural soils, arable and horticultural land, farm woodland, hedgerows, improved grassland, improved grassland soils, low and no input grassland and waterbody buffering (Defra, 2021c). Landholders entering the scheme commit all features on their land to the scheme's management requirements and receive an area-based payment which varies depending on whether they select Introductory, Intermediate or Advanced level of management.

The land-based standards (Arable and Horticultural Land, Farm Woodland, Improved Grassland, Low/No-Input Grassland, Waterbody buffering) contain the management requirements most relevant wild bees and pollination services, and cover most of the interventions studied in this thesis, with the key exception of tree planting. The key details of the initial proposed standards (as of August 2021) are as follows (Defra, 2021c):

- In the **Arable and Horticultural Land Standard Introductory Level**, for all the land entered, farmers would need to provide 1% area under management suitable for nesting and 2% under management that provides florally rich habitat. Farmers have flexibility on how to implement but nesting actions suggested include bare ground, fallow plots, grass margins / field corners, and herbal leys. Suggested floral actions include floral margins / plots and legume-rich ley/fallow. These percentages increase in the Intermediate and Advanced levels.

- **The Hedgerows Standard** sets out a cutting regime which, at Introductory Level is similar to the requirements of the legacy CS option. At Intermediate or Advanced levels, the cutting regime is slightly less frequent, and a grass buffer is required on both sides of a certain percentage of the hedgerow.

- **The improved grassland standard** requires some land to be kept out of intensive grazing and cutting: 2% of land to develop into tall vegetation / scrub and a third of hay/silage fields margins uncut. Low/no input grassland requires all of the hay/silage margins to be uncut and a grazing regime that maintains a minimum sward height to allow flowers to develop.

- **Waterbody buffering** required the establishment of grass or flower rich buffer strips.

- **The Farm Woodland standard** makes no mention of woodland edge management but does require landholders to maintain gaps/rides between blocks of woodland which provide similar opportunities for wild bees.

The 2022 formal launch will only cover arable and horticultural soils, improved grassland soils and moorland which do not contain measures explicitly focused on wild bees and pollination services (Defra, 2022a). According to Defra (2022c), the Hedgerows Standard is expected to be launched in 2023, whilst 2024 should see the start of the Low/no-input Grassland Standard and Waterbody Buffering Standard . There is no mention of the Arable and Horticultural Land and Improved Grassland Standards, but a Farmland Biodiversity standard is due to be released in 2024 which may be an amalgamation of these. The Farm Woodland standard will not be formally launched until 2025 but an Agroforestry Standard may precede it in 2024. There is no detail to date as to what project types will be funded under the LNR. However, since it is focussed on local requirements it is likely that this could be the vehicle to fund investments to support wild bees with more specialised habitat requirements whose populations are currently more geographically constrained. As mentioned above, the Landscape Recovery tier will be the vehicle for large scale tree planting. This is not likely to include agroforestry (given that there will be a specialised standard) but could include hedgerow planting where needed on a landscape scale.

5.3.2 How ELMS could enhance wild bee populations and crop pollination services

5.3.2.1 Encouraging sufficient early floral cover and nesting resource

The predictions from Chapter 2 suggest that existing schemes enhance intra-year population growth more than they enhance the number of nests (compare Figure 2.2 vs. Figure 2.3). This may explain why crops flowering in early spring (i.e., orchards) which are reliant on solitary bees and bumblebee queens, experience no pollination service benefit (Figure 2.4). Even OSR and field beans flowering in late spring when bumblebee workers are foraging receive a geographically variable enhancement (Figure 2.8), which may be related to inconsistent uptake of early-flowering interventions (Chapter 3). To provide a more long-term population increase and to support greater and more consistent pollination service across crop types, schemes need to increase both nesting resource and early spring floral resource provision. The other possible reason for the lack of effect on orchards and soft fruit (which flower in the summer) is that overall uptake of interventions was insufficiently high in areas growing these crops.

The recognition in the SFI Arable and Horticultural Land Standard that farmers need to provide both nesting and floral resources to support pollinators is therefore welcome, especially on the nesting side which was not an emphasis in previous schemes. The proposed 2% land allocation to floral cover interventions within AES (including flower-rich leys) would be in line with other estimates of minimum requirement to sustain common wild bee species (Dicks *et al.*, 2015). Minimum provision of 1% nesting resource at this level would be addressed in the SFI through fallow plots and grass margins, which Chapter 3 has shown to be especially important in resource-poor landscapes, and bare ground.

The average percentage uptake of current scheme interventions in 2016 of these categories (combined floral margin + floral ley, combined fallow + grass margin) within a given 10km^2 tile was 0.29% and 0.97% of the tile's arable cropping area respectively (Figure 3.3). Therefore, under the current scheme, the average farm is likely to already meet the proposed minimum nesting habitat requirement but fall well short of the proposed minimum floral resource requirements. Assuming no loss of existing resource upon transition to the new scheme, this implies that that the area of floral margin / ley cover would increase. This would address the issue of low uptake, though only if extended to areas growing orchards and soft fruit, and may benefit field beans, which are (currently) rarer in the landscape and, Chapter 2 indicates, are generally not benefitting from the existing scheme. However, the current specification for floral margins promotes plants that flower in the summer, so the sowing mix would benefit from the inclusion of some early-flowering plants as suggested in Section 3.4.2. Moreover, the results of Chapter 2 also point to a nesting limitation in the existing scheme, so achieving the 1% nesting target through maintaining the existing fallow and nesting provision may not be sufficient to enhance pollinator populations and pollination services. Incorporating hedgerows and other woody vegetation (which also offer good quality nesting resources for most guilds – see Figure 3.3 and Figure A2.1 - Figure A2.3) would be one way of doing this (Requier and Leonhardt, 2020), and was shown to be valuable in Chapter 4. However, under the currently proposed programming farmers can choose which standards to take up so more integration and cohesion may be required to ensure sufficient nesting resource is created across farms. Alternatively, schemes could seek to provide nesting resource through more bespoke interventions (see 5.3.2.2 below).

The prediction that the move to the SFI will increase floral margin uptake and thus benefit pollinators and pollination services relies on the presumption that farmers will be willing to participate in the Arable and Horticultural Land Standard to an extent that overall uptake of measures will be greater, and that the distribution of those interventions will be aligned with crop distributions. In its pilot form, the payments on offer to farmers would not offset the current BPS and direct income from crops that would be replaced by this habitat (AHDB, 2021) , so this may reduce uptake or at least bias it towards farms with greater availability of less economically productive land. It may also be challenging to encourage uptake on farms growing orchard fruit and strawberries, where economic returns from crop production are already higher and AES uptake has always tended to be lower (Lastra-Bravo *et al.*, 2015). Payment rates will need to increase to encourage wider uptake.

5.3.2.2 Resource diversity and considerations for solitary bees

Chapter 2's results suggest that current schemes are only supporting ground-nesting guilds for abundance and bumblebees for crop pollination (of mass-flowering crops only). The requirements of tree-nesting bumblebees are not met by the schemes assessed because woodland creation and other tree-planting interventions did not factor prominently. From a bee conservation perspective, this is not a criticism of previous schemes design: *Bombus hypnorum* has only become established in England within the past 10 years and has expanded its range in the absence of policy support (Huml *et al.*, 2021). Indeed, Chapter 4 demonstrates that, if suitable trees are planted in arable landscapes, tree-nesting bumblebees would increase in abundance and indeed crop pollination service.

The foraging needs of cavity-nesting solitary bees are quite specialised and no interventions in the schemes assessed adequately provide them (Gresty *et al.*, 2018), which is reflected in the parameterisation (Table A1.10). Even though the simulations predict significant increases for ground-nesting solitary bees, this is a very broad guild and empirical evidence suggests that many species within it do not benefit from interventions as they are insufficiently customised to foraging needs (Wood *et al.*, 2017). Greater customisation and diversity of sowing mixes or habitat types may be required to benefit a greater range of solitary bee species. None of the interventions assessed include explicit interventions aimed at providing nesting resources for solitary bees (e.g., bee hotels for cavity-nesters, bare ground patches for ground-nesters). If well-designed and sited, these have been shown to increase populations in the field (MacIvor, 2017; Nichols *et al.*, 2020) and should be a consideration in ELMS. Achieving greater pollination service from solitary bees also needs to reflect their shorter foraging and dispersal range. Small field corner or field edge features that are several hundred metres apart may suit bumblebees (Cranmer *et al.*, 2012), but may be too far apart to facilitate solitary bee dispersal (Martínez-Núñez *et al.*, 2020; Woodcock *et al.*, 2013). Scheme design should seek to ensure interventions (and existing habitat) are sufficiently contiguous across the landscape.

5.3.2.3 Hedgerows

Hedgerow management had the largest unit contribution of any intervention to net mass-flowering crop pollination service due to its combined early-flowering and nesting resource provision (Chapter 3), so ensuring that this management is maintained or ideally more widely adopted is important for future schemes. The proposed cutting regime set out in the pilot phase of the Hedgerow Standard would require a similar regime to, and therefore provide a level of resource quality as, the CS option (BE3 – Management of Hedgerows) and so would maintain that level of pollination service enhancement if uptake remains the same. It may even be more effective at a farm level, as it is required to be applied to all hedgerows on a holding rather than being applied to 100 m stretches. It is possible that the SFI budget limitations may constrain uptake to certain farms only, which might be a concern for pollination services. However, as demonstrated with hedgerow planting in Chapter 4, as long as the overall uptake within a region remains the same, a more concentrated set of hedgerows under management may not underperform a more distributed set, though this may not be ideal for solitary bee pollination (see 5.3.2.2 above).

In the 2016 dataset, the mean percentage of the woody linear feature resource under AES management (BE3 or a legacy ES hedgerow option) was 68% which suggests there is only limited scope for expansion of enhanced management (unless new hedgerows are created), especially as the woody linear feature layer does not distinguish between true hedgerows and other woody linear features (shelterbelts etc.). As discussed in Section 3.4.6, the potential of hedgerow management for enhancing bee populations might be greater compared to under the current AES if the additional grass margin feature required in the higher levels of the standard were also applied, as this would further increase the quality of nesting habitat for ground-nesting bees. Again, this requires more cohesion between SFI standards.

The value of hedgerows may be better realised if support for hedgerow planting is incorporated into the scheme, which was shown in Chapter 4 to be an effective mechanism to enhance ground-nesting bumblebee abundance and mass-flowering crop pollination service. Indeed, if hedgerows were planted at the rate planned for woodland expansion, then the simulations show that even tree-nesting bumblebee populations would benefit. Hedgerows also have an advantage over woodland from a crop pollination perspective because they are distributed more widely through the landscape, and so can be closer to the pollinator dependent crops even allowing for crop rotation. Hedgerow planting was not factored into the SFI pilot, so may be something planned for a higher tier. The challenge with delivering this through LNR and Landscape Recovery is whether such schemes are likely to draw interest in arable-dominated areas. This may require hedgerow expansion to be set as a local priority or else is specifically targeted in Landscape Recovery. Alternatively, the requirement of the Hedgerow Standard could set more explicit targets for hedgerow planting, assuming payment rates can rise so that farmers are appropriately compensated.

5.3.2.4 Woodland creation and Agroforestry

Tree planting interventions have high potential to enhance both wild bee populations and crop pollination service because they can provide a combination of attractive early-season floral resource and nesting resource (see Figure 3.4). The potential for hedgerow creation has been discussed above, but woodland planting and agroforestry will be important components of ELMS, especially if the government's tree-planting ambitions are to be met.

Detail of the proposed Agroforestry Standard is not available at the current time, but it is nonetheless encouraging that Defra is planning to provide incentives for farmers to be in the measure. Chapter 4 demonstrates that Agroforestry will provide the greatest enhancement in crop pollination service by bumblebees on a unit area basis, but only if fruit trees and willow are used. Clearly, this may not suit all farmers but support within the Standard should reflect the wider benefits that fruit trees and willow could provide (Staton *et al.*, 2021) or at least farmers made aware of the possible co-benefits to crop pollination (Varah *et al.*, 2020; Staton *et al.*, 2022), which may incentivise greater uptake. Chapter 4 also showed that the agroforestry effects on crop pollination service were very sensitive to placement pattern, meaning they are likely to vary with crop rotation. Combining some agroforestry interventions with some hedgerow planting would reduce that variability in exchange for a lower pollination service enhancement, so the design of the Agroforestry Standard and any other aspect of ELMS that incorporates hedgerows should be mutually compatible.

There was very little woodland creation in the 2016 dataset studied for Chapters 2 and 3, so not surprisingly there was no relationship found between woodland creation and scheme net pollination service. If uptake increases considerably (to the government's policy ambition rate of ~7,000 ha yr^{-1} then Chapter 4 demonstrated that woodland creation would increase bumblebee populations and would provide some pollination service benefit to mass-flowering crops. Woodland creation itself will still benefit wild bees once trees are established, and especially the tree-nesting bumblebee. However, it will take decades before the trees deliver a woodland feature of equivalent quality to the one modelled in this study and the benefits are localised around the plot rather than distributed across the landscape like hedgerows and agroforestry.

Large-scale tree planting and/or establishment through passive management and succession will be delivered through the Landscape Recovery tier. Given the planning constraints on woodland creation and economic barriers, woodland creation is unlikely to be a focus of investment in predominantly arable areas except possibly where there are other drivers such as local targets for, say, carbon sequestration or flood risk management under Local Nature Recovery Strategies (Defra, 2021b). Delivery could be achieved in arable areas by promoting smaller plot sizes that are more widely distributed, which would achieve a similar effect to hedgerows.

5.3.3 Summary of recommendation for ELMS

In order to boost populations of wild bees, enhance the quantity of pollination service provided to crops and wider plants, and improve the resilience of pollination service, ELMS should:

- Aim to achieve 2% floral resource land cover through sown margins/plots and flower-rich leys but adjust sowing mixes to provide more early-flowering plant species.

- Maintain support for fallow and grass-margins but offer and promote further interventions that increase the quality of nesting resources (e.g., hedgerows, bare ground). This will require greater cohesion between scheme components than is currently programmed.
- Promote hedgerow and woodland edge management and extend the hedgerow network in arable areas.
- Promote fruit-tree and willow silvoarable agroforestry.
- Where woodland is created for other environmental objectives in arable landscapes, encourage a wider distribution of smaller area projects where feasible.
- Increase the range of interventions that provide resources for solitary bees to support a wider range of species and improve placement of interventions to create habitat contiguity over shorter distances to facilitate better dispersal.
- Consider existing levels of pollination service when targeting uptake: interventions will be more effective when located in areas growing pollinator-dependent crops with limited pre-existing habitat. Payment rates may need to rise to overcome this hurdle.

5.4 Limitations and Recommendations for future study

5.4.1 Improving model parameterisation

Considerable effort was expended to create and parameterise a landscape that was as reflective as possible of agricultural, non-agricultural, and agri-environment feature cover in 2016, and floral visitation rate predictions for this scenario (*AES_Present*) were validated against field data for the four modelled bee guilds. The hypothetical *AES_Absent* scenario's parameterisation was informed by the BD2302/5007 studies (University of Hertfordshire, 2009; University of Hertfordshire, 2011) which was itemised for every intervention in the scheme and also accounted for additionality and quality of implementation. Nevertheless, the parameters underlying both scenarios ultimately relied on expert opinion on bee habitat preferences, which for some land classes was quite variable. Moreover, although the use of BD2302/5007 applied a consistent protocol for adjusting land cover, these changes are still based on the authors' assumptions about typical AES outcomes which may be quite variable in practice. In addition, where BD2302/5007 did not provide relevant information, bespoke assumptions were needed (e.g., that AES hedgerows are twice the width of non-AES hedgerows).

The approach used to compare scenarios accounted for this uncertainty, meaning that the net impact of any given land cover change between *AES_Present* and *AES_Absent* was also quite variable. To a certain extent this has captured true variability in intervention outcomes (i.e., the level floral cover or attractiveness actually achieved), so interventions whose outcomes were more uncertain would need a greater mean impact to achieve significance. However, this was only based on an expert opinion driven estimate of that variability, and the central point of that variation reflects the BD2302/5007 and other assumptions. For example, the effect of AES on tree-nesting bumblebee and cavity-nesting solitary bee populations across all land cover types is still positive (Figure A1.1- Figure A1.4) but the change is not large enough to reach the 2 standard deviation significance threshold. If there was less uncertainty in the change in cover and attractiveness, then this might have led to different conclusions and greater discussion of relative effect size (AES effect on ground-nesting guilds is clearly stronger). Meanwhile, the conclusion that hedgerows are contributing the most to the net effect of AES on crop pollination service could also have been influenced by the parameterisation assumption made, though that assumption was supported by empirical evidence (see section 3.4.1).

Ideally, the parameters used in both scenarios would be populated from robust data so that a fairer distribution of their parameters could be used. Future applications of the model would therefore benefit from methods to parameterise the attractiveness and floral cover values more accurately. Advances in remote sensing methods could allow for floral cover to be mapped in real time across the country, or perhaps more realistically for an area of interest (Gonzales *et al.*, 2022). This would mean that a specific floral cover parameter could be applied to each cell on the map for a given season and so also incorporate geographic variation in habitat quality rather than drawing random parameters from a generic expert-derived distribution of scores for each habitat. Where such techniques can also differentiate the composition of floral cover (Barnsley *et al.*, 2022), then this could further refine the floral attractiveness score in the model (where pollination – plant interaction dynamics and preferences are known). Even if these techniques could not give this level of detail, they may at least be able to narrow the uncertainty range. Remote sensing methods would also need to improve to distinguish small features of differential nesting value within a given land cover class (e.g., south-facing patches of bare earth for ground-nesting solitary bees) which could then be given higher nesting value relative to the rest of the land cover and at the same time reduce the overall uncertainty. More empirical work on nesting preferences is also needed to narrow the uncertainty range for nesting attractiveness across guilds (Antoine and Forrest, 2020; Requier and Leonhardt, 2020).

5.4.2 Multi-year assessments

The approach used also used a single year (2016) as its reference point, therefore it only captures the effectiveness of schemes and interventions over one landscape configuration. In reality, landscape configuration is dynamic as OSR and field beans rotate around the landscape with other crops, usually in blocks. Therefore, interventions that were ineffective for mass-flowering crop pollination due to location in 2016 may become effective in subsequent years when the crops are closer. A further complicated not accounted for in the single year assessment is that the AES pattern will also change as some features rotate with crops (e.g., grass margins, fallow plots) and also as new agreements start, and old ones expire.

Only focussing on one year has also meant that changes in crop choice due to external factors are not captured. Crop choice also varies over time due to external factors. In England the area of OSR coverage has dropped from 713,570 ha in 2016 to 268,400 ha in 2021 (Defra, 2021a). This decline in area has been partly attributed to the 2013 moratorium on neonicotinoid plant protection products which has made control of the cabbage stem flea beetle more challenging but was also related to declining market prices for the crop (AHDB, 2020a). The moratorium itself was introduced to protect bees from the toxic effect of the products. Although this may have led to a reduced area of pollinator dependent crop, by making the crop area scarcer it may actually increase the dependency on AES features as seen for field beans in Chapters 3 and 4.

Capturing the change in rotational AES features would be a challenge based on the lack of spatial explicitness in current AES datasets, though assumptions could be made. Accounting for external factors such as pesticide bans, relative pricing etc is challenging from an *a priori* perspective, but an improvement to the study would have been to at least allow for a full cycle of crop rotation. To a certain extent this was accounted for in Chapter 4 by allowing for spatial variation in the interventions, though it would have been helpful to have accounted for both. A full rotation cycle may not have made such a difference to the results of Chapters 2 and 3 where the national averaging would have smoothed out local configuration changes but would be important to consider if the spatial outputs are used at smaller spatial scale. A multi-year assessment would also have helped capture the extent to which interventions affect the variability in pollination service enhancement over time. Indeed, subsequent applications of the model incorporating six year crop rotations have predicted both higher and more stable wild bee populations and pollination service in landscapes containing more boundary features (Gardner *et al.*, 2021).

In Chapter 4 the interventions were compared as if they were mature habitats, whereas in practice agroforestry and hedgerow trees take 10 – 20 years and woodland 80 – 160 years to reach this state (see section 4.4.3). A multi-year assessment would also potentially allow for these differences to be accounted for in the study and may have further demonstrated the importance of agroforestry and hedgerow systems in supporting wild bee populations and pollination services. Parameterisation would also need to be adapted to reflect the maturity profile. A multi-year assessment could also capture the effect of climate change on floral and nesting resource availability and suitability across guilds which may have a bearing on the effectiveness of interventions.

5.4.3 Measuring pollination services

The metric for pollination service used in the study was visitation rate but the relationship between visitation rate and crop yield is not always linear and may saturate since each flower visited only requires a certain number of visits to be fully pollinated (Park *et al.*, 2016; Garratt, Coston, *et al.*, 2014). Additional visitation above this threshold will not matter from a yield perspective. Hence crops that were already above or close to this threshold in the *AES_Absent* scenario would not have benefited in terms of yield increases from further visitation rate increases due to the AES interventions. Similarly, if existing AES schemes already take visitation above that threshold rate, then applying additional tree-planting interventions will not affect crop yield.

There is empirical evidence that apples and OSR suffer some pollination service deficit (i.e. the actual visitation rate is below threshold) in the UK (Garratt *et al.*, 2013; Holland *et al.*, 2020), but the national spatial configuration of these deficits is not known. Pollination service deficits do not appear to have been studied for field beans or strawberries in the UK, so again there is no national scale map. As such, it is not clear where interventions should be targeted to meet economic or food security considerations. It was not possible to extrapolate to yield effects in this thesis as robust relationships between predicted visitation rate in the *poll4pop* model and field measurements of crop yield had not yet been determined for any of the crops in question. However, future applications of the model will incorporate recently derived yield relationships (Gardner E., *pers comm*) and thus will be able to identify locations of pollination service deficits to inform economic and food security assessments. However, this will also require model outputs to integrated across pollinator guilds (see 5.4.4) including hoverflies (see 5.4.5) to account for the fact that some crops are visited by more than one guild (Hutchinson *et al.*, 2021).

5.4.4 Model limitations

The *poll4pop* model itself has certain limitations. Firstly, it does not account for intra-year mortality: in the model the populations grow proportional to the quantity of resources collected, but never reduce. In reality, if resources become scarce during the year due, say to extreme weather, then some mortality will occur (Vanderplanck *et al.*, 2019). It also means that the model cannot be used to accurately model the impact of the autumn season for social bees because it will does not account for death of workers and current reproductive individuals through old age and/or resource shortage. The most common ground-nesting bumblebee in England (*Bombus terrestris*) remains active well into the autumn and even into the winter in locations that are sufficiently warm and where there are late flowering resources (Stelzer *et al.*, 2010).

Farmland floral provision in September through ivy (*Helix hedera*) or red clover (*Trifolium pretense*) has been shown to be a strong predictor of subsequent year *Bombus terrestris* colony growth (Timberlake *et al.*, 2021). If an intra-year mortality element based on declining resource availability and old age were available in the *poll4pop* model then the importance of later flowering resources could be demonstrated. This would have increased the value of grassland creation/restoration and hedgerow / woodland edge interventions where red clover and ivy (respectively) would be more abundant) and so would have affected the results of all Chapters but especially 3 and 4, with implications for future AES design. Inclusion of an intra-year mortality effect would also help incorporate impacts of extreme weather events as well as average temperature rises that are predicted to occur with climate change. An advancement, 'LandscapePhenoBee' has recently been developed to incorporate temperature effects and resource scarcity (Blasi *et al.*, 2022). The model improves *poll4pop*'s temporal resolution from seasonal to weekly, so fluctuations in resource availability and crop flowering windows can also be more accurately represented. Interestingly, the model predicts that the adverse consequences of drought on bumblebee populations are higher in landscapes with lower proportions of semi-natural habitat, thus emphasising the importance of providing AES interventions in more intensive landscapes (Blasi *et al.*, 2022). Obviously, these advancements increase the data requirements and thus add to the challenge of repeating the study at a national scale but would enable more robust assessment of scheme effectiveness.

Secondly, the model assumes that new reproductive females disperse at the end of their active period to find new nest sites whereas actually this nest search happens at the beginning of the subsequent active period (Antoine and Forrest, 2020). This means that early spring foraging will actually start near the old nesting locations and then migrate to the new nest site when it becomes established. This may have implications for the configuration of early season floral resources to maximise the number of nests which then become established. Indeed, availability of early spring floral resources will become a more important component, because nests are more likely to be established where these resources are abundant. If this functionality had been available, the effect of early flowering resource features such as hedgerows and agroforestry (fruit trees, willow) would have been amplified, potentially affecting the results of all three Chapters and further strengthening the recommendation to promote them in ELMS.

Thirdly, the model is currently constrained to study species or guilds in isolation. In practice, species are competing for the same resources with other wild bee species with similar preferences and also with domesticated pollinators such as the European honeybee (*Apis mellifera*) (Goulson *et al.*, 1998). There is evidence that honeybee competition can moderate population sizes of wild bees, especially where floral resources are limited (Goulson and Sparrow, 2009; Elbgami *et al.*, 2014). Bumblebees can also be a source of competition pressure on solitary bee species (Wignall *et al.*, 2020), and generalist species such as *Bombus terrestris* can also exert competitive pressure on more specialist bumblebees especially where they are introduced (Nagamitsu *et al.*, 2010). Indeed, honeybees and commercially managed bumblebees can also spread parasites to wild bees, further affecting colony growth (Graystock *et al.*, 2014). This work has focused on guild-level abundance, but accounting for intra-specific competition and location of managed pollinators would enable the effectiveness of interventions for supporting bee diversity to also be assessed, which is important since pollinator diversity is known to also affect the level and resilience of pollination service (Eeraerts *et al.*, 2019). Integrating model runs for multiple guilds or species is also a necessary step to determine if interventions affect crop yield and not just visitation rate (see Section 5.4.3).

5.4.5 Model expansion

The thesis only considered wild bees as a pollinator. Hoverflies were not included because the model has not yet been developed to account for their foraging and dispersal which differs from bees: adults only collect pollen or nectar for themselves, and disperse linearly rather than returning to the same site (Jauker *et al.*, 2009). Yet hoverflies also benefit from provision of AES interventions (Holland *et al.*, 2015; Rotchés-Ribalta *et al.*, 2018; Berkley *et al.*, 2018) so their non-inclusion in this study was a limitation in the completeness of the modelled scheme effect because hoverflies make an important contribution to OSR pollination (Garratt, Coston, *et al.*, 2014). Managed pollinators (honeybees and commercially managed bumblebees) were not included in the model because data was not available on the location of hives and nests. Although honeybees are not the most important contributor to crop pollination, there were approximately 260,000 hives in the UK (Animal Plant & Health Agency, 2022) which would still account for up to 34% of UK pollination service demand under optimistic assumptions (Breeze *et al.*, 2011; Hutchinson *et al.*, 2021). There were 21,799 licensed commercial bumblebee nests in 2013, mainly used to pollinate soft fruit and tomatoes in glasshouses or polytunnels (Defra, 2014) and they are known to forage outside the target crop (Foulis and Goulson, 2014). Including the contribution of hoverflies and accounting for managed pollinators would be an important step towards a more complete model of pollinator populations and services. It would also be an important progression if the model can be enhanced to calculate effect on yield where visitation from multiple pollinator types needs to be considered.

The scenarios explored in Chapter 4 were discrete alternatives in tree-planting policy. In reality, policy would likely promote a mixture of these, intended to optimise across a set of objectives that might include pollinator abundance, species richness, pollination service and wider ecosystem services such as carbon sequestration, water quality, flood risk alleviation etc. In addition to scenario comparisons, future work could seek to apply mathematical optimisation processes such as genetic algorithms to search for landscape scenarios that provide a pareto-optimal allocation of interventions across the landscape (Seppelt *et al.*, 2013). Although an allocation that is optimal for pollination services may be hard to achieve in practice due to constraints on uptake, optimisation studies offer insights into improved spatial targeting and intervention combinations and can be adapted to include multiple constraints. There has been little landscape optimisation work of this nature on crop pollination services to date, with existing studies using either habitat-based models (Verhagen *et al.*, 2018) or the Lonsdorf model (Rahimi *et al.*, 2021) and so the landscapes generated may be suboptimal in practice due to the limitations of those models (see Section 1.6.1). Using the *poll4pop* model to quantify crop pollination and/or pollinator abundance objectives within an optimisation would therefore be an important advancement. Given the extensive data requirements of the model, the number of potential variables (interventions) and the computational requirements of optimisation algorithms, this would likely need to be focussed at a regional or local scale.

5.5 Concluding Remarks

This thesis has for the first time explored the impact of a national agri-environment scheme in its entirety on pollinator abundance and crop pollination services. It has predicted that the scheme was effective at supporting populations of more generalist, ground-nesting species but that the indirect pollination service enhancement is inconsistent across crop type and geography and has explored the reasons behind this finding. No pollination service effect was predicted for orchards or strawberries, which likely reflects low uptake in areas growing the crops but may also reflect limited nesting resource provision in schemes. Predicted pollination service enhancements to OSR and field beans were mainly driven by hedgerow and woodland edge management, which is a high value intervention providing both floral and nesting resources. However, interventions that provide fewer resources, such as grass margins and fallow plots, can still be valuable if they are widely implemented or co-located effectively with pollinator-dependent crops. Increasing the coverage of hedgerows across the landscape would benefit both abundance and pollination services of wild bees, but the findings suggest the greatest enhancement to pollination services could be delivered by incentivising willow or fruit tree agroforestry systems. These predictions have important policy implementations as the governments in the UK and elsewhere plan the next generation of agri-environment schemes and have informed a series of recommendations to be included in their design and implementation.

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Appendices

1 Does agri-environment scheme participation in England increase pollinator populations and crop pollination services? Supplementary Material

1.1 Land Classes

Table A1.1: Land classes. For each land class used in the model, the table indicates how it has been parameterised relative to G2020, and to what land category for purposes of broad analysis. The final column provides additional information about land class development relative to G2020 and other datasets.

Land class	***Parameterisation relative to G2020***	***Land Category***	***Notes***
Beaches, Sand Dunes/Plane	Beaches, Sand Dunes/Plane	Semi-natural Habitat	
Berries (exc. Strawberries & Raspberries)	Berries (exc. Strawberries & Raspberries)	Other Crops	
Broad/Field Beans	Broad/Field Beans	Field Beans	
Buckwheat	Buckwheat	Other Crops	
Cereal	Cereal	Other Crops	
Cereal - Organic	Organic Cereal	Other Crops	
Ditch	Ditch	Semi-natural Habitat	Ditches in AES are 2m wide. Ditches not in AES are 1m wide.
Fallow	Fallow	Semi-natural Habitat	
Flower Rich Margin	Unimproved Meadow	Semi-natural Habitat	Matched to highest floral value class to distinguish from "Grassy Field Edge"
Gardens	Gardens	Suburban	Match to LCM 'Suburban' includes suburban parks, greens as well as domestic gardens
Golf Courses	Golf Courses	Suburban	
Grassland Acid - Improved	Improved Grassland	Improved Grassland	Acid and Neutral grassland both mapped to Improved Grassland in improved state.
Grassland Neutral - Improved	Improved Grassland	Improved Grassland	Acid and Neutral grassland both mapped to Improved Grassland in improved state.
Grassland Calcareous – Improved	Improved Meadow	Improved Grassland	Calcareous grassland mapped to Meadow spectrum
Grassland Acid – Semi-improved	50% Improved Grassland, 50% Moorland	Semi-natural Habitat	No semi-improved category in G2020. Assumed to be halfway between improved and unimproved.
Grassland Neural – Semi-improved	50% Improved Grassland, 50% Unimproved Grassland	Semi-natural Habitat	No semi-improved category in G2020. Assumed to be halfway between improved and unimproved.
Grassland Calcareous – Semi-improved	50% Improved Meadow, 50% Unimproved Meadow	Semi-natural Habitat	No semi-improved category in G2020. Assumed to be halfway between improved and unimproved.
Grassland Acid - Unimproved	Moorland	Semi-natural Habitat	Acid Grassland treated as equivalent to Moorland as often in mosaic.
Grassland Neutral - Unimproved	Unimproved Grassland	Semi-natural Habitat	Unimproved Grassland in G2020 mapped to Neutral Grassland.
Grassland Calcareous - Unimproved	Unimproved Meadow	Semi-natural Habitat	Calcareous grassland mapped to Meadow spectrum
Grassy Field Margin	Grassy Field Edge	Semi-natural Habitat	
Hedgerow	Hedgerow	Semi-natural Habitat	Hedgerows in AES are 5m wide. Hedgerows not in AES are 2.5m wide. The 5m width is that specified in EFA rules for hedgerow management. Hedgerow Regulations (1997) mean that hedgerows are unlikely to be absent in *AES_Absent*. Rather, unmanaged hedgerows are thinner and have more gaps.
Ley - Grass and Legume	Grass and Legume Ley	Semi-natural Habitat	
Ley - Grass	Grass Ley	Semi-natural Habitat	
Ley - Organic	Organic Ley	Semi-natural Habitat	

Land class	*Parameterisation relative to G2020*	*Land Category*	*Notes*
Linseed/Flax	Linseed/Flax	Other Crops	
Maize	Maize	Other Crops	
Moorland	Moorland	Semi-natural Habitat	Includes all Heathland.
Moorland - Degraded	75% Moorland, 25% Improved Grassland	Semi-natural Habitat	Positioned half-way between unimproved and semi-improved condition. This is closest match to baseline condition for ES “Restoration of Moorland” option in BD2302/5007.
Null	Water, Rock	Urban	
Oilseed Rape	Oilseed Rape	Oilseed Rape	
Oilseed Rape - Organic	Organic Oilseed Rape	Oilseed Rape	
Orchards	Orchards	Orchards	No distinction between Orchard and Traditional Orchard as BD2302/5007 does not distinguish between unproductive and productive Traditional Orchards, and not distinguished in G2020 either.
Orchards – Degraded	80% Orchards, 20% Scrub	Semi-natural Habitat	Match to baseline condition for ES “Traditional Orchard” options in BD2302/5007.
Peas	Peas	Other Crops	
Poplar	Poplar	Other Crops	
Potatoes	Potatoes	Other Crops	
Reed Canary Grass	Reed Canary Grass	Other Crops	
Salix	Salix	Other Crops	
Salt Marsh	Salt Marsh	Semi-natural Habitat	
Scrub	Scrub	Semi-natural Habitat	
Scrub – Degraded	50% Scrub, 25% Unimproved Grassland, 25% Improved Grassland	Semi-natural Habitat	Match to baseline condition for ES “Restoration of Scrub” options in BD2302/5007.
Strawberry/Raspberry in Polytunnels	Strawberry/Raspberry in Polytunnels	Other Crops	
Strawberry/Raspberry in the open	Strawberry/Raspberry in the open	Strawberries	
Sugar Beet	Sugar Beet	Other Crops	
Urban	Urban	Urban	
Vegetables	Vegetables	Other Crops	
Wetlands	Wetlands	Semi-natural Habitat	
Wetlands – Degraded	90% Wetlands, 10% Scrub	Semi-natural Habitat	Match to baseline condition for ES “Restoration of Reedbed” options in BD2302/5007.
Woodland - Afforestation	Afforestation	Semi-natural Habitat	
Woodland - Coniferous	Coniferous Woodland	Semi-natural Habitat	
Woodland - Deciduous	Deciduous Woodland	Semi-natural Habitat	Assumed that most woodland under AES will be deciduous or aiming to create more deciduous.
Woodland – Degraded	80% Deciduous Woodland, 10% Unimproved Grassland, 10% Improved Grassland.	Semi-natural Habitat	Match to baseline condition for ES “Woodland management/restoration” options in BD2302/5007.
Woodland Edge	Woodland Edge	Semi-natural Habitat	Woodland edges in AES are 5m wide. Woodland edges outside AES are 2.5m wide. Width specified in AES rules for woodland edge options. Woodland edge itself cannot disappear but managed area is smaller.
Wood Pasture	45% Unimproved Grassland, 45% Improved Grassland, 10% Deciduous Woodland	Semi-natural Habitat	No wood pasture in G2020. Match to with-AES condition for ES “Wood Pasture” options in BD2302/5007.
Wood Pasture - Degraded	50% Improved Grassland, 50% Unimproved Grassland	Semi-natural Habitat	No wood pasture in G2020. Match to baseline condition for ES “Wood Pasture” options in BD2302/5007.

1.2 Land Cover Generation

The poll4pop model requires a rasterised input where each cell represents a land cover type to which a specific floral and nesting value can be assigned for a given guild. The different scenarios (*AES_Present* and *AES_Absent*) would be represented by generating two separate raster maps covering the same area but with different land cover classes for cells where AES features were present. However, the underlying spatial data sources for non-agricultural, agricultural and AES land cover are in various vector formats (polygon, polyline and point) so the following process was used to combine them and allocate a land class from which the *AES_Present* and *AES_Absent* raster layers could then be built.

Table A1.2: Datasets used in land cover generation including brief description and license.

Name	Alias	Description	License
Centre for Ecology and Hydrology (CEH) Land Cover Map 2015 (Rowland *et al.*, 2017)	LCM	The standard CEH land cover map as a polygon which breaks Great Britain into 21 land cover classes.	© NERC (CEH) 2011. Contains Ordnance Survey data © Crown Copyright 2007, Licence number 100017572.
Ordnance Survey (OS) MasterMap Orchards 2017	MMOrch	A polygon layer which provides the location of orchards	© Crown Copyright and Database Right 2018. Ordnance Survey (Digimap Licence)
CEH Woody Linear Features Framework (Scholefield *et al.*, 2016)	WLF	A polyline layer which provides the location of woody linear features in Great Britain (hedgerows, shelterbelts etc.)	© NERC (CEH). Contains Ordnance Survey data © Crown Copyright 2007, Licence number 100017572.
Crop Map of England (CROME) 2016	CROME	A polygon layer consisting of hexagonal pixels which represent one of a set of crop types or non-crop features	Open Government License © Crown copyright 2016.
Land Parcel Information System (LPIS) – England polygons 2016	LPIS	A polygon layer representing land parcels in England for which a BPS payment has been claimed	RPA/Ops/LoB2/124
Basic Payment Scheme (BPS) Claims 2016	Claims	A data table showing all the direct payment claims associated with each land parcel in the RPA database. This is used to associate the land parcel with a crop type as well as other features outside ESS or CS (i.e. buffer strips, fallow, catch/cover)	RPA/Ops/LoB2/124
OpenStreetMap	OSM	A polyline layer showing the location of linear infrastructure features including roads, railways, and waterways.	© OpenStreetMap contributors. www.openstreetmap.org/copyright.
Countryside Stewardship Management Options 2016 (shapefile)	CS	Point layer identifying CS options by land parcel code, business id, type, area, payment etc.…	Open Government License
Environmental Stewardship Scheme Agreements (shapefile)	ES	Point layer identifying ES options by land parcel code, business id, type, area, payment etc.…	Open Government License

1.2.1 Agricultural Land Cover

The agricultural component of the land cover for England was generated by merging the LPIS parcel and MMOrch layers, after erasing area from MMOrch which overlapped with LPIS. MMOrch parcels in this merged layer were assigned as Orchards. LPIS polygons in this merged layer were assigned a land cover type based on the corresponding BPS claim for that parcel in the Claims layer for that parcel. This information includes productive features: a set of arable crops; a set of leguminous crops; watercress; temporary and permanent grassland; commercially grown trees (permanent crops, short rotation coppice and nursery crops). It also includes claims for eligible non-productive 'crops' (fallow, catch crops, cover crops), non-eligible land cover and land which would normally be non-eligible for BPS but is included because it is under an eligible RDP scheme (typically woodland options). The Claims dataset also contains information about EFA edge features (buffer strips; hedge features) but these are handled in the section on AES land cover generation.

Where there was more than one land cover type associated with a parcel[5], the polygon was assigned the land cover type which had the largest area. The only exception to this rule was to allow for permanent areas of fallow land to occupy parts of the parcel where the total area of productive crop claims was less than the total area of the parcel and where there was also a fallow claim associated with that parcel. In this case the parcel was split into a fallow area (assigned to fallow) and a non-fallow area (assigned to the largest declared area of non-fallow). Fallow areas were not treated as equivalent to AES features as, unlike boundary features now included as EFA, they were not funded as such under the previous AES.

Catch/cover crops areas and temporary fallow (area of fallow claims exceeding the available area of the parcel) were calculated but were not used, again for simplicity reasons. Non-inclusion of catch/cover crops does not matter as the implementation of the Poll4pop model in this case does not include an autumn/winter season when these features would be present. Non-inclusion of temporary fallow understates the potential area of semi-natural habitat available to pollinators in early spring, but this understatement is consistent across both scenarios as fallow claims were not treated as AES.

In some cases, parcels in the LPIS layer did not have a match with a claim in the RPA Claims dataset or had an undefined crop code. Where this occurred, the polygon was intersected with the CROME layer and a crop assigned according to the CROME feature with the largest area within that parcel. If this

[5] Many parcels have more than one claim associated with them because more than one crop can be grown in a given parcel at any one time and or during the year (including temporary fallow and catch/cover crops) and because boundary features (buffer strips, hedgerows) also coexist with crops or grassland in the main part of the field. For simplicity, it was decided to constrain agricultural land cover to a single crop rather than allowing for multiple crops

was not an agricultural land class, then a crop was assigned based on the crop of the nearest matched LPIS polygon.

Where the assignment was to Permanent Crops a check was needed to establish if these would map to orchards or to berries (excl. strawberry/raspberry). Parcels which intersected the MMOrch layer were assigned as Orchards and the remainder were assigned as Berries (excl. Strawberry/Raspberry). Where the assignment was to the RDP code (even after removal of AES features) the land was deemed to under a woodland scheme outside the scope of ES and CS and was assigned as Woodland in AES in both *AES_Present* and *AES_Absent* scenarios.

Where the assignment was to Permanent Grassland, a further process was needed to identify what type of grassland (improved grassland or semi-natural habitat that would have been claimed as permanent grassland). In this case, the polygon was intersected against the LCM layer and a code assigned based on the area of a relevant LCM feature (Improved Grassland, Neutral Grassland, Acid Grassland, Calcareous Grassland, Fen Marsh Swamp, Heather, Heather Grassland, Bog, Saltmarsh) with the largest intersecting area. Where there was no relevant feature interacting, the grassland type of the nearest matched LPIS polygon was assigned.

1.2.2 Non-Agricultural Land Cover

The remaining area of land cover for England and the 5km Scotland / Wales buffer was created from LCM polygons. In most cases the land cover type was assigned directly from the LCM modal class. However, there were some instances where additional processing was required.

Firstly, due to classification errors and spatial resolution limitations[6] the area not captured by LPIS polygons still included some land indicated as 'Arable and Horticulture' which required a more specific crop assignment. From visual inspection these polygons appeared to fall into two types:

- Larger, field shaped features that are clearly crops missing from the LPIS database or else non-agricultural land cover wrongly misclassified due to spectral quality (e.g. airfields and industrial parks);
- Smaller, linear-shaped features (e.g. verges, hedgerows, in-field trees, boundary trees, gardens), including hardstanding (road, railway) or water features which have been misclassified in the LCM, most likely because of their resolution. This also included small slivers of crop or non-crop where the LCM and LPIS boundaries did not perfectly match.

[6] See CEH (2017) for more details on these limitations.

The non-matched polygons then passed through the following process to determine their land cover class.

- Non-matched polygons in England were split into two groups: a ‘probable field’ group with area >= 0.5ha and length to area ratio <= 0.05; a ‘probable linear feature’ group which represented the other polygons. The area and ratio thresholds were chosen based on visual inspection of a polygons from a sample 10km grid.
- Probable field features were matched against the CROME layer and assigned the land cover class with the largest percentage representation from CROME within that polygon. Non-agricultural features were assigned as ‘Urban’.
- Probable linear features were matched against the OSM and features which intersected roads or rail were assigned the ‘Urban’ land cover class and those intersecting water were assigned ‘Water’. Remaining features were checked for intersect with the WLF layer and those intersecting were assigned a ‘Hedgerow’ land cover. Remaining features were then checked against the CROME layer: those corresponding to a crop land cover class (most likely a crop sliver) were assigned the crop given to the closest LPIS polygon (see next phase); those which corresponded to a non-crop land cover (non-crop slivers) were assigned the land cover class of the closest non-agricultural LCM polygon.
- Non-matched polygons in the Wales / Scotland 5km buffer zone were not linked to LPIS as this dataset refers only to England. Instead, an arable or leguminous crop was assigned at random from the Claims dataset, weighted by the proportion of land area associated with that crop. Pollination visitation rates to these polygons are not considered in the results. The allocation was only made so that the poll4pop model could function.

Secondly, in the Scotland / Wales buffer zone the LCM polygons assigned to ‘Arable and Horticulture’ needed a specific crop assignment but the Claims dataset only covered England. A simpler process was used here as the precise configuration of crop types in the buffer zone is of less importance to the final output as we ignore these cells in calculating summary values. An arable or leguminous crop was therefore assigned at random from the list in the Claims database, with the selection weighted according to the total proportional area of coverage of each crop in the database.

Two polyline layers were also created. One was derived from the WLF layer and marked as Woody Linear Feature. A second was created from the boundary of contiguous woodland features in the land cover and marked as Woodland Edge.

1.3 AES Land Cover

The ES and CS datasets provide information about the option (code), location (parcel or farm), coverage, and level (agreement or parcel), start date and end date, *inter alia*. The Claims dataset provides information about the area of certain types of buffer strip and hedge feature claimed for each parcel.

The first task was to reduce the ES and CS option datasets to only relevant options. After selecting only those features which were live during 2016, the dataset was further reduce to extract only options which created, restored, or maintained habitat likely to be of some floral or nesting value. This was determined with reference to the baseline and with-AES habitat descriptions used for ESS in BD2302/5007 (and CS options by equivalence) and the expert opinion parameters from G2020. If both baseline and with-AES scenarios were arable crops, improved grassland or a land cover associated with low habitat quality (e.g. open water) then the option was excluded. Most management options were included except for some water-related options. Most capital items were excluded except for items relating to hedgerow / tree planting and stone wall / earth bank restoration. Supplement options[7] were excluded to simplify the *AES_Present* vs *AES_Absent* scenarios. These apply primarily to less intensive farm systems and have less bearing on the crop pollination outcomes.

Next, items were separated into 'Agreement' level and 'Parcel' level features. Parcel level features are applicable to one parcel only and could be matched to specific LPIS polygons by matching the parcel references. Agreement level features are rotational options which are associated with arable parcels and can move around the farm to accompany the field rotation pattern in use. These could not be linked to an explicit parcel and required a rule-based allocation.

Features were further split into groups according to their functional unit of measurement as this affected how their coverage was calculated and how they were represented in the land cover map (as polygon or polyline).

- 'Field' options were features measured in hectares, which are typically not linear and are sufficiently large that there would be little information loss upon conversion to a 25m raster. These would be preserved as polygons.
- 'Plot / Tree' options were features found within the field measured in number of units and would potentially be lost upon conversion to a 25m raster due to their small size (e.g. *AB4 - Skylark plots*, in-field tree management options). These would be converted to polylines representing the

[7] Options which do not occur in isolation and must be combined with another option.

perimeter of the plot or tree canopy and located randomly within the field subject to rules on plot or tree density.

- 'Margin' options were features measured in hectares, but which are typically linear and occupy land just inside the field boundary. These would potentially be lost in raster conversion if represented as polygons (e.g. field margins). These would be converted to polylines located 10m within the field boundary.
- 'Transect' options are features measured in hectares, but which are typically linear and go across a field rather than around its boundary. These would potentially be lost in raster conversion if represented as polygons (e.g. beetle banks). These would be converted to polylines which cross the field itself.
- 'Perimeter' options were features measured in metres, which are linear and occupy land on the field boundary itself. These would be lost in raster conversion if represented as polygons (e.g. hedgerows). These would be converted to polyline and placed on the field boundary itself.

Allocation was as follows.

Parcel – Field

Many parcels had more than one AES option assigned to them. This was either because the options occupied different parts of the field, or because the options were co-located as management was complementary. For simplicity, an assumption was made that only one option could occupy any given location within the parcel and an algorithm was used to fill the available space as follows:

- The parcel was cut North-South, South-North, East-West, or West-East (chosen at random) to create a slice of area equal to the smallest option by area allocated to that parcel. This was assigned to that option.
- The remaining parcel was then sliced (again in a random orientation) so create a slice of area equal to the next smallest option.
- And so on until all the available area of the parcel allocated to AES was used up.

Any surplus area (a result of rounding error, input error, or co-location of options) was ignored. Where co-location occurred, the larger option was typically a more generic AES option (e.g. UX3 – generic prescriptions for Moorland) whilst the smaller option had more specific habitat value. Because the algorithm assigned from smallest to largest, failure to represent co-location was unlikely to understate of pollinator value.

Agreement – Field

These features have an area in hectares representing the total area covered by that option on that farm, but all agreements for a given farm are assigned to a representative parcel rather than the actual parcels as the locations change from year to year as per that farm's crop rotation.

First, a set of option to crop type assignment rules was created to ensure that these features could only be placed in parcels containing an appropriate crop as per the option description in the ES or CS Manual. This also contained a set of rules indicating how much of the parcel could be filled up, again as per the option description. Then, all the agreements were assigned to a specific farm in the LPIS database. In most cases this was possible by matching the farm associated with the representative parcel but in a few cases where a match could not be found the agreement was assigned to the nearest farm. Parcels which already had a Parcel – Field feature allocation were excluded. This produced a list of suitable parcels from the agricultural land cover database where the feature could be located and a total area of allocation. However, because the actual parcels are not known, a random allocation was made according to an algorithm:

- Starting with the first farm, each agreement is assigned a random parcel from the list of suitable parcels.
- The parcel is filled up (using the random North-South, South-North, East-West, or West-East slicing approach) up to the parcel limit.
- If there is remaining unallocated area for that agreement, the next random parcel was selected and filled, and so on until the area of that agreement was used or all suitable parcels were fully occupied[8].
- The process was repeated for the next agreement (but excluding parcels already assigned) until all the agreements for that farm were assigned.
- The algorithm then moved to the next farm and repeated until all the farms had been assigned.

Parcel – Plot/Tree

This category includes Skylark Plots in CS (AB4) and in-field tree options in ES (EC1, EC2, HC1, HC2, HC5, HC6, OC1, OC2, OHC1, OHC2). Skylark plots have a minimum area of 16m^2 according to option description. Assuming that a typical plot is the minimum area, the typical plot would have a radius of 2.25m. In-field tree options protect an area extending 2m beyond the crown radius. A typical mature tree has a radius of around 3m (Pretzsch *et al.*, 2015) so this would infer a radius of 5m.

[8] In practice this never occurred. There was always surplus parcel area.

The features were deemed too small to be captured in the raster as polygons. So polyline circles of the aforementioned radii for all plots / tree within a given parcel were generated and then randomly allocated to locations within the polygon such that they were still enclosed by the field boundary.

Agreement – Plot/Tree

This category includes Skylark plots in ES (EF8, HF8, OF8, OHF8), which are agreement features and thus can rotate around the farm. Assignment rules were developed as per the option description (winter cereal fields greater than 5ha, and at least 2 plots/ha) and a set of suitable parcels was selected as per the process for the Agreement – Field parcels (avoiding parcels already containing AB4).

A similar allocation algorithm to the Agreement – Field algorithm was used to allocate plots to appropriate parcels (using a density of 2 plots/ha) except that the features created were circular polylines of the same circumference as the AB4 features.

Parcel – Margin

Parcel margin features are those which are located just inside the field boundary, and which are represented in the databases as an area value in hectares. However, due to their shape (typically long, thin strips) they were converted to linear features to minimise information loss upon conversion to raster. This was achieved by converting the area to m^2 and then dividing by a fixed width parameter applicable to each AES type (Table A1.4). Widths were derived from the option description in the relevant scheme handbook where available. Where not, widths were set to the default width of associated LC class (Margin = 5m). For EFA features (Fallow Buffer Strip, Temporary Grass Buffer, Sown Mixed Cover Buffer, Buffer Strip, and Permanent Grassland Buffer Strips), the width adjustment used was 9m, as per the BPS 2016 rule book (Rural Payments Agency, 2015).

For each parcel, a list of margin features and lengths was produced. A polyline was created 5m inside the parcel boundary for each feature, starting with the shortest feature and continuing with the next feature and so on until the length of features or the total available length of polyline was used up (which ever occurred first).

Agreement – Margin

Agreement margin features have an area value in hectares but were converted to linear features (m) to minimise information loss upon conversion to raster as per the Parcel – Margin features process set out above. All agreements for a given farm are assigned to a representative parcel rather than the actual parcel as the locations change from year to year as per that farm's crop rotation.

As per the Agreement – Field features a set of rules for parcel type and max length was created and agreements were matched to specific farms. A similar algorithm to the Agreement – Field process was used to assign agreements to specific parcels, but the assignment was to a polyline 5m inside the parcel edge as per the Parcel – Margin features.

Parcel – Perimeter

Parcel perimeter features have a value in metres and so could be converted directly into polylines, except for hedge features in EFA are in hectares and were converted to metres using a width parameter of five[9]. For each parcel, a list of perimeter features and lengths was produced. A polyline was created along the parcel boundary for each feature, starting with the shortest feature and continuing with the next feature and so on until the length of features or the total available length of polyline was used up (which ever occurred first).

Agreement – Perimeter

Agreement - perimeter features have a length in metres so could be converted directly into polylines. All agreements for a given farm are assigned to a representative parcel rather than the actual parcel as the locations change from year to year as per that farm's crop rotation.

As per the Agreement – Field features a set of rules for parcel type and max length was created and agreements were matched to specific farms. A similar algorithm to the Agreement – Field process was used to assign agreements to specific parcels, but the assignment was to a polyline along the parcel edge as per the Parcel – Perimeter features.

Parcel – Transect

Parcel margin features have an area value in hectares but were converted to linear features to minimise information loss upon conversion to raster. This was achieved by converting the area to m^2 and then dividing by a fixed width parameter applicable to each AES type (Table A1.4). Widths were derived from the option description in the relevant scheme handbook where available.

For each parcel, a list of transect features and lengths was produced. For each feature, a polyline was created running North-South, South-North, East-West or West-East (at random) across the parcel that would be at least as long as the feature. This was allocated to that feature. If there was still available length of the feature, another line was generated along the same axis until the available length was used up; and so on until the length of features was used up.

Agreement – Transect

[9] In EFA claims the hedge is deemed to occupy $10m^2$ for every metre of hedge where both sides are under management and $5m^2$ where only one side is. For simplicity, a conservative assumption was made that only one side of the hedge was in management and no adjustments were made to allow for reductions to area that may have been made where hedges were adjacent to fallow land.

There were no Agreement – Transect features.

Areas assigned to Parcel – Field and Agreement – Field features were erased from the agricultural parcels layer and the agricultural, non-agricultural and AES polygon layers were merged to create a single land cover polygon layer providing full coverage for England the 5km buffer into Wales and Scotland. Each polygon in the layer had a field indicating its LC class in the *AES_Present* and *AES_Absent* scenarios.

Lines assigned to the same LC class were merged into polyline layers representing that class. This created lines for Grassy Field Margins, Flower Rich Margins and Fallow buffer features, Hedgerows, Ditches and Woodland Edges. Hedgerow and WLF polylines from the non-agricultural layers which exactly overlaid hedgerow and WLF polylines from the AES layers were removed to avoid duplication.

The single land cover polygon layer was converted to two separate 25m raster layers based, one showing land cover for *AES_Present* and the other for *AES_Absent* using the MAXIMUM_COMBINED_AREA rule in ArcGIS. Cell alignment was matched to the British National Grid.

Each polyline in its respective layer was split into individual lines covering only the area within each 25m raster cell. These lines were then converted to 25m raster based such that the entry for each cell was the total length of that LC class in that 25m cell.

1.4 Land Class Assignment

Allocation of land class to non-AES features is set out in Table A1.3. As per the LCM metadata descriptions semi-natural grassland habitat was assigned as semi-improved rather than unimproved status (CEH, 2017). Polylines from the WLF layer were assigned as Hedgerow (unless they were already captured as an AES Hedgerow feature. Woodland edges that form the perimeter of contiguous areas of woodland (and were not already captured as an AES Woodland Edge feature) were allocated to the Woodland Edge land class. Permanent crops were either assigned to Orchard or to Berries (excl. Strawberry/Raspberry) depending on their alignment with the MMOrch layer, as described in the previous section.

Table A1.3: Land class assignment: non-AES features (non-agricultural, agricultural)

Land cover description	Source	Land class (*AES_Present*)
Broadleaved Woodland	LCM	Woodland - Deciduous
Coniferous Woodland	LCM	Woodland - Coniferous
Improved Grassland	LCM	Grassland – Improved
Neutral Grassland	LCM	Grassland Neutral - Semi-Improved
Calcareous Grassland	LCM	Grassland Calcareous - Semi-Improved
Acid Grassland	LCM	Grassland Acid – Semi-Improved
Fen, Marsh and Swamp	LCM	Wetlands
Heather	LCM	Moorland
Heather Grassland	LCM	Moorland
Bog	LCM	Wetlands
Inland Rock	LCM	Null
Saltwater	LCM	Null
Freshwater	LCM	Null
Supra-littoral Rock	LCM	Null
Supra-littoral Sediment	LCM	Beaches, Sand Dunes/Plane
Littoral Rock	LCM	Null
Littoral Sediment	LCM	Beaches, Sand Dunes/Plane
Saltmarsh	LCM	Salt Marsh
Urban	LCM	Urban
Suburban	LCM	Gardens
Woody linear features	WLF	Hedgerow
Woodland edges	LCM, CROME	Woodland Edge
Barley (Spring)	Claims	Cereal
Basil	Claims	Cereal
Beet	Claims, CROME	Sugar Beet
Borage	Claims	Linseed/Flax
Buckwheat	Claims	Buckwheat
Canary Seed	Claims	Reed Canary Grass
Carrot	Claims	Vegetables
Celery	Claims	Vegetables
Chicory	Claims	Cereal
Daffodil	Claims	Cereal
Ryegrass	Claims	Reed Canary Grass
Dill	Claims	Cereal
Evening Primrose	Claims	Linseed/Flax
Fennel	Claims	Vegetables
Hemp	Claims	Cereal
Lettuce	Claims	Vegetables
Linseed (Spring)	Claims, CROME	Linseed/Flax

Land cover description	Source	Land class (*AES_Present*)
Maize	Claims, CROME	Maize
Millet	Claims	Cereal
Oats (Spring)	Claims	Cereal
Onion	Claims	Vegetables
Oregano	Claims	Cereal
Parsley	Claims	Cereal
Parsnip	Claims	Vegetables
Rye (Spring)	Claims	Cereal
Sage	Claims	Cereal
Spinach	Claims	Vegetables
Strawberry	Claims	Strawberry / Raspberry in the open
Sweet Potato	Claims	Vegetables
Thyme	Claims	Cereal
Triticale (Spring)	Claims	Cereal
Tulip	Claims	Cereal
Wheat (Spring)	Claims	Cereal
Yam	Claims	Vegetables
Cabbage (Spring)	Claims	Vegetables
Turnip	Claims	Vegetables
Oilseed (Spring)	Claims, CROME	OSR
Brown Mustard	Claims	OSR
Mustard	Claims	OSR
Crambe	Claims	OSR
Rocket	Claims	Cereal
Radish	Claims	Vegetables
Horseradish	Claims	Vegetables
Tobacco	Claims	Cereal
Potato	Claims, CROME	Potatoes
Tomato	Claims	Null
Aubergine	Claims	Vegetables
Pepper	Claims	Vegetables
Chilli	Claims	Vegetables
Tree Chilli	Claims	Vegetables
Squash	Claims	Vegetables
Japanese Pie Squash	Claims	Vegetables
Siam Pumpkin	Claims	Vegetables
Banana Squash	Claims	Vegetables
Butternut Squash	Claims	Vegetables
Watermelon	Claims	Null
Cucumber	Claims	Null
Melon	Claims	Null
Mixed Arable	Claims	Cereal
Barley (Winter)	Claims	Cereal
Linseed (Winter)	Claims, CROME	Linseed/Flax
Oats (Winter)	Claims	Cereal
Wheat (Winter)	Claims	Cereal
Oilseed (Winter)	Claims, CROME	OSR
Rye (Winter)	Claims	Cereal
Triticale (Winter)	Claims	Cereal
Cabbage (Winter)	Claims	Vegetables
Coriander	Claims	Cereal
Corn Gromwell	Claims	Linseed/Flax
Camelina	Claims	Cereal
Phacelia	Claims	Linseed/Flax
Oca	Claims	Vegetables
German Chamomile	Claims	Linseed/Flax
Corn Chamomile	Claims	Linseed/Flax
Corn Cockle	Claims	Linseed/Flax
Corn Flower	Claims	Linseed/Flax
Corn Marigold	Claims	Linseed/Flax

Land cover description	Source	Land class (*AES_Present*)
Poppy	Claims	Linseed/Flax
Field Forgetmenot	Claims	Linseed/Flax
Foxglove	Claims	Linseed/Flax
Hay Rattle	Claims	Linseed/Flax
Hedge Bedstraw	Claims	Linseed/Flax
Teasel	Claims	Cereal
Quinoa	Claims	Cereal
Sunflower	Claims	OSR
Cress	Claims	Vegetables
Gladioli	Claims	Linseed/Flax
Echium	Claims	Linseed/Flax
Sorghum	Claims	Cereal
Sticky Nightshade	Claims	Linseed/Flax
Sweet William	Claims	Linseed/Flax
Wallflower	Claims	Cereal
Samphire	Claims	Vegetables
Aster	Claims	Linseed/Flax
Larkspur	Claims	Linseed/Flax
Nigella	Claims	Linseed/Flax
Catch Crop	Claims	Not used
Cover Crop	Claims	Not used
Watercress	Claims	Vegetables
Fallow	Claims, CROME	Fallow
Chickpea	Claims	Peas
Fenugreek	Claims	Peas
Field Beans (Spring)	Claims	Broad/Field Beans
Green Beans	Claims	Broad/Field Beans
Lentil	Claims	Peas
Lupin	Claims	Peas
Pea (Spring)	Claims, CROME	Peas
Soya	Claims	Broad/Field Beans
Cowpea	Claims	Peas
Birds Foot Trefoil	Claims	Linseed/Flax
Lucerne	Claims	Cereal
Sweet Clover	Claims	Linseed/Flax
Sainfoin	Claims	Linseed/Flax
Clover	Claims	Linseed/Flax
Mixed Legumes	Claims	Broad/Field Beans
Field Beans (Winter)	Claims	Broad/Field Beans
Pea (Winter)	Claims, CROME	Peas
Ineligible Area	Claims	Null
Nursery Crops	Claims	Woodland - Deciduous
Permanent Grassland	Claims, CROME	Grassland – see text for assignment process
Short Rotation Coppice	Claims	Woodland - Deciduous
Permanent Crops	Claims	Orchards or Berries (excl. Strawberry/Raspberry). See text.
Temporary Grassland	Claims	Ley - Grass
Beans	CROME	Field Beans
Berries	CROME	Berries (excl. Strawberry/Raspberry)
Cereal	CROME	Cereal
Non-Agricultural	CROME	Urban
Vegetables	CROME	Vegetables
Water	CROME	Null
Wood	CROME	Woodland - Deciduous
Orchards	MMOrch	Orchards
Road	OSM	Urban
Rail	OSM	Urban
Water	OSM	Null

Assignment of specific AES options to land classes is set out in Table A1.4. The broad process is already described in the previous section. A brief rationale is provided for each option as required. The width column indicates the width parameter used to assign correct lengths to perimeter, margin or transect feature types. AES options from the CS and ES schemes that do not appear here have been excluded either because they are not relevant to pollinators or because there were no options of that type taken up during 2016. In some cases, there is no difference in land class assignment between *AES_Present* and *AES_Absent* scenarios because BD2302/5007 indicates as such. These options have not been excluded from the dataset as the BD2302/5007 information was useful to distinguish land class and maintain consistency in categorisation. Capital items (one-off land use change such as hedgerow planting, hedgerow coppicing, scrub removal) were not included as the datasets are not precise on whether management took place within the calendar year 2016. In any case the number of capital items is very small: there are just 2273 items in the potentially relevant ES agreement dataset (0.32%) prior to allocation and no items in the relevant CS agreement dataset. The list of management options not included in the analysis including reasons for exclusion is provided in Table A1.5.

Table A1.4: Land class assignment - AES features. Underlying LC means land class for non-AES feature underlying the AES feature.

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
AB1	Nectar flower mix	CS	Parcel	Field	Flower Rich Margin	Underlying LC		
AB10	Unharvested cereal headland	CS	Parcel	Margin	Fallow	No feature	15	
AB11	Cultivated areas for arable plants	CS	Parcel	Field	Fallow	Underlying LC		
AB15	Two-year sown legume fallow	CS	Parcel	Field	Ley – Legume and Grass	Underlying LC		
AB16	Autumn sown bumblebird mix	CS	Parcel	Field	Flower Rich Margin	Underlying LC		
AB3	Beetle banks	CS	Parcel	Transect	Ditch	No feature	3	
AB4	Skylark plots	CS	Parcel	Plot/Tree	Fallow	No feature		
AB5	Nesting plots for lapwing and stone curlew	CS	Parcel	Field	Fallow	Underlying LC		
AB8	Flower-rich margins and plots	CS	Parcel	Field	Flower Rich Margin	Underlying LC		
ABS01	Temporary Grass Buffer Strip	EFA	Parcel	Margin	Grassy Field Margin	No feature	9	
ABS02	Sown Mixed Cover Buffer Strip	EFA	Parcel	Margin	Grassy Field Margin	No feature	9	
ABS03	Fallow Buffer Strip	EFA	Parcel	Margin	Fallow	No feature	9	
BE1	Protection of in-field trees on arable land	CS	Parcel	Plot/Tree	Hedgerow	Hedgerow (half)		Treat as short hedgerow
BE2	Protection of in-field trees on intensive grassland	CS	Parcel	Plot/Tree	Hedgerow	Hedgerow (half)		Treat as short hedgerow
BE3	Management of hedgerows	CS	Parcel	Perimeter	Hedgerow	Hedgerow (half)	5	
BE4	Management of traditional orchards	CS	Parcel	Field	Orchard	Orchard - Degraded		Equivalent to HC18
BE5	Creation of traditional orchards	CS	Parcel	Field	Orchard	Grassland Neutral – Semi-Improved		Equivalent to HC21
BF11	Half Hedge	EFA	Parcel	Perimeter	Hedgerow	Hedgerow (half)		Adjustment for half-hedge already implicit in declared area
BF12	Adjacent Hedge	EFA	Parcel	Perimeter	Hedgerow	Hedgerow (half)		
BF15	Buffer Strip	EFA	Parcel	Margin	Grassy Field Margin	No feature	9	
CT1	Management of coastal sand dunes and vegetated shingle	CS	Parcel	Field	Beaches, Sand Dunes/Plane	Beaches, Sand Dunes/Plane		Equivalent to HP1
CT2	Creation of coastal sand dunes and vegetated shingle on arable land and improved grassland	CS	Parcel	Field	Beaches, Sand Dunes/Plane	Grassland Neutral – Improved		Equivalent to HP4
CT3	Management of coastal saltmarsh	CS	Parcel	Field	Saltmarsh	Saltmarsh		Equivalent to HP5
CT4	Creation of inter-tidal and saline habitat on arable land	CS	Parcel	Field	Saltmarsh	Nearest arable crop		Equivalent to HP7
CT5	Creation of inter-tidal and saline habitat by non-intervention	CS	Parcel	Field	Saltmarsh	Grassland Neutral – Semi-Improved		Equivalent to HP9

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
CT7	Creation of inter-tidal and saline habitat on intensive grassland	CS	Parcel	Field	Saltmarsh	Grassland Neutral – Improved		Equivalent to HP8
EB1	Hedgerow management for landscape (on both sides of a hedge)	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	
EB10	Combined hedge and ditch management (incorporating EB3)	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	
EB11	Stone wall protection and maintenance	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Closest match in G2020
EB12	Earth bank management (on both sides)	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Closest match in G2020
EB13	Earth bank management (on one side)	ES	Agreement	Perimeter	Ditch	Ditch (half)	1	Closest match in G2020
EB14	Hedgerow restoration	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	
EB2	Hedgerow management for landscape (on one side of a hedge)	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	2.5	
EB3	Hedgerow management for landscape and wildlife	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	
EB4	Stone faced hedge bank management on both sides	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Closest match in G2020
EB5	Stone faced hedge bank management on one side	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Closest match in G2020
EB6	Ditch management	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	
EB7	Half ditch management	ES	Agreement	Perimeter	Ditch	Ditch (half)	1	
EB8	Combined hedge and ditch management (incorporating EB1)	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	
EB9	Combined hedge and ditch management (incorporating EB2)	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	2.5	
EC1	Protection of in-field trees (arable)	ES	Parcel	Plot/Tree	Hedgerow	Hedgerow (half)	5	
EC2	Protection of in-field trees (grassland)	ES	Parcel	Plot/Tree	Hedgerow	Hedgerow (half)	5	
EC24	Hedgerow tree buffer strips on cultivated land	ES	Parcel	Margin	Hedgerow	Hedgerow (half)	6	
EC25	Hedgerow tree buffer strips on grassland	ES	Parcel	Margin	Hedgerow	Hedgerow (half)	6	
EC3	Maintenance of woodland fences	ES	Agreement	Perimeter	Woodland Edge	Woodland Edge (half)	5	Creates a woodland edge
EC4	Management of woodland edges	ES	Parcel	Perimeter	Woodland Edge	Woodland Edge (half)	5	
ED2	Take archaeological features out of cultivation	ES	Parcel	Field	Grassland Neutral – Semi-Improved	Underlying LC		Option description
EE1	2m buffer strips on cultivated land	ES	Parcel	Margin	Grassy Field Margin	No feature	2	
EE10	6m buffer strips on intensive grassland next to a watercourse	ES	Parcel	Margin	Grassy Field Margin	No feature	6	

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
EE2	4m buffer strips on cultivated land	ES	Parcel	Margin	Grassy Field Margin	No feature	4	
EE3	6m buffer strips on cultivated land	ES	Parcel	Margin	Grassy Field Margin	No feature	6	
EE4	2m buffer strips on intensive grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	2	
EE5	4m buffer strips on intensive grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	4	
EE6	6m buffer strips on intensive grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	6	
EE7	Buffering in-field ponds in improved grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	10	
EE8	Buffering in-field ponds in arable land	ES	Parcel	Margin	Grassy Field Margin	No feature	10	
EE9	6m buffer strips on cultivated land next to a watercourse	ES	Parcel	Margin	Grassy Field Margin	No feature	6	
EF1	Field corner management	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
EF10	Unharvested cereal headlands for birds and rare arable plants	ES	Agreement	Margin	Fallow	No feature	15	Option description
EF11	Uncropped, cultivated margins for rare plants on arable land	ES	Parcel	Margin	Fallow	No feature	4.5	Option description
EF13	Uncropped cultivated areas for ground-nesting birds - arable	ES	Agreement	Field	Fallow	No feature		Option description
EF4	Nectar Flower mixture	ES	Agreement	Field	Grassland Calcareous - Unimproved	Underlying LC		
EF4NR	Nectar Flower mixture (Non-rotational)	ES	Parcel	Field	Grassland Calcareous - Unimproved	Underlying LC		
EF7	Beetle banks	ES	Parcel	Transect	Ditch	Ditch (half)	3	Closest match in G2020
EF8	Skylark plots	ES	Agreement	Plot/Tree	Fallow	No feature		Option description
EF9	Cereal headlands for birds	ES	Agreement	Margin	Fallow	No feature	15	Option description
EG3	ASD to Jan 2010 Nectar flower mixture in grassland areas	ES	Parcel	Field	Grassland Calcareous - Unimproved	Underlying LC		
EJ11	Maintenance of watercourse fencing	ES	Parcel	Perimeter	Grassy Field Margin	No feature	1	Creates grass strip
EJ5	In-field grass areas	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
EJ9	12m buffer strips for watercourses on cultivated land	ES	Parcel	Margin	Grassy Field Margin	No feature	12	
EK1	Take field corners out of management: outside SDA & ML	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
EK2	Permanent grassland with low inputs: outside SDA & ML	ES	Parcel	Field	Grassland Neutral – Unimproved	Grassland Neutral – Semi-improved		BD2302/5007
EK21	Legume- and herb-rich swards	ES	Agreement	Field	Ley - Grass and Legume	Underlying LC		Option description
EK3	Permanent grassland with very low inputs: outside SDA & ML	ES	Parcel	Field	Grassland Neutral – Unimproved	Grassland Neutral – Semi-improved		BD2302/5007

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
EK4	Manage rush pastures: outside SDA & ML	ES	Parcel	Field	Grassland Acid – Semi-improved	Grassland Acid – Semi-improved		BD2302/5007
EL1	Field corner management: SDA land	ES	Parcel	Field	Grassy Field Margin	Underlying LC		
EL2	Permanent in-bye grassland with low inputs: SDA land	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Semi-improved		BD2302/5007
EL3	In-bye pasture & meadows with very low inputs: SDA land	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Semi-improved		BD2302/5007
EL4	Manage rush pastures: SDA land & ML parcels under 15ha	ES	Parcel	Field	Grassland Acid – Semi-improved	Grassland Acid – Semi-improved		BD2302/5007
EL5	Enclosed rough grazing: SDA land & ML parcels under 15ha	ES	Parcel	Field	Moorland	Moorland		BD2302/5007
EL6	Moorland and rough grazing: ML land only	ES	Parcel	Field	Moorland	Moorland		BD2302/5007
GS1	Take field corners out of management	CS	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
GS10	Management of wet grassland for wintering waders and wildfowl	CS	Parcel	Field	Wetland	Wetland		Equivalent to HK10
GS11	Creation of wet grassland for breeding waders	CS	Parcel	Field	Wetland	Nearest arable crop		Equivalent to HK11
GS12	Creation of wet grassland for wintering waders and wildfowl	CS	Parcel	Field	Wetland	Nearest arable crop		Equivalent to HK12
GS13	Management of grassland for target features	CS	Parcel	Field	Grassland Calcareous – Semi-improved	Grassland Calcareous – Semi-improved		Equivalent to HK15
GS14	Creation of grassland for target features	CS	Parcel	Field	Grassland Calcareous – Semi-improved	Nearest arable crop		Equivalent to HK17
GS2	Permanent grassland with very low inputs (outside SDAs)	CS	Parcel	Field	Grassland Neutral – Unimproved	Grassland Neutral – Semi-improved		Equivalent to HK2
GS4	Legume and herb-rich swards	CS	Parcel	Field	Ley - Grass and Legume	Underlying LC		Equivalent to HK21
GS5	Permanent grassland with very low inputs in SDAs	CS	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Semi-improved		Equivalent to HL3
GS6	Management of species-rich grassland	CS	Parcel	Field	Grassland Calcareous – Unimproved	Grassland Calcareous – Unimproved		Equivalent to HK6
GS7	Restoration towards species-rich grassland	CS	Parcel	Field	Grassland Calcareous – Semi-improved	Grassland Calcareous –Improved		Option description (not equivalent to HK7)
GS8	Creation of species-rich grassland	CS	Parcel	Field	Grassland Calcareous – Unimproved	Nearest arable crop		Equivalent to HK8
GS9	Management of wet grassland for breeding waders	CS	Parcel	Field	Wetland	Wetland		Equivalent to HK9
HAE1	Hedge	EFA	Parcel	Perimeter	Hedgerow	Hedgerow (half)	5	
HAE2	Hedge	EFA	Parcel	Perimeter	Hedgerow	Hedgerow (half)	5	
HPE1	Hedge	EFA	Parcel	Perimeter	Hedgerow	Hedgerow (half)	5	

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
HPE2	Hedge	EFA	Parcel	Perimeter	Hedgerow	Hedgerow (half)	5	
HB11	Maintenance of hedges of very high environmental value (2 sides)	ES	Parcel	Perimeter	Hedgerow	Hedgerow (half)	5	
HB12	Maintenance of hedges of very high environmental value (1 side)	ES	Parcel	Perimeter	Hedgerow	Hedgerow (half)	2.5	
HB14	Management of ditches of very high environmental value	ES	Parcel	Perimeter	Ditch	Ditch (half)	2	
HC1	Protection of in-field trees on arable land	ES	Parcel	Plot/Tree	Hedgerow	Hedgerow (half)	5	
HC10	Creation of woodland outside of the SDA & ML	ES	Parcel	Field	Woodland - Afforestation	Grassland Neutral – Semi-improved		BD2302/5007
HC12	Maintenance of wood pasture and parkland	ES	Parcel	Field	Wood Pasture	Wood Pasture		BD2302/5007
HC13	Restoration of wood pasture and parkland	ES	Parcel	Field	Wood Pasture	Wood Pasture - Degraded		BD2302/5007
HC14	Creation of wood pasture	ES	Parcel	Field	Wood Pasture	Near arable crop		BD2302/5007
HC15	Maintenance of successional areas and scrub	ES	Parcel	Field	Scrub	Scrub		
HC16	Restoration of successional areas and scrub	ES	Parcel	Field	Scrub	Degraded Scrub		BD2302/5007
HC17	Creation of successional areas and scrub	ES	Parcel	Field	Scrub	Grassland Neutral – Semi-improved		BD2302/5007
HC18	Maintenance of high value traditional orchards	ES	Parcel	Field	Orchard	Orchard		BD2302/5007
HC19	Maintenance of traditional orchards in production	ES	Parcel	Field	Orchard	Orchard		BD2302/5007
HC2	Protection of in-field trees on grassland	ES	Parcel	Plot/Tree	Hedgerow	Hedgerow (half)		Treat as short hedgerow
HC20	Restoration of traditional orchards	ES	Parcel	Field	Orchard	Orchard - Degraded		BD2302/5007
HC21	Creation of traditional orchards	ES	Parcel	Field	Orchard	Grassland Neutral – Semi-improved		BD2302/5007
HC24	Hedgerow tree buffer strips on cultivated land	ES	Parcel	Perimeter	Hedgerow	Hedgerow (half)	6	
HC25	Hedgerow tree buffer strips on grassland	ES	Parcel	Perimeter	Hedgerow	Hedgerow (half)	6	
HC4	Management of woodland edges	ES	Parcel	Perimeter	Woodland Edge	Woodland Edge	5	
HC5	Ancient trees in arable fields	ES	Parcel	Plot/Tree	Hedgerow	Hedgerow (half)		Treat as short hedgerow
HC6	Ancient trees in intensively-managed grass fields	ES	Parcel	Plot/Tree	Hedgerow	Hedgerow (half)		Treat as short hedgerow
HC7	Maintenance of woodland	ES	Parcel	Field	Woodland - Deciduous	Woodland – Deciduous		BD2302/5007
HC8	Restoration of woodland	ES	Parcel	Field	Woodland - Deciduous	Woodland – Degraded		BD2302/5007

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
HC9	Creation of woodland in the SDA	ES	Parcel	Field	Woodland - Deciduous	Grassland Acid – Semi-improved		BD2302/5007
HD10	Maintenance of traditional water meadows	ES	Parcel	Field	Wetland	Wetland		BD2302/5007
HD11	Restoration of traditional water meadows	ES	Parcel	Field	Wetland	Scrub		BD2302/5007
HD2	Take archaeological features out of cultivation	ES	Parcel	Field	Grassland Neutral – Semi-improved	Underlying LC		Option description
HD7	Arable reversion by natural regeneration	ES	Parcel	Field	Grassland Neutral – Semi-improved	Near arable crop		Option description
HE1	2 m buffer strips on cultivated land	ES	Parcel	Margin	Grassy Field Margin	No feature	2	
HE10	Floristically enhanced grass margin	ES	Parcel	Margin	Flower Rich Margin	No feature	6	
HE11	Enhanced strips for target species on intensive grassland	ES	Parcel	Margin	Flower Rich Margin	No feature	2	
HE2	4 m buffer strips on cultivated land	ES	Parcel	Margin	Grassy Field Margin	No feature	4	
HE3	6 m buffer strips on cultivated land	ES	Parcel	Margin	Grassy Field Margin	No feature	6	
HE4	2 m buffer strips on intensive grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	2	
HE5	4 m buffer strips on intensive grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	4	
HE6	6 m buffer strips on intensive grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	6	
HE7	Buffering in-field ponds in improved permanent grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	10	
HE8	Buffering in-field ponds in arable land	ES	Parcel	Margin	Grassy Field Margin	No feature	10	
HF1	Management of field corners	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
HF10	Unharvested cereal headlands for birds and rare arable plants	ES	Agreement	Margin	Fallow	No feature	15	
HF10NR	Unharvested cereal headlands for birds and rare arable plants (Non-Rotational)	ES	Parcel	Margin	Fallow	No feature	15	
HF11	Uncropped, cultivated margins for rare plants	ES	Parcel	Margin	Fallow	No feature	4.5	
HF13	Uncropped cultivated areas for ground-nesting birds - arable	ES	Agreement	Field	Fallow	No feature		
HF13NR	Uncropped cultivated areas for ground-nesting birds - arable	ES	Parcel	Field	Fallow	No feature		
HF14	Unharvested, fertiliser-free conservation headland	ES	Agreement	Margin	Fallow	No feature	15	
HF14NR	Unharvested, fertiliser-free conservation headland	ES	Parcel	Margin	Fallow	No feature	15	
HF17	ASD to Dec 2008 Fallow plots for ground-nesting birds (setaside)	ES	Agreement	Field	Fallow	No feature		
HF19	ASD to Dec 2008 Unharvested conservation headland with setaside	ES	Agreement	Margin	Fallow	No feature	15	

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
HF20	Cultivated fallow plots or margins for arable plants	ES	Agreement	Margin	Fallow	No feature	4	
HF20NR	Cultivated fallow plots or margins for arable plants	ES	Parcel	Margin	Fallow	No feature	4	
HF4	Nectar flower mixture	ES	Agreement	Field	Flower Rich Margin	No feature		
HF4NR	Nectar flower mixture	ES	Parcel	Field	Flower Rich Margin	No feature		
HF7	Beetle banks	ES	Parcel	Transect	Ditch	No feature	3	Closest match in G2020
HF8	Skylark plots	ES	Agreement	Plot/Tree	Fallow	No feature		
HF9	Cereal headlands for birds	ES	Agreement	Margin	Fallow	No feature	15	
HF9NR	Cereal headlands for birds	ES	Parcel	Margin	Fallow	No feature	15	
HG3	ASD to Jan 2010 Nectar flower mixture in grassland areas	ES	Parcel	Field	Flower Rich Margin	Underlying LC		Option description
HJ11	Maintenance of watercourse fencing	ES	Parcel	Perimeter	Grassy Field Margin	No feature	1	
HJ3	Reversion to unfertilised grassland to prevent erosion/run-off	ES	Parcel	Field	Grassland Neutral – Unimproved	Nearest arable crop		BD2302/5007
HJ4	Reversion to low input grassland to prevent erosion/run-off	ES	Parcel	Field	Grassland Neutral – Semi-improved	Nearest arable crop		BD2302/5007
HJ5	In-field grass areas to prevent erosion or run-off	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
HJ9	12 m buffer strips for watercourses on cultivated land	ES	Parcel	Margin	Grassy Field Margin	No feature	12	
HK1	Take field corners out of management	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
HK10	Maintenance of wet grassland for wintering waders and wildfowl	ES	Parcel	Field	Wetland	Wetland		BD2302/5007
HK11	Restoration of wet grassland for breeding waders	ES	Parcel	Field	Wetland	Grassland Neutral – Semi-improved		BD2302/5007
HK12	Restoration of wet grassland for wintering waders and wildfowl	ES	Parcel	Field	Wetland	Grassland Neutral – Semi-improved		BD2302/5007
HK13	Creation of wet grassland for breeding waders	ES	Parcel	Field	Wetland	Nearest arable crop		BD2302/5007
HK14	Creation of wet grassland for wintering waders and wildfowl	ES	Parcel	Field	Wetland	Nearest arable crop		BD2302/5007
HK15	Maintenance of grassland for target features	ES	Parcel	Field	Grassland Calcareous – Semi-improved	Grassland Calcareous – Semi-improved		BD2302/5007
HK16	Restoration of grassland for target features	ES	Parcel	Field	Grassland Calcareous – Semi-improved	Grassland Calcareous – Semi-improved		BD2302/5007
HK17	Creation of grassland for target features	ES	Parcel	Field	Grassland Calcareous – Semi-improved	Nearest arable crop		BD2302/5007

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
HK2	Permanent grassland with low inputs	ES	Parcel	Field	Grassland Neutral – Unimproved	Grassland Neutral – Semi-improved		BD2302/5007
HK21	Legume- and herb-rich swards	ES	Agreement	Field	Ley - Grass and Legume	Underlying LC		Option description
HK3	Permanent grassland with very low inputs	ES	Parcel	Field	Grassland Neutral – Unimproved	Grassland Neutral – Semi-improved		BD2302/5007
HK4	Management of rush pastures	ES	Parcel	Field	Grassland Acid – Semi-improved	Grassland Acid – Semi-improved		BD2302/5007
HK6	Maintenance of species-rich, semi-natural grassland	ES	Parcel	Field	Grassland Calcareous – Unimproved	Grassland Calcareous – Unimproved		BD2302/5007
HK7	Restoration of species-rich, semi-natural grassland	ES	Parcel	Field	Grassland Calcareous – Unimproved	Grassland Calcareous – Semi-improved		BD2302/5007
HK8	Creation of species-rich, semi-natural grassland	ES	Parcel	Field	Grassland Calcareous – Unimproved	Nearest arable crop		BD2302/5007
HK9	Maintenance of wet grassland for breeding waders	ES	Parcel	Field	Wetlands	Wetlands		BD2302/5007
HL1	Take field corners out of management in SDAs	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
HL10	Restoration of moorland	ES	Parcel	Field	Moorland	Moorland - Degraded		BD2302/5007
HL11	Creation of upland heathland	ES	Parcel	Field	Moorland	Moorland - Degraded		BD2302/5007
HL12	Management of heather, gorse and grass	ES	Parcel	Field	Moorland	Moorland		BD2302/5007
HL2	Permanent grassland with low inputs in SDAs	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Semi-improved		BD2302/5007
HL3	Permanent grassland with very low inputs in SDAs	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Semi-improved		BD2302/5007
HL4	Management of rush pastures in SDAs	ES	Parcel	Field	Grassland Acid – Semi-improved	Grassland Acid – Semi-improved		BD2302/5007
HL5	Enclosed rough grazing	ES	Parcel	Field	Moorland	Moorland		BD2302/5007
HL6	Unenclosed moorland rough grazing	ES	Parcel	Field	Moorland	Moorland		BD2302/5007
HL7	Maintenance of rough grazing for birds	ES	Parcel	Field	Moorland	Moorland		BD2302/5007
HL8	Restoration of rough grazing for birds	ES	Parcel	Field	Moorland	Moorland - Degraded		BD2302/5007
HL9	Maintenance of moorland	ES	Parcel	Field	Moorland	Moorland		BD2302/5007
HO1	Maintenance of lowland heathland	ES	Parcel	Field	Moorland	Moorland		BD2302/5007
HO2	Restoration of lowland heath	ES	Parcel	Field	Moorland	Scrub		BD2302/5007
HO3	Restoration of forestry areas to lowland heathland	ES	Parcel	Field	Moorland	Nearest woodland LC		Option description
HO4	Creation of lowland heathland from arable or improved grassland	ES	Parcel	Field	Moorland	Nearest arable or improved grassland LC		Option description

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
HO5	Creation of lowland heathland on worked mineral sites	ES	Parcel	Field	Moorland	Urban		Option description
HP1	Maintenance of sand dunes	ES	Parcel	Field	Beaches, Sand Dune/Plane	Beaches, Sand Dune/Plane		BD2302/5007
HP2	Restoration of sand dune systems	ES	Parcel	Field	Beaches, Sand Dune/Plane	Beaches, Sand Dune/Plane		BD2302/5007
HP4	Creation of vegetated shingle and sand dune on grassland	ES	Parcel	Field	Beaches, Sand Dune/Plane	Grassland Neutral – Semi-improved		BD2302/5007
HP5	Maintenance of coastal saltmarsh	ES	Parcel	Field	Saltmarsh	Saltmarsh		BD2302/5007
HP6	Restoration of coastal saltmarsh	ES	Parcel	Field	Saltmarsh	Grassland Neutral – Semi-improved		BD2302/5007
HP7	Creation of inter-tidal and saline habitat on arable land	ES	Parcel	Field	Saltmarsh	Nearest arable LC		BD2302/5007
HP8	Creation of inter-tidal and saline habitat on grassland	ES	Parcel	Field	Saltmarsh	Grassland Neutral – Semi-improved		BD2302/5007
HP9	Creation of inter-tidal and saline habitat by non-intervention	ES	Parcel	Field	Saltmarsh	Grassland Neutral – Unimproved		BD2302/5007
HQ10	Restoration of lowland raised bog	ES	Parcel	Field	Wetland	Scrub		BD2302/5007
HQ3	Maintenance of reedbeds	ES	Parcel	Field	Wetland	Wetland		BD2302/5007
HQ4	Restoration of reedbeds	ES	Parcel	Field	Wetland	Wetland - Degraded		BD2302/5007
HQ5	Creation of reedbeds	ES	Parcel	Field	Wetland	Nearest arable LC		BD2302/5007
HQ6	Maintenance of fen	ES	Parcel	Field	Wetland	Wetland		BD2302/5007
HQ7	Restoration of fen	ES	Parcel	Field	Wetland	Scrub		BD2302/5007
HQ8	Creation of fen	ES	Parcel	Field	Wetland	Nearest arable LC		BD2302/5007
HQ9	Maintenance of lowland raised bog	ES	Parcel	Field	Wetland	Wetland		BD2302/5007
HS7	Management of historic water meadows through traditional irrigation	ES	Parcel	Field	Wetland	Wetland		BD2302/5007
LH1	Management of lowland heathland	CS	Parcel	Field	Moorland	Moorland		Equivalent to HO1
LH2	Restoration of forestry and woodland to lowland heathland	CS	Parcel	Field	Moorland	Nearest woodland LC		Equivalent to HO3
LH3	Creation of heathland from arable or improved grassland	CS	Parcel	Field	Moorland	Nearest arable or improved grassland LC		Equivalent to HO4
OB1	Hedgerow management for landscape (on both sides of a hedge)	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	
OB10	Combined hedge and ditch management (incorporating OB3)	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	
OB11	Stonewall protection and maintenance	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
OB12	Earth bank management (on both sides)	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
OB13	Earth bank management (on one side)	ES	Agreement	Perimeter	Ditch	Ditch (half)	1	Nearest match to G2020
OB14	Hedgerow restoration	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	
OB2	Hedgerow management for landscape (on one side of a hedge)	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	
OB3	Hedgerow management for landscape and wildlife	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	
OB4	Stone faced Hedge bank management on both sides	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
OB5	Stone faced Hedge bank management on one side	ES	Agreement	Perimeter	Ditch	Ditch (half)	1	Nearest match to G2020
OB6	Ditch management	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	
OB7	Half ditch management	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	
OB8	Combined hedge and ditch management (incorporating OB1)	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	
OB9	Combined hedge and ditch management (incorporating OB2)	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	2.5	
OC1	Protection of in field trees - rotational land	ES	Parcel	Plot/Tree	Hedgerow	Hedgerow (half)		
OC2	Protection of in field trees - grassland	ES	Parcel	Plot/Tree	Hedgerow	Hedgerow (half)		
OC24	Hedgerow tree buffer strips on rotational land	ES	Parcel	Margin	Hedgerow	Hedgerow (half)	6	Option description
OC25	Hedgerow tree buffer strips on organic grassland	ES	Parcel	Margin	Hedgerow	Hedgerow (half)	6	Option description
OC3	Maintenance of woodland fences	ES	Agreement	Perimeter	Woodland Edge	Woodland Edge (half)		Creates an un-grazed woodland edge
OC4	Management of wood edges	ES	Parcel	Perimeter	Woodland Edge	Woodland Edge (half)	5	
OD2	Take archaeological features out of cultivation	ES	Parcel	Field	Grassland Neutral – Semi-improved	Underlying LC		Option description
OE1	2m buffer strips on rotational land	ES	Parcel	Margin	Grassy Field Margin	No feature	2	
OE10	6m buffer strip on organic grassland next to a watercourse	ES	Parcel	Margin	Grassy Field Margin	No feature	6	
OE2	4m buffer strips on rotational land	ES	Parcel	Margin	Grassy Field Margin	No feature	4	
OE3	6m buffer strips on rotational land	ES	Parcel	Margin	Grassy Field Margin	No feature	6	
OE4	2m buffer strip on organic grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	2	
OE5	4m buffer strip on organic grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	4	
OE6	6m buffer strip on organic grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	6	
OE7	Buffering in-field ponds in organic grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	10	Option description

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
OE8	Buffering in-field ponds in rotational land	ES	Parcel	Margin	Grassy Field Margin	No feature	10	Option description
OE9	6m buffer strips on rotational land next to a watercourse	ES	Parcel	Margin	Grassy Field Margin	No feature	6	
OF1	Field corner management	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
OF11	Uncropped, cultivated margins for rare plants on arable land	ES	Parcel	Margin	Fallow	No feature	4.5	Option description
OF13	Uncropped cultivated areas for ground-nesting birds - rotational	ES	Agreement	Field	Fallow	No feature		Option description
OF4	Nectar Flower mixture	ES	Agreement	Field	Flower Rich Margin	Underlying LC		Option description
OF4NR	Nectar Flower mixture	ES	Parcel	Field	Flower Rich Margin	Underlying LC		Option description
OF7	Beetle banks	ES	Parcel	Transect	Ditch	No feature	3	Closest match in G2020
OF8	Skylark plots	ES	Agreement	Plot/Tree	Fallow	No feature		Option description
OG3	ASD to Jan 2010 Nectar flower mixture in grassland areas	ES	Parcel	Field	Flower Rich Margin	Underlying LC		Option description
OHC1	Protection of in-field trees on rotational land	ES	Parcel	Plot/Tree	Hedgerow	Hedgerow (half)		
OHC2	Protection of in-field trees on organic grassland	ES	Parcel	Plot/Tree	Hedgerow	Hedgerow (half)		
OHC24	Hedgerow tree buffer strips on rotational land	ES	Parcel	Margin	Hedgerow	Hedgerow (half)	6	
OHC4	Management of woodland edges	ES	Parcel	Perimeter	Woodland Edge	Woodland Edge (half)	5	
OHD2	Take archaeological features out of cultivation (Org)	ES	Parcel	Field	Grassland Neutral – Semi-improved	Underlying LC		Option description
OHE1	2m buffer strips on rotational land	ES	Parcel	Margin	Grassy Field Margin	No feature	2	
OHE2	4m buffer strips on rotational land	ES	Parcel	Margin	Grassy Field Margin	No feature	4	
OHE3	6m buffer strips on rotational land	ES	Parcel	Margin	Grassy Field Margin	No feature	6	
OHE4	2m buffer strip on organic grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	2	
OHE5	4m buffer strip on organic grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	4	
OHE6	6m buffer strip on organic grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	6	
OHE7	Buffering in-field ponds in organic grassland	ES	Parcel	Margin	Grassy Field Margin	No feature	10	
OHE8	Buffering in-field ponds in rotational land	ES	Parcel	Margin	Grassy Field Margin	No feature	10	
OHF1	Management of field corners	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
OHF11	Uncropped, cultivated margins for rare plants	ES	Parcel	Margin	Fallow	No feature	4.5	Option description
OHF13	Uncropped, cultivated areas for ground-nesting birds	ES	Agreement	Field	Fallow	No feature		Option description
OHF13NR	Uncropped, cultivated areas for ground-nesting birds	ES	Parcel	Field	Fallow	No feature		Option description
OHF4	Nectar Flower mixture	ES	Agreement	Field	Flower Rich Margin	Underlying LC		Option description

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
OHF4NR	Nectar Flower mixture	ES	Parcel	Field	Flower Rich Margin	Underlying LC		Option description
OHF7	Beetle banks	ES	Parcel	Transect	Ditch	No feature	3	Closest match in G2020
OHF8	Skylark plots	ES	Agreement	Plot/Tree	Fallow	No feature		Option description
OHG3	ASD to Jan 2010 Nectar flower mixture in grassland areas	ES	Parcel	Field	Flower Rich Margin	Underlying LC		Option description
OHJ11	Maintenance of watercourse fencing	ES	Parcel	Perimeter	Grassy Field Margin	No feature	1	Narrow strip
OHJ5	In-field grass areas to prevent erosion and run-off	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
OHJ9	12 m buffer strips for watercourses on rotational land	ES	Parcel	Margin	Grassy Field Margin	No feature	12	
OHK1	Take field corners out of management	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
OHK2	Permanent grassland with low inputs	ES	Parcel	Field	Grassland Neutral – Unimproved	Grassland Neutral – Semi-improved		BD2302/5007
OHK21	Legume- and herb-rich swards	ES	Agreement	Field	Ley - Grass and Legume	Underlying LC		Option description
OHK3	Permanent grassland with very low inputs	ES	Parcel	Field	Grassland Neutral – Unimproved	Grassland Neutral – Semi-improved		BD2302/5007
OHK4	Management of rush pastures	ES	Parcel	Field	Grassland Acid – Semi-improved	Grassland Acid – Semi-improved		BD2302/5007
OHL2	Permanent grassland with low inputs in SDAs	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Semi-improved		BD2302/5007
OHL3	Permanent grassland with very low inputs in SDAs	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Semi-improved		BD2302/5007
OHL4	Management of rush pastures in SDAs	ES	Parcel	Field	Grassland Acid – Semi-improved	Grassland Acid – Semi-improved		BD2302/5007
OHL5	Enclosed rough grazing	ES	Parcel	Field	Moorland	Moorland		BD2302/5007
OJ11	Maintenance of watercourse fencing	ES	Agreement	Margin	Grassy Field Margin	No feature	1	Narrow strip
OJ5	In-field grass areas to prevent erosion and run-off	ES	Parcel	Field	Grassy Field Margin	No feature		
OJ9	12m buffer strips for watercourses on cultivated land	ES	Parcel	Field	Grassy Field Margin	No feature	12	
OK1	Take field corners out of management: outside SDA & ML (organic)	ES	Parcel	Field	Grassy Field Margin	No feature		
OK2	Permanent grassland with low inputs: outside SDA & ML (organic)	ES	Parcel	Field	Grassland Neutral – Unimproved	Grassland Neutral – Semi-improved		BD2302/5007
OK21	Legume- and herb-rich swards	ES	Agreement	Field	Ley - Grass and Legume	Underlying LC		Option description
OK3	Permanent grassland with very low inputs:outside SDA&ML (organic)	ES	Parcel	Field	Grassland Neutral – Unimproved	Grassland Neutral – Semi-improved		BD2302/5007

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
OK4	Manage rush pastures: outside SDA & ML (organic)	ES	Parcel	Field	Grassland Acid – Semi-improved	Grassland Acid – Semi-improved		BD2302/5007
OL1	Field corner management: SDA land (organic)	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
OL2	Permanent in-bye grassland with low inputs: SDA land (organic)	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Semi-improved		BD2302/5007
OL3	In-bye pasture & meadows with very low inputs: SDA land (organic)	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Semi-improved		BD2302/5007
OL4	Manage rush pastures: SDA land & ML parcels under 15ha (organic)	ES	Parcel	Field	Grassland Acid – Semi-improved	Grassland Acid – Semi-improved		BD2302/5007
OL5	Enclosed rough grazing:SDA land & ML parcels under 15ha (organic)	ES	Parcel	Field	Moorland	Moorland		BD2302/5007
OP4	Multi species ley	CS	Parcel	Field	Ley – Organic	Underlying LC		Option description
OR1	Organic conversion - improved permanent grassland	CS	Parcel	Field	Grassland Neutral – Improved	Grassland Neutral – Improved		Option description
OR2	Organic conversion - unimproved permanent grassland	CS	Parcel	Field	Grassland Neutral – Unimproved	Grassland Neutral – Unimproved		Option description
OR3	Organic conversion - rotational land	CS	Parcel	Field	Cereal – Organic	Cereal		Option description
OT3	Organic land management - rotational land	CS	Agreement	Field	Cereal – Organic	Cereal		Option description
PG02	Permanent grassland buffer strip	EFA	Parcel	Margin	Grassy Field Margin	No feature		
RD01	Non-Agricultural Land Under Rural Development Programme	Other	Parcel	Field	Woodland - Deciduous	Woodland - Deciduous		Assumed to be woodland in other equivalent schemes (see text)
SW1	4 - 6 m buffer strip on cultivated land	CS	Parcel	Margin	Grassy Field Margin	No feature	5	
SW11	Riparian management strip	CS	Parcel	Margin	Grassy Field Margin	No feature	8	
SW2	4 - 6 m buffer strip on intensive grassland	CS	Parcel	Margin	Grassy Field Margin	No feature	5	
SW3	In-field grass strips	CS	Parcel	Field	Grassy Field Margin	No feature		
SW4	12 - 24m watercourse buffer strip on cultivated land	CS	Parcel	Margin	Grassy Field Margin	No feature	18	
SW7	Arable reversion to grassland with low fertiliser input	CS	Parcel	Field	Grassland Neutral – Semi-improved	Near arable LC		Option description
UB11	Stone wall protection and maintenance on/above the moorland line	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
UB12	Earth bank management (both sides) on/above the moorland line	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
UB13	Earth bank management (one side) on/above the moorland line	ES	Agreement	Perimeter	Ditch	Ditch (half)	1	Nearest match to G2020
UB14	Hedgerow restoration	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
UB15	Stone-faced hedgebank restoration	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
UB16	Earth bank restoration	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
UB17	Stone wall restoration	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
UB4	Stone-faced hedgebank management (both sides) on/above ML	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
UB5	Stone-faced hedgebank management (one side) on/above ML	ES	Agreement	Perimeter	Ditch	Ditch (half)	1	Nearest match to G2020
UC5	Sheep fencing around small woodlands	ES	Agreement	Perimeter	Woodland Edge	Woodland Edge (half)	5	Creates un-grazed woodland edge
UHL21	No cutting strip within meadows	ES	Parcel	Field	Grassy Field Margin			
UHL23	Management of upland grassland for birds	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Unimproved		Option description
UL21	No cutting strip within meadows	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description
UL22	Management of enclosed rough grazing for birds	ES	Parcel	Field	Moorland	Moorland		Option description
UL23	Management of upland grassland for birds	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Unimproved		Option description
UOB11	Stone wall protection and maintenance on/above the moorland line	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
UOB12	Earth bank management (both sides) on/above the moorland line	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
UOB14	Hedgerow restoration	ES	Agreement	Perimeter	Hedgerow	Hedgerow (half)	5	
UOB15	Stone-faced hedgebank restoration	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
UOB16	Earth bank restoration	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
UOB17	Stone wall restoration	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
UOB4	Stone-faced hedgebank management (both sides) on/above ML	ES	Agreement	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020r
UOB5	Stone-faced hedgebank management (one side) on/above ML	ES	Agreement	Perimeter	Ditch	Ditch (half)	1	Nearest match to G2020
UOC5	Sheep fencing around small woodlands	ES	Agreement	Perimeter	Woodland Edge	Woodland Edge (half)	5	Creates un-grazed woodland edge
UOJ3	Post and wire fencing along watercourses	ES	Agreement	Perimeter	Grassy Field Margin	No feature	1	Creates un-grazed strip
UOL21	No cutting strip within meadows	ES	Parcel	Field	Grassy Field Margin	Underlying LC		Option description

Option Code	Option Description	Scheme	Option Level	Feature Type	Land Class (*AES_Present*)	Land Class (*AES_Absent*)	Width (*AES_Present*) (m)	Notes
UOL22	Management of enclosed rough grazing for birds	ES	Parcel	Field	Moorland	Moorland		Option description
UOL23	Management of upland grassland for birds	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Unimproved		Option description
UOX2	Grassland and arable	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Unimproved		Option description
UOX3	Moorland	ES	Parcel	Field	Moorland	Moorland		Option description
UP1	Enclosed rough grazing	ES	Parcel	Field	Moorland	Moorland		Option description
UP2	Management of rough grazing for birds	ES	Parcel	Field	Moorland	Moorland		Option description
UP3	Management of moorland	ES	Parcel	Field	Moorland	Moorland		Option description
UX2	Grassland and arable	ES	Parcel	Field	Grassland Acid – Unimproved	Grassland Acid – Unimproved		Option description
UX3	Moorland	ES	Parcel	Field	Moorland	Moorland		Option description
WD1	Woodland creation – maintenance payments	CS	Parcel	Field	Afforestation	Grassland Neutral – Semi-improved		Equivalent to HC10
WD2	Woodland improvement	CS	Parcel	Field	Woodland – Deciduous	Woodland - Degraded		Equivalent to HC8
WD3	Woodland edges on arable land	CS	Parcel	Perimeter	Woodland Edge	Woodland Edge (half)	5	Option description
WD4	Management of wood pasture and parkland	CS	Parcel	Field	Wood Pasture	Wood Pasture		Equivalent to HC12
WD5	Restoration of wood pasture and parkland	CS	Parcel	Field	Wood Pasture	Wood Pasture - Degraded		Equivalent to HC13
WD6	Creation of wood pasture	CS	Parcel	Field	Wood Pasture	Near arable LC		Equivalent to HC14
WD7	Management of successional areas and scrub	CS	Parcel	Field	Scrub	Scrub		Equivalent to HC15
WD8	Creation of successional areas and scrub	CS	Parcel	Field	Scrub	Grassland Neutral – Semi-improved		Equivalent to HC17
WT1	Buffering in-field ponds and ditches in improved grassland	CS	Parcel	Margin	Grassy Field Margin	No feature	15	
WT10	Management of lowland raised bog	CS	Parcel	Field	Wetland	Wetland		Equivalent to HQ9
WT2	Buffering in-field ponds and ditches in arable land	CS	Parcel	Margin	Grassy Field Margin	No feature	15	
WT3	Management of ditches of high environmental value	CS	Parcel	Perimeter	Ditch	Ditch (half)	2	Nearest match to G2020
WT6	Management of reedbed	CS	Parcel	Field	Wetland	Wetland		Equivalent to HQ3
WT7	Creation of reedbed	CS	Parcel	Field	Wetland	Near arable LC		Equivalent to HQ5
WT8	Management of fen	CS	Parcel	Field	Wetland	Wetland		Equivalent to HQ6
WT9	Creation of fen	CS	Parcel	Field	Wetland	Near arable LC		Equivalent to HQ8

Table A1.5: Management Options Excluded from Analysis

Option Code	Option Description	Scheme	Reason for exclusion
A13	Non payment option - permanent grassland for Article 13	ES	No impact on land use
AB2	Basic overwinter stubble	CS	Impact on land cover outside season considered in model
AB6	Enhanced overwinter stubble	CS	Impact on land cover outside season considered in model
AB7	Wholecrop cereals	CS	No impact on floral or nesting resources
AB9	Winter bird food	CS	Impact on land cover outside season considered in model
AB12	Supplementary winter feeding for farmland birds	CS	Impact on land cover outside season considered in model
AB13	Brassica fodder crop	CS	No impact on floral or nesting resources
AB14	Harvested low input cereal	CS	No impact on floral or nesting resources
EA1	Farm Environment Record (FER)	ES	No impact on land use
ED1	Educational Access	CS	No impact on floral or nesting resources
ED1	Maintenance of traditional farm buildings	ES	No impact on floral or nesting resources
ED3	Low depth, non-inversion cultivation on archaeological features	ES	No impact on floral or nesting resources
ED4	Management of scrub on archaeological features	ES	No impact on floral or nesting resources
ED5	Management of archaeological features on grassland	ES	No impact on floral or nesting resources
EF2	Wild bird seed mixture	ES	Impact on land cover outside season considered in model
EF2NR	Wild bird seed mixture (Non-Rotational)	ES	Impact on land cover outside season considered in model
EF3	ASD to Dec 2008 Wild bird seed mixture on set-aside land	ES	Impact on land cover outside season considered in model
EF6	Over-wintered stubbles	ES	Impact on land cover outside season considered in model
EG2	ASD to Jan 2010 Wild bird seed mixture in grassland areas	ES	Impact on land cover outside season considered in model
EG2NR	ASD to Jan 2010 Wild bird seed mixture in grassland areas (Non-Rotational)	ES	Impact on land cover outside season considered in model
EJ1	Management of high erosion risk cultivated land	ES	Impact on land cover outside season considered in model
EK5	Mixed stocking	ES	Impact on land cover outside season considered in model
GS15	Haymaking supplement	CS	Supplements were excluded
GS16	Rush infestation control supplement	CS	Supplements were excluded
GS17	Lenient grazing supplement	CS	Supplements were excluded
HD1	Maintenance of weatherproof traditional farm buildings	ES	No impact on floral or nesting resources
HD3	Low depth, non-inversion cultivation on archaeological features	ES	No impact on floral or nesting resources
HD4	Management of scrub on archaeological features	ES	No impact on floral or nesting resources
HD5	Management of archaeological features on grassland	ES	No impact on floral or nesting resources
HD6	Crop establishment by direct drilling (non-rotational)	ES	No impact on floral or nesting resources

Option Code	Option Description	Scheme	Reason for exclusion
HD8	Maintaining high water levels to protect archaeology	ES	No impact on floral or nesting resources
HD9	Maintenance of designed/engineered water bodies	ES	No impact on floral or nesting resources
HF12	Enhanced wild bird seed mix plots	ES	Impact on land cover outside season considered in model
HF12NR	Enhanced wild bird seed mix plots (Non-Rotational)	ES	Impact on land cover outside season considered in model
HF2	Wild bird seed mixture	ES	Impact on land cover outside season considered in model
HF2NR	Wild bird seed mixture	ES	Impact on land cover outside season considered in model
HF3	ASD to Dec 2008 Wild bird seed mixture on set-aside land	ES	Impact on land cover outside season considered in model
HF6	Overwintered stubble	ES	Impact on land cover outside season considered in model
HG2	ASD to Jan 2010 Wild bird seed mixture	ES	Impact on land cover outside season considered in model
HG2NR	ASD to Jan 2010 Wild bird seed mixture	ES	Impact on land cover outside season considered in model
HG6	Fodder crop management to retain or re-create an arable mosaic	ES	No impact on floral or nesting resources
HG6NR	Fodder crop management to retain or re-create an arable mosaic	ES	No impact on floral or nesting resources
HIOS1	Landscape management	ES	Applicable only to Isles of Scilly
HIOS2	Management of rare arable bulb/flora	ES	Applicable only to Isles of Scilly
HIOS3	Reintroduction of conservation grazing to St Mary's	ES	Applicable only to Isles of Scilly
HIOS4	Reintroduction of conservation grazing other than St Mary's	ES	Applicable only to Isles of Scilly
HJ1	Cropping restrictions on high erosion risk fields	ES	No impact on floral or nesting resources
HJ8	Nil fertiliser supplement	ES	Supplements were excluded
HK19	Raised water levels supplement	ES	Supplements were excluded
HK5	Mixed stocking	ES	No impact on floral or nesting resources
HL13	Moorland re-wetting supplement	ES	Supplements were excluded
HL16	Shepherding supplement	ES	Supplements were excluded
HN1	ASD to Nov 2010 Linear and open access base payment	ES	No impact on floral or nesting resources
HN2	ASD to Nov 2010 Permissive open access	ES	No impact on floral or nesting resources
HN3	ASD to Nov 2010 Permissive footpath access	ES	No impact on floral or nesting resources
HN4	ASD to Nov 2010 Permissive bridleway / cycle path access	ES	No impact on floral or nesting resources
HN5	ASD to Nov 2010 Access for people with reduced mobility	ES	No impact on floral or nesting resources
HN6	ASD to Nov 2010 Upgrading access for cyclists/horses	ES	No impact on floral or nesting resources
HN7	ASD to Nov 2010 Upgrading access - people with reduced mobility	ES	No impact on floral or nesting resources
HN8	Educational access - base payment	ES	No impact on floral or nesting resources
HN8CW	Educational access - base payment	ES	No impact on floral or nesting resources
HN9	Educational access - payment per visit	ES	No impact on floral or nesting resources
HN9CW	Educational access - payment per visit	ES	No impact on floral or nesting resources
HR1	Grazing supplement for cattle	ES	Supplements were excluded

Option Code	Option Description	Scheme	Reason for exclusion
HR2	Grazing supplement for native breeds at risk	ES	Supplements were excluded
HR4	Supplement for control of invasive plant species	ES	Supplements were excluded
HR5	Bracken control supplement	ES	Supplements were excluded
HR6	Supplement for small fields	ES	Supplements were excluded
HR7	Supplement for difficult sites	ES	Supplements were excluded
HR8	Supplement for group applications	ES	Supplements were excluded
HR8WF	Supplement for group applications	ES	Supplements were excluded
HS1	Maintenance of weatherproof traditional farm buildings	CS	No impact on floral or nesting resources
HS3	Reduced-depth, non-inversion cultivation on historic and archaeological features	CS	No impact on floral or nesting resources
HS4	Scrub control on historic and archaeological features	CS	No impact on floral or nesting resources
HS5	Management of historic and archaeological features on grassland	CS	No impact on floral or nesting resources
HS6	Maintenance of designed/engineered water bodies	CS	No impact on floral or nesting resources
HS7	Management of historic water meadows through traditional irrigation	CS	No impact on floral or nesting resources
HS8	Maintenance of weatherproof traditional farm buildings in remote areas	CS	No impact on floral or nesting resources
HS9	Restricted depth crop establishment to protect archaeology under an arable rotation	CS	No impact on floral or nesting resources
OA1	Farm Environment Record (FER)	ES	No impact on land use
OD1	Maintenance of traditional farm buildings	ES	No impact on floral or nesting resources
OD3	Low depth, non-inversion cultivation on archaeological features	ES	No impact on floral or nesting resources
OD4	Management of scrub on archaeological features	ES	No impact on floral or nesting resources
OD5	Management of archaeological features on grassland	ES	No impact on floral or nesting resources
OF2	Wild bird seed mixture	ES	Impact on land cover outside season considered in model
OF2NR	Wild bird seed mixture	ES	Impact on land cover outside season considered in model
OF6	Over-wintered stubbles	ES	Impact on land cover outside season considered in model
OH1	Otter holt - log construction	ES	No impact on floral or nesting resources
OH2	Otter holt - concrete pipe & chamber construction	ES	No impact on floral or nesting resources
OHD1	Maintenance of weatherproof traditional farm buildings	ES	No impact on floral or nesting resources
OHD3	Low depth, non-inversion cultivation on archaeological features	ES	No impact on floral or nesting resources
OHD4	Management of scrub on archaeological features	ES	No impact on floral or nesting resources
OHD5	Management of archaeological features on grassland	ES	No impact on floral or nesting resources
OHF2	Wild bird seed mixture	ES	Impact on land cover outside season considered in model
OHF2NR	Wild bird seed mixture	ES	Impact on land cover outside season considered in model

Option Code	Option Description	Scheme	Reason for exclusion
OHF6	Overwintered stubble	ES	Impact on land cover outside season considered in model
OHG2NR	ASD to Jan 2010 Wild bird seed mix in grassland areas (organic)	ES	Impact on land cover outside season considered in model
OHK5	Mixed stocking	ES	No impact on floral or nesting resources
OJ1	Management of high erosion risk cultivated land	ES	No impact on floral or nesting resources
OK5	Mixed stocking	ES	No impact on floral or nesting resources
OP1	Overwintered stubble	CS	Impact on land cover outside season considered in model
OP2	Wild bird seed mixture	CS	Impact on land cover outside season considered in model
OP3	Supplementary feeding for farmland birds	CS	Impact on land cover outside season considered in model
OR1	Organic conversion - improved permanent grassland	CS	No impact on land class
OT1	Organic land management - improved permanent grassland	CS	No impact on land class
OT4	Organic land management - horticulture	CS	No impact on land class
OT5	Organic land management - top fruit	CS	No impact on land class
OT6	Organic land management - enclosed rough grazing	CS	No impact on land class
OU1	Organic Management	ES	No change in management
SW12	Making space for water	CS	No impact on floral or nesting resources
SW13	Very low nitrogen inputs to groundwater	CS	No impact on floral or nesting resources
SW14	Nil fertiliser supplement	CS	Supplements were excluded
SW5	Enhanced management of maize crops	CS	No impact on floral or nesting resources
SP1	Difficult sites supplement	CS	Supplements were excluded
SP2	Raised water level supplement	CS	Supplements were excluded
SP3	Bracken control supplement	CS	Supplements were excluded
SP4	Control of invasive plant species supplement	CS	Supplements were excluded
SP5	Shepherding supplement	CS	Supplements were excluded
SP6	Cattle grazing supplement	CS	Supplements were excluded
SP7	Introduction of cattle grazing on the Isles of Scilly	CS	Applicable of Isles of Scilly only
SP8	Native breeds at risk supplement	CS	Supplements were excluded
SP9	Threatened species supplement	CS	Supplements were excluded
SP10	Administration of group managed agreements supplement	CS	No impact on land cover
UD12	Maintenance of remote weatherproof traditional farm buildings	ES	Negligible impact on floral or nesting resources
UD13	Maintaining visibility of archaeological features on moorland	ES	Negligible impact on floral or nesting resources
UHD12	Maintenance of remote weatherproof traditional farm buildings	ES	Negligible impact on floral or nesting resources
UHD13	Maintaining visibility of archaeological features on moorland	ES	Negligible impact on floral or nesting resources
UJ12	Winter livestock removal next to streams, rivers and lakes	ES	No impact on floral or nesting resources
UOD12	Maintenance of remote weatherproof traditional farm buildings	ES	No impact on floral or nesting resources

Option Code	Option Description	Scheme	Reason for exclusion
UOD13	Maintaining visibility of archaeological features on moorland	ES	Negligible impact on floral or nesting resources
UOJ12	Winter livestock removal next to streams, rivers and lakes	ES	No impact on floral or nesting resources

1.5 Parameters

Parameters for nest density, dispersal distance, population growth rates and proportion of foraging workers are taken from literature data showing values adapted for bumblebees - Häussler et al (2017) and solitary bees – G2020.

Table A1.6: Fixed parameters used to populate poll4pop model

Parameter	Description	Unit	Bumblebee	Solitary
n_{max}	Number of nests per unit area of maximum nesting quality	nests/ha	19	20
β_f	Mean dispersal distance for foraging	m	530	191
β_n	Mean dispersal distance to new nesting sites	m	1000	100
a_w	Median of the growth rate for workers	-	100	-
b_w	Steepness of the growth rate for workers	-	200	-
a_q	Median of the growth rate for reproductive females	-	15000	42
b_q	Steepness of the growth rate for reproductive females	-	30000	12
w_{max}	Max. number of workers produced by a reproductive female	-	600	-
q_{max}	Max. number of new reproductive females produced	-	160	2
p_w	Fraction of foraging workers	-	0.5	-

The parameterisation approach for nesting attractiveness, floral attractiveness for the four guilds for each land class and floral cover for the three seasons for each land cover class has already been set out in the main document.

To estimate the uncertainty in the log ratio caused by uncertainty in the underlying parameter values, 100 simulations were run where the nesting attractiveness, floral attractiveness and floral cover score for each land class were randomly drawn from a beta distribution (*B(a, b)*) with mean ($\mu = a / (a + b)$) and variance ($\sigma^2 = \mu(1 - \mu) / (a + b + 1)$) equal to the mean and variance of the G2020 expert opinion scores for that parameter. A beta distribution was used as the scores are bounded and, since *B(a, b)* is only defined on the interval (0,1), the randomly drawn scores are rescaled to the appropriate scale for that parameter. For land classes where means and variances were both close to zero, the variances were adjusted upwards to slightly higher than the minimum value required to generate a solution for *a* and *b*. For new land classes where the mean value was generated by blending the scores of two existing classes, the variances were calculated by means of propagation (Hughes and Hase, 2010).

To calculate variance of a floral or nesting attractiveness parameter of blended land cover class C ($\sigma^2_{C\_att}$) Equation 2 was used:

$$\sigma^2{}_{C\_att} = a^2\sigma^2{}_{A\_att} + b^2\sigma^2{}_{B\_att} \qquad 2$$

Where the mean parameter for blended land class C is weighted sum of the parameters for land classes A and B with blend weights *a* and *b*, respectively, and $\sigma^2_{A\_att}$ and $\sigma^2_{B\_att}$ are their respective variances.

In the case of floral cover, the parameter is the product of abundance and duration parameters provided by the experts. The variance of the blended land cover class abundance ($\sigma^2_{C\_abu}$) and duration

($\sigma^2_{C\_dur}$) was first calculated as per Equation 2 using the component blend weights and variances, then the variance of the floral cover ($\sigma^2_{C\_cov}$) were propagated according to Equation 3.

$$\sigma^2{}_{C\_cov} = C\_cov^2 \left[\left(\frac{\sigma^2{}_{C\_abu}}{C\_abu^2} \right) + \left(\frac{\sigma^2{}_{C\_dur}}{C\_dur^2} \right) \right] \quad 3$$

Where *C_cov* is the mean blended floral cover, *C_abu* is the mean abundance, and *C_dur* is the mean duration. The final parameter values (mean, *a*, *b*) used for the draws are provided in Table A1.7 to Table A1.11 below.

Draws for land classes parameterised directly from G2020 were constrained to within a quantile range (0.075, 0.925), i.e., 85% of the distribution. This excluded extreme draws from the distribution and ensured that draws did not unreasonably exceed the range of scores provided by the experts. The range of 85% was chosen after trials of 95% and 90% were found to be insufficient to exclude outliers. Blended land classes were also constrained by limiting draws to the distribution bounded by the lowest and highest values of the component land class draws. This maintained the relative parameterisation between *AES_Present* and *AES_Absent* scenarios whilst still allowing them to vary independently. For example, the values for semi-improved grassland land classes will always be in between the values for improved grassland and unimproved grassland, but not necessarily half-way. Hedgerow, ditch and woodland edge land classes have the same mean, *a* and *b* values in *AES_Present* and *AES_Absent* but are twice the width in the former. To simulate the variance of improved management on 50% of the width, the draw for these land classes in the *AES_Present* scenario was set at 50% of the draw in *AES_Absent* plus 50% of a draw from a distribution between this value and the upper quantile (0.925) of the distribution.

Table A1.7: Ground Nesting Bumblebee - Floral (scale 0 - 20) and nesting (scale 0 - 1) mean attractiveness and associated beta distribution parameters (a,b)

	Floral			**Nesting**		
Land Class	***mean***	***a***	***b***	***mean***	***a***	***b***
Beaches, Sand Dunes/Plane	9.18	0.8316	0.98	0.26	0.3751	1.09
Berries (exc. Strawberries & Raspberries)	14.21	5.2152	2.12	0.00	0.0000	0.01
Broad/Field Beans	15.72	6.8012	1.85	0.20	0.2518	1.01
Buckwheat	0.77	0.1364	3.41	0.06	0.2500	3.75
Cereal	0.26	0.3266	25.20	0.06	0.3875	6.36
Cereal - Organic	5.19	0.0695	0.20	0.04	0.4110	9.71
Ditch	8.81	2.2009	2.80	0.58	2.3981	1.77
Fallow	10.28	1.7224	1.63	0.46	1.2470	1.46
Flower Rich Margin	14.47	1.4130	0.54	0.57	1.0523	0.79
Gardens	16.54	5.5358	1.16	0.72	20.5357	8.04
Golf Courses	6.63	0.7373	1.49	0.32	1.2731	2.72
Grassland Acid - Improved	2.29	0.8813	6.80	0.14	1.0669	6.48
Grassland Neutral - Improved	2.29	0.8813	6.80	0.14	1.0669	6.48
Grassland Calcareous - Improved	5.30	0.5593	1.55	0.27	0.7187	1.96
Grassland Acid - Semi-Improved	7.77	4.5995	7.24	0.27	6.8200	18.71
Grassland Neutral - Semi-Improved	7.37	2.9388	5.04	0.29	2.6371	6.43

	Floral			Nesting		
Land Class	***mean***	***a***	***b***	***mean***	***a***	***b***
Grassland Calcareous - Semi-Improved	9.88	3.2988	3.38	0.42	2.5111	3.47
Grassland Acid - Unimproved	13.25	1.7135	0.87	0.39	5.7292	8.85
Grassland Neutral - Unimproved	12.44	0.9675	0.59	0.44	1.1618	1.48
Grassland Calcareous - Unimproved	14.47	1.4130	0.54	0.57	1.0523	0.79
Grassy Field Margin	10.63	1.8288	1.61	0.70	2.2479	0.97
Hedgerow	15.95	3.6910	0.94	0.77	8.0500	2.45
Ley - Grass and Legume	16.07	5.4250	1.33	0.28	0.9741	2.47
Ley - Grass	2.57	1.0973	7.46	0.24	0.8253	2.65
Ley - Organic	11.95	1.7730	1.19	0.21	5.5257	20.55
Linseed/Flax	9.62	26.5625	28.69	0.14	0.2659	1.66
Maize	1.14	0.4000	6.60	0.01	0.2969	24.64
Moorland	13.25	1.7135	0.87	0.39	5.7292	8.85
Moorland - Degraded	10.51	3.1350	2.83	0.33	7.3520	14.93
Null	0.00	-	-	0.00	-	-
Oilseed Rape	16.33	12.9391	2.90	0.00	-	-
Oilseed Rape - Organic	16.50	11.8800	2.52	0.22	0.1494	0.53
Orchard	15.69	22.5693	6.21	0.46	3.3971	4.01
Orchard - Degraded	15.31	22.0471	6.76	0.48	5.3592	5.80
Peas	14.25	4.6426	1.87	0.18	0.1081	0.48
Poplar	9.00	1.4063	1.72	0.15	1.1250	6.38
Potatoes	7.14	1.2500	2.25	0.09	0.1849	1.81
Reed Canary Grass	0.86	5.7000	127.30	0.17	2.3286	11.37
Salix	15.94	6.3494	1.62	0.17	0.6176	3.09
Salt Marsh	7.00	2.6833	4.98	0.06	0.2416	3.99
Scrub	13.79	1.7820	0.80	0.57	2.8257	2.15
Scrub - Degraded	10.58	5.6274	5.01	0.43	2.8257	8.51
Strawberry/Raspberry in Polytunnels	10.09	0.4957	0.49	0.00	-	-
Strawberry/Raspberry in the open	15.13	8.3710	2.70	0.32	0.4218	0.89
Sugar Beet	0.00	-	-	0.00	-	-
Urban	0.00	-	-	0.00	-	-
Vegetables	4.38	0.5203	1.86	0.10	0.5000	4.50
Wetland	8.08	6.1688	9.11	0.14	0.3454	2.11
Wetland - Degraded	8.65	8.0045	10.51	0.18	0.7729	3.44
Wood Pasture	12.21	6.7340	0.85	0.45	1.1576	1.92
Wood Pasture - Degraded	7.37	2.7091	5.04	0.29	1.0975	6.43
Woodland - Afforestation	5.93	1.3273	2.17	0.40	1.5559	5.32
Woodland - Coniferous	1.76	1.3273	6.53	0.23	1.5559	3.43
Woodland - Deciduous	10.08	0.9128	2.68	0.51	3.5202	2.72
Woodland - Degraded	9.54	0.6316	4.50	0.47	1.0276	4.73
Woodland Edge	13.97	2.7265	2.17	0.73	2.8619	2.83

Table A1.8: Tree Nesting Bumblebees - Floral (scale 0 - 20) and nesting (scale 0 - 1) mean attractiveness and associated beta distribution parameters (a,b)

	Floral			Nesting		
Land Class	***mean***	***a***	***b***	***mean***	***a***	***b***
Beaches, Sand Dunes/Plane	0.50	0.9500	37.05	0.00	-	-
Berries (exc. Strawberries & Raspberries)	16.00	2.0444	0.51	0.00	-	-
Broad/Field Beans	15.40	2.0359	0.61	0.00	-	-
Buckwheat	0.00	-	-	0.00	-	-
Cereal	0.25	0.3167	25.02	0.00	-	-
Cereal - Organic	0.00	-	-	0.00	-	-
Ditch	7.86	5.7292	8.85	0.02	0.6333	31.03
Fallow	10.71	1.6406	1.42	0.02	0.4750	28.03
Flower Rich Margin	19.00	17.1000	0.90	0.02	0.6333	31.03
Gardens	19.00	17.1000	0.90	0.95	17.1000	0.90
Golf Courses	2.50	0.7500	5.25	0.08	0.3750	4.13

	Floral			Nesting		
Land Class	***mean***	***a***	***b***	***mean***	***a***	***b***
Grassland Acid - Improved	2.86	1.0000	6.00	0.01	0.1583	22.01
Grassland Neutral - Improved	2.86	1.0000	6.00	0.01	0.1583	22.01
Grassland Calcareous - Improved	0.57	1.2667	43.07	0.00	-	-
Grassland Acid - Semi-Improved	9.13	6.6315	7.90	0.09	0.4069	4.28
Grassland Neutral - Semi-Improved	10.13	19.8237	19.32	0.004	0.0145	4.06
Grassland Calcareous - Semi-Improved	9.79	156.6516	163.51	0.01	0.1177	11.66
Grassland Acid - Unimproved	15.40	2.0359	0.61	0.17	0.2500	1.25
Grassland Neutral - Unimproved	17.40	9.3797	1.40	0.00	-	-
Grassland Calcareous - Unimproved	19.00	17.1000	0.90	0.02	0.6333	31.03
Grassy Field Margin	12.50	8.7500	5.25	0.00	-	-
Hedgerow	17.40	9.3797	1.40	0.20	0.3333	1.33
Ley - Grass and Legume	16.00	2.0444	0.51	0.00	-	-
Ley - Grass	2.14	0.5625	4.69	0.00	-	-
Ley - Organic	5.00	2.7500	8.25	0.02	0.6333	31.03
Linseed/Flax	10.00	7.5000	7.50	0.00	-	-
Maize	0.00	-	-	0.00	-	-
Moorland	15.40	2.0359	0.61	0.17	0.2500	1.25
Moorland - Degraded	12.26	2.0359	2.86	0.13	0.3221	2.22
Null	0.00	-	-	0.00	-	-
Oilseed Rape	19.00	17.1000	0.90	0.00	-	-
Oilseed Rape - Organic	17.40	9.3797	1.40	0.00	-	-
Orchard	19.00	17.1000	0.90	0.50	7.5000	7.50
Orchard - Degraded	18.20	19.7925	1.96	0.42	9.2321	12.75
Peas	14.33	0.6198	0.25	0.00	-	-
Poplar	0.00	-	-	0.00	-	-
Potatoes	0.00	-	-	0.00	-	-
Reed Canary Grass	0.00	-	-	0.00	-	-
Salix	19.00	-	-	0.02	0.6333	31.03
Salt Marsh	0.00	-	-	0.00	-	-
Scrub	15.00	2.0625	0.69	0.10	0.5000	4.50
Scrub - Degraded	12.56	9.8100	5.81	0.05	0.5960	10.91
Strawberry/Raspberry in Polytunnels	16.00	2.0444	0.51	0.00	-	-
Strawberry/Raspberry in the open	17.67	9.3578	1.24	0.00	-	-
Sugar Beet	0.00	-	-	0.00	-	-
Urban	0.00	-	-	0.00	-	-
Vegetables	10.00	49.5000	49.50	0.00	-	-
Wetland	1.00	0.1020	1.94	0.00	-	-
Wetland - Degraded	2.40	0.8432	6.18	0.01	0.0355	3.52
Wood Pasture	17.16	36.1893	2.08	0.08	2.1024	25.20
Wood Pasture - Degraded	10.13	31.9901	19.32	0.004	0.0145	4.06
Woodland - Afforestation	3.33	12.5422	1.25	0.33	5.0000	10.00
Woodland - Coniferous	0.33	12.5422	28.03	0.42	6.8750	9.63
Woodland - Deciduous	15.00	0.2500	18.50	0.77	2.0359	0.61
Woodland - Degraded	14.03	0.4750	33.54	0.62	4.0658	2.53
Woodland Edge	19.00	55.5000	0.90	0.77	2.0359	0.61

Table A1.9: Ground Nesting Solitary Bees - Floral (scale 0 - 20) and nesting (scale 0 - 1) mean attractiveness and associated beta distribution parameters (a,b)

	Floral			Nesting		
Land Class	***mean***	***a***	***b***	***mean***	***a***	***b***
Beaches, Sand Dunes/Plane	11.19	3.3639	2.65	0.54	2.0461	1.76
Berries (exc. Strawberries & Raspberries)	10.96	4.1430	3.42	0.21	0.3637	1.35
Broad/Field Beans	6.65	1.1025	2.22	0.28	0.5813	1.50
Buckwheat	5.00	1.8333	5.50	0.25	1.8333	5.50
Cereal	0.46	0.8000	34.20	0.29	0.5787	1.42
Cereal - Organic	6.33	0.5903	1.27	0.27	0.4682	1.25

	Floral			Nesting		
Land Class	***mean***	***a***	***b***	***mean***	***a***	***b***
Ditch	8.45	1.2238	1.67	0.49	0.8500	0.88
Fallow	10.19	3.0315	2.92	0.54	2.0647	1.77
Flower Rich Margin	14.88	2.5946	0.89	0.46	3.7297	4.35
Gardens	14.81	3.4137	1.20	0.68	11.4700	5.30
Golf Courses	5.86	2.4975	6.03	0.50	2.3750	2.38
Grassland Acid - Improved	2.00	0.8458	7.61	0.25	0.4471	1.34
Grassland Neutral - Improved	2.00	0.8458	7.61	0.25	0.4471	1.34
Grassland Calcareous - Improved	6.36	1.3329	2.86	0.27	0.9115	2.41
Grassland Acid - Semi-Improved	6.11	4.8619	11.06	0.41	3.7011	5.22
Grassland Neutral - Semi-Improved	7.23	3.8896	6.86	0.39	2.0798	3.29
Grassland Calcareous - Semi-Improved	10.62	5.7473	5.08	0.37	4.2954	7.38
Grassland Acid - Unimproved	10.22	2.6301	2.52	0.58	4.0348	2.93
Grassland Neutral - Unimproved	12.47	1.4959	0.90	0.52	1.0768	0.98
Grassland Calcareous - Unimproved	14.88	2.5946	0.89	0.46	3.7297	4.35
Grassy Field Margin	8.15	1.7720	2.58	0.36	2.4919	4.48
Hedgerow	15.91	17.5432	4.50	0.57	1.7854	1.35
Ley - Grass and Legume	9.21	2.8438	3.33	0.21	0.7471	2.81
Ley - Grass	4.88	2.6981	8.37	0.21	0.6412	2.40
Ley - Organic	6.77	1.8231	3.56	0.32	5.1750	10.93
Linseed/Flax	10.00	2.1000	2.10	0.12	0.8924	6.84
Maize	0.56	1.2091	41.97	0.23	0.5941	2.03
Moorland	10.22	2.6301	2.52	0.58	4.0348	2.93
Moorland - Degraded	8.16	3.7952	5.50	0.50	5.3058	5.37
Null	0.00	-	-	0.00	-	-
Oilseed Rape	14.89	3.1509	1.08	0.30	1.3407	3.10
Oilseed Rape - Organic	16.06	3.5914	0.88	0.26	2.0391	5.78
Orchard	16.43	3.9495	0.86	0.65	9.1477	4.97
Orchard - Degraded	15.19	7.3384	2.33	0.59	12.5409	8.57
Peas	5.00	18.5000	55.50	0.30	1.8549	4.40
Poplar	3.00	1.7625	9.99	0.13	1.3333	9.33
Potatoes	5.00	18.5000	55.50	0.18	2.5200	11.88
Reed Canary Grass	1.00	0.9000	17.10	0.05	0.9000	17.10
Salix	11.25	11.2500	8.75	0.28	0.9574	2.45
Salt Marsh	8.20	2.6511	3.81	0.21	5.2336	19.69
Scrub	10.22	4.7342	4.53	0.38	2.4669	4.05
Scrub - Degraded	8.73	9.3224	12.04	0.38	4.8967	7.90
Strawberry/Raspberry in Polytunnels	7.68	0.6821	1.09	0.11	0.2326	1.98
Strawberry/Raspberry in the open	11.60	9.8088	7.10	0.30	1.2253	2.86
Sugar Beet	0.00	-	-	0.00	-	-
Urban	0.00	-	-	0.00	-	-
Vegetables	5.00	0.7917	2.38	0.15	1.7625	9.99
Wetland	5.00	18.5000	55.50	0.17	2.3286	11.37
Wetland - Degraded	5.52	24.0494	63.06	0.19	3.4520	14.64
Wood Pasture	12.27	4.4750	1.24	0.51	2.5947	1.34
Wood Pasture - Degraded	7.23	3.9926	6.86	0.39	2.3305	3.29
Woodland - Afforestation in AES	6.43	1.9737	1.57	0.37	1.4169	1.18
Woodland - Coniferous not in AES	1.54	1.9737	10.74	0.13	1.4169	9.43
Woodland - Deciduous not in AES	10.47	0.7448	3.66	0.42	0.7019	3.46
Woodland - Degraded	9.82	0.8947	6.12	0.42	1.4514	5.37
Woodland Edge	12.24	4.0186	5.57	0.54	2.5282	13.14

Table A1.10: Cavity Nesting Solitary Bees - Floral (scale 0 - 20) and nesting (scale 0 - 1) mean attractiveness and associated beta distribution parameters (a,b)

	Floral			Nesting		
Land Class	***mean***	***a***	***b***	***mean***	***a***	***b***
Beaches, Sand Dunes/Plane	7.22	0.3275	0.58	0.25	18.5000	55.50
Berries (exc. Strawberries & Raspberries)	7.62	0.6019	0.98	0.16	2.0436	10.64
Broad/Field Beans	10.38	0.5984	0.55	0.15	1.0500	6.15
Buckwheat	5.00	1.8333	5.50	0.25	1.8333	5.50
Cereal	0.60	1.4250	46.08	0.03	1.5200	47.88
Cereal - Organic	3.18	1.9870	10.50	0.06	0.4224	6.34
Ditch	8.18	6.4286	9.29	0.25	18.5000	55.50
Fallow	6.82	4.9554	9.58	0.25	18.5000	55.50
Flower Rich Margin	11.33	1.0921	0.84	0.32	5.2500	11.25
Gardens	14.71	4.1832	1.50	0.68	10.9250	5.18
Golf Courses	6.67	5.0000	10.00	0.42	6.8750	9.63
Grassland Acid - Improved	3.77	3.1944	13.76	0.15	1.2000	6.60
Grassland Neutral - Improved	3.77	3.1944	13.76	0.15	1.2000	6.60
Grassland Calcareous - Improved	5.31	1.3875	3.84	0.23	0.7241	2.41
Grassland Acid - Semi-Improved	6.20	3.6889	8.21	0.29	3.0217	7.57
Grassland Neutral - Semi-Improved	7.23	1.9014	3.36	0.20	2.5527	10.23
Grassland Calcareous - Semi-Improved	8.32	3.0937	4.34	0.27	3.6794	9.73
Grassland Acid - Unimproved	8.64	1.3996	1.84	0.42	1.4063	1.97
Grassland Neutral - Unimproved	10.69	0.4224	0.37	0.25	1.1945	3.67
Grassland Calcareous - Unimproved	11.33	1.0921	0.84	0.32	5.2500	11.25
Grassy Field Margin	9.55	2.5559	2.80	0.42	6.8750	9.63
Hedgerow	13.57	10.9250	5.18	0.81	14.5841	3.48
Ley - Grass and Legume	10.00	49.5000	49.50	0.23	1.0416	3.50
Ley - Grass	5.00	18.5000	55.50	0.17	2.2143	11.07
Ley - Organic	5.00	18.5000	55.50	0.18	2.6160	12.14
Linseed/Flax	10.38	2.5022	2.32	0.17	0.3158	1.55
Maize	0.60	1.4250	46.08	0.03	1.7100	51.49
Moorland	8.64	1.3996	1.84	0.42	1.4063	1.97
Moorland - Degraded	7.42	2.2465	3.81	0.35	2.1338	3.95
Null	0.00	-	-	0.00	-	-
Oilseed Rape	13.00	2.6361	1.42	0.18	0.3596	1.60
Oilseed Rape - Organic	11.67	9.6250	6.88	0.18	0.3596	1.60
Orchard	16.43	12.2986	2.67	0.48	0.2642	0.28
Orchard - Degraded	15.48	20.2796	5.93	0.52	0.7295	0.68
Peas	7.50	5.2500	8.75	0.28	0.8080	2.13
Poplar	3.00	1.7625	9.99	0.25	18.5000	55.50
Potatoes	5.00	18.5000	55.50	0.13	1.4016	9.38
Reed Canary Grass	1.00	0.9000	17.10	0.39	2.0300	3.22
Salix	5.00	18.5000	55.50	0.38	5.2500	8.75
Salt Marsh	4.20	5.2336	19.69	0.21	5.2336	19.69
Scrub	11.67	9.6250	6.88	0.67	10.0000	5.00
Scrub - Degraded	9.45	8.8051	9.83	0.43	16.2632	21.28
Strawberry/Raspberry in Polytunnels	8.85	0.6752	0.85	0.07	0.3000	3.90
Strawberry/Raspberry in the open	10.83	2.8261	2.39	0.45	10.6875	13.06
Sugar Beet	0.00	-	-	0.00	-	-
Urban	0.00	-	-	0.00	-	-
Vegetables	5.00	0.7917	2.38	0.11	0.6000	4.80
Wetland	5.00	18.5000	55.50	0.25	18.5000	55.50
Wetland - Degraded	5.67	26.3042	66.53	0.29	27.5552	66.92
Wood Pasture	10.66	5.0285	0.56	0.28	1.2294	4.84
Wood Pasture - Degraded	7.23	5.7745	3.36	0.20	1.3309	10.23
Woodland - Afforestation	7.22	0.6412	0.58	0.31	1.8884	0.60
Woodland - Coniferous	3.67	0.6412	12.94	0.16	1.8884	10.88
Woodland - Deciduous	10.36	0.3275	2.54	0.60	0.2721	1.42
Woodland - Degraded	9.73	2.9047	4.24	0.52	2.1383	3.01
Woodland Edge	15.00	2.7260	18.50	0.75	2.0990	1.10

Table A1.11: Floral cover mean by season (scale 0 - 100) and associated beta distribution parameters (a,b)

	Early Spring			Late Spring			Summer		
Land Class	**mean**	**a**	**b**	**mean**	**a**	**b**	**mean**	**a**	**b**
Beaches, Sand Dunes/Plane	2.37	2.0525	84.45	2.37	2.0525	84.45	14.88	1.4273	8.17
Berries (exc. Strawberries & Raspberries)	0.84	1.5582	183.58	7.57	1.3845	16.89	23.31	0.9613	3.16
Broad/Field Beans	0.51	0.9830	192.07	4.58	0.9015	18.78	12.10	1.2793	9.29
Buckwheat	0.00	-	-	0.00	-	-	1.67	0.1372	8.10
Cereal	0.30	0.5100	166.70	0.30	0.5100	166.70	1.63	0.9044	54.49
Cereal - Organic	1.70	1.0801	62.42	1.70	1.0801	62.42	10.41	2.5075	21.58
Ditch	4.66	1.7399	35.58	4.66	1.7399	35.58	15.38	9.4015	51.71
Fallow	4.89	1.5748	30.64	4.89	1.5748	30.64	17.63	2.7875	13.02
Flower Rich Margin	5.75	0.9358	15.34	5.75	0.9358	15.34	42.99	1.3727	1.82
Gardens	11.15	1.8647	14.85	11.15	1.8647	14.85	39.39	3.0986	4.77
Golf Courses	2.98	2.2621	73.58	2.98	2.2621	73.58	12.40	2.9452	20.81
Grassland Acid - Improved	1.59	1.0919	67.72	1.59	1.0919	67.72	6.77	4.5330	62.45
Grassland Neutral - Improved	1.59	1.0919	67.72	1.59	1.0919	67.72	6.77	4.5330	62.45
Grassland Calcareous - Improved	2.61	4.0458	150.85	2.61	4.0458	150.85	14.17	6.5425	39.64
Grassland Acid - Semi-Improved	2.03	2.9712	143.48	2.03	2.9712	143.48	15.45	7.3703	40.35
Grassland Neutral - Semi-Improved	2.77	2.3584	82.91	2.77	2.3584	82.91	21.43	1.6779	6.15
Grassland Calcareous - Semi-Improved	4.33	1.7507	38.72	4.33	1.7507	38.72	29.03	3.6318	8.88
Grassland Acid - Unimproved	2.31	2.8904	122.08	2.31	2.8904	122.08	21.42	3.2735	12.01
Grassland Neutral - Unimproved	3.91	1.9248	47.33	3.91	1.9248	47.33	36.93	0.7288	1.24
Grassland Calcareous - Unimproved	5.75	0.9358	15.34	5.75	0.9358	15.34	42.99	1.3727	1.82
Grassy Field Edges	3.48	3.2114	89.18	3.48	3.2114	89.18	13.06	1.2390	8.25
Hedgerow	10.56	4.7317	40.07	10.56	4.7317	40.07	20.60	1.8688	7.20
Ley - Grass and Legume	5.42	1.7726	30.95	5.42	1.7726	30.95	38.00	1.5839	2.58
Ley - Grass	1.19	1.0324	85.69	1.19	1.0324	85.69	6.27	1.2658	18.93
Ley - Organic	4.39	9.2218	200.89	4.39	9.2218	200.89	21.39	4.6787	17.19
Linseed/Flax	0.87	0.7184	81.83	7.83	0.5977	7.03	9.47	2.8302	27.06
Maize	0.00	0.0476	1006.52	0.00	0.0476	1006.52	2.21	1.0265	45.40
Moorland	2.31	2.8904	122.08	2.31	2.8904	122.08	21.42	3.2735	12.01
Moorland - Degraded	2.19	3.6513	163.03	2.19	3.6513	163.03	18.77	5.1396	22.24
Null	0.00	-	-	0.00	-	-	0.00	-	-
Oilseed Rape	2.12	7.0520	326.26	19.04	5.6597	24.06	9.29	0.5698	5.57
Oilseed Rape - Organic	2.21	4.6144	204.41	19.87	3.6004	14.52	13.97	0.9378	5.77
Orchard	20.30	2.9168	11.46	2.26	3.8033	164.86	13.33	0.4206	2.74
Orchard - Degraded	19.51	4.7208	19.47	2.17	5.9536	268.65	14.28	0.7068	4.24
Peas	0.03	0.2000	733.60	0.24	0.1970	80.27	9.97	8.6946	78.47
Poplar	7.98	1.4502	16.73	7.98	1.4502	16.73	0.99	0.3862	38.71
Potatoes	0.00	-	-	0.00	-	-	3.33	0.8535	24.75
Reed Canary Grass	0.00	-	-	0.00	-	-	0.00	0.0000	0.01
Salix	12.10	5.4408	39.53	12.10	5.4408	39.53	3.75	0.8343	21.43
Salt Marsh	0.99	0.9756	97.40	0.99	0.9756	97.40	14.04	0.9498	5.81
Scrub	4.72	1.6452	33.22	4.72	1.6452	33.22	14.46	6.1393	36.32
Scrub - Degraded	3.69	3.4969	91.28	3.69	3.4969	91.28	17.82	4.8715	22.47
Strawberry/Raspberry in Polytunnels	2.61	1.4932	55.74	23.48	0.9589	3.13	38.14	0.9030	1.46
Strawberry/Raspberry in the open	0.23	0.5980	261.10	2.06	0.5690	27.08	38.07	1.1672	1.90
Sugar Beet	0.00	-	-	0.00	-	-	6.67	2.6784	37.50
Urban	0.00	-	-	0.00	-	-	0.00	-	-
Vegetables	0.23	0.2970	126.40	0.23	0.2970	126.40	12.38	2.9611	20.96
Wetland	1.33	6.2261	462.56	1.33	6.2261	462.56	14.44	4.3346	25.67
Wetland - Degraded	1.59	7.7310	479.99	1.59	7.7310	479.99	14.45	5.3721	31.81
Wood Pasture	4.08	2.4393	57.34	4.08	2.4393	57.34	34.45	0.8973	1.71
Wood Pasture - Degraded	2.77	2.3584	82.91	2.77	2.3584	82.91	21.43	1.6779	6.15
Woodland - Afforestation	2.27	0.9967	42.84	2.27	0.9967	42.84	9.70	0.6137	5.71
Woodland - Coniferous	0.35	0.3670	105.33	0.35	0.3670	105.33	2.21	0.7134	31.50
Woodland - Deciduous	5.80	2.4867	40.38	5.80	2.4867	40.38	13.44	3.1143	20.05
Woodland - Degraded	5.12	3.2875	60.91	5.12	3.2875	60.91	15.00	4.6276	26.23
Woodland Edge	6.77	1.9809	27.29	6.77	1.9809	27.29	19.07	2.6771	11.36

1.6 Validation

G2020 validated the Poll4pop model visitation rates against observed pollinator abundances along transects at 239 sites across Great Britain. We repeated this validation process to check our improvements to the model and more detailed mapping data still produced visitation rates that significantly agree with the observed pollinator abundances. Because our model version only applies to England, only the English transect sites (215 of 239) were used which included 9 urban sites, 104 non-crop sites (semi-natural habitat, nature reserves) and 103 crop sites covering the four focal crops.

For each survey site, the visitation rate per m^2 within the survey area for the relevant season (V_s) was calculated in the *AES_Present* scenario. This was then compared to the number of observed bees (N_{obs}) by fitting Equation 4:

$$\log\left(\frac{N_{obs}+1}{L}\right) = \beta \log V_s + \gamma \log W + \begin{pmatrix}\zeta_{S1}\\ \vdots \\ \zeta_{S2}\end{pmatrix} S + \eta(S * logW) + \theta Y + \begin{pmatrix}\alpha_{2011}\\ \vdots \\ \alpha_{2016}\end{pmatrix} Z \qquad 4$$

Where *L* is the total transect length walked during the survey, *W* is week of the year that the survey was carried out, S is a factor representing the season used for visitation rate (S1 = early spring, S2 = late spring), *Y* is the Y coordinate of the British National Grid reference for the survey site, and *Z* is the year in which the survey took place. Early spring visitation rates were used for all sites except for oilseed rape, field beans and strawberries, for which late spring visitation rates were used to match their peak floral cover. Fitting to $N_{obs} + 1$ avoids taking logarithms of zero. Including week and year as covariables accounts for variability of pollinator populations within and between years due to external factors such as weather. Including the Y grid reference accounts for beneficial temperature and weather effects associated with more southerly latitudes. A significant positive value of β indicates significant model-data agreement. As in G2020, the model is fitted with a Gaussian error term as this yields the smallest and most uniform residuals.

All four guilds show significant agreement (statistically significant $\beta > 0$) between the predicted visitation rate for the survey area as calculated by the model (*AES_Present* scenario) and the observed number of bees from the survey data. β and R^2 values are comparable to those reported in G2020, with R^2 values for ground nesting guilds slightly higher in this modelling scenario.

Table A1.12: Agreement between model predictions and observed bee numbers as assessed by fitting equation 4. Statistically significant coefficients are marked with asterisks (= p <0.05, ** = p < 0.01, *** = p < 0.001). GNBB, TNBB, GNSB and CNSB refer to ground-nesting bumblebees, tree-nesting bumblebees, ground-nesting solitary bees and cavity-nesting solitary bees, respectively.*

Parameter	Coefficient	GNBB	TNBB	GNSB	CNSB
V_s	β	0.14 ± 0.03 ***	0.16 ± 0.02 ***	0.15 ± 0.02 ***	0.10 ± 0.01 ***
log W	γ	0.3 ± 0.2 *	-0.3 ± 0.1 *	-0.70 ± 0.15 ***	-0.40 ± 0.09 ***
S = Late Spring	ζ_{S2}	-2.0 ± 1.0 *	-3.8 ± 0.7 ***	-5.5 ± 0.9 ***	-4.0 ± 0.6 ***
*S * log W*	η	2.4 ± 0.8 **	3.1 ± 0.5 ***	4.5 ± 0.7 **	3.4 ± 0.5 ***
Y	θ	-1.2E-6 ± 1E-7 ***	-5.5E-7 ± 9E-8***	-1.8E-6 ± 1E-7 ***	-6.3E-7 ± 8E-8***
Z = 2012	α_{2012}	-0.36 ± 0.04 ***	-0.13 ± 0.03 ***	0.03 ± 0.04	0.06 ± 0.03 *
Z = 2013	α_{2013}	-0.28 ± 0.04 ***	-0.17 ± 0.03 ***	0.02 ± 0.04	0.04 ± 0.02
Z = 2014	α_{2014}	0.18 ± 0.09 *	0.24 ± 0.06 ***	0.54 ± 0.08 ***	0.42 ± 0.05 ***
Z = 2015	α_{2015}	-0.20 ± 0.07 **	0.02 ± 0.05	0.31 ± 0.07 ***	0.17 ± 0.04 ***
Z = 2016	α_{2016}	-0.03 ± 0.09	0.29 ± 0.07 ***	0.27 ± 0.09 **	0.45 ± 0.06 ***
R^2		0.416	0.433	0.378	0.445

We have not directly validated abundance outputs (Q, R, W_s) though their validity is implicit in the validation of V_s. Although there is significant model-data agreement, the actual value of V_s in the model is an indicator of visitation rate due to floral and nesting resource availability rather than a number that reflects the absolute number of visits by bees during that season. As such, subsequent analysis focuses on the relative change in abundance and visitation rates between scenarios. We refer to absolute values only to illustrate differences between guilds and land categories, for example to where changes are significant but at relatively low magnitude.

1.7 Additional Figures

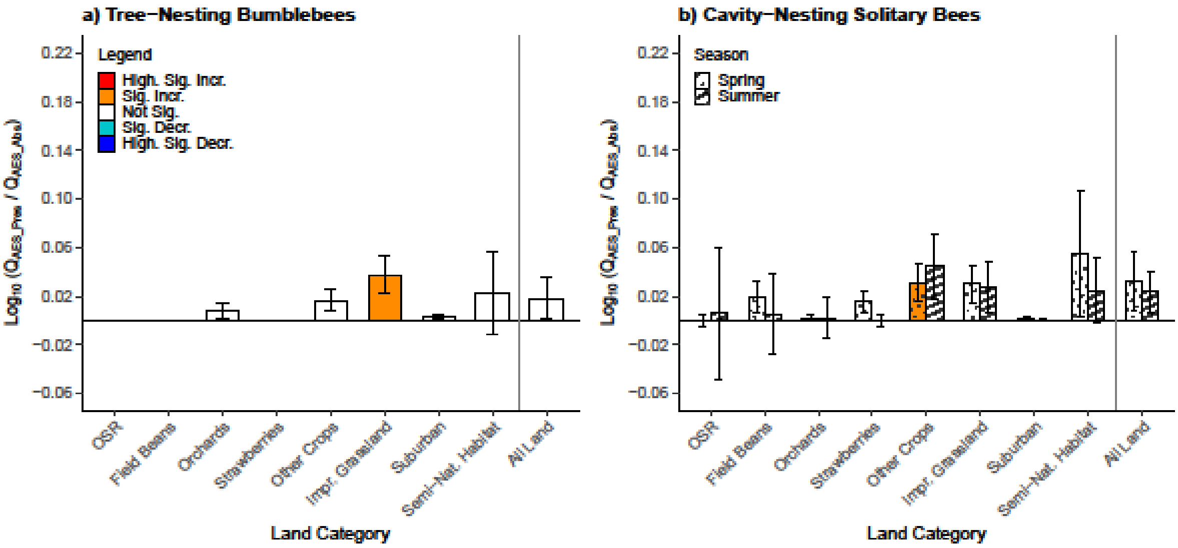

Figure A1.1: Predicted impact of Agri-environment schemes (AES) on nest productivity (Q; production of new reproductive females per 25m²) nationally to all land categories and subdivided by land category for (a) tree-nesting bumblebees and (b) cavity-nesting solitary bees (separated by active season). The impact is measured as the log of the ratio between the scenarios with AES features present and absent. Significance thresholds are number of standard deviations that the log ratio is above (increase) or below (decrease) zero: value >=|3| is highly significant, |2| <= value <|3|is significant.

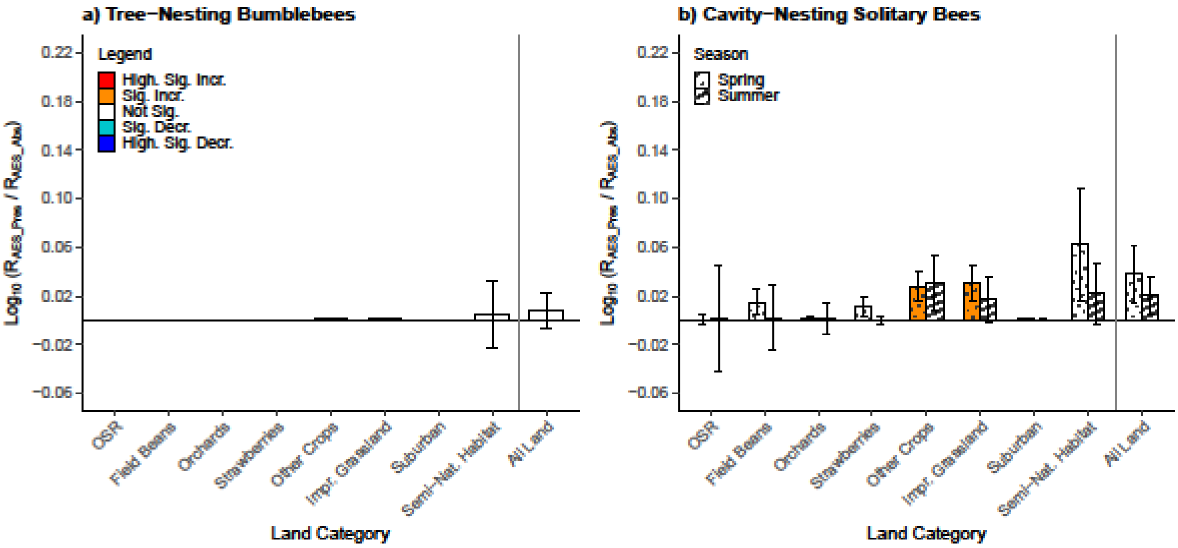

Figure A1.2: Predicted impact of Agri-environment schemes (AES) on nest density (R; nests per 25m² cell) nationally to all land categories and subdivided by land category for (a) tree-nesting bumblebees and (b) cavity-nesting solitary bees (separated by active season). The impact is measured as the log of the ratio between the scenarios with AES features present and absent. Significance thresholds are number of standard deviations that the log ratio is above (increase) or below (decrease) zero: value >=|3| is highly significant, |2| <= value <|3|is significant.

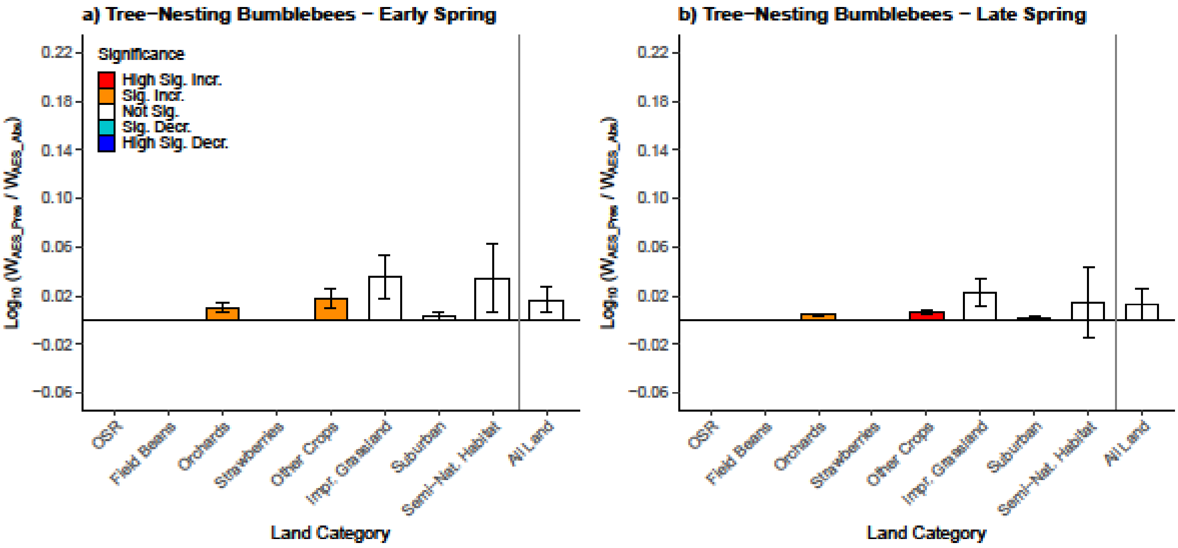

Figure A1.3 Predicted impact of Agri-environment schemes on tree-nesting bumblebee worker production (W; workers produced per $25m^2$ cell) nationally to all land classes (AL) and subdivided by land category for (a) Early Spring and (b) Late Spring. The impact is measured as the log ratio between the scenarios with AES feature present and absent. Significance thresholds are number of standard deviations that the log ratio is above (increase) or below (decrease) zero: value >=|3| is highly significant, |2| <= value <|3|is significant:

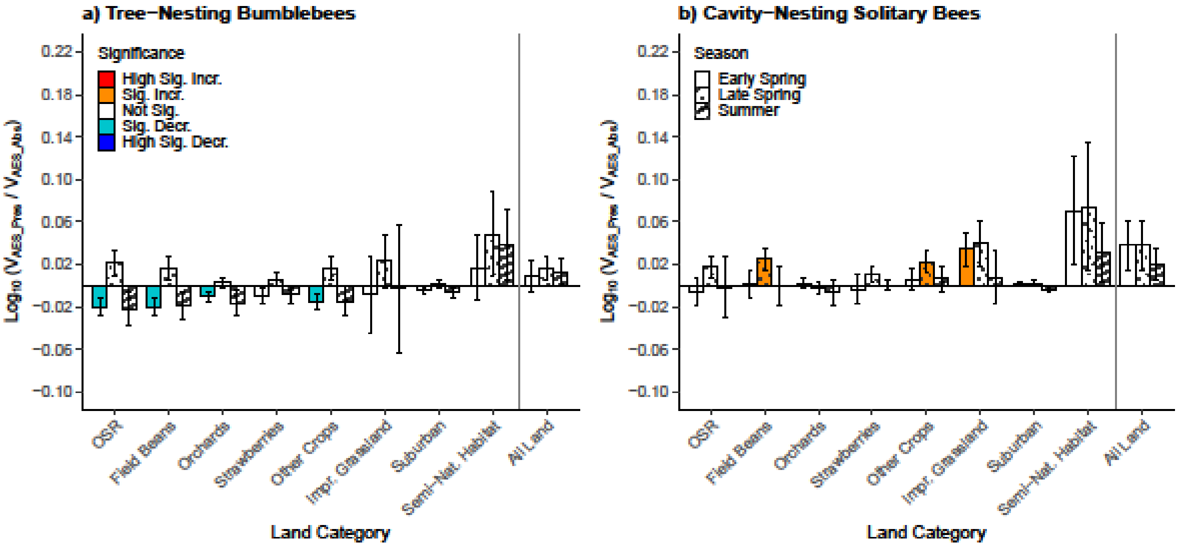

Figure A1.4: Predicted impact of Agri-environment schemes (AES) on floral visitation rate (V; visits per $25m^2$ cell) nationally to all land classes (ALL) and subdivided by land category for a) tree-nesting bumblebees and b) cavity-nesting solitary bees in each season. The impact is measured as the log ratio between the scenarios with AES feature present and absent. Significance thresholds are number of standard deviations that the log ratio is above (increase) or below (decrease) zero: value >=|3| is highly significant, |2| <= value <|3|is significant

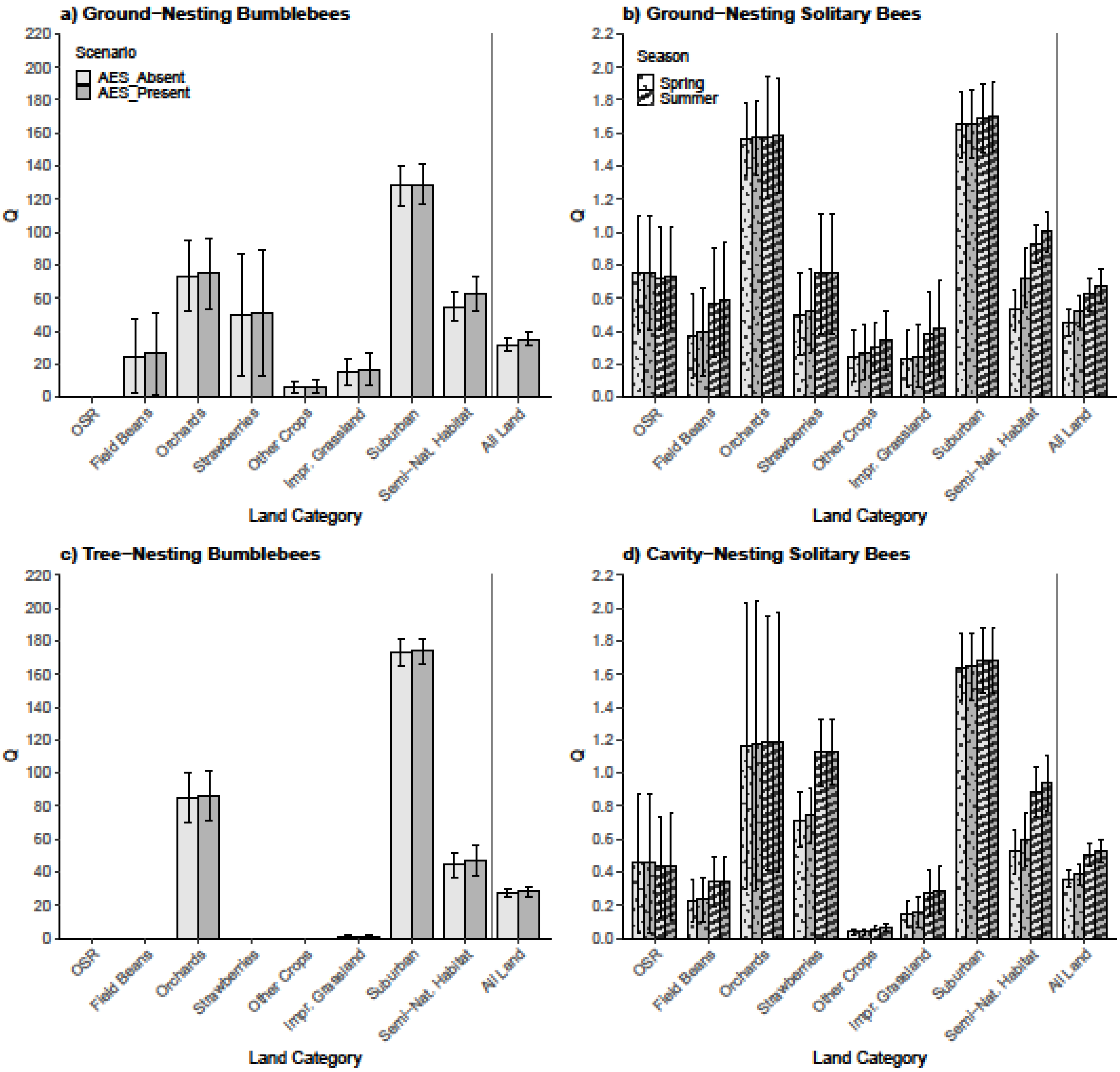

Figure A1.5: Nest productivity (Q) by land category, scenario, and guild. Q represents the number of new reproductive females produced on average per cell (25m^2) of that land category in England at the end of the active season for that year.

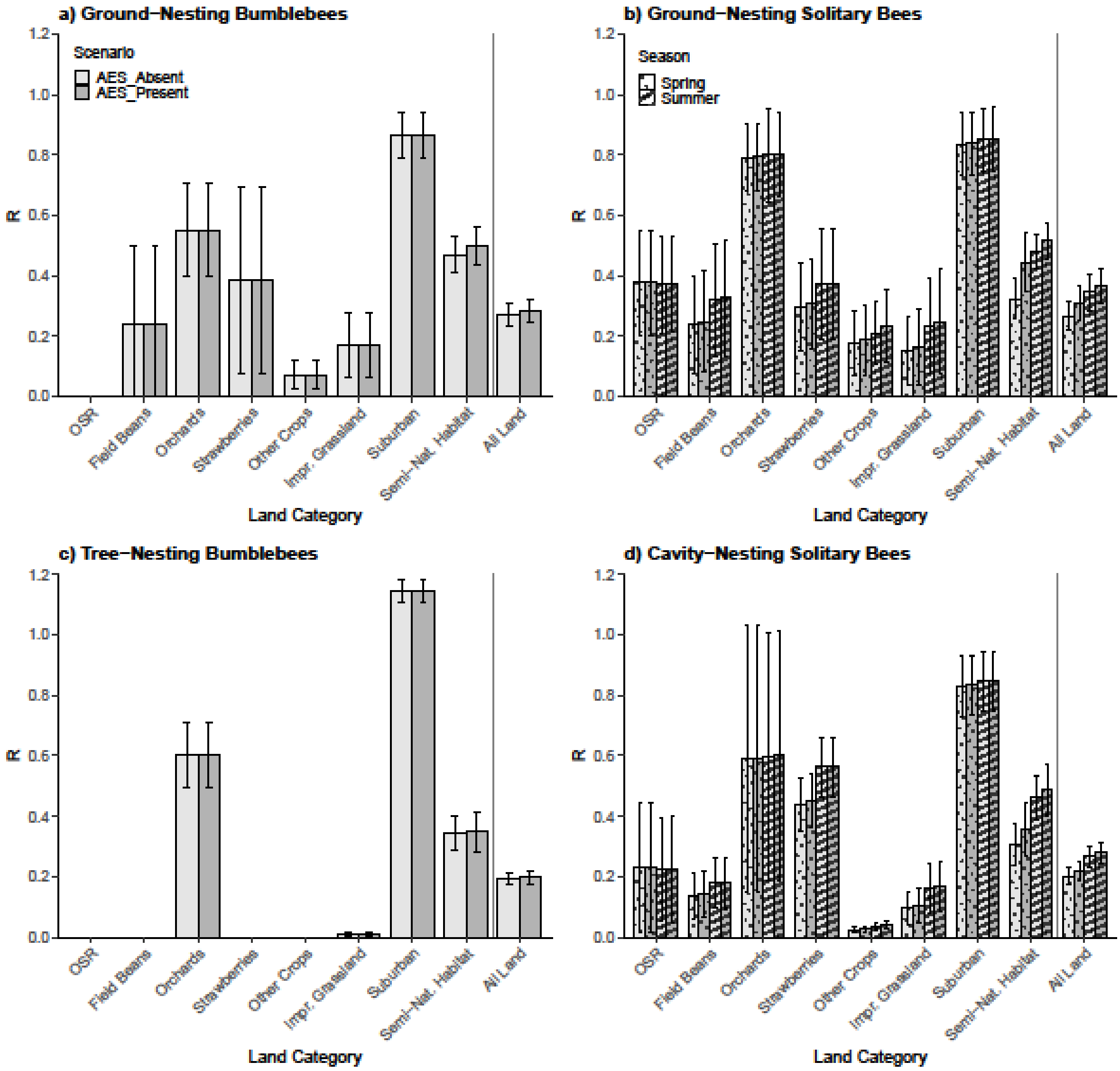

Figure A1.6: Nest density (R) by land category, scenario, and guild. R represents the number of nests found on average per cell (25m²) of that land category in England at the beginning of the active season for the next year.

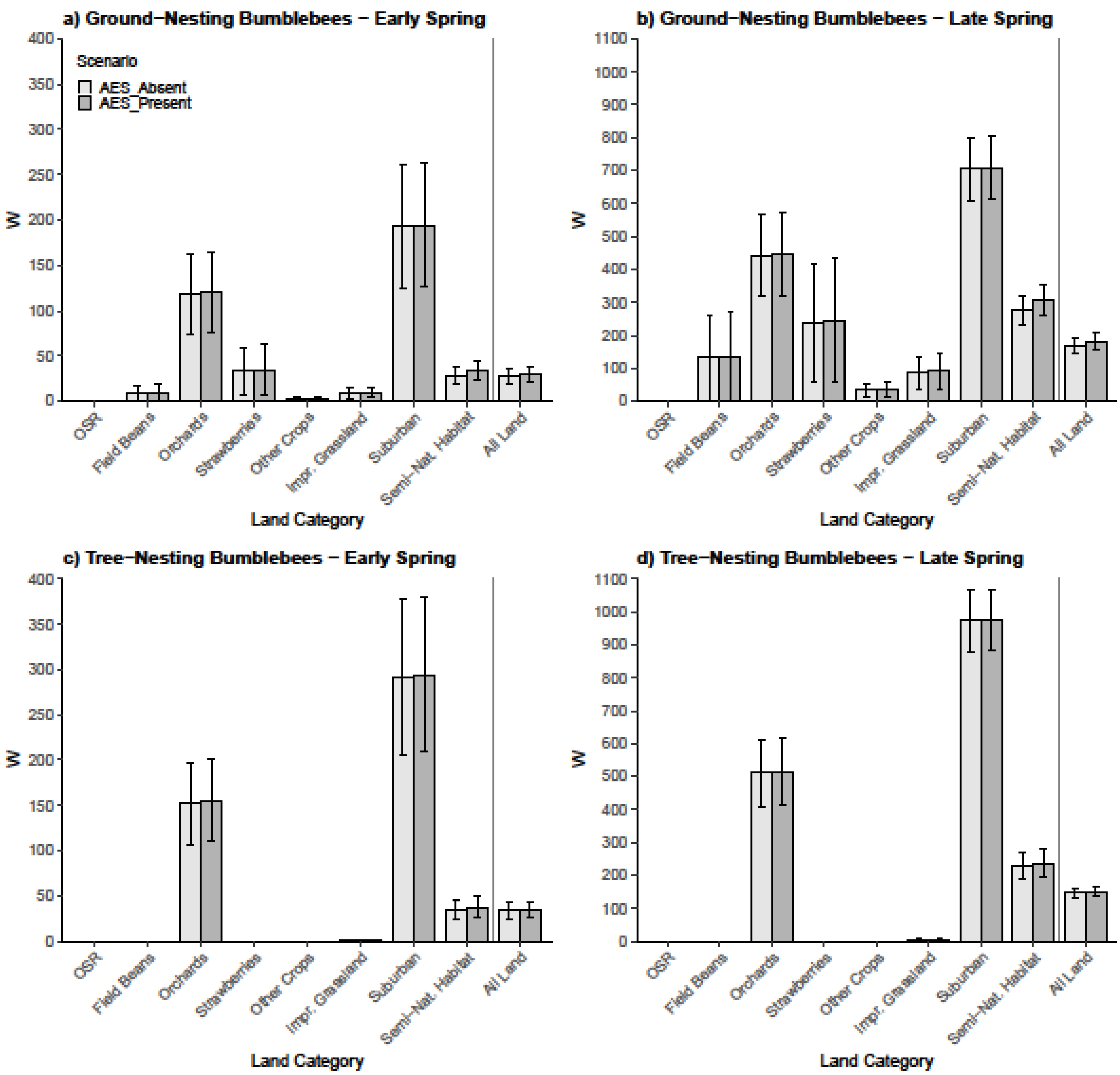

Figure A1.7: Worker generation (W) by land category, scenario, and bumblebee guild. W represents the number of new workers produced on average per cell (25m^2) of that land category in England during the captioned season and thus foraging in the next season.

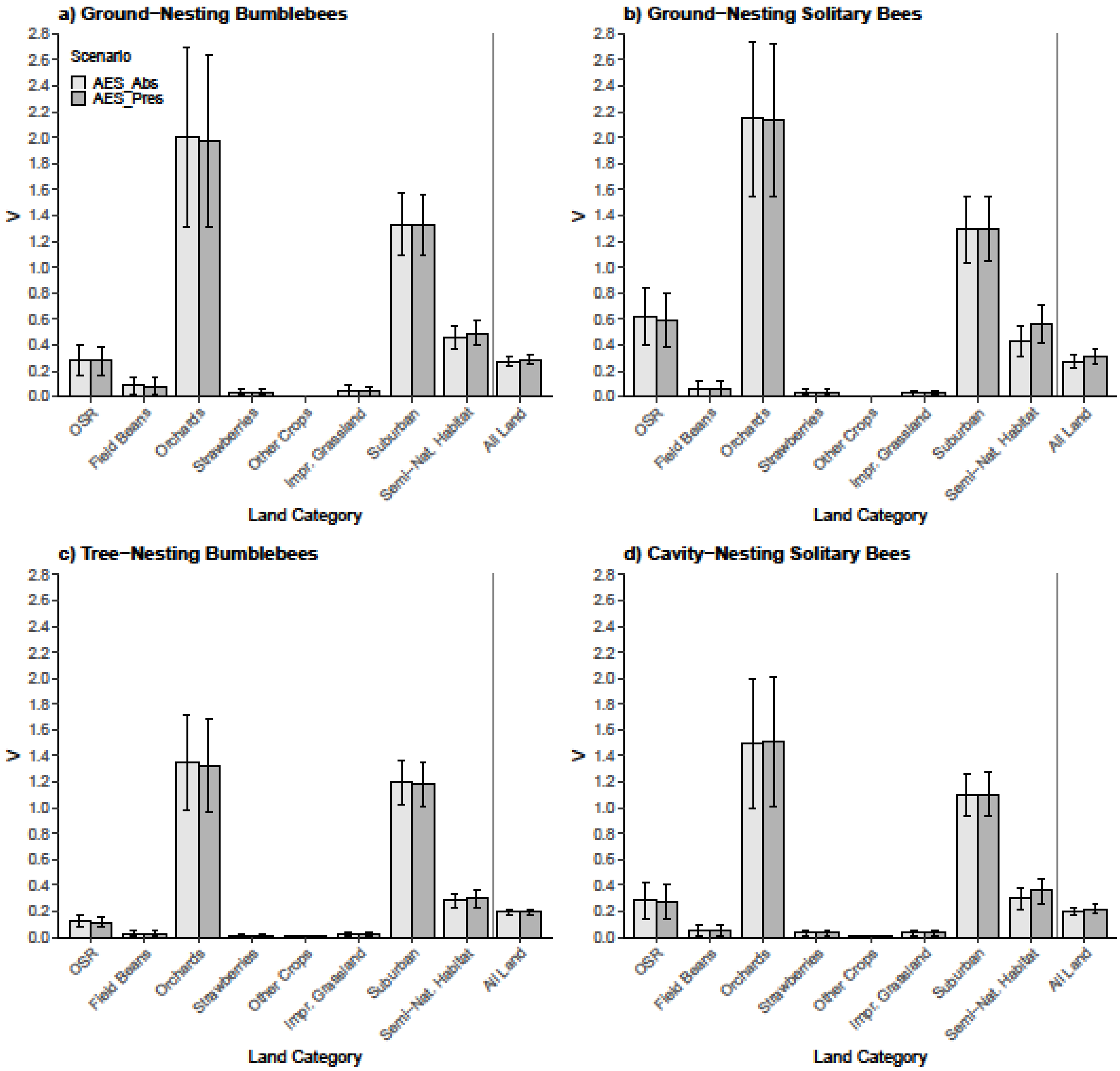

Figure A1.8: Early Spring visitation (V) by land category, scenario, and guild. V represents the number of visits received on average per cell (25m^2) of that land category in England during this season. Early spring: early/mid-March – late April/early May.

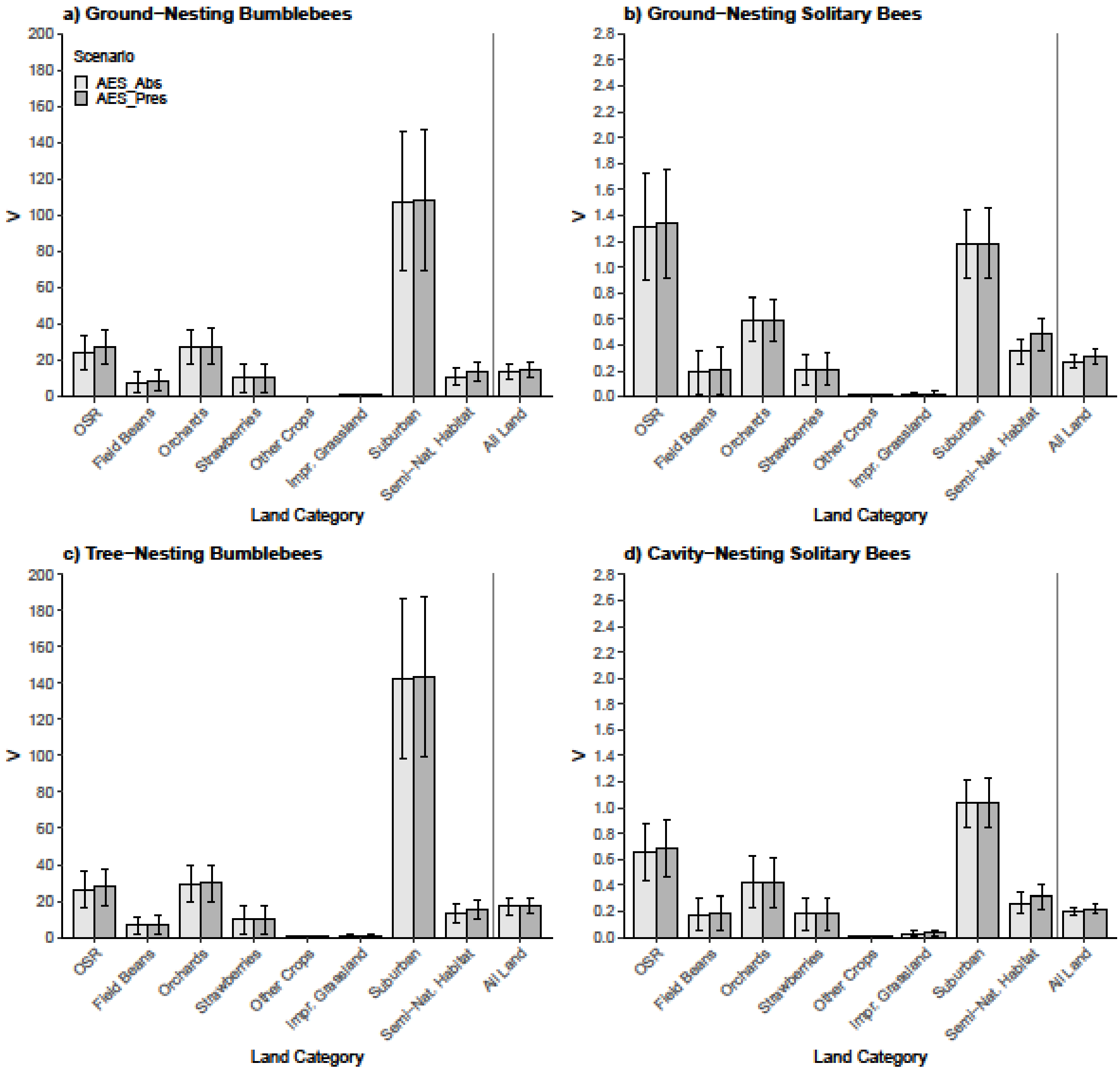

Figure A1.9: Late Spring visitation (V) by land category, scenario, and guild. V represents the number of visits received on average per cell (25m^2) of that land category in England during this season. Late spring: late April/early May - early/mid-June.

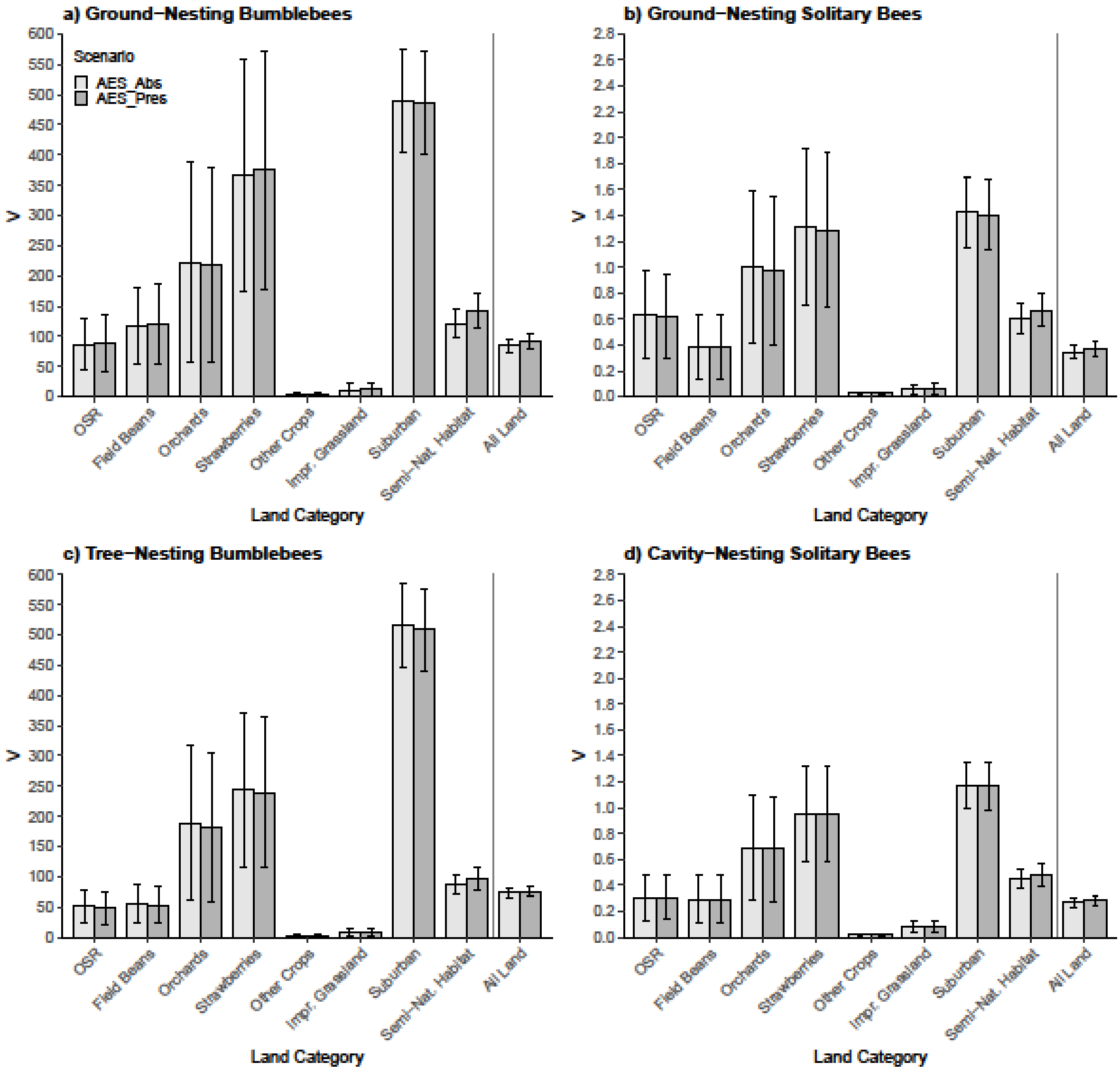

Figure A1.10 : Summer visitation (V) by land category, scenario, and guild. V represents the number of visits received on average per cell (25m²) of that land category in England during this season. Summer: early/mid-June – early/mid-September.

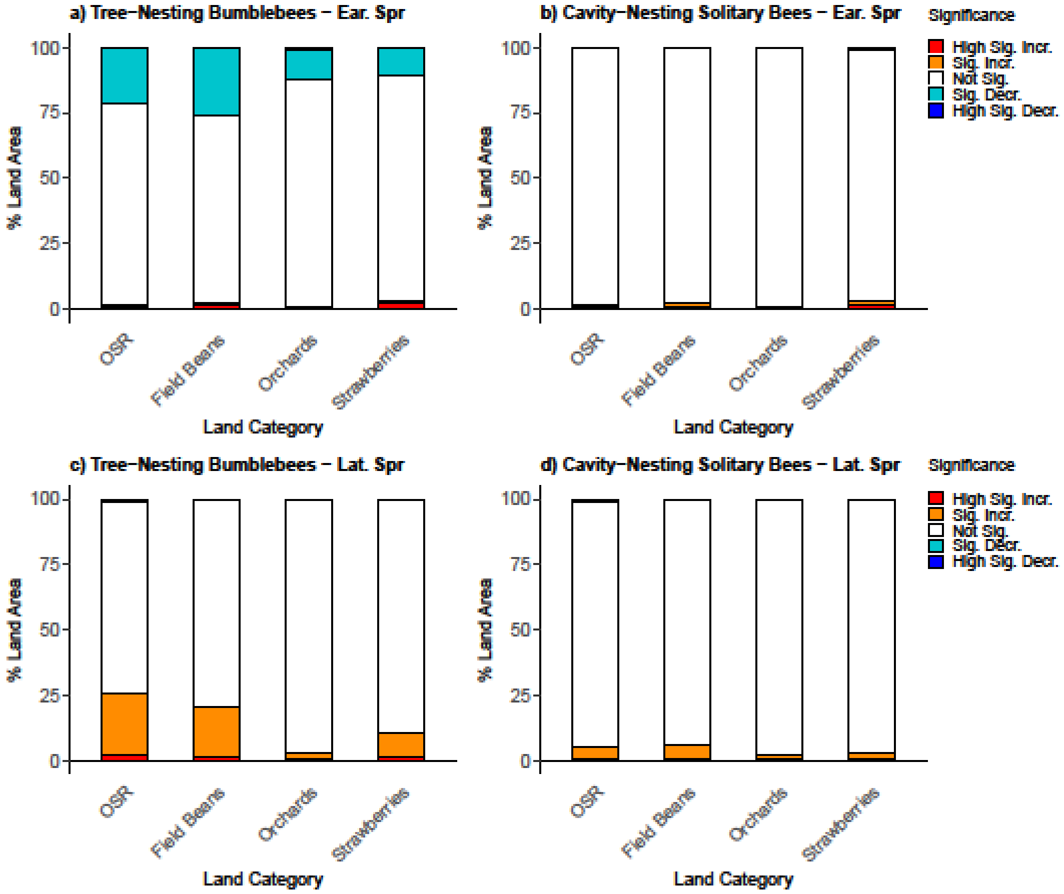

Figure A1.11: Percentage of land area in significance thresholds for predicted impact of Agri-environment schemes (AES) on floral visitation rate (V; visits per 25m² cell) nationally to selected land categories for tree and cavity-nesting guilds in early (a,b) and late (c,d) spring. The impact is measured as the log ratio between the scenarios with AES feature present and absent. Significance thresholds are number of standard deviations that the log ratio is above (increase) or below (decrease) zero: value >=|3| is highly significant, |2| <= value <|3|is significant. Early spring: early/mid-March - late April/early May; Late spring: late April/early May - early/mid-June.

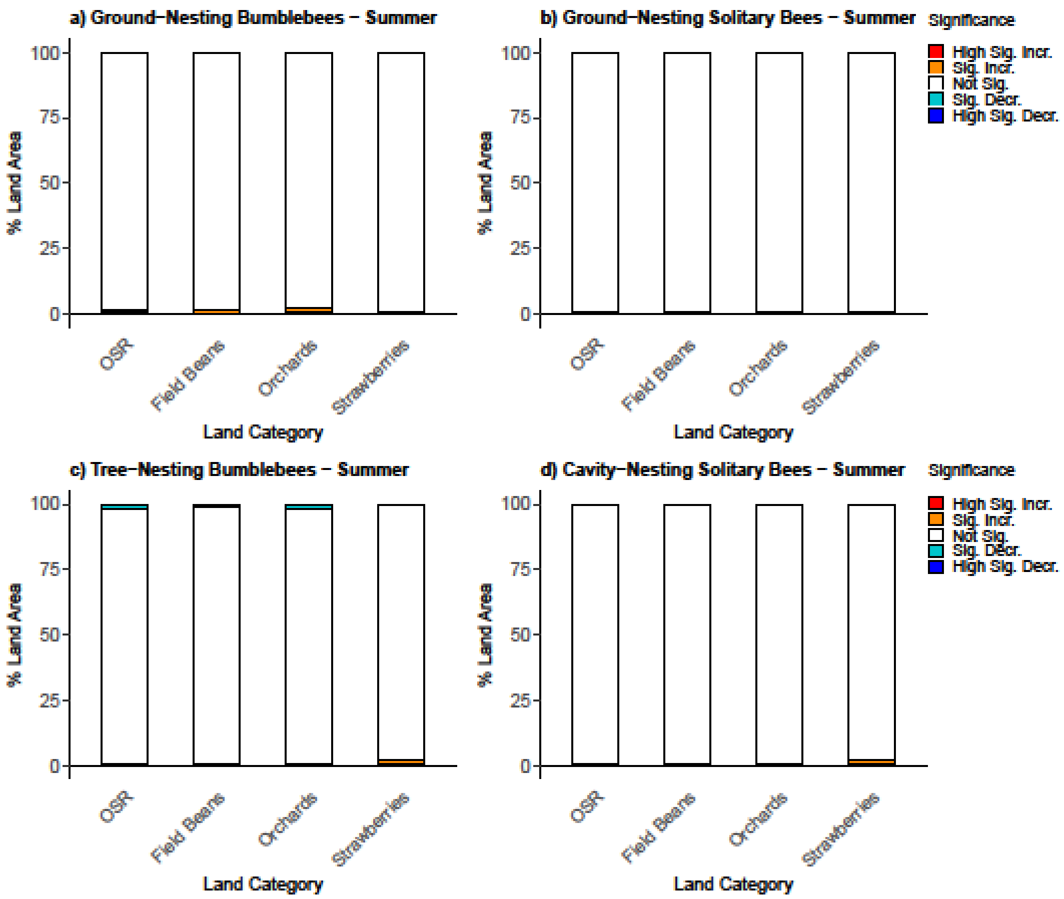

Figure A1.12: Percentage of land area in significance thresholds for predicted impact of Agri-environment schemes (AES) on floral visitation rate (V; visits per 25m² cell) nationally to all guilds in summer. The impact is measured as the log ratio between the scenarios with AES feature present and absent. Significance thresholds are number of standard deviations that the log ratio is above (increase) or below (decrease) zero: value >=|3| is highly significant, |2| <= value <|3|is significant. Summer: early/mid-June - early/mid-September

1.8 Additional Map Outputs

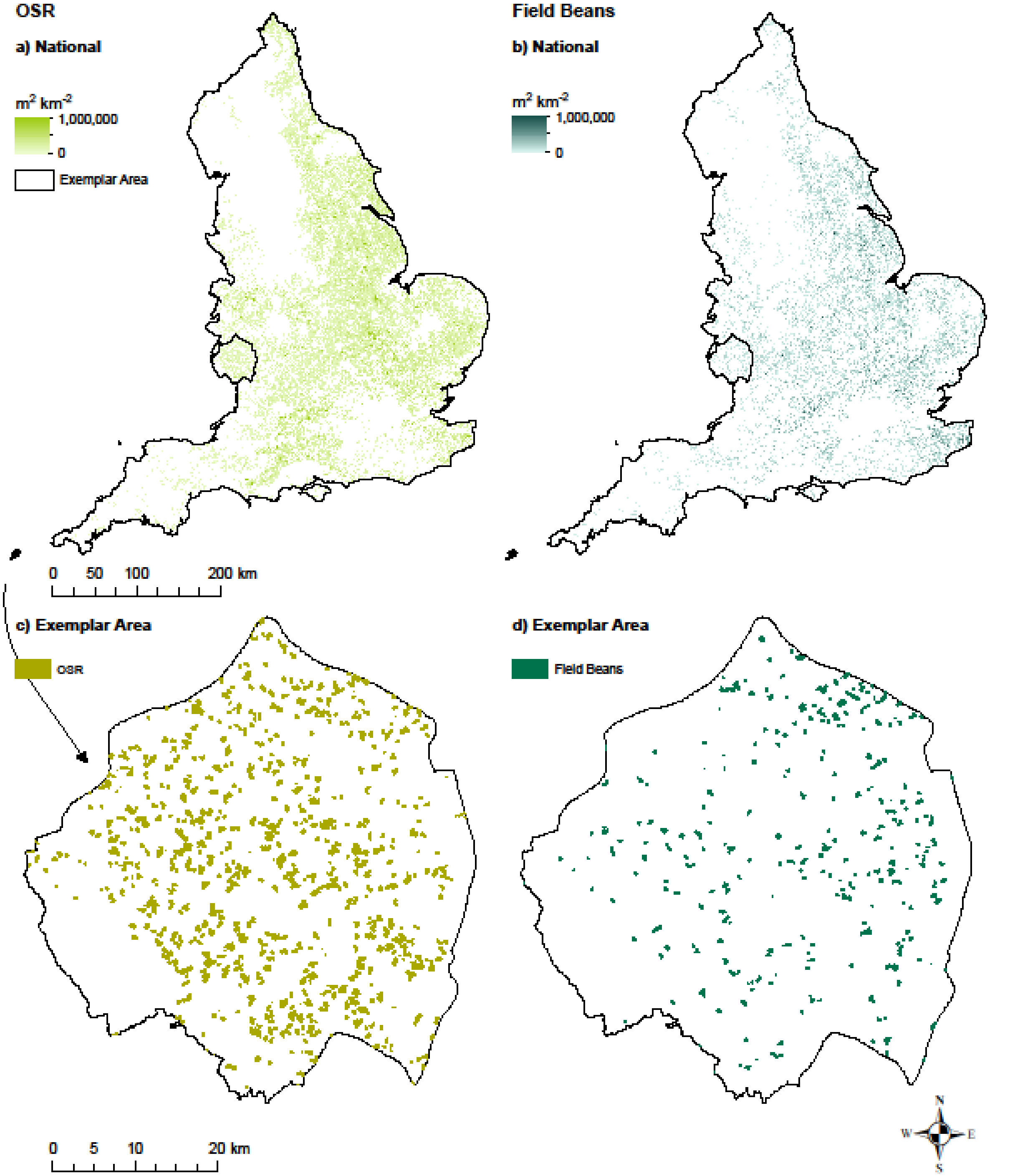

Figure A1.13: Geographical distribution of OSR and field beans across England (a, b) and an exemplar area (c, d) in 2016. The national maps show crop density (m^2) within a $1km^2$ grid. The exemplar area maps show actual features.

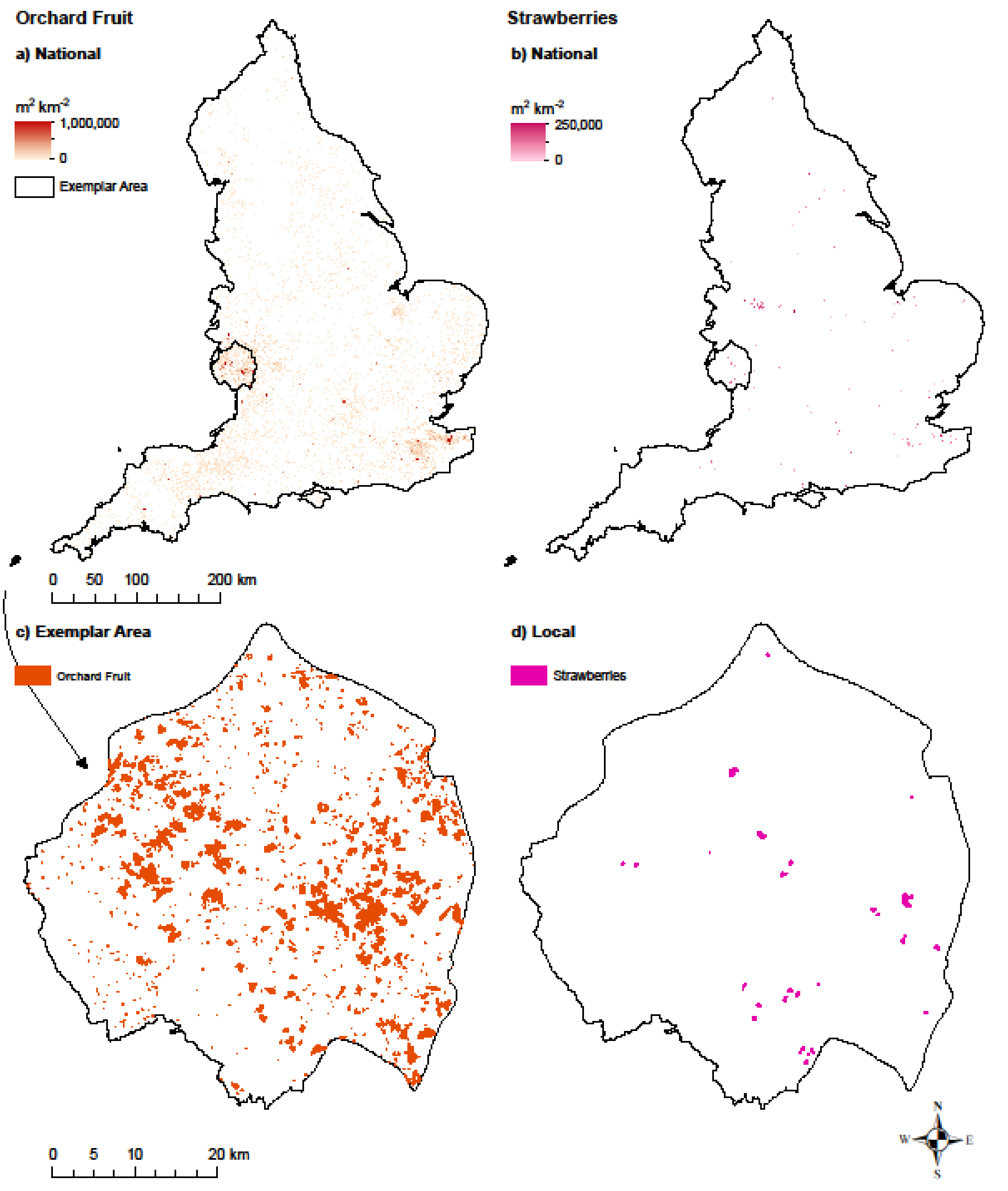

Figure A1.14: Geographical distribution of orchard fruit and strawberries across England (a, b) and an exemplar area (c, d) in 2016. The national maps show crop density (m^2) within a $1km^2$ grid. The exemplar area maps show actual features. Strawberries refers to both strawberries and raspberries not in polytunnels.

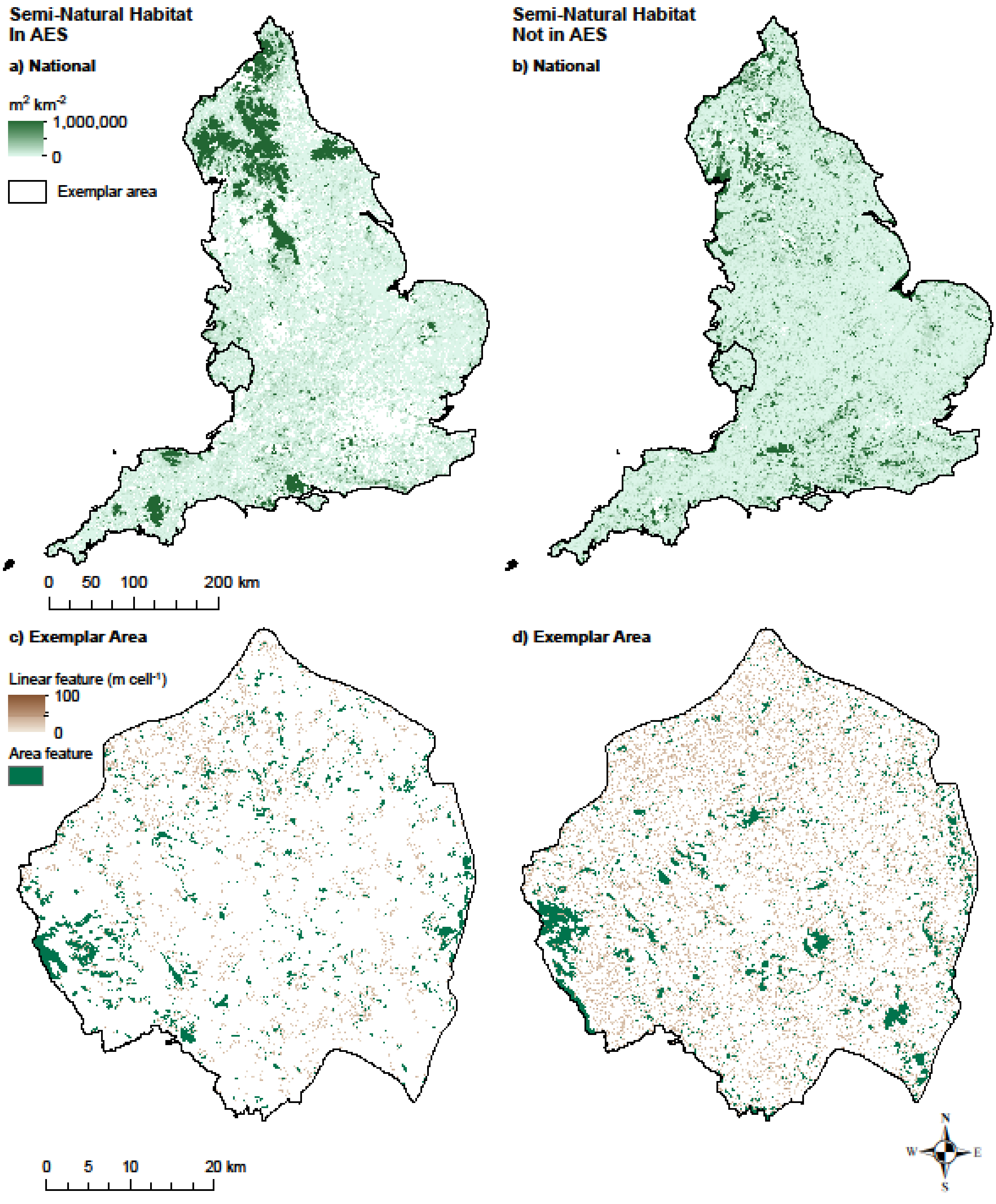

Figure A1.15: Geographical distribution of semi-natural habitat across England (a, b) and an exemplar area (c, d). Maps a) and c) show features under Agri-environment scheme (AES) management. Maps b) and d) show features outside AES management. National maps show total area (m^2) of all features within a $1km^2$ grid. Local maps show linear feature as length (m) per cell ($25m^2$) and area feature as whole cell ($25m^2$). Semi-natural habitat includes grasslands, heathlands, wetlands, moorlands, woodland features, fallow, ley, grass margin, buffer strips, hedgerows, ditches, woodland edge.

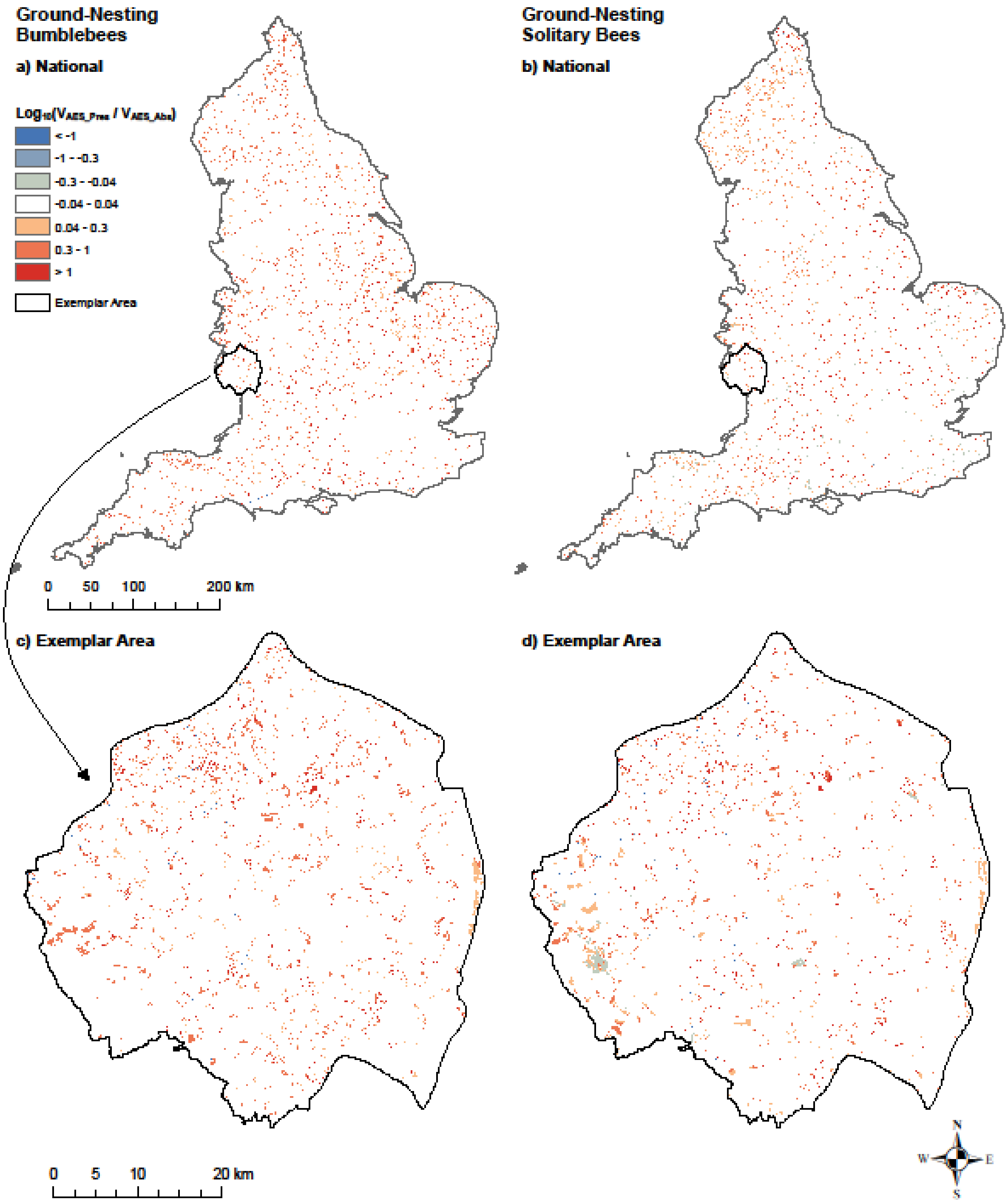

Figure A1.16: Impact of Agri-environment schemes on floral visitation rate (V) for ground-nesting guilds in England for summer 2016 at national scale (a, b) and for an exemplar area (c, d) in western England. The impact is shown as the log of the ratio of V (visitation/25m2) between scenarios with AES present and absent. Only cells with significant change are shown - where the log ratio is at least 2 standard deviations from zero. Summer: early/mid-June– early/mid-September

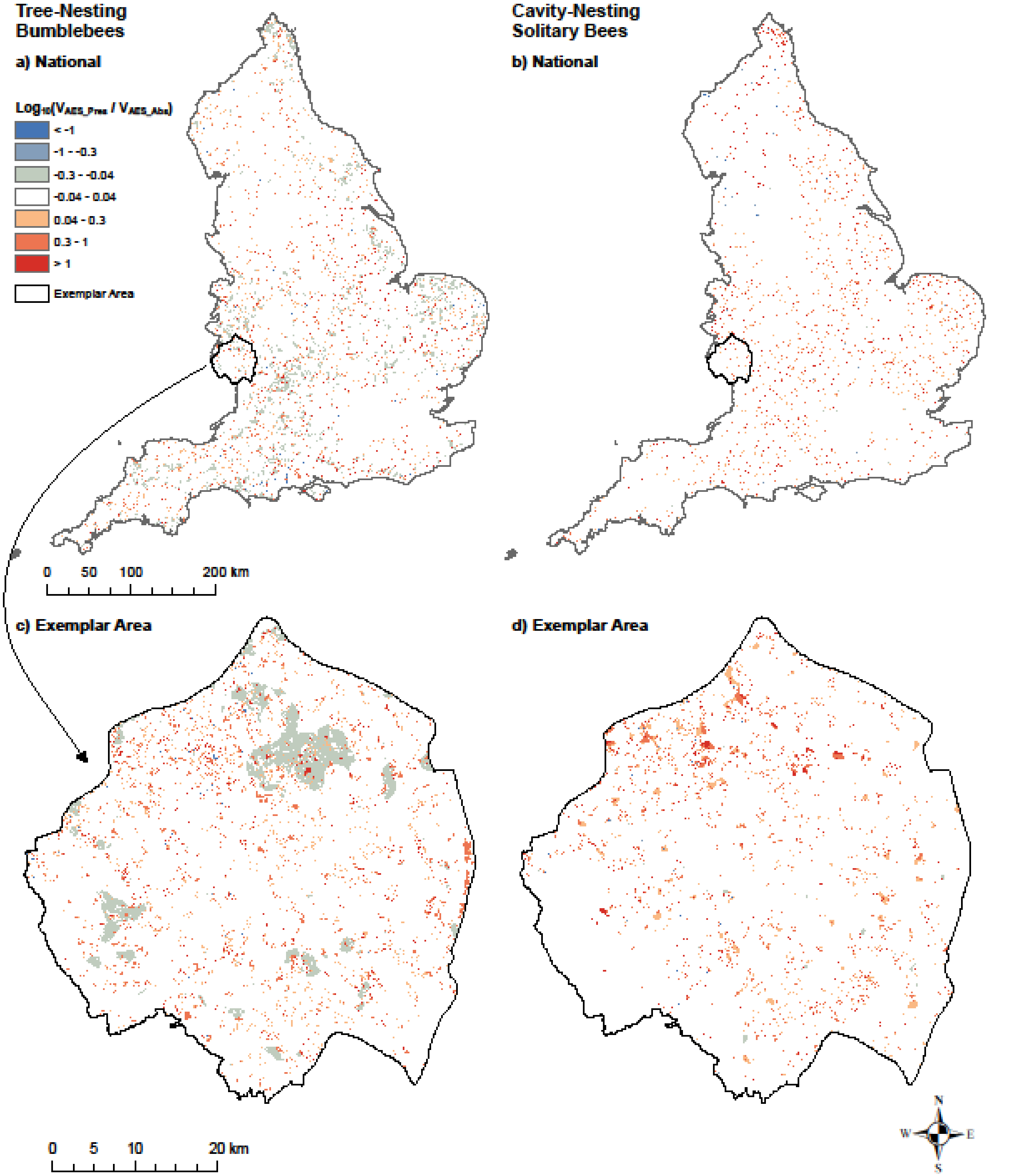

Figure A1.17: Impact of Agri-environment schemes on floral visitation rate (V) for tree and cavity-nesting guilds in England for early spring 2016 at national scale (a, b) and for an exemplar area (c, d) in western England. The impact is shown as the log of the ratio of V (visitation/25m2) between scenarios with AES present and absent. Only cells with significant change are shown - where the log ratio is at least 2 standard deviations from zero. Early spring: early/mid-March – late April/early May.

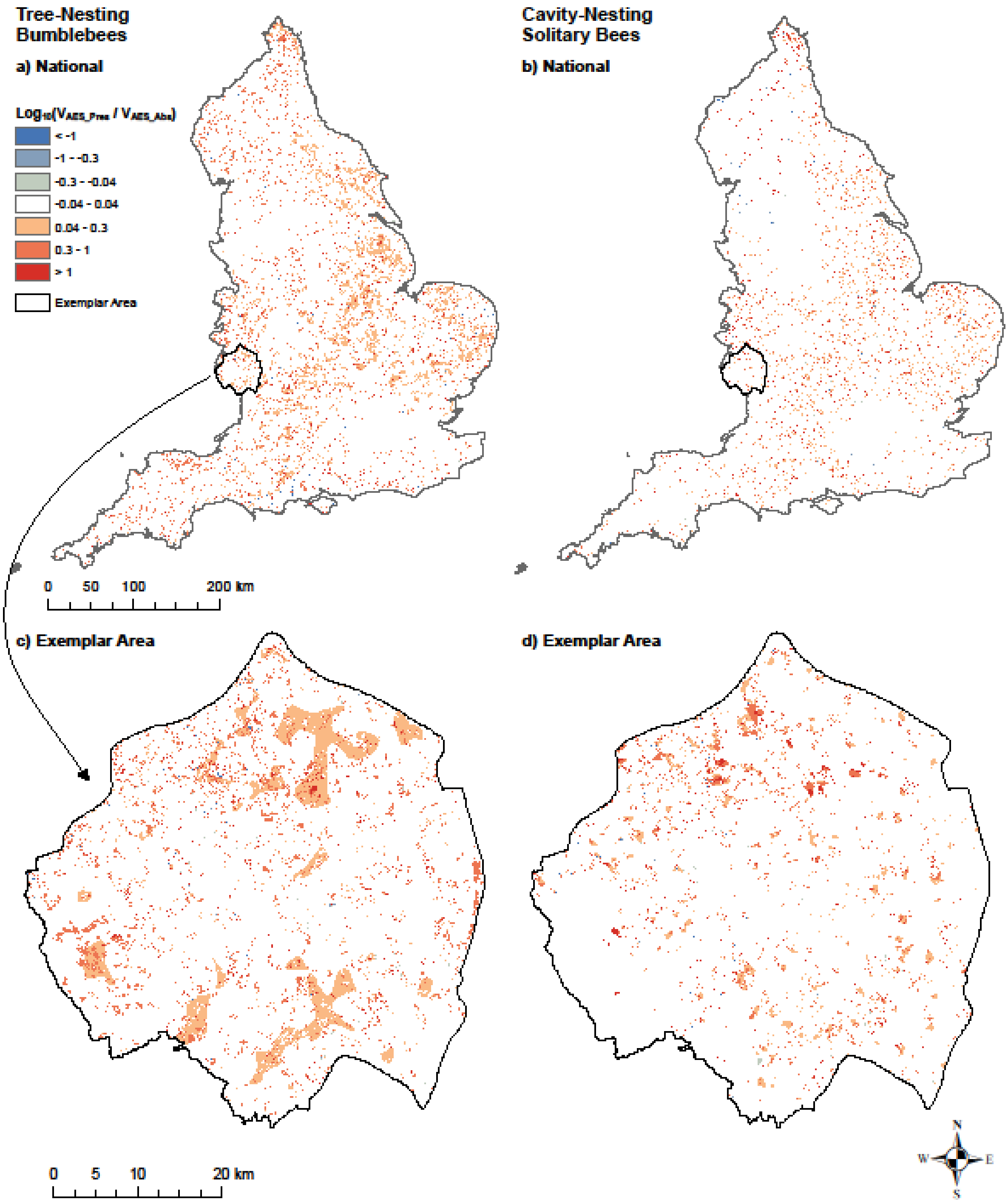

Figure A1.18: Impact of Agri-environment schemes on floral visitation rate (V) for tree and cavity-nesting guilds in England for late spring 2016 at national scale (a, b) and for an exemplar area (c, d) in western England. The impact is shown as the log of the ratio of V (visitation/25m2) between scenarios with AES present and absent. Only cells with significant change are shown - where the log ratio is at least 2 standard deviations from zero. Late spring: late April/early May - early/mid-June.

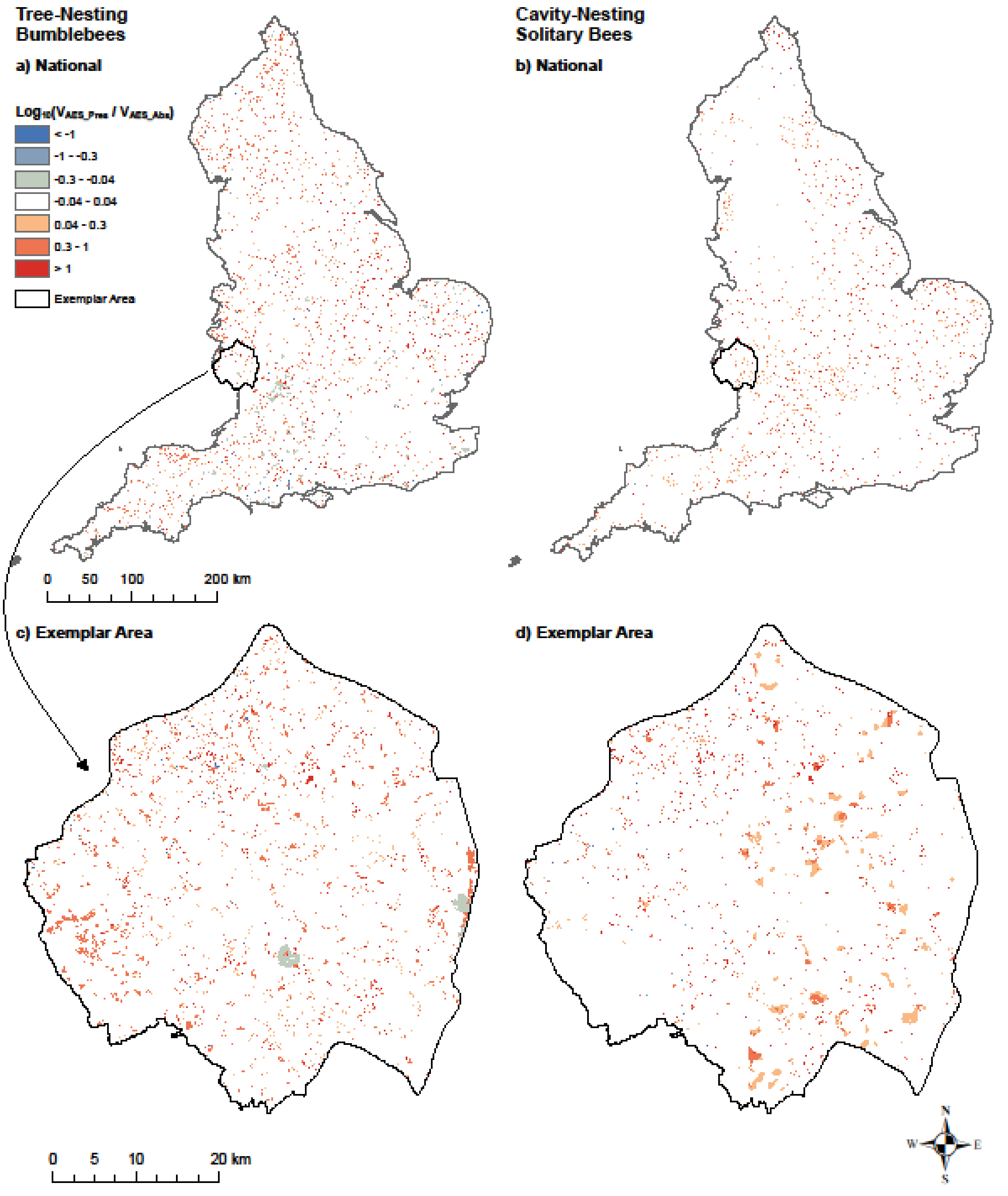

Figure A1.19: Impact of Agri-environment schemes on floral visitation rate (V) for tree and cavity-nesting guilds in England for summer 2016 at national scale (a, b) and for an exemplar area (c, d) in western England. The impact is shown as the log of the ratio of V (visitation/25m2) between scenarios with AES present and absent. Only cells with significant change are shown - where the log ratio is at least 2 standard deviations from zero. Summer: early/mid-June– early/mid-September

2 Which interventions contribute most to the net effect of England's agri-environment schemes on pollination services? Supplementary Material

2.1 AES categorisation

AES were categorised into groups that reflect change in nesting and floral resource value from AES_Present to AES_Absent as well as functional differences. Grassland creation and heath creation options were grouped into a common category as grassland and heath habitats sit on a continuum. Although hedgerow and woodland edge interventions are mostly management rather than creation, the parameterisation and land class allocation rules in IM2022 assumes an increase in width from 2.5m to 5m. Because hedgerow and woodland edge have a large floral and nesting value relative to underlying crop or improved grassland replaced, this leads to a large increase in nesting and floral resource value across the 5m wide area. By contrast ditch management options whose area increases from 1m to 2m do not have such a large value-add and have been incorporated in general habitat management.

Absolute and relative values for each AES option in the AES_Present and AES_Absent scenario can be found in IM2022 supplementary material by finding the land class allocation for the AES option and then cross-referencing with the table of parameters assigned to each land class. Relative values for each option for ground-nesting bumblebees are shown in Table A2.1. This table also shows the total area of each option in England in 2016 according to the Countryside Stewardship, Environmental Stewardship and other datasets used. Rules for converting options whose source data quantity was in length or units rather than area are also provided in IM2022. These area values are used to produce weighted-average floral and nesting resource value add in Fig. 6 of the main text. Relative values for other guilds are shown in Table A2.2.

Table A2.1: Complete AES intervention to AES category assignment for all AES options included in IM2022; Area of coverage for each intervention in England in 2016; Difference (Δ) in ground-nesting bumblebees (GNBB) nesting resource and early spring floral resource value (AES_Present minus AES_Absent), where AES_Present is scenario with AES management and AES_Absent is scenario without AES management. See IM2022 for parameterisation details.

Option Code	Option Description	Scheme	Category	Coverage (ha)	Δ Nesting (GNBB)	Δ Floral (GNBB)
AB1	Nectar flower mix	CS	Floral Margin	800	0.51	83
AB10	Unharvested cereal headland	CS	Fallow	17	0.40	50
AB11	Cultivated areas for arable plants	CS	Fallow	150	0.40	50
AB15	Two-year sown legume fallow	CS	Fallow	675	0.23	87
AB16	Autumn sown bumblebird mix	CS	Floral Margin	333	0.51	83
AB3	Beetle banks	CS	Grass Margin	5	1.09	82
AB4	Skylark plots	CS	Fallow	7	0.40	50
AB5	Nesting plots for lapwing and stone curlew	CS	Fallow	216	0.40	50
AB8	Flower-rich margins and plots	CS	Floral Margin	1065	0.51	83
ABS01	Temporary Grass Buffer Strip	EFA	Grass Margin	155	0.64	37
ABS02	Sown Mixed Cover Buffer Strip	EFA	Grass Margin	52	0.64	37
ABS03	Fallow Buffer Strip	EFA	Fallow	2747	0.40	50
BE1	Protection of in-field trees on arable land	CS	Hedgerow/Woodland Edge	39	0.77	168
BE2	Protection of in-field trees on intensive grassland	CS	Hedgerow/Woodland Edge	39	0.77	168
BE3	Management of hedgerows	CS	Hedgerow/Woodland Edge	1224	0.77	168
BE4	Management of traditional orchards	CS	Habitat Management	29	-0.02	20
BE5	Creation of traditional orchards	CS	Trad Orchard Creation	37	0.17	298
BF11	Half Hedge	EFA	Hedgerow/Woodland Edge	0	0.77	168
BF12	Adjacent Hedge	EFA	Hedgerow/Woodland Edge	0	0.77	168
BF15	Buffer Strip	EFA	Grass Margin	0	0.64	37
CT1	Management of coastal sand dunes and vegetated shingle	CS	Habitat Management	483	0.00	0
CT2	Creation of coastal sand dunes and vegetated shingle on arable land and improved grassland	CS	Wetland/Coast Creation	7	0.11	18
CT3	Management of coastal saltmarsh	CS	Habitat Management	1081	0.00	0
CT4	Creation of inter-tidal and saline habitat on arable land	CS	Wetland/Coast Creation	0	0.00	7
CT5	Creation of inter-tidal and saline habitat by non-intervention	CS	Wetland/Coast Creation	0	-0.23	-13
CT7	Creation of inter-tidal and saline habitat on intensive grassland	CS	Wetland/Coast Creation	0	-0.08	3
EB1	Hedgerow management for landscape (on both sides of a hedge)	ES	Hedgerow/Woodland Edge	5680	0.77	168
EB10	Combined hedge and ditch management (incorporating EB3)	ES	Hedgerow/Woodland Edge	476	0.77	168
EB11	Stone wall protection and maintenance	ES	Habitat Management	2547	0.58	41

Option Code	Option Description	Scheme	Category	Coverage (ha)	∆ Nesting (GNBB)	∆ Floral (GNBB)
EB12	Earth bank management (on both sides)	ES	Habitat Management	580	0.58	41
EB13	Earth bank management (on one side)	ES	Habitat Management	434	0.58	41
EB14	Hedgerow restoration	ES	Hedgerow/Woodland Edge	3	0.77	168
EB2	Hedgerow management for landscape (on one side of a hedge)	ES	Hedgerow/Woodland Edge	9583	0.77	168
EB3	Hedgerow management for landscape and wildlife	ES	Hedgerow/Woodland Edge	3916	0.77	168
EB4	Stone faced hedge bank management on both sides	ES	Habitat Management	268	0.58	41
EB5	Stone faced hedge bank management on one side	ES	Habitat Management	189	0.58	41
EB6	Ditch management	ES	Habitat Management	1520	0.58	41
EB7	Half ditch management	ES	Habitat Management	588	0.58	41
EB8	Combined hedge and ditch management (incorporating EB1)	ES	Hedgerow/Woodland Edge	601	0.77	168
EB9	Combined hedge and ditch management (incorporating EB2)	ES	Hedgerow/Woodland Edge	401	0.77	168
EC1	Protection of in-field trees (arable)	ES	Hedgerow/Woodland Edge	69	0.77	168
EC2	Protection of in-field trees (grassland)	ES	Hedgerow/Woodland Edge	395	0.77	168
EC24	Hedgerow tree buffer strips on cultivated land	ES	Hedgerow/Woodland Edge	33	0.77	168
EC25	Hedgerow tree buffer strips on grassland	ES	Hedgerow/Woodland Edge	9	0.77	168
EC3	Maintenance of woodland fences	ES	Hedgerow/Woodland Edge	542	0.73	95
EC4	Management of woodland edges	ES	Hedgerow/Woodland Edge	172	0.73	95
ED2	Take archaeological features out of cultivation	ES	Grassland/Heath Creation	1053	0.23	20
EE1	2m buffer strips on cultivated land	ES	Grass Margin	2037	0.64	37
EE10	6m buffer strips on intensive grassland next to a watercourse	ES	Grass Margin	141	0.56	33
EE2	4m buffer strips on cultivated land	ES	Grass Margin	3348	0.64	37
EE3	6m buffer strips on cultivated land	ES	Grass Margin	7394	0.64	37
EE4	2m buffer strips on intensive grassland	ES	Grass Margin	230	0.56	33
EE5	4m buffer strips on intensive grassland	ES	Grass Margin	193	0.56	33
EE6	6m buffer strips on intensive grassland	ES	Grass Margin	337	0.56	33
EE7	Buffering in-field ponds in improved grassland	ES	Grass Margin	12	0.56	33
EE8	Buffering in-field ponds in arable land	ES	Grass Margin	38	0.64	37
EE9	6m buffer strips on cultivated land next to a watercourse	ES	Grass Margin	1669	0.64	37
EF1	Field corner management	ES	Grass Margin	9251	0.64	37
EF10	Unharvested cereal headlands for birds and rare arable plants	ES	Fallow	42	0.40	50
EF11	Uncropped, cultivated margins for rare plants on arable land	ES	Fallow	162	0.40	50
EF13	Uncropped cultivated areas for ground-nesting birds - arable	ES	Fallow	253	0.40	50
EF4	Nectar Flower mixture	ES	Floral Margin	950	0.51	83
EF4NR	Nectar Flower mixture (Non-rotational)	ES	Floral Margin	1315	0.51	83
EF7	Beetle banks	ES	Grass Margin	39	0.58	41
EF8	Skylark plots	ES	Fallow	72	0.40	50

Option Code	Option Description	Scheme	Category	Coverage (ha)	∆ Nesting (GNBB)	∆ Floral (GNBB)
EF9	Cereal headlands for birds	ES	Fallow	32	0.40	50
EG3	ASD to Jan 2010 Nectar flower mixture in grassland areas	ES	Floral Margin	3	0.51	83
EJ11	Maintenance of watercourse fencing	ES	Grass Margin	452	0.64	37
EJ5	In-field grass areas	ES	Grass Margin	432	0.64	37
EJ9	12m buffer strips for watercourses on cultivated land	ES	Grass Margin	113	0.64	37
EK1	Take field corners out of management: outside SDA & ML	ES	Grass Margin	167	0.56	33
EK2	Permanent grassland with low inputs: outside SDA & ML	ES	Habitat Management	114583	0.15	28
EK21	Legume- and herb-rich swards	ES	Ley	346	0.14	83
EK3	Permanent grassland with very low inputs: outside SDA & ML	ES	Habitat Management	71722	0.15	28
EK4	Manage rush pastures: outside SDA & ML	ES	Habitat Management	1587	0.00	0
EL1	Field corner management: SDA land	ES	Grass Margin	29	0.43	21
EL2	Permanent in-bye grassland with low inputs: SDA land	ES	Habitat Management	84177	0.13	15
EL3	In-bye pasture & meadows with very low inputs: SDA land	ES	Habitat Management	44147	0.13	15
EL4	Manage rush pastures: SDA land & ML parcels under 15ha	ES	Habitat Management	8581	0.02	5
EL5	Enclosed rough grazing: SDA land & ML parcels under 15ha	ES	Habitat Management	8362	0.00	0
EL6	Moorland and rough grazing: ML land only	ES	Habitat Management	113413	0.00	0
GS1	Take field corners out of management	CS	Grass Margin	111	0.56	33
GS10	Management of wet grassland for wintering waders and wildfowl	CS	Habitat Management	1376	0.00	0
GS11	Creation of wet grassland for breeding waders	CS	Wetland/Coast Creation	33	0.08	11
GS12	Creation of wet grassland for wintering waders and wildfowl	CS	Wetland/Coast Creation	34	0.08	11
GS13	Management of grassland for target features	CS	Habitat Management	2488	0.00	0
GS14	Creation of grassland for target features	CS	Grassland/Heath Creation	63	0.36	43
GS2	Permanent grassland with very low inputs (outside SDAs)	CS	Habitat Management	15309	0.15	28
GS4	Legume and herb-rich swards	CS	Ley	588	0.14	83
GS5	Permanent grassland with very low inputs in SDAs	CS	Habitat Management	2323	0.13	15
GS6	Management of species-rich grassland	CS	Habitat Management	1039	0.00	0
GS7	Restoration towards species-rich grassland	CS	Habitat Management	718	0.15	29
GS8	Creation of species-rich grassland	CS	Grassland/Heath Creation	42	0.51	83
GS9	Management of wet grassland for breeding waders	CS	Habitat Management	677	0.00	0
HAE1	Hedge	EFA	Hedgerow/Woodland Edge	5980	0.77	168
HAE2	Hedge	EFA	Hedgerow/Woodland Edge	85	0.77	168
HB11	Maintenance of hedges of very high environmental value (2 sides)	ES	Hedgerow/Woodland Edge	345	0.77	168
HB12	Maintenance of hedges of very high environmental value (1 side)	ES	Hedgerow/Woodland Edge	283	0.77	168
HB14	Management of ditches of very high environmental value	ES	Habitat Management	53	0.58	41
HC1	Protection of in-field trees on arable land	ES	Hedgerow/Woodland Edge	5	0.77	168
HC10	Creation of woodland outside of the SDA & ML	ES	Scrub/Wood Creation	352	0.11	-7

Option Code	Option Description	Scheme	Category	Coverage (ha)	∆ Nesting (GNBB)	∆ Floral (GNBB)
HC12	Maintenance of wood pasture and parkland	ES	Habitat Management	13581	0.00	0
HC13	Restoration of wood pasture and parkland	ES	Habitat Management	17449	0.16	29
HC14	Creation of wood pasture	ES	Scrub/Wood Creation	1031	0.39	50
HC15	Maintenance of successional areas and scrub	ES	Habitat Management	4225	0.00	0
HC16	Restoration of successional areas and scrub	ES	Habitat Management	4166	0.14	26
HC17	Creation of successional areas and scrub	ES	Scrub/Wood Creation	4057	0.28	45
HC18	Maintenance of high value traditional orchards	ES	Habitat Management	735	0.00	0
HC19	Maintenance of traditional orchards in production	ES	Habitat Management	56	0.00	0
HC2	Protection of in-field trees on grassland	ES	Hedgerow/Woodland Edge	17	0.77	168
HC20	Restoration of traditional orchards	ES	Habitat Management	803	-0.02	20
HC21	Creation of traditional orchards	ES	Trad Orchard Creation	290	0.17	298
HC24	Hedgerow tree buffer strips on cultivated land	ES	Hedgerow/Woodland Edge	4	0.77	168
HC25	Hedgerow tree buffer strips on grassland	ES	Hedgerow/Woodland Edge	1	0.77	168
HC4	Management of woodland edges	ES	Hedgerow/Woodland Edge	19	0.73	95
HC5	Ancient trees in arable fields	ES	Hedgerow/Woodland Edge	2	0.77	168
HC6	Ancient trees in intensively-managed grass fields	ES	Hedgerow/Woodland Edge	3	0.77	168
HC7	Maintenance of woodland	ES	Habitat Management	16393	0.00	0
HC8	Restoration of woodland	ES	Habitat Management	13607	0.04	10
HC9	Creation of woodland in the SDA	ES	Scrub/Wood Creation	229	0.11	-7
HD10	Maintenance of traditional water meadows	ES	Habitat Management	70	0.00	0
HD11	Restoration of traditional water meadows	ES	Wetland/Coast Creation	44	-0.43	-54
HD2	Take archaeological features out of cultivation	ES	Grassland/Heath Creation	5117	0.23	20
HD7	Arable reversion by natural regeneration	ES	Grassland/Heath Creation	1166	0.23	20
HE1	2 m buffer strips on cultivated land	ES	Grass Margin	569	0.64	37
HE10	Floristically enhanced grass margin	ES	Floral Margin	4343	0.51	83
HE11	Enhanced strips for target species on intensive grassland	ES	Floral Margin	17	0.43	80
HE2	4 m buffer strips on cultivated land	ES	Grass Margin	1260	0.64	37
HE3	6 m buffer strips on cultivated land	ES	Grass Margin	3716	0.64	37
HE4	2 m buffer strips on intensive grassland	ES	Grass Margin	24	0.56	33
HE5	4 m buffer strips on intensive grassland	ES	Grass Margin	43	0.56	33
HE6	6 m buffer strips on intensive grassland	ES	Grass Margin	186	0.56	33
HE7	Buffering in-field ponds in improved permanent grassland	ES	Grass Margin	4	0.56	33
HE8	Buffering in-field ponds in arable land	ES	Grass Margin	28	0.64	37
HF1	Management of field corners	ES	Grass Margin	2512	0.64	37
HF10	Unharvested cereal headlands for birds and rare arable plants	ES	Fallow	25	0.40	50

Option Code	Option Description	Scheme	Category	Coverage (ha)	∆ Nesting (GNBB)	∆ Floral (GNBB)
HF10NR	Unharvested cereal headlands for birds and rare arable plants (Non-Rotational)	ES	Fallow	0	0.40	50
HF11	Uncropped, cultivated margins for rare plants	ES	Fallow	134	0.40	50
HF13	Uncropped cultivated areas for ground-nesting birds - arable	ES	Fallow	4620	0.40	50
HF13NR	Uncropped cultivated areas for ground-nesting birds - arable	ES	Fallow	678	0.40	50
HF14	Unharvested, fertiliser-free conservation headland	ES	Fallow	413	0.40	50
HF14NR	Unharvested, fertiliser-free conservation headland	ES	Fallow	31	0.40	50
HF17	ASD to Dec 2008 Fallow plots for ground-nesting birds (setaside)	ES	Fallow	10	0.40	50
HF19	ASD to Dec 2008 Unharvested conservation headland with setaside	ES	Fallow	2	0.40	50
HF20	Cultivated fallow plots or margins for arable plants	ES	Fallow	904	0.40	50
HF20NR	Cultivated fallow plots or margins for arable plants	ES	Fallow	678	0.40	50
HF4	Nectar flower mixture	ES	Floral Margin	1306	0.51	83
HF4NR	Nectar flower mixture	ES	Floral Margin	3310	0.51	83
HF7	Beetle banks	ES	Grass Margin	61	0.58	41
HF8	Skylark plots	ES	Fallow	69	0.40	50
HF9	Cereal headlands for birds	ES	Fallow	43	0.40	50
HF9NR	Cereal headlands for birds	ES	Fallow	1	0.40	50
HG3	ASD to Jan 2010 Nectar flower mixture in grassland areas	ES	Floral Margin	9	0.51	83
HJ11	Maintenance of watercourse fencing	ES	Grass Margin	11	0.56	33
HJ3	Reversion to unfertilised grassland to prevent erosion/run-off	ES	Grassland/Heath Creation	2339	0.38	49
HJ4	Reversion to low input grassland to prevent erosion/run-off	ES	Grassland/Heath Creation	1977	0.23	20
HJ5	In-field grass areas to prevent erosion or run-off	ES	Grass Margin	976	0.64	37
HJ9	12 m buffer strips for watercourses on cultivated land	ES	Grass Margin	89	0.64	37
HK1	Take field corners out of management	ES	Grass Margin	30	0.56	33
HK10	Maintenance of wet grassland for wintering waders and wildfowl	ES	Habitat Management	20306	0.00	0
HK11	Restoration of wet grassland for breeding waders	ES	Wetland/Coast Creation	6882	-0.15	-10
HK12	Restoration of wet grassland for wintering waders and wildfowl	ES	Wetland/Coast Creation	4311	-0.15	-10
HK13	Creation of wet grassland for breeding waders	ES	Wetland/Coast Creation	3462	0.08	11
HK14	Creation of wet grassland for wintering waders and wildfowl	ES	Wetland/Coast Creation	1479	0.08	11
HK15	Maintenance of grassland for target features	ES	Habitat Management	64674	0.00	0
HK16	Restoration of grassland for target features	ES	Habitat Management	30562	0.00	0
HK17	Creation of grassland for target features	ES	Grassland/Heath Creation	8278	0.36	43
HK2	Permanent grassland with low inputs	ES	Habitat Management	2911	0.15	28
HK21	Legume- and herb-rich swards	ES	Ley	426	0.14	83
HK3	Permanent grassland with very low inputs	ES	Habitat Management	3393	0.15	28
HK4	Management of rush pastures	ES	Habitat Management	63	0.00	0

Option Code	Option Description	Scheme	Category	Coverage (ha)	∆ Nesting (GNBB)	∆ Floral (GNBB)
HK6	Maintenance of species-rich, semi-natural grassland	ES	Habitat Management	28952	0.00	0
HK7	Restoration of species-rich, semi-natural grassland	ES	Habitat Management	58623	0.15	40
HK8	Creation of species-rich, semi-natural grassland	ES	Grassland/Heath Creation	3800	0.51	83
HK9	Maintenance of wet grassland for breeding waders	ES	Habitat Management	15174	0.00	0
HL1	Take field corners out of management in SDAs	ES	Grass Margin	7	0.43	21
HL10	Restoration of moorland	ES	Habitat Management	411877	0.06	8
HL11	Creation of upland heathland	ES	Habitat Management	1985	0.06	8
HL12	Management of heather, gorse and grass	ES	Habitat Management	8638	0.00	0
HL2	Permanent grassland with low inputs in SDAs	ES	Habitat Management	583	0.13	15
HL3	Permanent grassland with very low inputs in SDAs	ES	Habitat Management	1657	0.13	15
HL4	Management of rush pastures in SDAs	ES	Habitat Management	206	0.00	0
HL5	Enclosed rough grazing	ES	Habitat Management	97	0.00	0
HL6	Unenclosed moorland rough grazing	ES	Habitat Management	410	0.00	0
HL7	Maintenance of rough grazing for birds	ES	Habitat Management	17160	0.00	0
HL8	Restoration of rough grazing for birds	ES	Habitat Management	16222	0.06	8
HL9	Maintenance of moorland	ES	Habitat Management	29466	0.00	0
HO1	Maintenance of lowland heathland	ES	Habitat Management	7595	0.00	0
HO2	Restoration of lowland heath	ES	Grassland/Heath Creation	31939	-0.18	-34
HO3	Restoration of forestry areas to lowland heathland	ES	Grassland/Heath Creation	1315	0.16	30
HO4	Creation of lowland heathland from arable or improved grassland	ES	Grassland/Heath Creation	179	0.25	27
HO5	Creation of lowland heathland on worked mineral sites	ES	Grassland/Heath Creation	12	0.39	31
HP1	Maintenance of sand dunes	ES	Habitat Management	0	0.00	0
HP2	Restoration of sand dune systems	ES	Habitat Management	0	0.00	0
HP4	Creation of vegetated shingle and sand dune on grassland	ES	Wetland/Coast Creation	0	-0.03	1
HP5	Maintenance of coastal saltmarsh	ES	Habitat Management	9781	0.00	0
HP6	Restoration of coastal saltmarsh	ES	Wetland/Coast Creation	1259	-0.23	-13
HP7	Creation of inter-tidal and saline habitat on arable land	ES	Wetland/Coast Creation	129	0.00	7
HP8	Creation of inter-tidal and saline habitat on grassland	ES	Wetland/Coast Creation	231	-0.23	-13
HP9	Creation of inter-tidal and saline habitat by non-intervention	ES	Wetland/Coast Creation	157	-0.38	-42
HPE1	Hedge	EFA	Hedgerow/Woodland Edge	1894	0.77	168
HPE2	Hedge	EFA	Hedgerow/Woodland Edge	0	0.77	168
HQ10	Restoration of lowland raised bog	ES	Wetland/Coast Creation	1947	-0.43	-54
HQ3	Maintenance of reedbeds	ES	Habitat Management	2275	0.00	0
HQ4	Restoration of reedbeds	ES	Habitat Management	358	-0.04	-3
HQ5	Creation of reedbeds	ES	Wetland/Coast Creation	275	0.08	11
HQ6	Maintenance of fen	ES	Habitat Management	2998	0.00	0

Option Code	Option Description	Scheme	Category	Coverage (ha)	Δ Nesting (GNBB)	Δ Floral (GNBB)
HQ7	Restoration of fen	ES	Wetland/Coast Creation	2190	-0.43	-54
HQ8	Creation of fen	ES	Wetland/Coast Creation	537	0.08	11
HQ9	Maintenance of lowland raised bog	ES	Habitat Management	355	0.00	0
HS7	Management of historic water meadows through traditional irrigation	ES	Habitat Management	11	0.00	0
LH1	Management of lowland heathland	CS	Habitat Management	60	0.00	0
LH2	Restoration of forestry and woodland to lowland heathland	CS	Grassland/Heath Creation	0	0.16	30
LH3	Creation of heathland from arable or improved grassland	CS	Grassland/Heath Creation	0	0.25	27
OB1	Hedgerow management for landscape (on both sides of a hedge)	ES	Hedgerow/Woodland Edge	344	0.77	168
OB10	Combined hedge and ditch management (incorporating OB3)	ES	Hedgerow/Woodland Edge	25	0.77	168
OB11	Stonewall protection and maintenance	ES	Habitat Management	61	0.58	41
OB12	Earth bank management (on both sides)	ES	Habitat Management	30	0.58	41
OB13	Earth bank management (on one side)	ES	Habitat Management	25	0.58	41
OB14	Hedgerow restoration	ES	Hedgerow/Woodland Edge	0	0.77	168
OB2	Hedgerow management for landscape (on one side of a hedge)	ES	Hedgerow/Woodland Edge	564	0.77	168
OB3	Hedgerow management for landscape and wildlife	ES	Hedgerow/Woodland Edge	291	0.77	168
OB4	Stone faced Hedge bank management on both sides	ES	Habitat Management	15	0.58	41
OB5	Stone faced Hedge bank management on one side	ES	Habitat Management	8	0.58	41
OB6	Ditch management	ES	Habitat Management	49	0.58	41
OB7	Half ditch management	ES	Habitat Management	16	0.58	41
OB8	Combined hedge and ditch management (incorporating OB1)	ES	Hedgerow/Woodland Edge	25	0.77	168
OB9	Combined hedge and ditch management (incorporating OB2)	ES	Hedgerow/Woodland Edge	19	0.77	168
OC1	Protection of in field trees - rotational land	ES	Hedgerow/Woodland Edge	5	0.77	168
OC2	Protection of in field trees - grassland	ES	Hedgerow/Woodland Edge	25	0.77	168
OC24	Hedgerow tree buffer strips on rotational land	ES	Hedgerow/Woodland Edge	1	0.77	168
OC25	Hedgerow tree buffer strips on organic grassland	ES	Hedgerow/Woodland Edge	0	0.77	168
OC3	Maintenance of woodland fences	ES	Hedgerow/Woodland Edge	42	0.73	95
OC4	Management of wood edges	ES	Hedgerow/Woodland Edge	11	0.73	95
OD2	Take archaeological features out of cultivation	ES	Grassland/Heath Creation	90	0.25	12
OE1	2m buffer strips on rotational land	ES	Grass Margin	151	0.66	28
OE10	6m buffer strip on organic grassland next to a watercourse	ES	Grass Margin	13	0.56	33
OE2	4m buffer strips on rotational land	ES	Grass Margin	133	0.66	28
OE3	6m buffer strips on rotational land	ES	Grass Margin	200	0.66	28
OE4	2m buffer strip on organic grassland	ES	Grass Margin	29	0.56	33
OE5	4m buffer strip on organic grassland	ES	Grass Margin	19	0.56	33
OE6	6m buffer strip on organic grassland	ES	Grass Margin	36	0.56	33
OE7	Buffering in-field ponds in organic grassland	ES	Grass Margin	0	0.56	33

Option Code	Option Description	Scheme	Category	Coverage (ha)	∆ Nesting (GNBB)	∆ Floral (GNBB)
OE8	Buffering in-field ponds in rotational land	ES	Grass Margin	1	0.66	28
OE9	6m buffer strips on rotational land next to a watercourse	ES	Grass Margin	32	0.66	28
OF1	Field corner management	ES	Grass Margin	153	0.66	28
OF11	Uncropped, cultivated margins for rare plants on arable land	ES	Fallow	0	0.42	41
OF13	Uncropped cultivated areas for ground-nesting birds - rotational	ES	Fallow	0	0.42	41
OF4	Nectar Flower mixture	ES	Floral Margin	39	0.53	74
OF4NR	Nectar Flower mixture	ES	Floral Margin	15	0.53	74
OF7	Beetle banks	ES	Grass Margin	3	0.58	41
OF8	Skylark plots	ES	Fallow	1	0.42	41
OG3	ASD to Jan 2010 Nectar flower mixture in grassland areas	ES	Floral Margin	1	0.53	74
OHC1	Protection of in-field trees on rotational land	ES	Hedgerow/Woodland Edge	0	0.77	168
OHC2	Protection of in-field trees on organic grassland	ES	Hedgerow/Woodland Edge	1	0.77	168
OHC24	Hedgerow tree buffer strips on rotational land	ES	Hedgerow/Woodland Edge	2	0.77	168
OHC4	Management of woodland edges	ES	Hedgerow/Woodland Edge	1	0.73	95
OHD2	Take archaeological features out of cultivation (Org)	ES	Grassland/Heath Creation	581	0.25	12
OHE1	2m buffer strips on rotational land	ES	Grass Margin	39	0.66	28
OHE2	4m buffer strips on rotational land	ES	Grass Margin	61	0.66	28
OHE3	6m buffer strips on rotational land	ES	Grass Margin	308	0.66	28
OHE4	2m buffer strip on organic grassland	ES	Grass Margin	2	0.56	33
OHE5	4m buffer strip on organic grassland	ES	Grass Margin	8	0.56	33
OHE6	6m buffer strip on organic grassland	ES	Grass Margin	39	0.56	33
OHE7	Buffering in-field ponds in organic grassland	ES	Grass Margin	0	0.56	33
OHE8	Buffering in-field ponds in rotational land	ES	Grass Margin	1	0.66	28
OHF1	Management of field corners	ES	Grass Margin	105	0.66	28
OHF11	Uncropped, cultivated margins for rare plants	ES	Fallow	1	0.42	41
OHF13	Uncropped, cultivated areas for ground-nesting birds	ES	Fallow	97	0.42	41
OHF13NR	Uncropped, cultivated areas for ground-nesting birds	ES	Fallow	20	0.42	41
OHF4	Nectar Flower mixture	ES	Floral Margin	176	0.53	74
OHF4NR	Nectar Flower mixture	ES	Floral Margin	239	0.53	74
OHF7	Beetle banks	ES	Grass Margin	7	1.11	73
OHF8	Skylark plots	ES	Fallow	1	0.42	41
OHG3	ASD to Jan 2010 Nectar flower mixture in grassland areas	ES	Floral Margin	1	0.53	74
OHJ11	Maintenance of watercourse fencing	ES	Grass Margin	1	0.56	33
OHJ5	In-field grass areas to prevent erosion and run-off	ES	Grass Margin	43	0.66	28
OHJ9	12 m buffer strips for watercourses on rotational land	ES	Grass Margin	5	0.66	28
OHK1	Take field corners out of management	ES	Grass Margin	3	0.56	33

Option Code	Option Description	Scheme	Category	Coverage (ha)	∆ Nesting (GNBB)	∆ Floral (GNBB)
OHK2	Permanent grassland with low inputs	ES	Habitat Management	188	0.15	28
OHK21	Legume- and herb-rich swards	ES	Ley	209	0.14	83
OHK3	Permanent grassland with very low inputs	ES	Habitat Management	857	0.15	28
OHK4	Management of rush pastures	ES	Habitat Management	16	0.00	0
OHL2	Permanent grassland with low inputs in SDAs	ES	Habitat Management	15	0.13	15
OHL3	Permanent grassland with very low inputs in SDAs	ES	Habitat Management	328	0.13	15
OHL4	Management of rush pastures in SDAs	ES	Habitat Management	25	0.00	0
OHL5	Enclosed rough grazing	ES	Habitat Management	11	0.00	0
OJ11	Maintenance of watercourse fencing	ES	Grass Margin	23	0.56	33
OJ5	In-field grass areas to prevent erosion and run-off	ES	Grass Margin	9	0.66	28
OJ9	12m buffer strips for watercourses on cultivated land	ES	Grass Margin	2	0.66	28
OK1	Take field corners out of management: outside SDA & ML (organic)	ES	Grass Margin	12	0.56	33
OK2	Permanent grassland with low inputs: outside SDA & ML (organic)	ES	Habitat Management	8181	0.15	28
OK21	Legume- and herb-rich swards	ES	Ley	512	0.14	83
OK3	Permanent grassland with very low inputs:outside SDA&ML (organic)	ES	Habitat Management	9201	0.15	28
OK4	Manage rush pastures: outside SDA & ML (organic)	ES	Habitat Management	217	0.00	0
OL1	Field corner management: SDA land (organic)	ES	Grass Margin	0	0.43	21
OL2	Permanent in-bye grassland with low inputs: SDA land (organic)	ES	Habitat Management	2269	0.13	15
OL3	In-bye pasture & meadows with very low inputs: SDA land (organic)	ES	Habitat Management	4568	0.13	15
OL4	Manage rush pastures: SDA land & ML parcels under 15ha (organic)	ES	Habitat Management	188	0.00	0
OL5	Enclosed rough grazing:SDA land & ML parcels under 15ha (organic)	ES	Habitat Management	222	0.00	0
OP4	Multi species ley	CS	Ley	79	0.17	44
OR1	Organic conversion - improved permanent grassland	CS	Habitat Management	8	0.00	0
OR2	Organic conversion - unimproved permanent grassland	CS	Habitat Management	0	0.00	0
OR3	Organic conversion - rotational land	CS	Habitat Management	232	-0.02	9
OT3	Organic land management - rotational land	CS	Habitat Management	0	-0.02	9
PG02	Permanent grassland buffer strip	EFA	Grass Margin	744	0.56	33
RD01	Non-Agricultural Land Under Rural Development Programme	Other	Habitat Management	0	0.00	0
SW1	4 - 6 m buffer strip on cultivated land	CS	Grass Margin	1550	0.64	37
SW11	Riparian management strip	CS	Grass Margin	10	0.56	33
SW2	4 - 6 m buffer strip on intensive grassland	CS	Grass Margin	71	0.56	33
SW3	In-field grass strips	CS	Grass Margin	152	0.64	37
SW4	12 - 24m watercourse buffer strip on cultivated land	CS	Grass Margin	59	0.64	37
SW7	Arable reversion to grassland with low fertiliser input	CS	Grassland/Heath Creation	301	0.21	16
UB11	Stone wall protection and maintenance on/above the moorland line	ES	Habitat Management	702	0.58	41
UB12	Earth bank management (both sides) on/above the moorland line	ES	Habitat Management	18	0.58	41

Option Code	Option Description	Scheme	Category	Coverage (ha)	∆ Nesting (GNBB)	∆ Floral (GNBB)
UB13	Earth bank management (one side) on/above the moorland line	ES	Habitat Management	12	0.58	41
UB14	Hedgerow restoration	ES	Hedgerow/Woodland Edge	0	0.77	168
UB15	Stone-faced hedgebank restoration	ES	Habitat Management	0	0.58	41
UB16	Earth bank restoration	ES	Habitat Management	0	0.58	41
UB17	Stone wall restoration	ES	Habitat Management	1	0.58	41
UB4	Stone-faced hedgebank management (both sides) on/above ML	ES	Habitat Management	8	0.58	41
UB5	Stone-faced hedgebank management (one side) on/above ML	ES	Habitat Management	13	0.58	41
UC5	Sheep fencing around small woodlands	ES	Hedgerow/Woodland Edge	1	0.73	95
UHL21	No cutting strip within meadows	ES	Grass Margin	1	0.43	21
UHL23	Management of upland grassland for birds	ES	Habitat Management	28	0.00	0
UL21	No cutting strip within meadows	ES	Grass Margin	193	0.43	21
UL22	Management of enclosed rough grazing for birds	ES	Habitat Management	1208	0.00	0
UL23	Management of upland grassland for birds	ES	Habitat Management	2489	0.00	0
UOB11	Stone wall protection and maintenance on/above the moorland line	ES	Habitat Management	4	0.58	41
UOB12	Earth bank management (both sides) on/above the moorland line	ES	Habitat Management	0	0.58	41
UOB14	Hedgerow restoration	ES	Hedgerow/Woodland Edge	0	0.77	168
UOB15	Stone-faced hedgebank restoration	ES	Habitat Management	0	0.58	41
UOB16	Earth bank restoration	ES	Habitat Management	0	0.58	41
UOB17	Stone wall restoration	ES	Habitat Management	0	0.58	41
UOB4	Stone-faced hedgebank management (both sides) on/above ML	ES	Habitat Management	0	0.58	41
UOB5	Stone-faced hedgebank management (one side) on/above ML	ES	Habitat Management	0	0.58	41
UOC5	Sheep fencing around small woodlands	ES	Hedgerow/Woodland Edge	0	0.73	95
UOJ3	Post and wire fencing along watercourses	ES	Grass Margin	0	0.43	21
UOL21	No cutting strip within meadows	ES	Grass Margin	13	0.43	21
UOL22	Management of enclosed rough grazing for birds	ES	Habitat Management	33	0.00	0
UOL23	Management of upland grassland for birds	ES	Habitat Management	19	0.00	0
UOX2	Grassland and arable	ES	Habitat Management	4716	0.00	0
UOX3	Moorland	ES	Habitat Management	216	0.00	0
UP1	Enclosed rough grazing	ES	Habitat Management	218	0.00	0
UP2	Management of rough grazing for birds	ES	Habitat Management	1644	0.00	0
UP3	Management of moorland	ES	Habitat Management	1642	0.00	0
UX2	Grassland and arable	ES	Habitat Management	87067	0.00	0
UX3	Moorland	ES	Habitat Management	20174	0.00	0
WD1	Woodland creation – maintenance payments	CS	Scrub/Wood Creation	0	0.11	-7
WD2	Woodland improvement	CS	Habitat Management	11978	0.04	10
WD3	Woodland edges on arable land	CS	Hedgerow/Woodland Edge	24	0.73	95

Option Code	Option Description	Scheme	Category	Coverage (ha)	Δ Nesting (GNBB)	Δ Floral (GNBB)
WD4	Management of wood pasture and parkland	CS	Habitat Management	94	0.00	0
WD5	Restoration of wood pasture and parkland	CS	Habitat Management	343	0.16	29
WD6	Creation of wood pasture	CS	Scrub/Wood Creation	22	0.39	50
WD7	Management of successional areas and scrub	CS	Habitat Management	166	0.00	0
WD8	Creation of successional areas and scrub	CS	Scrub/Wood Creation	68	0.28	45
WT1	Buffering in-field ponds and ditches in improved grassland	CS	Grass Margin	1	0.56	33
WT10	Management of lowland raised bog	CS	Habitat Management	11	0.00	0
WT2	Buffering in-field ponds and ditches in arable land	CS	Grass Margin	14	0.64	37
WT3	Management of ditches of high environmental value	CS	Habitat Management	32	0.58	41
WT6	Management of reedbed	CS	Habitat Management	34	0.00	0
WT7	Creation of reedbed	CS	Wetland/Coast Creation	0	0.08	11
WT8	Management of fen	CS	Habitat Management	104	0.00	0
WT9	Creation of fen	CS	Wetland/Coast Creation	5	0.08	11

Table A2.2: Difference (Δ) in tree-nesting bumblebee (TNBB), ground-nesting solitary bee (GNSB) and cavity-nesting solitary bee (CNSB) nesting resource and early spring floral resource value (AES_Present minus AES_Absent), where AES_Present is scenario with AES management and AES_Absent is scenario without AES management. See IM2022 for parameterisation details.

Option Code	Option Description	Δ Nesting (TNBB)	Δ Floral (TNBB)	Δ Nesting (GNSB)	Δ Floral (GNSB)	Δ Nesting (CNSB)	Δ Floral (CNSB)
AB1	Nectar flower mix	0.02	109	0.17	85	0.29	65
AB10	Unharvested cereal headland	0.02	52	0.25	50	0.22	33
AB11	Cultivated areas for arable plants	0.02	52	0.25	50	0.22	33
AB15	Two-year sown legume fallow	0.00	87	-0.08	50	0.20	54
AB16	Autumn sown bumblebird mix	0.02	109	0.17	85	0.29	65
AB3	Beetle banks	0.04	73	0.69	79	0.47	76
AB4	Skylark plots	0.02	52	0.25	50	0.22	33
AB5	Nesting plots for lapwing and stone curlew	0.02	52	0.25	50	0.22	33
AB8	Flower-rich margins and plots	0.02	109	0.17	85	0.29	65
ABS01	Temporary Grass Buffer Strip	0.00	43	0.07	28	0.39	33
ABS02	Sown Mixed Cover Buffer Strip	0.00	43	0.07	28	0.39	33

Option Code	Option Description	Δ Nesting (TNBB)	Δ Floral (TNBB)	Δ Nesting (GNSB)	Δ Floral (GNSB)	Δ Nesting (CNSB)	Δ Floral (CNSB)
ABS03	Fallow Buffer Strip	0.02	52	0.25	50	0.22	33
BE1	Protection of in-field trees on arable land	0.20	184	0.57	168	0.81	143
BE2	Protection of in-field trees on intensive grassland	0.20	184	0.57	168	0.81	143
BE3	Management of hedgerows	0.20	184	0.57	168	0.81	143
BE4	Management of traditional orchards	0.08	30	0.05	37	-0.04	31
BE5	Creation of traditional orchards	0.50	358	0.26	313	0.28	313
BF11	Half Hedge	0.20	184	0.57	168	0.81	143
BF12	Adjacent Hedge	0.20	184	0.57	168	0.81	143
BF15	Buffer Strip	0.00	43	0.07	28	0.39	33
CT1	Management of coastal sand dunes and vegetated shingle	0.00	0	0.00	0	0.00	0
CT2	Creation of coastal sand dunes and vegetated shingle on arable land and improved grassland	-0.01	-3	0.29	23	0.10	11
CT3	Management of coastal saltmarsh	0.00	0	0.00	0	0.00	0
CT4	Creation of inter-tidal and saline habitat on arable land	0.00	0	-0.08	8	0.18	4
CT5	Creation of inter-tidal and saline habitat by non-intervention	0.00	-28	-0.18	-12	0.01	-16
CT7	Creation of inter-tidal and saline habitat on intensive grassland	-0.01	-5	-0.04	5	0.06	-2
EB1	Hedgerow management for landscape (on both sides of a hedge)	0.20	184	0.57	168	0.81	143
EB10	Combined hedge and ditch management (incorporating EB3)	0.20	184	0.57	168	0.81	143
EB11	Stone wall protection and maintenance	0.02	37	0.49	39	0.25	38
EB12	Earth bank management (on both sides)	0.02	37	0.49	39	0.25	38
EB13	Earth bank management (on one side)	0.02	37	0.49	39	0.25	38
EB14	Hedgerow restoration	0.20	184	0.57	168	0.81	143
EB2	Hedgerow management for landscape (on one side of a hedge)	0.20	184	0.57	168	0.81	143
EB3	Hedgerow management for landscape and wildlife	0.20	184	0.57	168	0.81	143
EB4	Stone faced hedge bank management on both sides	0.02	37	0.49	39	0.25	38
EB5	Stone faced hedge bank management on one side	0.02	37	0.49	39	0.25	38
EB6	Ditch management	0.02	37	0.49	39	0.25	38
EB7	Half ditch management	0.02	37	0.49	39	0.25	38
EB8	Combined hedge and ditch management (incorporating EB1)	0.20	184	0.57	168	0.81	143
EB9	Combined hedge and ditch management (incorporating EB2)	0.20	184	0.57	168	0.81	143
EC1	Protection of in-field trees (arable)	0.20	184	0.57	168	0.81	143
EC2	Protection of in-field trees (grassland)	0.20	184	0.57	168	0.81	143
EC24	Hedgerow tree buffer strips on cultivated land	0.20	184	0.57	168	0.81	143
EC25	Hedgerow tree buffer strips on grassland	0.20	184	0.57	168	0.81	143
EC3	Maintenance of woodland fences	0.77	129	0.54	83	0.75	102
EC4	Management of woodland edges	0.77	129	0.54	83	0.75	102

Option Code	Option Description	Δ Nesting (TNBB)	Δ Floral (TNBB)	Δ Nesting (GNSB)	Δ Floral (GNSB)	Δ Nesting (CNSB)	Δ Floral (CNSB)
ED2	Take archaeological features out of cultivation	0.00	28	0.10	20	0.17	20
EE1	2m buffer strips on cultivated land	0.00	43	0.07	28	0.39	33
EE10	6m buffer strips on intensive grassland next to a watercourse	-0.01	39	0.11	25	0.26	27
EE2	4m buffer strips on cultivated land	0.00	43	0.07	28	0.39	33
EE3	6m buffer strips on cultivated land	0.00	43	0.07	28	0.39	33
EE4	2m buffer strips on intensive grassland	-0.01	39	0.11	25	0.26	27
EE5	4m buffer strips on intensive grassland	-0.01	39	0.11	25	0.26	27
EE6	6m buffer strips on intensive grassland	-0.01	39	0.11	25	0.26	27
EE7	Buffering in-field ponds in improved grassland	-0.01	39	0.11	25	0.26	27
EE8	Buffering in-field ponds in arable land	0.00	43	0.07	28	0.39	33
EE9	6m buffer strips on cultivated land next to a watercourse	0.00	43	0.07	28	0.39	33
EF1	Field corner management	0.00	43	0.07	28	0.39	33
EF10	Unharvested cereal headlands for birds and rare arable plants	0.02	52	0.25	50	0.22	33
EF11	Uncropped, cultivated margins for rare plants on arable land	0.02	52	0.25	50	0.22	33
EF13	Uncropped cultivated areas for ground-nesting birds - arable	0.02	52	0.25	50	0.22	33
EF4	Nectar Flower mixture	0.02	109	0.17	85	0.29	65
EF4NR	Nectar Flower mixture (Non-rotational)	0.02	109	0.17	85	0.29	65
EF7	Beetle banks	0.02	37	0.49	39	0.25	38
EF8	Skylark plots	0.02	52	0.25	50	0.22	33
EF9	Cereal headlands for birds	0.02	52	0.25	50	0.22	33
EG3	ASD to Jan 2010 Nectar flower mixture in grassland areas	0.02	109	0.17	85	0.29	65
EJ11	Maintenance of watercourse fencing	0.00	43	0.07	28	0.39	33
EJ5	In-field grass areas	0.00	43	0.07	28	0.39	33
EJ9	12m buffer strips for watercourses on cultivated land	0.00	43	0.07	28	0.39	33
EK1	Take field corners out of management: outside SDA & ML	-0.01	39	0.11	25	0.26	27
EK2	Permanent grassland with low inputs: outside SDA & ML	0.00	40	0.14	29	0.05	22
EK21	Legume- and herb-rich swards	-0.01	82	-0.04	47	0.08	48
EK3	Permanent grassland with very low inputs: outside SDA & ML	0.00	40	0.14	29	0.05	22
EK4	Manage rush pastures: outside SDA & ML	0.00	0	0.00	0	0.00	0
EL1	Field corner management: SDA land	-0.09	25	-0.06	16	0.13	21
EL2	Permanent in-bye grassland with low inputs: SDA land	0.08	17	0.16	11	0.13	7
EL3	In-bye pasture & meadows with very low inputs: SDA land	0.08	17	0.16	11	0.13	7
EL4	Manage rush pastures: SDA land & ML parcels under 15ha	-0.08	9	-0.03	8	-0.09	7
EL5	Enclosed rough grazing: SDA land & ML parcels under 15ha	0.00	0	0.00	0	0.00	0
EL6	Moorland and rough grazing: ML land only	0.00	0	0.00	0	0.00	0
GS1	Take field corners out of management	-0.01	39	0.11	25	0.26	27

Option Code	Option Description	Δ Nesting (TNBB)	Δ Floral (TNBB)	Δ Nesting (GNSB)	Δ Floral (GNSB)	Δ Nesting (CNSB)	Δ Floral (CNSB)
GS10	Management of wet grassland for wintering waders and wildfowl	0.00	0	0.00	0	0.00	0
GS11	Creation of wet grassland for breeding waders	0.00	1	-0.12	7	0.22	6
GS12	Creation of wet grassland for wintering waders and wildfowl	0.00	1	-0.12	7	0.22	6
GS13	Management of grassland for target features	0.00	0	0.00	0	0.00	0
GS14	Creation of grassland for target features	0.01	42	0.08	46	0.24	36
GS2	Permanent grassland with very low inputs (outside SDAs)	0.00	40	0.14	29	0.05	22
GS4	Legume and herb-rich swards	-0.01	82	-0.04	47	0.08	48
GS5	Permanent grassland with very low inputs in SDAs	0.08	17	0.16	11	0.13	7
GS6	Management of species-rich grassland	0.00	0	0.00	0	0.00	0
GS7	Restoration towards species-rich grassland	0.01	41	0.09	29	0.04	22
GS8	Creation of species-rich grassland	0.02	109	0.17	85	0.29	65
GS9	Management of wet grassland for breeding waders	0.00	0	0.00	0	0.00	0
HAE1	Hedge	0.20	184	0.57	168	0.81	143
HAE2	Hedge	0.20	184	0.57	168	0.81	143
HB11	Maintenance of hedges of very high environmental value (2 sides)	0.20	184	0.57	168	0.81	143
HB12	Maintenance of hedges of very high environmental value (1 side)	0.20	184	0.57	168	0.81	143
HB14	Management of ditches of very high environmental value	0.02	37	0.49	39	0.25	38
HC1	Protection of in-field trees on arable land	0.20	184	0.57	168	0.81	143
HC10	Creation of woodland outside of the SDA & ML	0.33	-20	-0.01	-5	0.11	-4
HC12	Maintenance of wood pasture and parkland	0.00	0	0.00	0	0.00	0
HC13	Restoration of wood pasture and parkland	0.07	42	0.13	30	0.08	23
HC14	Creation of wood pasture	0.08	70	0.22	50	0.25	43
HC15	Maintenance of successional areas and scrub	0.00	0	0.00	0	0.00	0
HC16	Restoration of successional areas and scrub	0.05	24	0.00	16	0.23	20
HC17	Creation of successional areas and scrub	0.10	43	-0.01	28	0.47	35
HC18	Maintenance of high value traditional orchards	0.00	0	0.00	0	0.00	0
HC19	Maintenance of traditional orchards in production	0.00	0	0.00	0	0.00	0
HC2	Protection of in-field trees on grassland	0.20	184	0.57	168	0.81	143
HC20	Restoration of traditional orchards	0.08	30	0.05	37	-0.04	31
HC21	Creation of traditional orchards	0.50	358	0.26	313	0.28	313
HC24	Hedgerow tree buffer strips on cultivated land	0.20	184	0.57	168	0.81	143
HC25	Hedgerow tree buffer strips on grassland	0.20	184	0.57	168	0.81	143
HC4	Management of woodland edges	0.77	129	0.54	83	0.75	102
HC5	Ancient trees in arable fields	0.20	184	0.57	168	0.81	143
HC6	Ancient trees in intensively-managed grass fields	0.20	184	0.57	168	0.81	143
HC7	Maintenance of woodland	0.00	0	0.00	0	0.00	0

Option Code	Option Description	∆ Nesting (TNBB)	∆ Floral (TNBB)	∆ Nesting (GNSB)	∆ Floral (GNSB)	∆ Nesting (CNSB)	∆ Floral (CNSB)
HC8	Restoration of woodland	0.15	15	0.01	10	0.08	10
HC9	Creation of woodland in the SDA	0.33	-20	-0.01	-5	0.11	-4
HD10	Maintenance of traditional water meadows	0.00	0	0.00	0	0.00	0
HD11	Restoration of traditional water meadows	-0.10	-69	-0.21	-42	-0.42	-48
HD2	Take archaeological features out of cultivation	0.00	28	0.10	20	0.17	20
HD7	Arable reversion by natural regeneration	0.00	28	0.10	20	0.17	20
HE1	2 m buffer strips on cultivated land	0.00	43	0.07	28	0.39	33
HE10	Floristically enhanced grass margin	0.02	109	0.17	85	0.29	65
HE11	Enhanced strips for target species on intensive grassland	0.01	105	0.21	82	0.16	59
HE2	4 m buffer strips on cultivated land	0.00	43	0.07	28	0.39	33
HE3	6 m buffer strips on cultivated land	0.00	43	0.07	28	0.39	33
HE4	2 m buffer strips on intensive grassland	-0.01	39	0.11	25	0.26	27
HE5	4 m buffer strips on intensive grassland	-0.01	39	0.11	25	0.26	27
HE6	6 m buffer strips on intensive grassland	-0.01	39	0.11	25	0.26	27
HE7	Buffering in-field ponds in improved permanent grassland	-0.01	39	0.11	25	0.26	27
HE8	Buffering in-field ponds in arable land	0.00	43	0.07	28	0.39	33
HF1	Management of field corners	0.00	43	0.07	28	0.39	33
HF10	Unharvested cereal headlands for birds and rare arable plants	0.02	52	0.25	50	0.22	33
HF10NR	Unharvested cereal headlands for birds and rare arable plants (Non-Rotational)	0.02	52	0.25	50	0.22	33
HF11	Uncropped, cultivated margins for rare plants	0.02	52	0.25	50	0.22	33
HF13	Uncropped cultivated areas for ground-nesting birds - arable	0.02	52	0.25	50	0.22	33
HF13NR	Uncropped cultivated areas for ground-nesting birds - arable	0.02	52	0.25	50	0.22	33
HF14	Unharvested, fertiliser-free conservation headland	0.02	52	0.25	50	0.22	33
HF14NR	Unharvested, fertiliser-free conservation headland	0.02	52	0.25	50	0.22	33
HF17	ASD to Dec 2008 Fallow plots for ground-nesting birds (setaside)	0.02	52	0.25	50	0.22	33
HF19	ASD to Dec 2008 Unharvested conservation headland with setaside	0.02	52	0.25	50	0.22	33
HF20	Cultivated fallow plots or margins for arable plants	0.02	52	0.25	50	0.22	33
HF20NR	Cultivated fallow plots or margins for arable plants	0.02	52	0.25	50	0.22	33
HF4	Nectar flower mixture	0.02	109	0.17	85	0.29	65
HF4NR	Nectar flower mixture	0.02	109	0.17	85	0.29	65
HF7	Beetle banks	0.02	37	0.49	39	0.25	38
HF8	Skylark plots	0.02	52	0.25	50	0.22	33
HF9	Cereal headlands for birds	0.02	52	0.25	50	0.22	33
HF9NR	Cereal headlands for birds	0.02	52	0.25	50	0.22	33
HG3	ASD to Jan 2010 Nectar flower mixture in grassland areas	0.02	109	0.17	85	0.29	65

Option Code	Option Description	Δ Nesting (TNBB)	Δ Floral (TNBB)	Δ Nesting (GNSB)	Δ Floral (GNSB)	Δ Nesting (CNSB)	Δ Floral (CNSB)
HJ11	Maintenance of watercourse fencing	-0.01	39	0.11	25	0.26	27
HJ3	Reversion to unfertilised grassland to prevent erosion/run-off	0.00	68	0.23	49	0.21	42
HJ4	Reversion to low input grassland to prevent erosion/run-off	0.00	28	0.10	20	0.17	20
HJ5	In-field grass areas to prevent erosion or run-off	0.00	43	0.07	28	0.39	33
HJ9	12 m buffer strips for watercourses on cultivated land	0.00	43	0.07	28	0.39	33
HK1	Take field corners out of management	-0.01	39	0.11	25	0.26	27
HK10	Maintenance of wet grassland for wintering waders and wildfowl	0.00	0	0.00	0	0.00	0
HK11	Restoration of wet grassland for breeding waders	0.00	-27	-0.22	-13	0.05	-13
HK12	Restoration of wet grassland for wintering waders and wildfowl	0.00	-27	-0.22	-13	0.05	-13
HK13	Creation of wet grassland for breeding waders	0.00	1	-0.12	7	0.22	6
HK14	Creation of wet grassland for wintering waders and wildfowl	0.00	1	-0.12	7	0.22	6
HK15	Maintenance of grassland for target features	0.00	0	0.00	0	0.00	0
HK16	Restoration of grassland for target features	0.00	0	0.00	0	0.00	0
HK17	Creation of grassland for target features	0.01	42	0.08	46	0.24	36
HK2	Permanent grassland with low inputs	0.00	40	0.14	29	0.05	22
HK21	Legume- and herb-rich swards	-0.01	82	-0.04	47	0.08	48
HK3	Permanent grassland with very low inputs	0.00	40	0.14	29	0.05	22
HK4	Management of rush pastures	0.00	0	0.00	0	0.00	0
HK6	Maintenance of species-rich, semi-natural grassland	0.00	0	0.00	0	0.00	0
HK7	Restoration of species-rich, semi-natural grassland	0.01	67	0.09	40	0.04	29
HK8	Creation of species-rich, semi-natural grassland	0.02	109	0.17	85	0.29	65
HK9	Maintenance of wet grassland for breeding waders	0.00	0	0.00	0	0.00	0
HL1	Take field corners out of management in SDAs	-0.09	25	-0.06	16	0.13	21
HL10	Restoration of moorland	0.04	9	0.08	6	0.07	4
HL11	Creation of upland heathland	0.04	9	0.08	6	0.07	4
HL12	Management of heather, gorse and grass	0.00	0	0.00	0	0.00	0
HL2	Permanent grassland with low inputs in SDAs	0.08	17	0.16	11	0.13	7
HL3	Permanent grassland with very low inputs in SDAs	0.08	17	0.16	11	0.13	7
HL4	Management of rush pastures in SDAs	0.00	0	0.00	0	0.00	0
HL5	Enclosed rough grazing	0.00	0	0.00	0	0.00	0
HL6	Unenclosed moorland rough grazing	0.00	0	0.00	0	0.00	0
HL7	Maintenance of rough grazing for birds	0.00	0	0.00	0	0.00	0
HL8	Restoration of rough grazing for birds	0.04	9	0.08	6	0.07	4
HL9	Maintenance of moorland	0.00	0	0.00	0	0.00	0
HO1	Maintenance of lowland heathland	0.00	0	0.00	0	0.00	0
HO2	Restoration of lowland heath	0.07	-35	0.20	-25	-0.25	-35

Option Code	Option Description	Δ Nesting (TNBB)	Δ Floral (TNBB)	Δ Nesting (GNSB)	Δ Floral (GNSB)	Δ Nesting (CNSB)	Δ Floral (CNSB)
HO3	Restoration of forestry areas to lowland heathland	-0.25	36	0.45	23	0.25	19
HO4	Creation of lowland heathland from arable or improved grassland	0.16	31	0.33	20	0.26	14
HO5	Creation of lowland heathland on worked mineral sites	0.17	36	0.58	24	0.42	20
HP1	Maintenance of sand dunes	0.00	0	0.00	0	0.00	0
HP2	Restoration of sand dune systems	0.00	0	0.00	0	0.00	0
HP4	Creation of vegetated shingle and sand dune on grassland	0.00	-27	0.15	7	0.05	-3
HP5	Maintenance of coastal saltmarsh	0.00	0	0.00	0	0.00	0
HP6	Restoration of coastal saltmarsh	0.00	-28	-0.18	-12	0.01	-16
HP7	Creation of inter-tidal and saline habitat on arable land	0.00	0	-0.08	8	0.18	4
HP8	Creation of inter-tidal and saline habitat on grassland	0.00	-28	-0.18	-12	0.01	-16
HP9	Creation of inter-tidal and saline habitat by non-intervention	0.00	-68	-0.31	-41	-0.04	-38
HPE1	Hedge	0.20	184	0.57	168	0.81	143
HPE2	Hedge	0.20	184	0.57	168	0.81	143
HQ10	Restoration of lowland raised bog	-0.10	-69	-0.21	-42	-0.42	-48
HQ3	Maintenance of reedbeds	0.00	0	0.00	0	0.00	0
HQ4	Restoration of reedbeds	-0.01	-2	-0.02	-2	-0.04	-2
HQ5	Creation of reedbeds	0.00	1	-0.12	7	0.22	6
HQ6	Maintenance of fen	0.00	0	0.00	0	0.00	0
HQ7	Restoration of fen	-0.10	-69	-0.21	-42	-0.42	-48
HQ8	Creation of fen	0.00	1	-0.12	7	0.22	6
HQ9	Maintenance of lowland raised bog	0.00	0	0.00	0	0.00	0
HS7	Management of historic water meadows through traditional irrigation	0.00	0	0.00	0	0.00	0
LH1	Management of lowland heathland	0.00	0	0.00	0	0.00	0
LH2	Restoration of forestry and woodland to lowland heathland	-0.25	36	0.45	23	0.25	19
LH3	Creation of heathland from arable or improved grassland	0.16	31	0.33	20	0.26	14
OB1	Hedgerow management for landscape (on both sides of a hedge)	0.20	184	0.57	168	0.81	143
OB10	Combined hedge and ditch management (incorporating OB3)	0.20	184	0.57	168	0.81	143
OB11	Stonewall protection and maintenance	0.02	37	0.49	39	0.25	38
OB12	Earth bank management (on both sides)	0.02	37	0.49	39	0.25	38
OB13	Earth bank management (on one side)	0.02	37	0.49	39	0.25	38
OB14	Hedgerow restoration	0.20	184	0.57	168	0.81	143
OB2	Hedgerow management for landscape (on one side of a hedge)	0.20	184	0.57	168	0.81	143
OB3	Hedgerow management for landscape and wildlife	0.20	184	0.57	168	0.81	143
OB4	Stone faced Hedge bank management on both sides	0.02	37	0.49	39	0.25	38
OB5	Stone faced Hedge bank management on one side	0.02	37	0.49	39	0.25	38
OB6	Ditch management	0.02	37	0.49	39	0.25	38

Option Code	Option Description	∆ Nesting (TNBB)	∆ Floral (TNBB)	∆ Nesting (GNSB)	∆ Floral (GNSB)	∆ Nesting (CNSB)	∆ Floral (CNSB)
OB7	Half ditch management	0.02	37	0.49	39	0.25	38
OB8	Combined hedge and ditch management (incorporating OB1)	0.20	184	0.57	168	0.81	143
OB9	Combined hedge and ditch management (incorporating OB2)	0.20	184	0.57	168	0.81	143
OC1	Protection of in field trees - rotational land	0.20	184	0.57	168	0.81	143
OC2	Protection of in field trees - grassland	0.20	184	0.57	168	0.81	143
OC24	Hedgerow tree buffer strips on rotational land	0.20	184	0.57	168	0.81	143
OC25	Hedgerow tree buffer strips on organic grassland	0.20	184	0.57	168	0.81	143
OC3	Maintenance of woodland fences	0.77	129	0.54	83	0.75	102
OC4	Management of wood edges	0.77	129	0.54	83	0.75	102
OD2	Take archaeological features out of cultivation	0.00	28	0.11	9	0.14	15
OE1	2m buffer strips on rotational land	0.00	43	0.09	18	0.35	28
OE10	6m buffer strip on organic grassland next to a watercourse	-0.01	39	0.11	25	0.26	27
OE2	4m buffer strips on rotational land	0.00	43	0.09	18	0.35	28
OE3	6m buffer strips on rotational land	0.00	43	0.09	18	0.35	28
OE4	2m buffer strip on organic grassland	-0.01	39	0.11	25	0.26	27
OE5	4m buffer strip on organic grassland	-0.01	39	0.11	25	0.26	27
OE6	6m buffer strip on organic grassland	-0.01	39	0.11	25	0.26	27
OE7	Buffering in-field ponds in organic grassland	-0.01	39	0.11	25	0.26	27
OE8	Buffering in-field ponds in rotational land	0.00	43	0.09	18	0.35	28
OE9	6m buffer strips on rotational land next to a watercourse	0.00	43	0.09	18	0.35	28
OF1	Field corner management	0.00	43	0.09	18	0.35	28
OF11	Uncropped, cultivated margins for rare plants on arable land	0.02	52	0.27	39	0.19	28
OF13	Uncropped cultivated areas for ground-nesting birds - rotational	0.02	52	0.27	39	0.19	28
OF4	Nectar Flower mixture	0.02	109	0.19	75	0.26	60
OF4NR	Nectar Flower mixture	0.02	109	0.19	75	0.26	60
OF7	Beetle banks	0.02	37	0.49	39	0.25	38
OF8	Skylark plots	0.02	52	0.27	39	0.19	28
OG3	ASD to Jan 2010 Nectar flower mixture in grassland areas	0.02	109	0.19	75	0.26	60
OHC1	Protection of in-field trees on rotational land	0.20	184	0.57	168	0.81	143
OHC2	Protection of in-field trees on organic grassland	0.20	184	0.57	168	0.81	143
OHC24	Hedgerow tree buffer strips on rotational land	0.20	184	0.57	168	0.81	143
OHC4	Management of woodland edges	0.77	129	0.54	83	0.75	102
OHD2	Take archaeological features out of cultivation (Org)	0.00	28	0.11	9	0.14	15
OHE1	2m buffer strips on rotational land	0.00	43	0.09	18	0.35	28
OHE2	4m buffer strips on rotational land	0.00	43	0.09	18	0.35	28
OHE3	6m buffer strips on rotational land	0.00	43	0.09	18	0.35	28

Option Code	Option Description	Δ Nesting (TNBB)	Δ Floral (TNBB)	Δ Nesting (GNSB)	Δ Floral (GNSB)	Δ Nesting (CNSB)	Δ Floral (CNSB)
OHE4	2m buffer strip on organic grassland	-0.01	39	0.11	25	0.26	27
OHE5	4m buffer strip on organic grassland	-0.01	39	0.11	25	0.26	27
OHE6	6m buffer strip on organic grassland	-0.01	39	0.11	25	0.26	27
OHE7	Buffering in-field ponds in organic grassland	-0.01	39	0.11	25	0.26	27
OHE8	Buffering in-field ponds in rotational land	0.00	43	0.09	18	0.35	28
OHF1	Management of field corners	0.00	43	0.09	18	0.35	28
OHF11	Uncropped, cultivated margins for rare plants	0.02	52	0.27	39	0.19	28
OHF13	Uncropped, cultivated areas for ground-nesting birds	0.02	52	0.27	39	0.19	28
OHF13NR	Uncropped, cultivated areas for ground-nesting birds	0.02	52	0.27	39	0.19	28
OHF4	Nectar Flower mixture	0.02	109	0.19	75	0.26	60
OHF4NR	Nectar Flower mixture	0.02	109	0.19	75	0.26	60
OHF7	Beetle banks	0.04	73	0.71	68	0.44	71
OHF8	Skylark plots	0.02	52	0.27	39	0.19	28
OHG3	ASD to Jan 2010 Nectar flower mixture in grassland areas	0.02	109	0.19	75	0.26	60
OHJ11	Maintenance of watercourse fencing	-0.01	39	0.11	25	0.26	27
OHJ5	In-field grass areas to prevent erosion and run-off	0.00	43	0.09	18	0.35	28
OHJ9	12 m buffer strips for watercourses on rotational land	0.00	43	0.09	18	0.35	28
OHK1	Take field corners out of management	-0.01	39	0.11	25	0.26	27
OHK2	Permanent grassland with low inputs	0.00	40	0.14	29	0.05	22
OHK21	Legume- and herb-rich swards	-0.01	82	-0.04	47	0.08	48
OHK3	Permanent grassland with very low inputs	0.00	40	0.14	29	0.05	22
OHK4	Management of rush pastures	0.00	0	0.00	0	0.00	0
OHL2	Permanent grassland with low inputs in SDAs	0.08	17	0.16	11	0.13	7
OHL3	Permanent grassland with very low inputs in SDAs	0.08	17	0.16	11	0.13	7
OHL4	Management of rush pastures in SDAs	0.00	0	0.00	0	0.00	0
OHL5	Enclosed rough grazing	0.00	0	0.00	0	0.00	0
OJ11	Maintenance of watercourse fencing	-0.01	39	0.11	25	0.26	27
OJ5	In-field grass areas to prevent erosion and run-off	0.00	43	0.09	18	0.35	28
OJ9	12m buffer strips for watercourses on cultivated land	0.00	43	0.09	18	0.35	28
OK1	Take field corners out of management: outside SDA & ML (organic)	-0.01	39	0.11	25	0.26	27
OK2	Permanent grassland with low inputs: outside SDA & ML (organic)	0.00	40	0.14	29	0.05	22
OK21	Legume- and herb-rich swards	-0.01	82	-0.04	47	0.08	48
OK3	Permanent grassland with very low inputs:outside SDA&ML (organic)	0.00	40	0.14	29	0.05	22
OK4	Manage rush pastures: outside SDA & ML (organic)	0.00	0	0.00	0	0.00	0
OL1	Field corner management: SDA land (organic)	-0.09	25	-0.06	16	0.13	21
OL2	Permanent in-bye grassland with low inputs: SDA land (organic)	0.08	17	0.16	11	0.13	7

Option Code	Option Description	Δ Nesting (TNBB)	Δ Floral (TNBB)	Δ Nesting (GNSB)	Δ Floral (GNSB)	Δ Nesting (CNSB)	Δ Floral (CNSB)
OL3	In-bye pasture & meadows with very low inputs: SDA land (organic)	0.08	17	0.16	11	0.13	7
OL4	Manage rush pastures: SDA land & ML parcels under 15ha (organic)	0.00	0	0.00	0	0.00	0
OL5	Enclosed rough grazing:SDA land & ML parcels under 15ha (organic)	0.00	0	0.00	0	0.00	0
OP4	Multi species ley	0.02	22	0.05	19	0.11	17
OR1	Organic conversion - improved permanent grassland	0.00	0	0.00	0	0.00	0
OR2	Organic conversion - unimproved permanent grassland	0.00	0	0.00	0	0.00	0
OR3	Organic conversion - rotational land	0.00	0	-0.02	11	0.03	5
OT3	Organic land management - rotational land	0.00	0	-0.02	11	0.03	5
PG02	Permanent grassland buffer strip	-0.01	39	0.11	25	0.26	27
RD01	Non-Agricultural Land Under Rural Development Programme	0.00	0	0.00	0	0.00	0
SW1	4 - 6 m buffer strip on cultivated land	0.00	43	0.07	28	0.39	33
SW11	Riparian management strip	-0.01	39	0.11	25	0.26	27
SW2	4 - 6 m buffer strip on intensive grassland	-0.01	39	0.11	25	0.26	27
SW3	In-field grass strips	0.00	43	0.07	28	0.39	33
SW4	12 - 24m watercourse buffer strip on cultivated land	0.00	43	0.07	28	0.39	33
SW7	Arable reversion to grassland with low fertiliser input	0.09	18	0.12	12	0.25	12
UB11	Stone wall protection and maintenance on/above the moorland line	0.02	37	0.49	39	0.25	38
UB12	Earth bank management (both sides) on/above the moorland line	0.02	37	0.49	39	0.25	38
UB13	Earth bank management (one side) on/above the moorland line	0.02	37	0.49	39	0.25	38
UB14	Hedgerow restoration	0.20	184	0.57	168	0.81	143
UB15	Stone-faced hedgebank restoration	0.02	37	0.49	39	0.25	38
UB16	Earth bank restoration	0.02	37	0.49	39	0.25	38
UB17	Stone wall restoration	0.02	37	0.49	39	0.25	38
UB4	Stone-faced hedgebank management (both sides) on/above ML	0.02	37	0.49	39	0.25	38
UB5	Stone-faced hedgebank management (one side) on/above ML	0.02	37	0.49	39	0.25	38
UC5	Sheep fencing around small woodlands	0.77	129	0.54	83	0.75	102
UHL21	No cutting strip within meadows	-0.09	25	-0.06	16	0.13	21
UHL23	Management of upland grassland for birds	0.00	0	0.00	0	0.00	0
UL21	No cutting strip within meadows	-0.09	25	-0.06	16	0.13	21
UL22	Management of enclosed rough grazing for birds	0.00	0	0.00	0	0.00	0
UL23	Management of upland grassland for birds	0.00	0	0.00	0	0.00	0
UOB11	Stone wall protection and maintenance on/above the moorland line	0.02	37	0.49	39	0.25	38
UOB12	Earth bank management (both sides) on/above the moorland line	0.02	37	0.49	39	0.25	38
UOB14	Hedgerow restoration	0.20	184	0.57	168	0.81	143
UOB15	Stone-faced hedgebank restoration	0.02	37	0.49	39	0.25	38
UOB16	Earth bank restoration	0.02	37	0.49	39	0.25	38

Option Code	Option Description	Δ Nesting (TNBB)	Δ Floral (TNBB)	Δ Nesting (GNSB)	Δ Floral (GNSB)	Δ Nesting (CNSB)	Δ Floral (CNSB)
UOB17	Stone wall restoration	0.02	37	0.49	39	0.25	38
UOB4	Stone-faced hedgebank management (both sides) on/above ML	0.02	37	0.49	39	0.25	38
UOB5	Stone-faced hedgebank management (one side) on/above ML	0.02	37	0.49	39	0.25	38
UOC5	Sheep fencing around small woodlands	0.77	129	0.54	83	0.75	102
UOJ3	Post and wire fencing along watercourses	-0.09	25	-0.06	16	0.13	21
UOL21	No cutting strip within meadows	-0.09	25	-0.06	16	0.13	21
UOL22	Management of enclosed rough grazing for birds	0.00	0	0.00	0	0.00	0
UOL23	Management of upland grassland for birds	0.00	0	0.00	0	0.00	0
UOX2	Grassland and arable	0.00	0	0.00	0	0.00	0
UOX3	Moorland	0.00	0	0.00	0	0.00	0
UP1	Enclosed rough grazing	0.00	0	0.00	0	0.00	0
UP2	Management of rough grazing for birds	0.00	0	0.00	0	0.00	0
UP3	Management of moorland	0.00	0	0.00	0	0.00	0
UX2	Grassland and arable	0.00	0	0.00	0	0.00	0
UX3	Moorland	0.00	0	0.00	0	0.00	0
WD1	Woodland creation – maintenance payments	0.33	-20	-0.01	-5	0.11	-4
WD2	Woodland improvement	0.15	15	0.01	10	0.08	10
WD3	Woodland edges on arable land	0.77	129	0.54	83	0.75	102
WD4	Management of wood pasture and parkland	0.00	0	0.00	0	0.00	0
WD5	Restoration of wood pasture and parkland	0.07	42	0.13	30	0.08	23
WD6	Creation of wood pasture	0.08	70	0.22	50	0.25	43
WD7	Management of successional areas and scrub	0.00	0	0.00	0	0.00	0
WD8	Creation of successional areas and scrub	0.10	43	-0.01	28	0.47	35
WT1	Buffering in-field ponds and ditches in improved grassland	-0.01	39	0.11	25	0.26	27
WT10	Management of lowland raised bog	0.00	0	0.00	0	0.00	0
WT2	Buffering in-field ponds and ditches in arable land	0.00	43	0.07	28	0.39	33
WT3	Management of ditches of high environmental value	0.02	37	0.49	39	0.25	38
WT6	Management of reedbed	0.00	0	0.00	0	0.00	0
WT7	Creation of reedbed	0.00	1	-0.12	7	0.22	6
WT8	Management of fen	0.00	0	0.00	0	0.00	0
WT9	Creation of fen	0.00	1	-0.12	7	0.22	6

2.2 Nesting and Floral Resource Change by Category – Other Guilds

The following three figures (Figure A2.1, Figure A2.2, Figure A2.3) show change in nesting and floral resource value for tree-nesting bumblebees, ground-nesting solitary bees and cavity-nesting solitary bees. Underlying nesting resource parameterisation for a given category in a given scenario can vary theoretically from 0 – 0.95. Underlying floral resource parameterisation can vary theoretically from 0 – 1520.

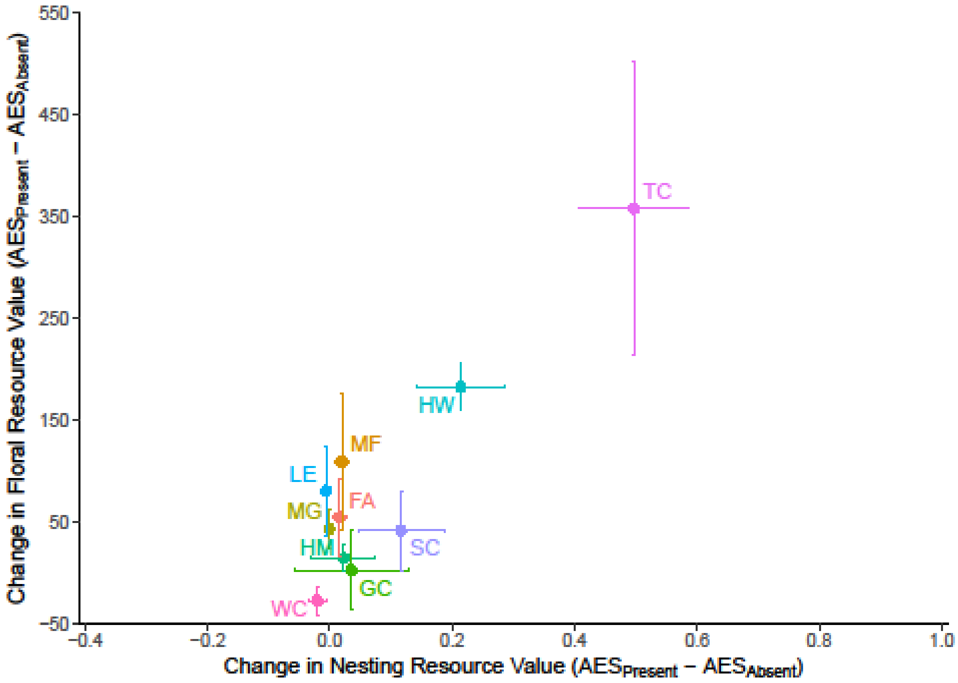

Figure A2.1: Change in tree-nesting bumblebee nesting resource value and change in early spring floral resource value for each agri-environment scheme (AES) option category between scenario without AES management and with AES management. Values are the average for the category, weighted by the national proportion of land area taken up by each component option for the reference year (2016). Horizontal and vertical bars represent the standard deviation of the average nesting and floral resource value respectively, also area weighted and taking into consideration error propagation (Hughes and Hase, 2010).

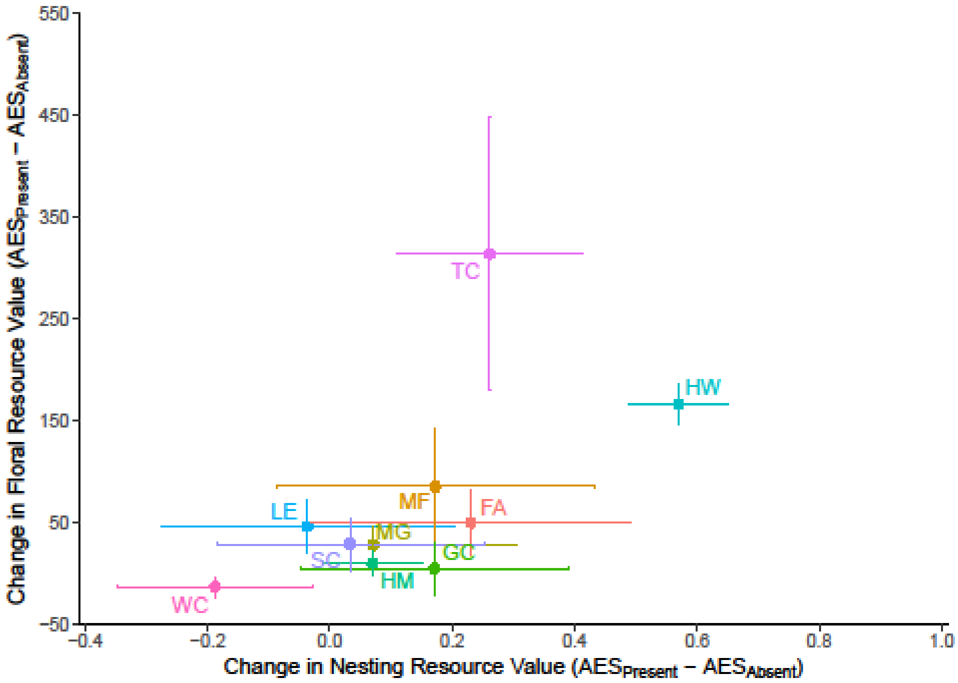

Figure A2.2: Change in ground-nesting solitary bee nesting resource value and change in early spring floral resource value for each agri-environment scheme (AES) option category between scenario without AES management and with AES management. Values are the average for the category, weighted by the national proportion of land area taken up by each component option for the reference year (2016). Horizontal and vertical bars represent the standard deviation of the average nesting and floral resource value respectively, also area weighted and taking into consideration error propagation (Hughes and Hase, 2010).

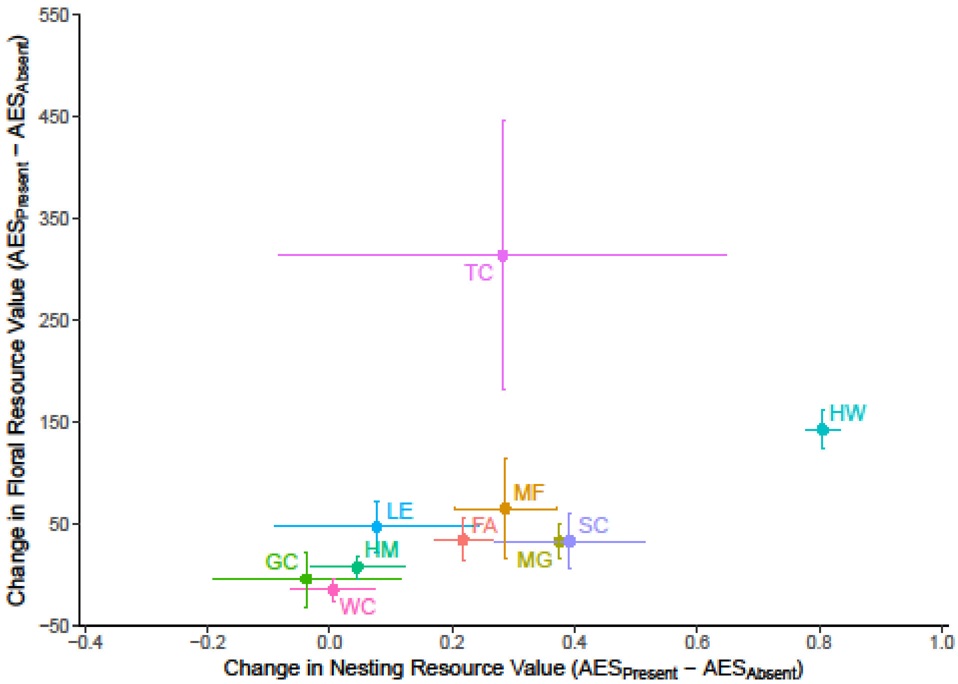

Figure A2.3: Change in cavity-nesting solitary bee nesting resource value and change in early spring floral resource value for each agri-environment scheme (AES) option category between scenario without AES management and with AES management. Values are the average for the category, weighted by the national proportion of land area taken up by each component option for the reference year (2016). Horizontal and vertical bars represent the standard deviation of the average nesting and floral resource value respectively, also area weighted and taking into consideration error propagation (Hughes and Hase, 2010).

2.3 Regression Outputs – Other Guilds

Tree-nesting bumblebees, ground-nesting solitary bees, and cavity-nesting solitary bees show a weaker fit for the explanatory variables than ground-nesting bumblebees. For tree-nesting bumblebees this is probably because few AES options offer attractive resource to this guild (see Figure A2.1). For solitary bees this is probably because the AES schemes as a whole were not predicted to have had much effect, especially on crop pollination due partly to resource quality (Figure A2.2, Figure A2.3) but also due to the pattern of uptake (see IM2022 for details).

Table A2.3: Results for linear regression of change in visitation by tree-nesting bumblebee (TNBB) to OSR (late spring), Field Beans (late spring) and non-crops (all seasons).

Variable	OSR	Field Beans	Non-Crop
(Intercept)	1.000 ± 0.003 ***	0.990 ± 0.003 ***	1.0E-5 ± 2.4E-5***
Fallow (FA)	0.039 ± 0.016 *	0.05 ± 0.015 **	-0.049 ± 0.010 ***
Grassland / Heath Creation (GC)	0.004 ± 0.002 *		
Habitat Management (HM)	0.0010 ± 0.0002 ***	0.0019 ± 0.0002 ***	0.0019 ± 0.0001 ***
Hedgerow / Woodland Edge (HW)	0.18 ± 0.01 ***	0.14 ± 0.01 ***	0.10 ± 0.01 ***
Ley (LE)	-0.03 ± 0.02	-0.022 ± 0.012	0.043 ± 0.016 **
Floral Margin (MF)	0.012 ± 0.015	0.00 ± 0.03	0.041 ± 0.017 *
Grass Margin (MG)	0.036 ± 0.008 ***	0.043 ± 0.009 ***	-0.047 ± 0.006 ***
Scrub / Wood Creation (SC)		0.024 ± 0.029	0.032 ± 0.01 **
Trad. Orchard Creation (TC)			0.14 ± 0.06 *
Wetland / Coastal Creation (WC)			-0.017 ± 0.002 ***
Non-Scheme Resource (NSR)	0.0003 ± 0.0001 **	2.5E-4 ± 0.8E-4 ***	0.0E-6 ± 1.1E-6
*FA * NSR*			0.0018 ± 0.0007 **
*HW * NSR*	-0.0074 ± 0.0008 ***	-0.0044 ± 0.0009 ***	-0.0042 ± 0.0004 ***
*MF * NSR*			-0.0020 ± 0.0009 *
*MG * NSR*	-0.0014 ± 0.0006 *		0.0011 ± 0.0003 **
*SC * NSR*			-0.0024 ± 0.0011 *
*WC * NSR*			0.0006 ± 0.0001 ***
*FA * HM*	0.005 ± 0.0002 **		
*HM * HW*			0.0014 ± 0.0006 *
*HM * LE*	0.016 ± 0.0031 ***	0.015 ± 0.004 ***	
*HM * MF*		0.0041 ± 0.0019 *	0.0023 ± 0.0012 *
*HW * MF*		0.093 ± 0.046 *	-0.10 ± 0.04 **
*FA * MG*	-0.081 ± 0.024 ***	-0.085 ± 0.023 ***	
*HM * MG*			0.0019 ± 0.0005 ***
*HW * MG*			
*HM * SC*		0.0058 ± 0.0027 *	
N	1189	1195	1495
R^2	0.61	0.59	0.53

Table A2.4: Results for linear regression of change in visitation by ground-nesting solitary bee (GNSB) to OSR (late spring), Field Beans (late spring) and non-crops (all seasons).

Variable	**OSR**	**Field Beans**	**Non-Crop**
(Intercept)	1.000 ± 0.002 ***	0.990 ± 0.009 ***	1.000 ± 0.005 ***
Fallow (FA)	0.012 ± 0.011		
Grassland / Heath Creation (GC)	0.0045 ± 0.0019 *		0.0094 ± 0.0042 *
Habitat Management (HM)	0.0009 ± 0.0001 ***	0.0029 ± 0.0007 ***	0.0059 ± 0.0004 ***
Hedgerow / Woodland Edge (HW)	0.070 ± 0.007 ***	0.11 ± 0.02 ***	0.28 ± 0.03 ***
Floral Margin (MF)	-0.044 ± 0.012 ***	0.078 ± 0.037 *	0.059 ± 0.028 *
Grass Margin (MG)	0.0056 ± 0.0053		-0.022 ± 0.017
Scrub / Wood Creation (SC)			0.14 ± 0.06 *
Trad. Orchard Creation (TC)			
Wetland / Coastal Creation (WC)			-0.025 ± 0.009 **
Non-Scheme Resource (NSR)	-9.0E-5 ± 6.0E-5	1.6E-4 ± 3.2E-4	1.1E-5 ± 4.6E-5
*FA * NSR*	0.0018 ± 0.0008 *		
*HM * NSR*			
*HW * NSR*	-0.0025 ± 0.0005 ***		-0.0093 ± 0.0015 ***
*MF * NSR*	0.0019 ± 0.0009 *	-0.010 ± 0.003 ***	
*MG * NSR*	0.00073 ± 0.00035 *		
*FA * HW*	-0.097 ± 0.025 ***		
*FA * MF*	0.11 ± 0.03 ***		
*HM * HW*	-0.0011 ± 0.0004 **		
*HM * MG*			0.0044 ± 0.0015 **
*HW * MG*	-0.03 ± 0.01 **		
*HM * SC*			0.0058 ± 0.0013 ***
N	1189	1189	1498
R^2	0.31	0.17	0.37

Table A2.5: Results for linear regression of change in visitation by cavity-nesting solitary bee (CNSB) to OSR (late spring), Field Beans (late spring) and non-crops (all seasons).

Variable	OSR	Field Beans	Non-Crop
(Intercept)	0.990 ± 0.002 ***	0.99 ± 0.01 ***	1.000 ± 0.003 ***
Fallow (FA)	0.0011 ± 0.014	0.084 ± 0.042 *	
Grassland / Heath Creation (GC)	0.0066 ± 0.0022 **		-0.0068 ± 0.0025 **
Habitat Management (HM)	0.00099 ± 0.00016 ***		0.0044 ± 0.0003***
Hedgerow / Woodland Edge (HW)	0.093 ± 0.008 ***	0.11 ± 0.02 ***	0.16 ± 0.02 ***
Floral Margin (MF)	-0.010 ± 0.009	0.055 ± 0.038	0.055 ± 0.018
Grass Margin (MG)	0.042 ± 0.005 ***		
Scrub / Wood Creation (SC)			-0.046 ± 0.03
Trad. Orchard Creation (TC)			
Wetland / Coastal Creation (WC)	0.002 ± 0.001 *		-0.014 ± 0.006 *
Non-Scheme Resource (NSR)	-2.4E-4 ± 0.8E-4 **	1.8E-4 ± 3.3E-4	5.1E-5 ± 6.4E-5
*FA * NSR*	0.0043 ± 0.0009 ***		
*HW * NSR*	-0.0016 ± 0.0005 ***		-0.0057 ± 0.0008 ***
*MF * NSR*		-0.0086 ± 0.0031 **	
*GC * HM*	0.0003 ± 0.0001 *		
*HM * HW*	-0.0018 ± 0.0005 ***		0.0033 ± 0.0014 *
*MF * HW*	0.069 ± 0.027 **		
*FA * MF*	0.099 ± 0.031 **		
*HM * MF*			0.0049 ± 0.0024 *
*FA * MG*	-0.045 ± 0.017 **		
*HM * MG*	0.0009 ± 0.0004 *		
*HW * MG*	-0.039 ± 0.011 ***		
*HM * SC*			0.0032 ± 0.0008 ***
N	1189	1193	1494
R^2	0.56	0.17	0.46

2.4 Interaction Effect Plots

The following are effect plots of statistically significant interactions where the fitted value of visitation ratio (y-axis) is plotted for the explanatory variable (x-axis) under different moderator variable conditions (+1 standard deviation, mean, -1 standard deviation). All other variables are mean-centred. Plots were produced with the interactions package (Long, 2019).

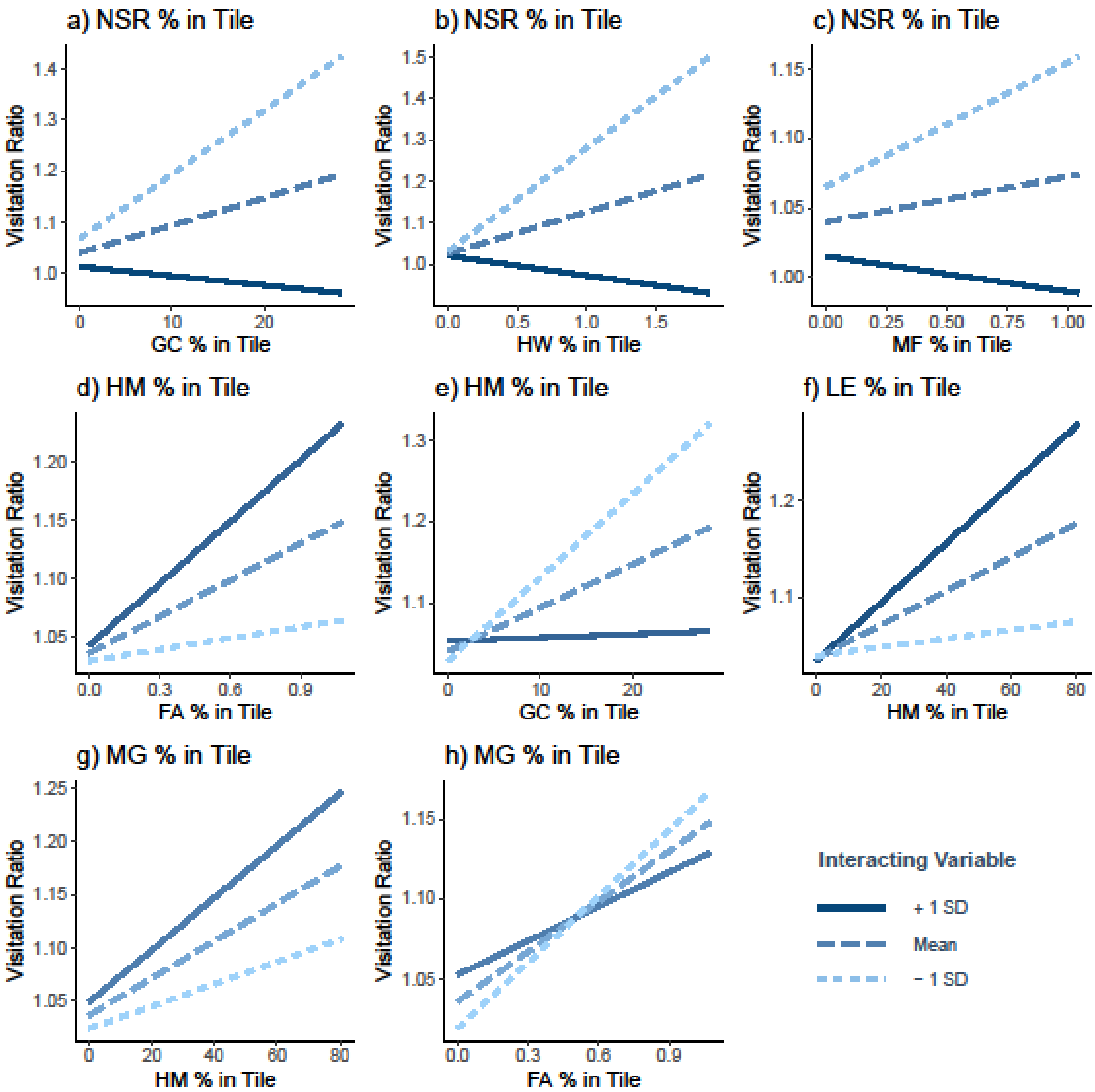

Figure A2.4: Effect plots of variables with significant interactions for ground-nesting bumblebee (GNBB) Visitation Ratio (visitation per tile to target land class (season) with AES features present / visitation per tile to target land class (season) with AES features absent) to OSR (late spring). Explanatory variable for each sub-plot (a – h) shown on x-axis, Moderator variable shown in sub-title. See Table 2 for definitions of all response and explanatory variables. See Table 3 for coefficients.

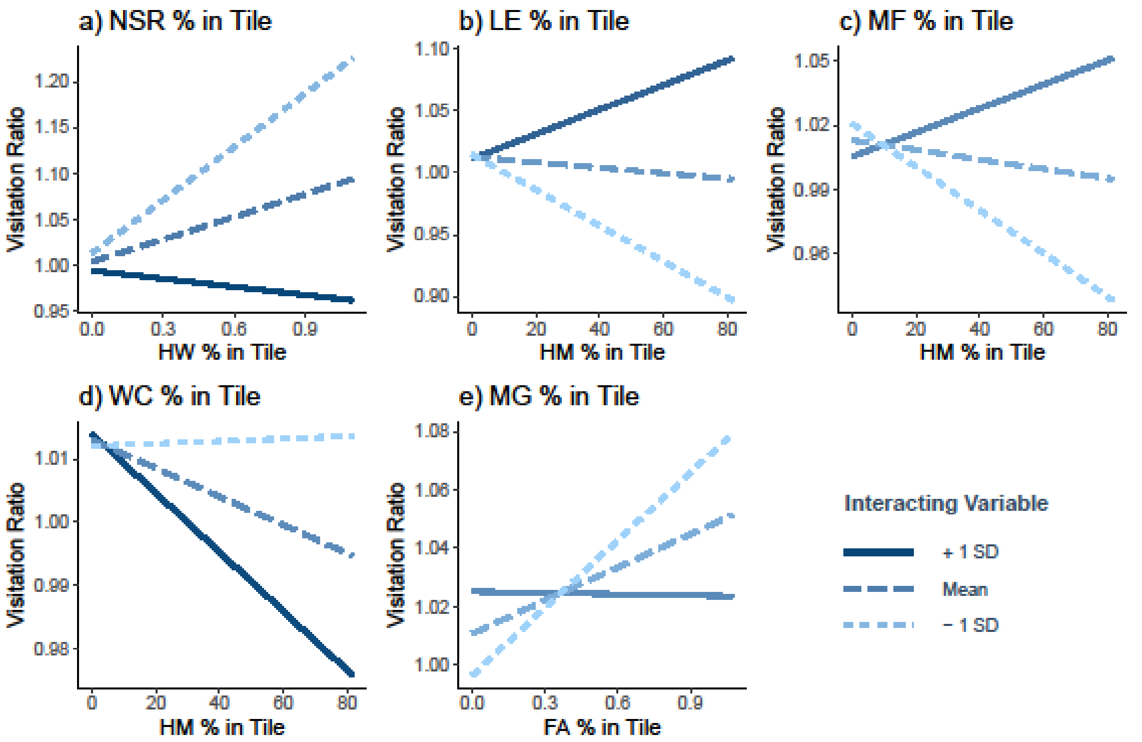

Figure A2.5: Effect plots of variables with significant interactions for ground-nesting bumblebee (GNBB) Visitation Ratio (visitation per tile to target land class (season) with AES features present / visitation per tile to target land class (season) with AES features absent) to Field Beans (late spring). Explanatory variable for each sub-plot (a – g) shown on x-axis, Moderator variable shown in sub-title. See Table 2 for definitions of all response and explanatory variables. See Table 3 for coefficients.

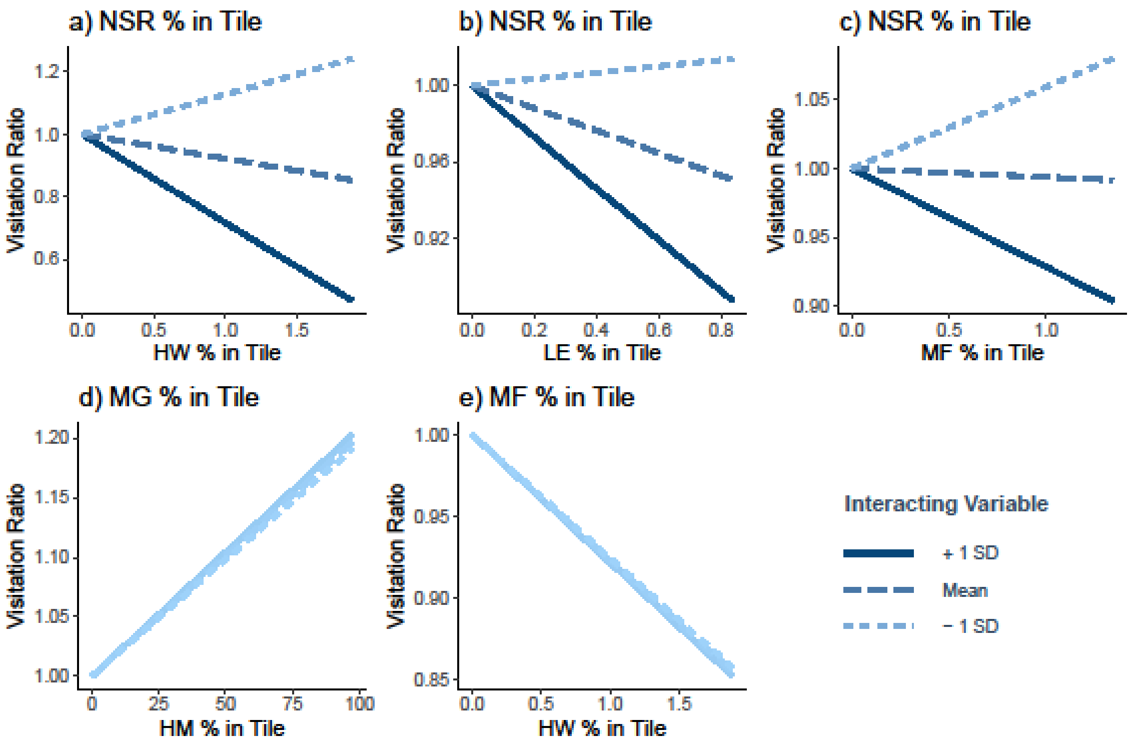

Figure A2.6: Effect plots of variables with significant interactions for ground-nesting bumblebee (GNBB) Visitation Ratio (visitation per tile to target land class (season) with AES features present / visitation per tile to target land class (season) with AES features absent) to Non-crops (all seasons). Explanatory variable for each *sub-plot (a – e) shown on x-axis, Moderator variable shown in sub-title. See Table 2 for definitions of all response and explanatory variables. See Table 3 for coefficients.*

2.5 Variance Inflation Factors

We used the *car* package (Fox and Weisberg, 2019) to calculate variance inflation factors (VIF) for each of our models, removing interactions as these would implicitly have high collinearity (Table A2.6).

Table A2.6: Variance Inflation Factors for ground-nesting bumblebee (GNBB) Visitation Ratio (visitation per tile to target land class (season) with AES features present / visitation per tile to target land class (season) with AES features absent) to OSR (late spring). See Table 3 for coefficients.

Variable	**OSR**	**Field Beans**	**Non-Crop**
Fallow (FA)	1.72	1.82	
Grassland / Heath Creation (GC)	1.03		1.10
Habitat Management (HM)	1.13	1.08	1.26
Hedgerow / Woodland Edge (HW)	1.70	1.73	2.72
Flower-Rich Ley (LE)	1.05	1.07	1.12
Floral Margin (MF)	1.96	2.18	2.63
Grass Margin (MG)	2.43	2.84	3.37
Scrub / Wood Creation (SC)		1.05	1.08
Trad. Orchard Creation (TC)			1.05
Wetland / Coastal Creation (WC)	1.07	1.09	1.14
Non-Scheme Resource (NSR)	1.64		

2.6 Quality / Quantity vs. Regression Coefficients – Other Guilds

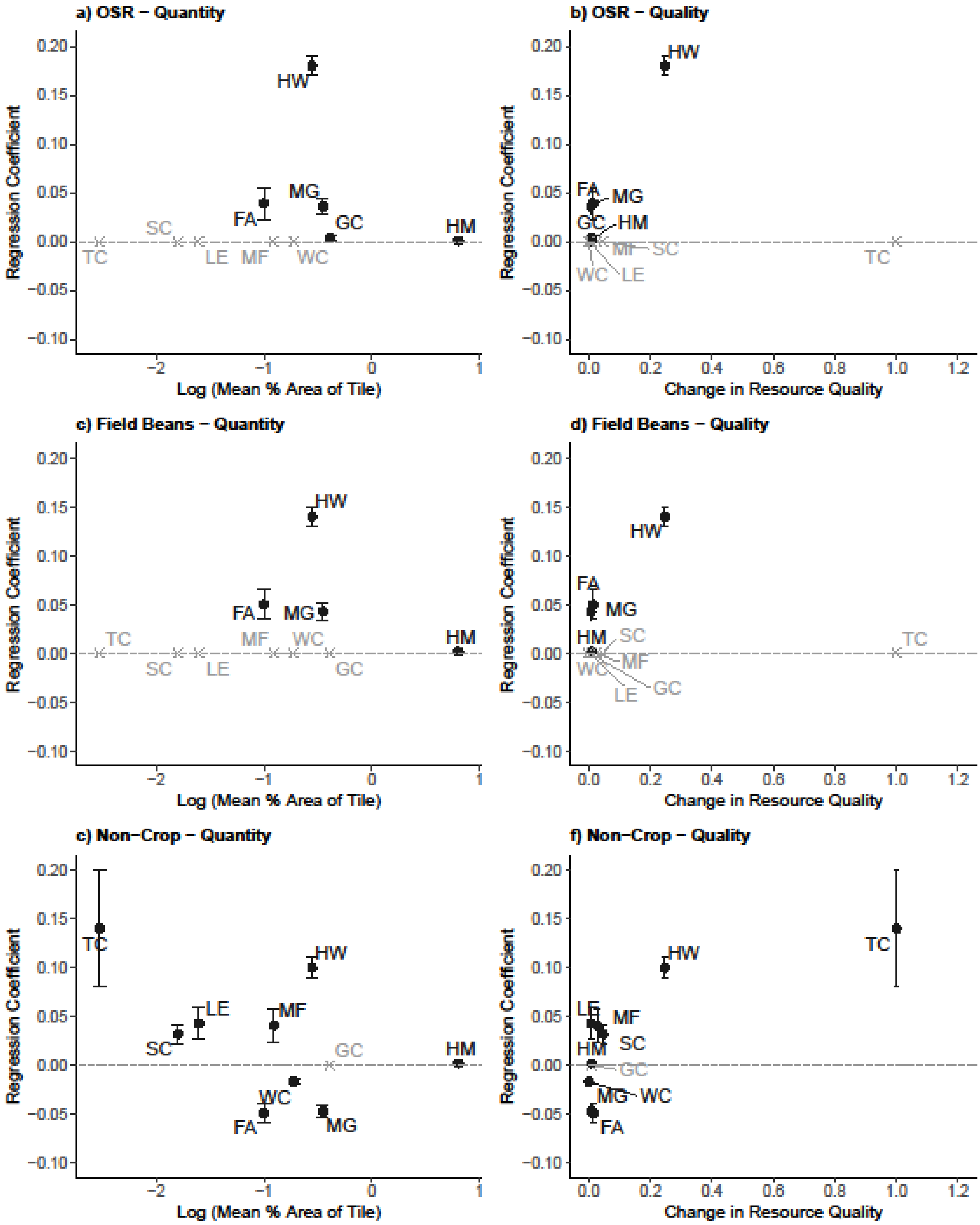

Figure A2.7: Distribution of AES categories within quality-quantity space according to intervention uptake recorded in the year 2016. Change in resource quality is the mean of the normalised change in nesting quality and the normalised change in early spring floral resource quality for tree-nesting bumblebees. Category quantity represents the mean percentage cover of that intervention across all 10km2 tiles. In each panel, the marker colour for each intervention denotes whether its presence significantly influences tree nesting bumblebee visitation to OSR (a), field bean (b) and non-crop landcovers (c), respectively. Labels give the size/direction of the regression coefficient (see Table A2.2).

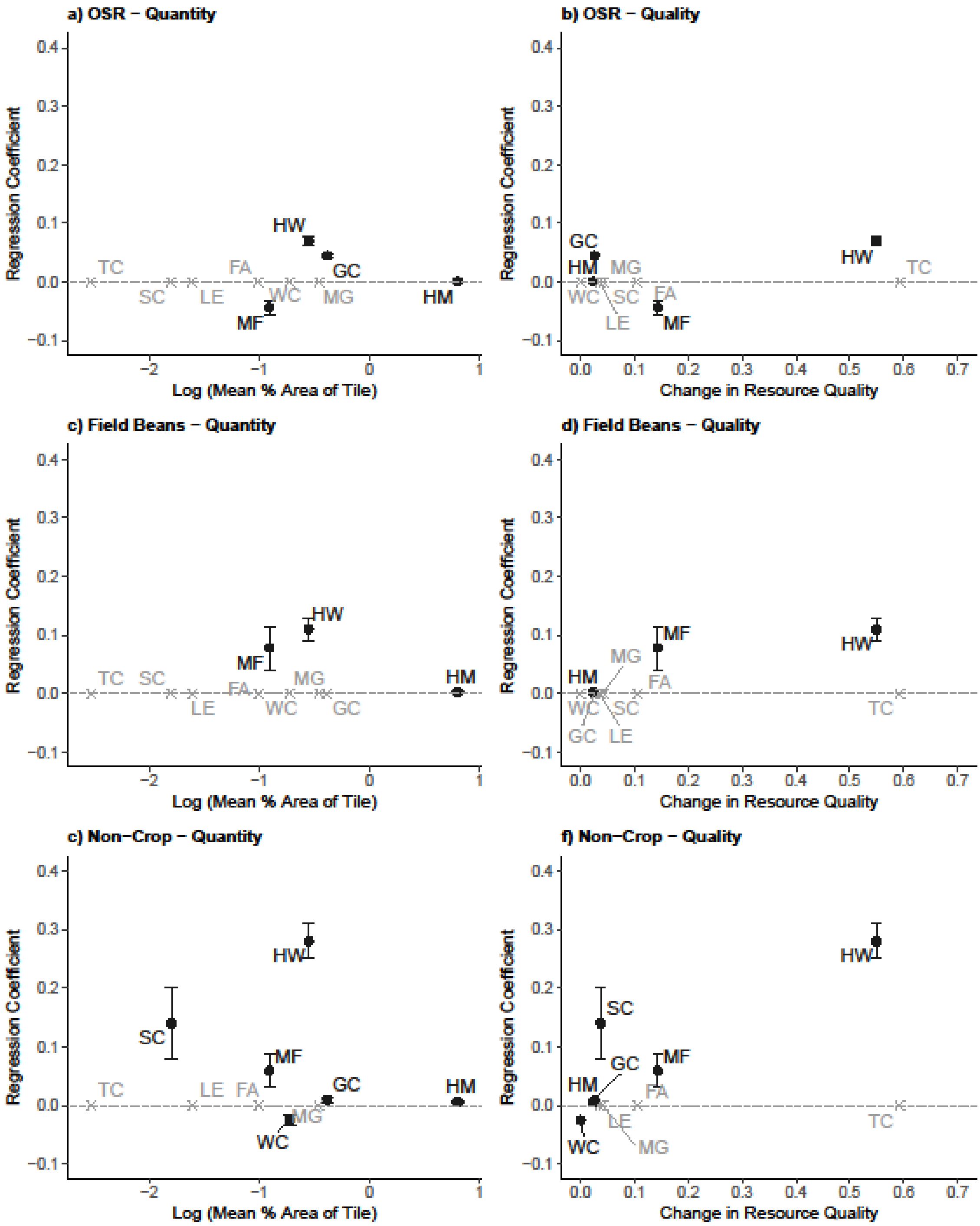

Figure A2.8: Distribution of AES categories within quality-quantity space according to intervention uptake recorded in the year 2016. Change in resource quality is the mean of the normalised change in nesting quality and the normalised change in early spring floral resource quality for ground-nesting solitary bees. Category quantity represents the mean percentage cover of that intervention across all 10km2 tiles. In each panel, the marker colour for each intervention denotes whether its presence significantly influences ground-nesting solitary bee visitation to OSR (a), field bean (b) and non-crop landcovers (c), respectively. Labels give the size/direction of the regression coefficient (see Table A2.3).

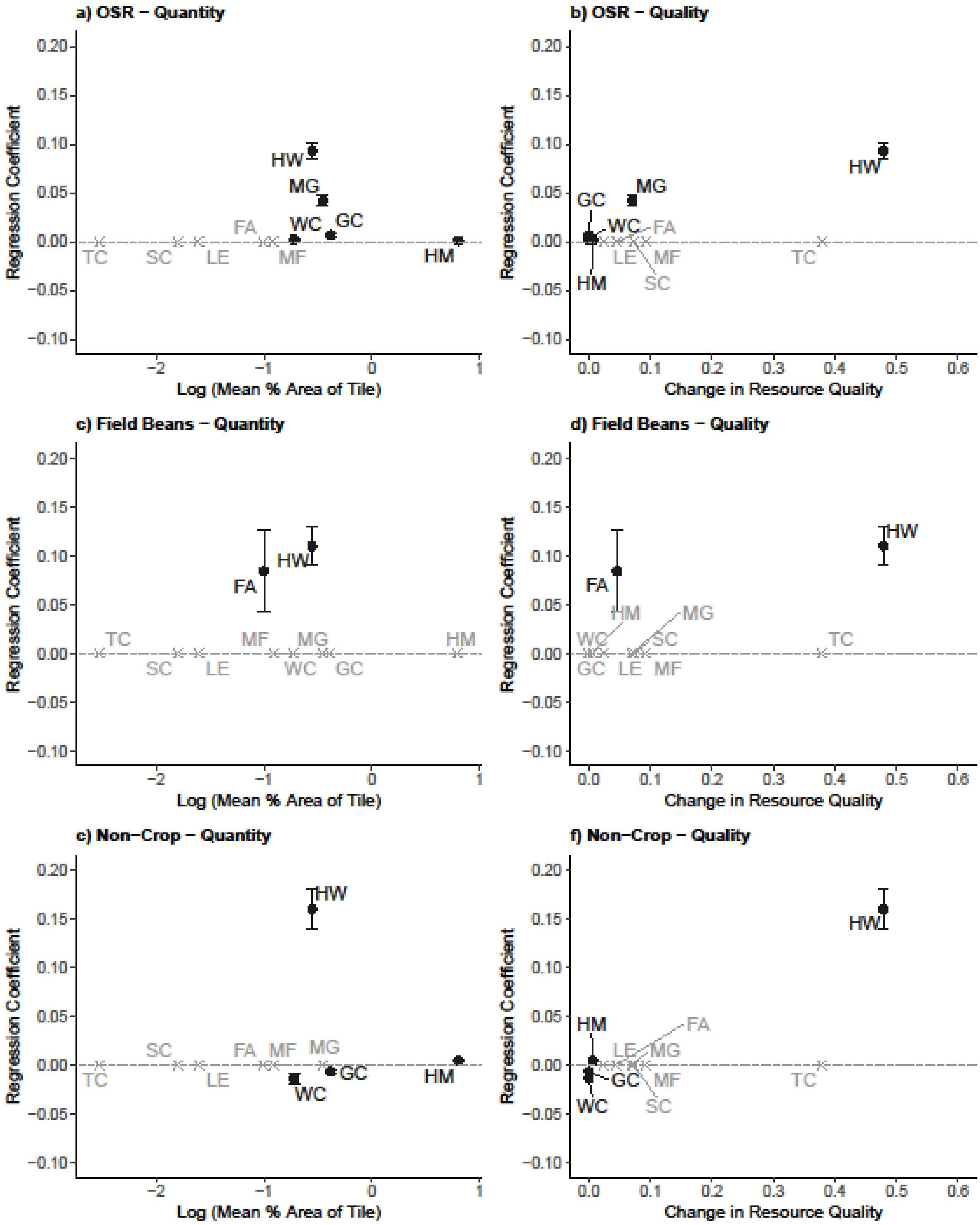

Figure A2.9: Distribution of AES categories within quality-quantity space according to intervention uptake recorded in the year 2016. Change in resource quality is the mean of the normalised change in nesting quality and the normalised change in early spring floral resource quality for cavity-nesting solitary bees. Category quantity represents the mean percentage cover of that intervention across all 10km2 tiles. In each panel, the marker colour for each intervention denotes whether its presence significantly influences cavity-nesting solitary bee visitation to OSR (a), field bean (b) and non-crop landcovers (c), respectively. Labels give the size/direction of the regression coefficient (see Table A2.4).

2.7 Residuals

The linear regression used has a good fit for ground-nesting bumblebees (R^2 = 0.73, 0.68, 0.74 for OSR, field beans and non-crop respectively) but fails to fit extreme values. Tiles with the largest increases in visitation rate likely have internal configurations of AES resource to crop/non-crop feature which are accounted for in the spatially explicit poll4pop model but are not accounted for in the non-spatial regression analysis. Some of the outliers may also be due to Ordnance Survey grid tiling leaving certain tiles in areas of landscape transition with crop/non-crop configurations that are likely to be more sensitive to AES provision in adjacent tiles.

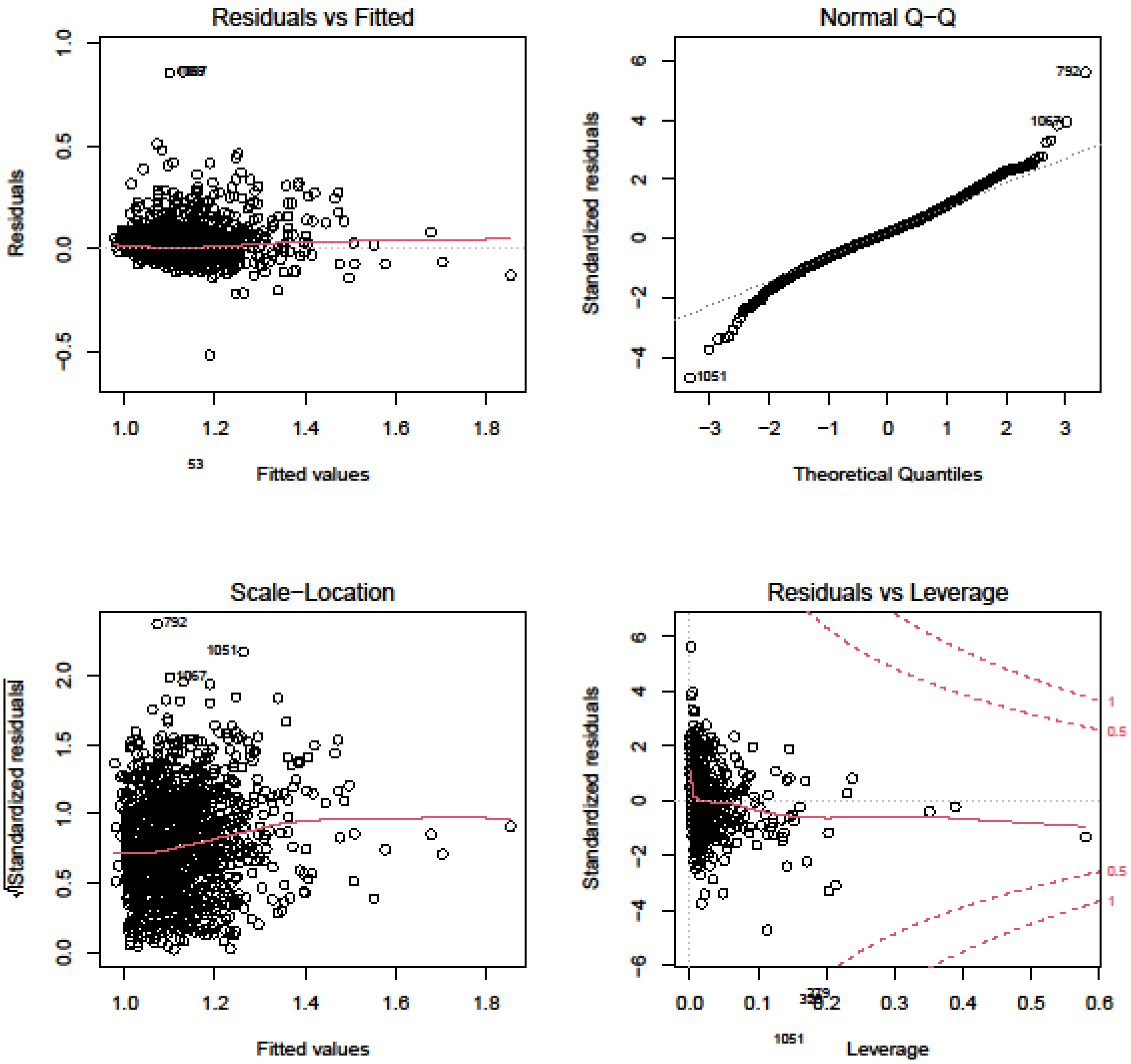

Figure A2.10: Plots of residuals for ground-nesting bumblebee to OSR regression analysis

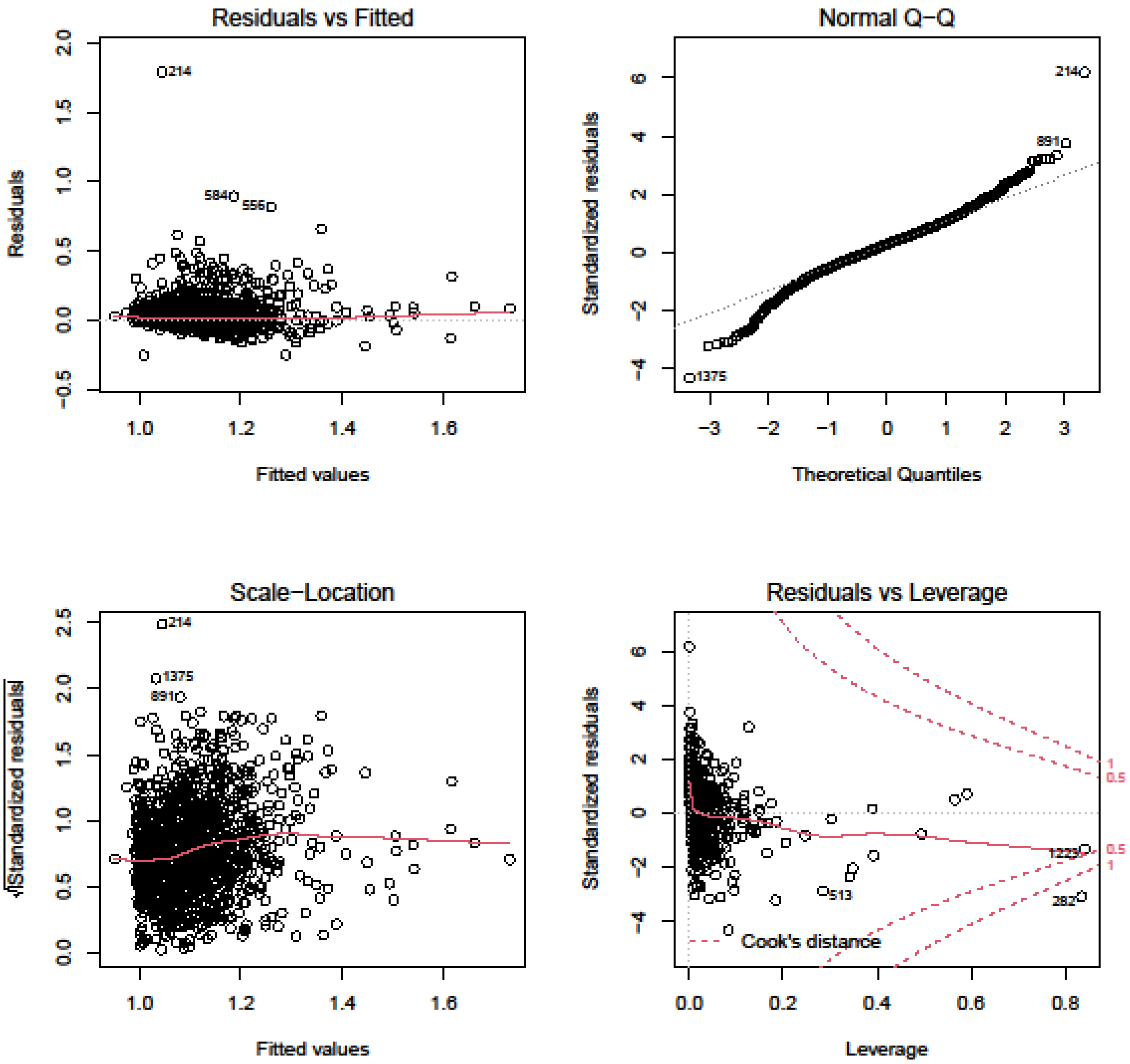

Figure A2.11: Plots of residuals for ground-nesting bumblebee to field beans regression analysis

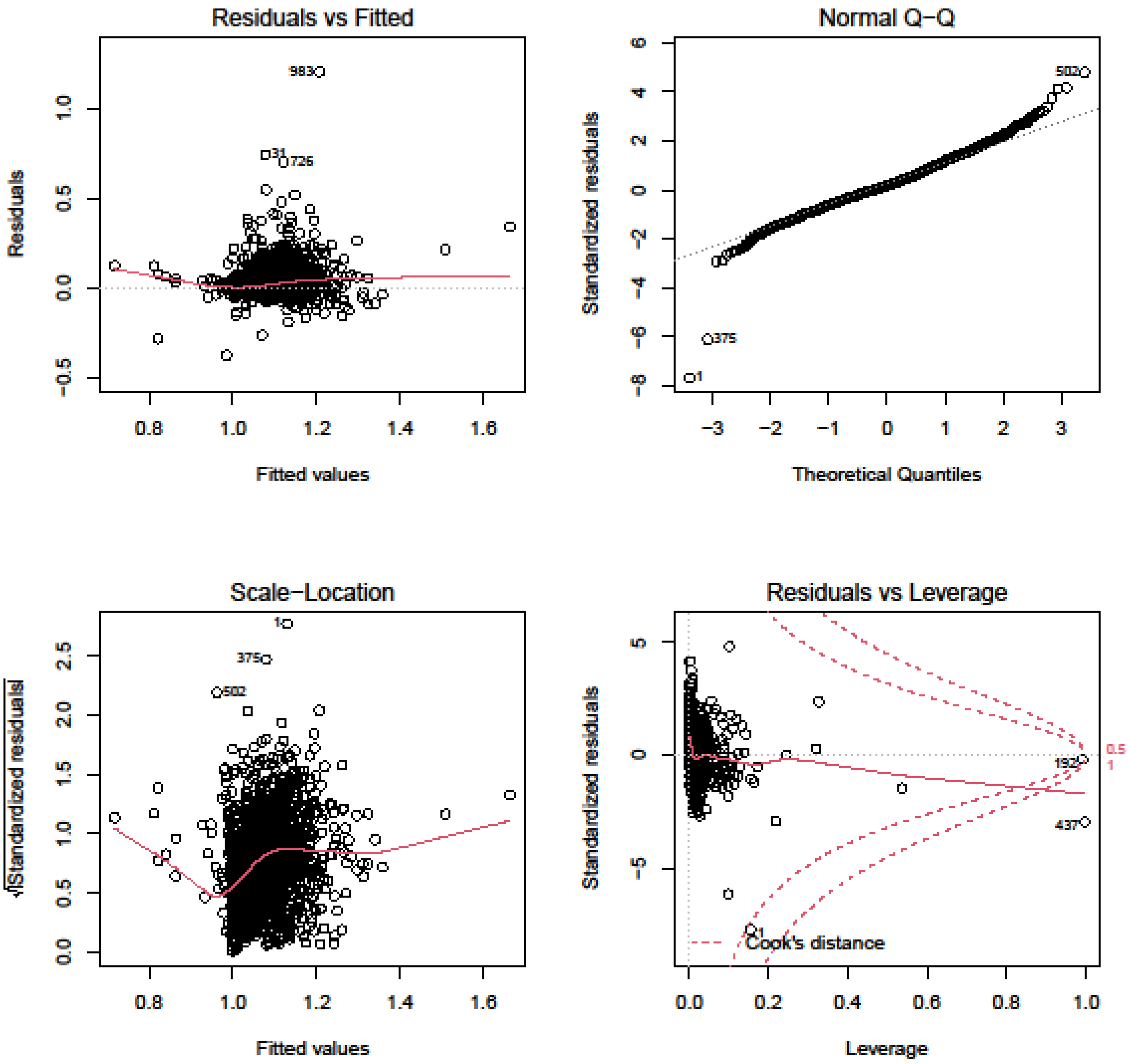

Figure A2.12: Plots of residuals for ground-nesting bumblebee to non-crop regression analysis

There is also spatial autocorrelation in the residuals (*Table A2.7*) which may reflect that tiles with the highest increases in visitation rate are likely to be in the same geographic areas.

Table A2.7: Test results for spatial autocorrelation (Moran's I) in regression residuals

Regression	Moran's I	Expected	P value
Ground-nesting bumblebee – OSR	0.02691	-0.00084	< 0.001
Ground-nesting bumblebee – Field Beans	0.01767	-0.00084	< 0.001
Ground-nesting bumblebee – Non-Crop	0.04533	-0.00067	< 0.001

3 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? Supplementary Material

3.1 Land cover allocation rules

3.1.1 Hedgerows (distributed):

We assumed new hedgerows were placed along existing agricultural land boundaries where there were currently no woody linear features. We assumed there were no land use constraints except that hedgerows would not be created around moorland/heathland parcels.

Algorithm:

1. Create a polyline layer from eligible field boundaries (agricultural land classes, but not moorland) and erase parts that overlay existing woody linear features.
2. Pick a polyline from this layer at random and assign as 'New Hedgerow' in a new layer. Remove from list (so it cannot be selected again). Remember length.
3. Repeat 2 until total length of hedgerow in the new layer > length target. Find a polyline to remove which will bring the total length to be as close to target as possible.

3.1.2 Hedgerows (clustered):

We assumed new hedgerows were placed along existing agricultural land boundaries where there were currently no woody linear features. We assumed there were no land use constraints except that hedgerows would not be created around moorland/heathland parcels. However, the pattern was clustered to represent the result of preferential uptake by certain farms, potentially operating in clusters. Spatially explicit farm boundary data for the study area was not available to us, only regional farm data. So, for each realisation we created 15 to 35 'seed' circles (number chosen randomly within that range) with a radius of 500 m to 1500 m (again chosen randomly within that range) within the tile + buffer area. Where these circles overlapped, they were dissolved to create a continuous shape ('seed area').

The central value of the radius chosen was informed by the mean farm area of ~100 ha in the East Midlands region (corresponding to the study area) in the 2020 June survey (Defra, 2020). This would lead to have a radius of ~500 m if represented as a circle so we used this as a minimum value (i.e., the smallest seed area should be at least the size of one average farm). The upper limit (1500 m) was set arbitrarily to prevent seed areas becoming so large that, if the number of seeds was also high, there would be no true clustering. The lower limit of seed area number was set to reflect a minimum percentage of farms becoming the central point of a cluster (15 is approximately equivalent to 5% of farms assuming mean farm area of ~100 ha and agricultural land area of ~30,000 ha in the tile + buffer). The upper limit (35) was set arbitrarily to prevent seed numbers becoming so large that, if the area of seeds was also high, there would be no true clustering. The draw between the seed number and radius bounds was uniform as we had no prior knowledge of likely cluster numbers or areas.

Algorithm:

1. Create a polyline layer from eligible field boundaries (agricultural land classes, but not moorland) and erase parts that overlay existing woody linear features.
2. Create a target areas layer or circular polygons located randomly in the tile + buffer and which are dissolved if they overlap. The number of circular polygons is drawn randomly from a uniform distribution between 15 and 35 inclusive. The radius of each policy is drawn randomly from a uniform distribution between 500 m and 1500 m.
3. Determine distance of each eligible polyline to the target areas layer (some will be within)
4. Pick a polyline from this layer with weighted probability of selection proportionate to inverse distance from the target areas layer (features within the target layer are given a small distance (0.001) to avoid division by zero and ensure that they are more likely to be selected) and assign as 'New Hedgerow' in a new layer. Remove from list (so it cannot be selected again). Remember length.
5. Repeat 2 until total length of hedgerow in the new layer > length target. Find a polyline to remove which will bring the total length to be as close to target as possible.

3.1.3 Agro-Forestry (all scenarios):

We assumed that agroforestry replaces existing crop with crop + trees in a north-south alley configuration where crop occupies 80% and trees 20%. To ensure that the visitation of the crop and tree components within a field can be accurately differentiated in the raster, we represented the alley system more coarsely (120m crop, 30m tree). We assumed only cereal, OSR and field bean parcels were eligible. We assume that the rows for poplar and fruit tree scenarios were created in the same place so that only difference between the scenarios is the land class.

Algorithm:

1. Create a polygon layer from eligible fields
2. Pick a polygon from this layer at random. Working from W to E, ignore the first 120m, then clip the polygon for the next 30m and assign to 'Agroforestry – Fruit Trees' in a new layer. Ignore

the next 120m, and so on until the easternmost point of the polygon has been reached. Remember the area of trees assigned.

3. Repeat 2 for more eligible polygons until the area target has been exceeded.
4. Find new tree polygons to remove to bring the area of trees created to as close to the target as possible.
5. Copy the new polygon layer and assign to 'Agroforestry – Poplar', Agroforestry - Willow)

3.1.4 Woodland

We assumed that woodland was created in contiguous patches ('projects') of equal area as close to but not exceeding the typical size of a project registered to the Woodland Carbon Code for England over the past 5 years (20 ha; Forest Research 2020). We also assumed that each project contains a mix of deciduous and coniferous woodland in the ratio of observed new planting over the past 5 years (86% / 14%). Eligible land was all arable + improved grassland that is Agricultural Land Classification (ALC) Grade 3, 4 or 5 and not on peat soils (arable / grassland in existing AES was also excluded). For simplicity we did not search for historic environment designations, nor did we buffer habitat designations.

Algorithm:

1. Create a polygon layer from eligible fields
2. Randomly select 4 seed polygons from which to build each project. These must be >1ha but less than 86% of project area (deciduous target) and must have sufficient eligible polygons within 500m to create a (mostly) contiguous block of at least the project area target. Assign these as New Deciduous Woodland.
3. Starting with the first of these seed polygons, assign the nearest eligible polygon to deciduous woodland unless this would cause the deciduous target to be exceeded. In which case clip the polygon so that only sufficient area is allocated and stop allocating. Repeat until deciduous target is met (making sure that these polygons cannot be reallocated).
4. Repeat 3 but assigning next nearest polygons from the remaining unallocated to coniferous woodland until the coniferous target is reached.
5. Repeat 3 and 4 for the remaining three seed polygons
6. Create a woodland edge polyline surrounding each project

3.2 Additional Result Tables

Table A3.1: Analysis of Variance results for nest density (R - total number of nests as a fraction of the number predicted with no AES interventions or tree planting present) between tree planting scenarios and baseline. Assessed separately for GNBB - ground-nesting bumblebees and TNBB – tree-nesting bumblebees and at low and high planting intensity.

Species	Intensity	F	DF	P
GNBB	Low	6.80 ***	6	< 0.001
GNBB	High	37.69 ***	6	< 0.001
TNBB	Low	27.11 ***	6	< 0.001
TNBB	High	120.19 ***	6	< 0.001

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.2: Post-hoc Tukey test for relative change in ground-nesting bumblebee nest density (R - total number of nests as a fraction of the number predicted with no AES interventions or tree planting present) between tree planting scenarios and baseline at low planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.005	-0.003	0.012	0.635	ns
Baseline	AF_Poplar	0.001	-0.007	0.009	1.000	ns
Baseline	AF_Willow	0.001	-0.007	0.009	1.000	ns
Baseline	Hedgerow_Clus	0.012	0.004	0.020	<0.001	***
Baseline	Hedgerow_Dist	0.012	0.004	0.020	<0.001	***
Baseline	Woodland	0.007	-0.001	0.015	0.124	ns
AF_Fruit	AF_Poplar	-0.003	-0.011	0.005	0.871	ns
AF_Fruit	AF_Willow	-0.003	-0.011	0.004	0.856	ns
AF_Fruit	Hedgerow_Clus	0.007	-0.001	0.015	0.099	ns
AF_Fruit	Hedgerow_Dist	0.007	-0.001	0.015	0.128	ns
AF_Fruit	Woodland	0.003	-0.005	0.011	0.966	ns
AF_Poplar	AF_Willow	0.000	-0.008	0.008	1.000	ns
AF_Poplar	Hedgerow_Clus	0.011	0.003	0.019	0.002	**
AF_Poplar	Hedgerow_Dist	0.010	0.002	0.018	0.002	**
AF_Poplar	Woodland	0.006	-0.002	0.014	0.299	ns
AF_Willow	Hedgerow_Clus	0.011	0.003	0.019	0.001	**
AF_Willow	Hedgerow_Dist	0.010	0.003	0.018	0.002	**
AF_Willow	Woodland	0.006	-0.002	0.014	0.281	ns
Hedgerow_Clus	Hedgerow_Dist	0.000	-0.008	0.008	1.000	ns
Hedgerow_Clus	Woodland	-0.005	-0.013	0.003	0.573	ns
Hedgerow_Dist	Woodland	-0.004	-0.012	0.004	0.644	ns

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.3: Post-hoc Tukey test for relative change in ground-nesting bumblebee nest density (R - total number of nests as a fraction of the number predicted with no AES interventions or tree planting present) between tree planting scenarios and baseline (AES_Present) at high planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.014	0.005	0.023	0.000	***
Baseline	AF_Poplar	0.004	-0.005	0.012	0.889	ns
Baseline	AF_Willow	0.003	-0.005	0.012	0.925	ns
Baseline	Hedgerow_Clus	0.030	0.021	0.038	<0.001	***
Baseline	Hedgerow_Dist	0.032	0.023	0.041	<0.001	***
Baseline	Woodland	0.018	0.009	0.027	<0.001	***
AF_Fruit	AF_Poplar	-0.010	-0.019	-0.001	0.012	*
AF_Fruit	AF_Willow	-0.011	-0.019	-0.002	0.008	**
AF_Fruit	Hedgerow_Clus	0.016	0.007	0.025	<0.001	***
AF_Fruit	Hedgerow_Dist	0.018	0.009	0.027	<0.001	***
AF_Fruit	Woodland	0.004	-0.004	0.013	0.764	ns
AF_Poplar	AF_Willow	0.000	-0.009	0.009	1.000	ns
AF_Poplar	Hedgerow_Clus	0.026	0.017	0.035	<0.001	***
AF_Poplar	Hedgerow_Dist	0.028	0.020	0.037	<0.001	***
AF_Poplar	Woodland	0.015	0.006	0.023	<0.001	***
AF_Willow	Hedgerow_Clus	0.026	0.017	0.035	<0.001	***
AF_Willow	Hedgerow_Dist	0.029	0.020	0.038	<0.001	***
AF_Willow	Woodland	0.015	0.006	0.024	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.003	-0.006	0.011	0.980	ns
Hedgerow_Clus	Woodland	-0.011	-0.020	-0.003	0.003	**
Hedgerow_Dist	Woodland	-0.014	-0.023	-0.005	<0.001	***

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.4: Post-hoc Tukey test for relative change in tree-nesting bumblebee nest density (R - total number of nests as a fraction of the number predicted with no AES interventions or tree planting present) between tree planting scenarios and baseline at low planting intensity.

Scenario 1	**Scenario 2**	**Estimate**	**Conf.Low**	**Conf.High**	**P.Adj**	**Signif.**
Baseline	AF_Fruit	0.010	0.004	0.016	<0.001	***
Baseline	AF_Poplar	0.000	-0.006	0.006	1.000	ns
Baseline	AF_Willow	0.000	-0.006	0.006	1.000	ns
Baseline	Hedgerow_Clus	0.004	-0.002	0.010	0.402	ns
Baseline	Hedgerow_Dist	0.004	-0.002	0.010	0.400	ns
Baseline	Woodland	0.020	0.014	0.026	<0.001	***
AF_Fruit	AF_Poplar	-0.010	-0.016	-0.004	<0.001	***
AF_Fruit	AF_Willow	-0.009	-0.015	-0.004	<0.001	***
AF_Fruit	Hedgerow_Clus	-0.006	-0.012	0.000	0.060	ns
AF_Fruit	Hedgerow_Dist	-0.006	-0.012	0.000	0.061	ns
AF_Fruit	Woodland	0.010	0.004	0.016	<0.001	***
AF_Poplar	AF_Willow	0.000	-0.006	0.006	1.000	ns
AF_Poplar	Hedgerow_Clus	0.004	-0.002	0.010	0.415	ns
AF_Poplar	Hedgerow_Dist	0.004	-0.002	0.010	0.413	ns
AF_Poplar	Woodland	0.020	0.014	0.026	<0.001	***
AF_Willow	Hedgerow_Clus	0.004	-0.002	0.010	0.520	ns
AF_Willow	Hedgerow_Dist	0.004	-0.002	0.010	0.518	ns
AF_Willow	Woodland	0.020	0.014	0.026	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.000	-0.006	0.006	1.000	ns
Hedgerow_Clus	Woodland	0.016	0.010	0.022	<0.001	***
Hedgerow_Dist	Woodland	0.016	0.010	0.022	<0.001	***

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.5: Post-hoc Tukey test for relative change in tree-nesting bumblebee nest density (R - total number of nests as a fraction of the number predicted with no AES interventions or tree planting present) between tree planting scenarios and baseline (AES_Present) at high planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.031	0.023	0.039	<0.001	***
Baseline	AF_Poplar	0.000	-0.008	0.008	1.000	ns
Baseline	AF_Willow	0.001	-0.007	0.009	0.999	ns
Baseline	Hedgerow_Clus	0.010	0.002	0.018	0.002	**
Baseline	Hedgerow_Dist	0.011	0.003	0.019	<0.001	***
Baseline	Woodland	0.053	0.046	0.061	<0.001	***
AF_Fruit	AF_Poplar	-0.031	-0.039	-0.023	<0.001	***
AF_Fruit	AF_Willow	-0.030	-0.038	-0.022	<0.001	***
AF_Fruit	Hedgerow_Clus	-0.021	-0.029	-0.013	<0.001	***
AF_Fruit	Hedgerow_Dist	-0.020	-0.028	-0.012	<0.001	***
AF_Fruit	Woodland	0.022	0.015	0.030	<0.001	***
AF_Poplar	AF_Willow	0.001	-0.007	0.009	1.000	ns
AF_Poplar	Hedgerow_Clus	0.010	0.002	0.018	0.003	**
AF_Poplar	Hedgerow_Dist	0.011	0.003	0.019	0.001	**
AF_Poplar	Woodland	0.053	0.046	0.061	<0.001	***
AF_Willow	Hedgerow_Clus	0.009	0.001	0.016	0.012	*
AF_Willow	Hedgerow_Dist	0.010	0.002	0.018	0.003	**
AF_Willow	Woodland	0.052	0.045	0.060	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.001	-0.007	0.009	1.000	ns
Hedgerow_Clus	Woodland	0.043	0.036	0.051	<0.001	***
Hedgerow_Dist	Woodland	0.042	0.035	0.050	<0.001	***

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Table A3.6: Analysis of Variance results for queen production (Q - number of new reproductive females as a fraction of the number predicted with no AES interventions or tree planting present) between tree planting scenarios and baseline. Assessed separately for GNBB - ground-nesting bumblebees and TNBB – tree-nesting bumblebees and at low and high planting intensity.

Species	Intensity	F	DF	P
GNBB	Low	6.25 ***	6	< 0.001
GNBB	High	25.91 ***	6	< 0.001
TNBB	Low	19.46 ***	6	< 0.001
TNBB	High	84.11 ***	6	< 0.001

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.7: Post-hoc Tukey test for relative change in ground-nesting bumblebee queen production (Q - number of new reproductive females as a fraction of the number predicted with no AES interventions or tree planting present) between tree planting scenarios and baseline at low planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.016	-0.002	0.034	0.135	ns
Baseline	AF_Poplar	0.004	-0.014	0.022	0.993	ns
Baseline	AF_Willow	0.013	-0.006	0.031	0.392	ns
Baseline	Hedgerow_Clus	0.029	0.010	0.047	<0.001	***
Baseline	Hedgerow_Dist	0.028	0.010	0.046	<0.001	***
Baseline	Woodland	0.012	-0.006	0.031	0.414	ns
AF_Fruit	AF_Poplar	-0.012	-0.030	0.007	0.492	ns
AF_Fruit	AF_Willow	-0.003	-0.022	0.015	0.998	ns
AF_Fruit	Hedgerow_Clus	0.013	-0.005	0.031	0.369	ns
AF_Fruit	Hedgerow_Dist	0.012	-0.006	0.030	0.419	ns
AF_Fruit	Woodland	-0.004	-0.022	0.015	0.998	ns
AF_Poplar	AF_Willow	0.008	-0.010	0.026	0.830	ns
AF_Poplar	Hedgerow_Clus	0.024	0.006	0.043	0.002	**
AF_Poplar	Hedgerow_Dist	0.024	0.006	0.042	0.002	**
AF_Poplar	Woodland	0.008	-0.010	0.026	0.847	ns
AF_Willow	Hedgerow_Clus	0.016	-0.002	0.034	0.124	ns
AF_Willow	Hedgerow_Dist	0.016	-0.003	0.034	0.149	ns
AF_Willow	Woodland	0.000	-0.018	0.018	1.000	ns
Hedgerow_Clus	Hedgerow_Dist	0.000	-0.019	0.018	1.000	ns
Hedgerow_Clus	Woodland	-0.016	-0.035	0.002	0.114	ns
Hedgerow_Dist	Woodland	-0.016	-0.034	0.002	0.138	ns

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.8: Post-hoc Tukey test for relative change in ground-nesting bumblebee queen production (Q - number of new reproductive females as a fraction of the number predicted with no AES interventions or tree planting present) between tree planting scenarios and baseline at high planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.051	0.028	0.074	0.000	***
Baseline	AF_Poplar	0.014	-0.009	0.037	0.554	ns
Baseline	AF_Willow	0.040	0.017	0.063	<0.001	***
Baseline	Hedgerow_Clus	0.072	0.048	0.095	<0.001	***
Baseline	Hedgerow_Dist	0.077	0.054	0.100	<0.001	***
Baseline	Woodland	0.033	0.010	0.056	0.001	**
AF_Fruit	AF_Poplar	-0.037	-0.060	-0.013	<0.001	***
AF_Fruit	AF_Willow	-0.011	-0.034	0.013	0.819	ns
AF_Fruit	Hedgerow_Clus	0.021	-0.002	0.044	0.114	ns
AF_Fruit	Hedgerow_Dist	0.026	0.003	0.050	0.015	*
AF_Fruit	Woodland	-0.018	-0.041	0.005	0.249	ns
AF_Poplar	AF_Willow	0.026	0.003	0.049	0.017	*
AF_Poplar	Hedgerow_Clus	0.058	0.034	0.081	<0.001	***
AF_Poplar	Hedgerow_Dist	0.063	0.040	0.086	<0.001	***
AF_Poplar	Woodland	0.019	-0.005	0.042	0.211	ns
AF_Willow	Hedgerow_Clus	0.032	0.008	0.055	0.001	**
AF_Willow	Hedgerow_Dist	0.037	0.014	0.060	<0.001	***
AF_Willow	Woodland	-0.007	-0.031	0.016	0.968	ns
Hedgerow_Clus	Hedgerow_Dist	0.005	-0.018	0.029	0.993	ns
Hedgerow_Clus	Woodland	-0.039	-0.062	-0.016	<0.001	***
Hedgerow_Dist	Woodland	-0.044	-0.068	-0.021	<0.001	***

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.9: Post-hoc Tukey test for relative change in tree-nesting bumblebee queen production (Q - number of new reproductive females as a fraction of the number predicted with no AES interventions or tree planting present) between tree planting scenarios and baseline at low planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.013	0.005	0.020	<0.001	***
Baseline	AF_Poplar	0.000	-0.008	0.007	1.000	ns
Baseline	AF_Willow	0.004	-0.004	0.012	0.695	ns
Baseline	Hedgerow_Clus	0.010	0.002	0.018	0.002	**
Baseline	Hedgerow_Dist	0.010	0.002	0.018	0.002	**
Baseline	Woodland	0.022	0.015	0.030	<0.001	***
AF_Fruit	AF_Poplar	-0.013	-0.021	-0.006	<0.001	***
AF_Fruit	AF_Willow	-0.009	-0.016	-0.001	0.012	*
AF_Fruit	Hedgerow_Clus	-0.003	-0.010	0.005	0.939	ns
AF_Fruit	Hedgerow_Dist	-0.003	-0.010	0.005	0.928	ns
AF_Fruit	Woodland	0.010	0.002	0.017	0.004	**
AF_Poplar	AF_Willow	0.004	-0.003	0.012	0.617	ns
AF_Poplar	Hedgerow_Clus	0.010	0.003	0.018	0.001	**
AF_Poplar	Hedgerow_Dist	0.010	0.003	0.018	0.001	**
AF_Poplar	Woodland	0.023	0.015	0.030	<0.001	***
AF_Willow	Hedgerow_Clus	0.006	-0.002	0.014	0.224	ns
AF_Willow	Hedgerow_Dist	0.006	-0.002	0.014	0.242	ns
AF_Willow	Woodland	0.018	0.011	0.026	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.000	-0.008	0.007	1.000	ns
Hedgerow_Clus	Woodland	0.012	0.005	0.020	<0.001	***
Hedgerow_Dist	Woodland	0.012	0.005	0.020	<0.001	***

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.10: Post-hoc Tukey test for relative change in tree-nesting bumblebee queen production (Q - number of new reproductive females as a fraction of the number predicted with no AES interventions or tree planting present) between tree planting scenarios and baseline at high planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.041	0.031	0.051	<0.001	***
Baseline	AF_Poplar	-0.001	-0.011	0.010	1.000	ns
Baseline	AF_Willow	0.013	0.003	0.023	0.003	**
Baseline	Hedgerow_Clus	0.024	0.014	0.034	<0.001	***
Baseline	Hedgerow_Dist	0.027	0.017	0.037	<0.001	***
Baseline	Woodland	0.060	0.050	0.071	<0.001	***
AF_Fruit	AF_Poplar	-0.042	-0.052	-0.032	<0.001	***
AF_Fruit	AF_Willow	-0.028	-0.038	-0.018	<0.001	***
AF_Fruit	Hedgerow_Clus	-0.017	-0.027	-0.007	<0.001	***
AF_Fruit	Hedgerow_Dist	-0.014	-0.024	-0.004	0.001	**
AF_Fruit	Woodland	0.019	0.009	0.029	<0.001	***
AF_Poplar	AF_Willow	0.014	0.003	0.024	0.002	**
AF_Poplar	Hedgerow_Clus	0.025	0.015	0.035	<0.001	***
AF_Poplar	Hedgerow_Dist	0.027	0.017	0.038	<0.001	***
AF_Poplar	Woodland	0.061	0.051	0.071	<0.001	***
AF_Willow	Hedgerow_Clus	0.011	0.001	0.021	0.018	*
AF_Willow	Hedgerow_Dist	0.014	0.004	0.024	0.001	**
AF_Willow	Woodland	0.047	0.037	0.058	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.003	-0.007	0.013	0.986	ns
Hedgerow_Clus	Woodland	0.036	0.026	0.046	<0.001	***
Hedgerow_Dist	Woodland	0.034	0.023	0.044	<0.001	***

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.11: Analysis of Variance results for worker production (W - total number of new worker bees produced as a fraction of the number produced with no AES interventions or tree planting present) between tree planting scenarios and baseline. Assessed separately for GNBB - ground-nesting bumblebees and TNBB – tree-nesting bumblebees; by season produced (foraging in the subsequent season); and at low and high planting intensity.

Species	Season	Intensity	F	DF	P
GNBB	Early Spring	Low	13.31 ***	6	< 0.001
GNBB	Early Spring	High	57.76 ***	6	< 0.001
TNBB	Early Spring	Low	26.59 ***	6	< 0.001
TNBB	Early Spring	High	95.67 ***	6	< 0.001
GNBB	Late Spring	Low	9.49 ***	6	< 0.001
GNBB	Late Spring	High	34.93 ***	6	< 0.001
TNBB	Late Spring	Low	27.84 ***	6	< 0.001
TNBB	Late Spring	High	106.02 ***	6	< 0.001

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.12: Post-hoc Tukey test for relative change in ground-nesting bumblebee worker production (W - total number of new worker bees produced as a fraction of the number produced with no AES interventions or tree planting present) between tree planting scenarios and baseline for early spring (foraging in late spring) at low planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.034	0.016	0.053	<0.001	***
Baseline	AF_Poplar	0.011	-0.007	0.029	0.572	ns
Baseline	AF_Willow	0.037	0.019	0.055	<0.001	***
Baseline	Hedgerow_Clus	0.038	0.020	0.057	<0.001	***
Baseline	Hedgerow_Dist	0.037	0.019	0.055	<0.001	***
Baseline	Woodland	0.013	-0.006	0.031	0.387	ns
AF_Fruit	AF_Poplar	-0.024	-0.042	-0.005	0.003	**
AF_Fruit	AF_Willow	0.002	-0.016	0.021	1.000	ns
AF_Fruit	Hedgerow_Clus	0.004	-0.014	0.022	0.995	ns
AF_Fruit	Hedgerow_Dist	0.003	-0.016	0.021	1.000	ns
AF_Fruit	Woodland	-0.022	-0.040	-0.004	0.008	**
AF_Poplar	AF_Willow	0.026	0.008	0.044	<0.001	***
AF_Poplar	Hedgerow_Clus	0.028	0.009	0.046	<0.001	***
AF_Poplar	Hedgerow_Dist	0.026	0.008	0.044	<0.001	***
AF_Poplar	Woodland	0.002	-0.017	0.020	1.000	ns
AF_Willow	Hedgerow_Clus	0.002	-0.017	0.020	1.000	ns
AF_Willow	Hedgerow_Dist	0.000	-0.018	0.019	1.000	ns
AF_Willow	Woodland	-0.024	-0.042	-0.006	0.002	**
Hedgerow_Clus	Hedgerow_Dist	-0.001	-0.020	0.017	1.000	ns
Hedgerow_Clus	Woodland	-0.026	-0.044	-0.008	<0.001	***
Hedgerow_Dist	Woodland	-0.024	-0.043	-0.006	0.002	**

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.13: Post-hoc Tukey test for relative change in ground-nesting bumblebee worker production (W - total number of new worker bees produced as a fraction of the number produced with no AES interventions or tree planting present) between tree planting scenarios and baseline for early spring (foraging in late spring) at high planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.114	0.087	0.140	<0.001	***
Baseline	AF_Poplar	0.035	0.009	0.062	0.002	**
Baseline	AF_Willow	0.123	0.096	0.149	<0.001	***
Baseline	Hedgerow_Clus	0.099	0.073	0.126	<0.001	***
Baseline	Hedgerow_Dist	0.107	0.080	0.133	<0.001	***
Baseline	Woodland	0.037	0.011	0.064	<0.001	***
AF_Fruit	AF_Poplar	-0.079	-0.105	-0.052	<0.001	***
AF_Fruit	AF_Willow	0.009	-0.018	0.035	0.960	ns
AF_Fruit	Hedgerow_Clus	-0.014	-0.041	0.012	0.680	ns
AF_Fruit	Hedgerow_Dist	-0.007	-0.034	0.019	0.986	ns
AF_Fruit	Woodland	-0.077	-0.103	-0.050	<0.001	***
AF_Poplar	AF_Willow	0.087	0.061	0.114	<0.001	***
AF_Poplar	Hedgerow_Clus	0.064	0.038	0.091	<0.001	***
AF_Poplar	Hedgerow_Dist	0.071	0.045	0.098	<0.001	***
AF_Poplar	Woodland	0.002	-0.025	0.029	1.000	ns
AF_Willow	Hedgerow_Clus	-0.023	-0.050	0.003	0.134	ns
AF_Willow	Hedgerow_Dist	-0.016	-0.042	0.011	0.574	ns
AF_Willow	Woodland	-0.085	-0.112	-0.059	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.007	-0.019	0.034	0.983	ns
Hedgerow_Clus	Woodland	-0.062	-0.089	-0.036	<0.001	***
Hedgerow_Dist	Woodland	-0.069	-0.096	-0.043	<0.001	***

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.14: Post-hoc Tukey test for relative change in tree-nesting bumblebee worker production (W - total number of new worker bees produced as a fraction of the number produced with no AES interventions or tree planting present) between tree planting scenarios and baseline for early spring (foraging in late spring) at low planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.027	0.018	0.036	<0.001	***
Baseline	AF_Poplar	0.000	-0.010	0.009	1.000	ns
Baseline	AF_Willow	0.024	0.015	0.033	<0.001	***
Baseline	Hedgerow_Clus	0.020	0.011	0.029	<0.001	***
Baseline	Hedgerow_Dist	0.020	0.011	0.029	<0.001	***
Baseline	Woodland	0.019	0.009	0.028	<0.001	***
AF_Fruit	AF_Poplar	-0.028	-0.037	-0.019	<0.001	***
AF_Fruit	AF_Willow	-0.003	-0.012	0.006	0.950	ns
AF_Fruit	Hedgerow_Clus	-0.007	-0.016	0.002	0.266	ns
AF_Fruit	Hedgerow_Dist	-0.007	-0.016	0.002	0.224	ns
AF_Fruit	Woodland	-0.009	-0.018	0.000	0.076	ns
AF_Poplar	AF_Willow	0.025	0.015	0.034	<0.001	***
AF_Poplar	Hedgerow_Clus	0.021	0.012	0.030	<0.001	***
AF_Poplar	Hedgerow_Dist	0.021	0.011	0.030	<0.001	***
AF_Poplar	Woodland	0.019	0.010	0.028	<0.001	***
AF_Willow	Hedgerow_Clus	-0.004	-0.013	0.005	0.878	ns
AF_Willow	Hedgerow_Dist	-0.004	-0.013	0.005	0.838	ns
AF_Willow	Woodland	-0.006	-0.015	0.004	0.556	ns
Hedgerow_Clus	Hedgerow_Dist	0.000	-0.009	0.009	1.000	ns
Hedgerow_Clus	Woodland	-0.002	-0.011	0.007	0.998	ns
Hedgerow_Dist	Woodland	-0.001	-0.011	0.008	0.999	ns

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.15: Post-hoc Tukey test for relative change in tree-nesting bumblebee worker production (W - total number of new worker bees produced as a fraction of the number produced with no AES interventions or tree planting present) between tree planting scenarios and baseline for early spring (foraging in late spring) at high planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.089	0.074	0.104	<0.001	***
Baseline	AF_Poplar	-0.001	-0.016	0.014	1.000	ns
Baseline	AF_Willow	0.078	0.063	0.093	<0.001	***
Baseline	Hedgerow_Clus	0.052	0.037	0.067	<0.001	***
Baseline	Hedgerow_Dist	0.057	0.042	0.072	<0.001	***
Baseline	Woodland	0.055	0.040	0.070	<0.001	***
AF_Fruit	AF_Poplar	-0.090	-0.105	-0.075	<0.001	***
AF_Fruit	AF_Willow	-0.011	-0.026	0.004	0.364	ns
AF_Fruit	Hedgerow_Clus	-0.036	-0.051	-0.021	<0.001	***
AF_Fruit	Hedgerow_Dist	-0.032	-0.047	-0.017	<0.001	***
AF_Fruit	Woodland	-0.034	-0.049	-0.019	<0.001	***
AF_Poplar	AF_Willow	0.079	0.064	0.094	<0.001	***
AF_Poplar	Hedgerow_Clus	0.053	0.038	0.068	<0.001	***
AF_Poplar	Hedgerow_Dist	0.058	0.043	0.073	<0.001	***
AF_Poplar	Woodland	0.056	0.041	0.071	<0.001	***
AF_Willow	Hedgerow_Clus	-0.026	-0.041	-0.011	<0.001	***
AF_Willow	Hedgerow_Dist	-0.021	-0.036	-0.006	<0.001	***
AF_Willow	Woodland	-0.023	-0.038	-0.008	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.005	-0.010	0.020	0.966	ns
Hedgerow_Clus	Woodland	0.002	-0.013	0.017	0.999	ns
Hedgerow_Dist	Woodland	-0.002	-0.017	0.013	0.999	ns

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.16: Post-hoc Tukey test for relative change in ground-nesting bumblebee worker production (W - total number of new worker bees produced as a fraction of the number produced with no AES interventions or tree planting present) between tree planting scenarios and baseline for late spring (foraging in summer) at low planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.018	0.004	0.031	0.002	**
Baseline	AF_Poplar	0.006	-0.008	0.019	0.880	ns
Baseline	AF_Willow	0.016	0.002	0.029	0.010	**
Baseline	Hedgerow_Clus	0.026	0.013	0.040	<0.001	***
Baseline	Hedgerow_Dist	0.026	0.013	0.039	<0.001	***
Baseline	Woodland	0.011	-0.003	0.024	0.198	ns
AF_Fruit	AF_Poplar	-0.012	-0.025	0.001	0.111	ns
AF_Fruit	AF_Willow	-0.002	-0.015	0.012	1.000	ns
AF_Fruit	Hedgerow_Clus	0.009	-0.005	0.022	0.477	ns
AF_Fruit	Hedgerow_Dist	0.008	-0.005	0.022	0.523	ns
AF_Fruit	Woodland	-0.007	-0.020	0.007	0.751	ns
AF_Poplar	AF_Willow	0.010	-0.003	0.024	0.274	ns
AF_Poplar	Hedgerow_Clus	0.021	0.007	0.034	<0.001	***
AF_Poplar	Hedgerow_Dist	0.020	0.007	0.034	<0.001	***
AF_Poplar	Woodland	0.005	-0.008	0.019	0.906	ns
AF_Willow	Hedgerow_Clus	0.011	-0.003	0.024	0.235	ns
AF_Willow	Hedgerow_Dist	0.010	-0.003	0.024	0.268	ns
AF_Willow	Woodland	-0.005	-0.018	0.009	0.936	ns
Hedgerow_Clus	Hedgerow_Dist	0.000	-0.014	0.013	1.000	ns
Hedgerow_Clus	Woodland	-0.015	-0.029	-0.002	0.013	*
Hedgerow_Dist	Woodland	-0.015	-0.029	-0.002	0.016	*

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.17: Post-hoc Tukey test for relative change in ground-nesting bumblebee worker production (W - total number of new worker bees produced as a fraction of the number produced with no AES interventions or tree planting present) between tree planting scenarios and baseline for late spring (foraging in summer) at high planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.056	0.038	0.075	<0.001	***
Baseline	AF_Poplar	0.018	-0.001	0.037	0.064	ns
Baseline	AF_Willow	0.050	0.031	0.069	<0.001	***
Baseline	Hedgerow_Clus	0.066	0.047	0.084	<0.001	***
Baseline	Hedgerow_Dist	0.071	0.053	0.090	<0.001	***
Baseline	Woodland	0.029	0.010	0.047	<0.001	***
AF_Fruit	AF_Poplar	-0.038	-0.057	-0.020	<0.001	***
AF_Fruit	AF_Willow	-0.006	-0.025	0.012	0.958	ns
AF_Fruit	Hedgerow_Clus	0.009	-0.009	0.028	0.759	ns
AF_Fruit	Hedgerow_Dist	0.015	-0.004	0.034	0.223	ns
AF_Fruit	Woodland	-0.028	-0.046	-0.009	<0.001	***
AF_Poplar	AF_Willow	0.032	0.013	0.051	<0.001	***
AF_Poplar	Hedgerow_Clus	0.048	0.029	0.066	<0.001	***
AF_Poplar	Hedgerow_Dist	0.053	0.034	0.072	<0.001	***
AF_Poplar	Woodland	0.011	-0.008	0.029	0.634	ns
AF_Willow	Hedgerow_Clus	0.016	-0.003	0.034	0.177	ns
AF_Willow	Hedgerow_Dist	0.021	0.002	0.040	0.016	*
AF_Willow	Woodland	-0.021	-0.040	-0.003	0.013	*
Hedgerow_Clus	Hedgerow_Dist	0.006	-0.013	0.024	0.977	ns
Hedgerow_Clus	Woodland	-0.037	-0.056	-0.018	<0.001	***
Hedgerow_Dist	Woodland	-0.042	-0.061	-0.024	<0.001	***

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.18: Post-hoc Tukey test for relative change in tree-nesting bumblebee worker production (W - total number of new worker bees produced as a fraction of the number produced with no AES interventions or tree planting present) between tree planting scenarios and baseline for late spring (foraging in summer) at low planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.015	0.009	0.021	<0.001	***
Baseline	AF_Poplar	0.000	-0.006	0.006	1.000	ns
Baseline	AF_Willow	0.007	0.001	0.013	0.017	*
Baseline	Hedgerow_Clus	0.010	0.004	0.016	<0.001	***
Baseline	Hedgerow_Dist	0.010	0.004	0.016	<0.001	***
Baseline	Woodland	0.021	0.015	0.027	<0.001	***
AF_Fruit	AF_Poplar	-0.015	-0.021	-0.009	<0.001	***
AF_Fruit	AF_Willow	-0.008	-0.014	-0.002	0.001	**
AF_Fruit	Hedgerow_Clus	-0.005	-0.011	0.001	0.139	ns
AF_Fruit	Hedgerow_Dist	-0.005	-0.011	0.001	0.129	ns
AF_Fruit	Woodland	0.006	0.000	0.012	0.048	*
AF_Poplar	AF_Willow	0.007	0.001	0.013	0.013	*
AF_Poplar	Hedgerow_Clus	0.010	0.004	0.016	<0.001	***
AF_Poplar	Hedgerow_Dist	0.010	0.004	0.016	<0.001	***
AF_Poplar	Woodland	0.021	0.015	0.028	<0.001	***
AF_Willow	Hedgerow_Clus	0.003	-0.003	0.009	0.793	ns
AF_Willow	Hedgerow_Dist	0.003	-0.003	0.009	0.809	ns
AF_Willow	Woodland	0.014	0.008	0.020	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.000	-0.006	0.006	1.000	ns
Hedgerow_Clus	Woodland	0.011	0.005	0.018	<0.001	***
Hedgerow_Dist	Woodland	0.012	0.005	0.018	<0.001	***

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Table A3.19: Post-hoc Tukey test for relative change in tree-nesting bumblebee worker production (W - total number of new worker bees produced as a fraction of the number produced with no AES interventions or tree planting present) between tree planting scenarios and baseline for late spring (foraging in summer) at high planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.049	0.040	0.057	<0.001	***
Baseline	AF_Poplar	0.000	-0.009	0.009	1.000	ns
Baseline	AF_Willow	0.022	0.013	0.030	<0.001	***
Baseline	Hedgerow_Clus	0.024	0.015	0.032	<0.001	***
Baseline	Hedgerow_Dist	0.026	0.017	0.035	<0.001	***
Baseline	Woodland	0.057	0.048	0.066	<0.001	***
AF_Fruit	AF_Poplar	-0.049	-0.058	-0.040	<0.001	***
AF_Fruit	AF_Willow	-0.027	-0.036	-0.018	<0.001	***
AF_Fruit	Hedgerow_Clus	-0.025	-0.034	-0.016	<0.001	***
AF_Fruit	Hedgerow_Dist	-0.022	-0.031	-0.013	<0.001	***
AF_Fruit	Woodland	0.009	0.000	0.018	0.057	ns
AF_Poplar	AF_Willow	0.022	0.013	0.031	<0.001	***
AF_Poplar	Hedgerow_Clus	0.024	0.015	0.033	<0.001	***
AF_Poplar	Hedgerow_Dist	0.026	0.018	0.035	<0.001	***
AF_Poplar	Woodland	0.058	0.049	0.067	<0.001	***
AF_Willow	Hedgerow_Clus	0.002	-0.007	0.011	0.994	ns
AF_Willow	Hedgerow_Dist	0.005	-0.004	0.014	0.726	ns
AF_Willow	Woodland	0.036	0.027	0.045	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.003	-0.006	0.012	0.977	ns
Hedgerow_Clus	Woodland	0.034	0.025	0.043	<0.001	***
Hedgerow_Dist	Woodland	0.031	0.022	0.040	<0.001	***

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.20: Analysis of Variance results for visitation rate (V – total number of visits as a fraction of the visitation with no AES interventions or tree planting present) between tree planting scenarios and baseline. Assessed separately for GNBB - ground-nesting bumblebees and TNBB – tree-nesting bumblebees; by crop visited (in late spring); and at low and high planting intensity.

Species	Crop	Intensity	F	DF	P
GNBB	OSR	Low	11.85 ***	6	< 0.001
GNBB	OSR	High	54.53 ***	6	< 0.001
TNBB	OSR	Low	23.59 ***	6	< 0.001
TNBB	OSR	High	90.55 ***	6	< 0.001
GNBB	Field Beans	Low	19.91 ***	6	< 0.001
GNBB	Field Beans	High	58.31 ***	6	< 0.001
TNBB	Field Beans	Low	35.64 ***	6	< 0.001
TNBB	Field Beans	High	90.39 ***	6	< 0.001

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.21: Post-hoc Tukey test for relative change in ground-nesting bumblebee visitation rate (V – total number of visits as a fraction of the visitation with no AES interventions or tree planting present) between tree planting scenarios and baseline to OSR at low planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.049	0.026	0.071	<0.001	***
Baseline	AF_Poplar	0.017	-0.006	0.040	0.293	ns
Baseline	AF_Willow	0.051	0.028	0.074	<0.001	***
Baseline	Hedgerow_Clus	0.034	0.012	0.057	<0.001	***
Baseline	Hedgerow_Dist	0.034	0.011	0.057	<0.001	***
Baseline	Woodland	0.014	-0.009	0.037	0.558	ns
AF_Fruit	AF_Poplar	-0.032	-0.054	-0.009	<0.001	***
AF_Fruit	AF_Willow	0.002	-0.021	0.025	1.000	ns
AF_Fruit	Hedgerow_Clus	-0.014	-0.037	0.009	0.527	ns
AF_Fruit	Hedgerow_Dist	-0.014	-0.037	0.008	0.498	ns
AF_Fruit	Woodland	-0.035	-0.058	-0.012	<0.001	***
AF_Poplar	AF_Willow	0.034	0.011	0.056	<0.001	***
AF_Poplar	Hedgerow_Clus	0.017	-0.005	0.040	0.270	ns
AF_Poplar	Hedgerow_Dist	0.017	-0.006	0.040	0.292	ns
AF_Poplar	Woodland	-0.003	-0.026	0.020	1.000	ns
AF_Willow	Hedgerow_Clus	-0.016	-0.039	0.007	0.352	ns
AF_Willow	Hedgerow_Dist	-0.017	-0.039	0.006	0.327	ns
AF_Willow	Woodland	-0.037	-0.060	-0.014	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.000	-0.023	0.023	1.000	ns
Hedgerow_Clus	Woodland	-0.021	-0.043	0.002	0.107	ns
Hedgerow_Dist	Woodland	-0.020	-0.043	0.003	0.119	ns

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.22: Post-hoc Tukey test for relative change in ground-nesting bumblebee visitation rate (V – total number of visits as a fraction of the visitation with no AES interventions or tree planting present) between tree planting scenarios and baseline to OSR at high planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.155	0.121	0.189	<0.001	***
Baseline	AF_Poplar	0.052	0.018	0.086	<0.001	***
Baseline	AF_Willow	0.162	0.128	0.196	<0.001	***
Baseline	Hedgerow_Clus	0.088	0.054	0.122	<0.001	***
Baseline	Hedgerow_Dist	0.098	0.064	0.132	<0.001	***
Baseline	Woodland	0.037	0.003	0.071	0.023	*
AF_Fruit	AF_Poplar	-0.103	-0.137	-0.069	<0.001	***
AF_Fruit	AF_Willow	0.008	-0.026	0.042	0.994	ns
AF_Fruit	Hedgerow_Clus	-0.067	-0.101	-0.033	<0.001	***
AF_Fruit	Hedgerow_Dist	-0.057	-0.091	-0.023	<0.001	***
AF_Fruit	Woodland	-0.118	-0.152	-0.084	<0.001	***
AF_Poplar	AF_Willow	0.111	0.077	0.145	<0.001	***
AF_Poplar	Hedgerow_Clus	0.036	0.002	0.070	0.029	*
AF_Poplar	Hedgerow_Dist	0.046	0.012	0.080	0.001	**
AF_Poplar	Woodland	-0.015	-0.049	0.019	0.864	ns
AF_Willow	Hedgerow_Clus	-0.075	-0.109	-0.041	<0.001	***
AF_Willow	Hedgerow_Dist	-0.065	-0.099	-0.031	<0.001	***
AF_Willow	Woodland	-0.125	-0.159	-0.091	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.010	-0.024	0.044	0.980	ns
Hedgerow_Clus	Woodland	-0.051	-0.085	-0.017	<0.001	***
Hedgerow_Dist	Woodland	-0.060	-0.095	-0.026	<0.001	***

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.23: Post-hoc Tukey test for relative change in tree-nesting bumblebee visitation rate (V – total number of visits as a fraction of the visitation with no AES interventions or tree planting present) between tree planting scenarios and baseline to OSR at low planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.041	0.028	0.054	<0.001	***
Baseline	AF_Poplar	0.002	-0.012	0.015	1.000	ns
Baseline	AF_Willow	0.034	0.021	0.047	<0.001	***
Baseline	Hedgerow_Clus	0.016	0.003	0.029	0.006	**
Baseline	Hedgerow_Dist	0.016	0.003	0.029	0.005	**
Baseline	Woodland	0.022	0.009	0.035	<0.001	***
AF_Fruit	AF_Poplar	-0.040	-0.053	-0.026	<0.001	***
AF_Fruit	AF_Willow	-0.007	-0.020	0.006	0.662	ns
AF_Fruit	Hedgerow_Clus	-0.025	-0.038	-0.012	<0.001	***
AF_Fruit	Hedgerow_Dist	-0.025	-0.038	-0.012	<0.001	***
AF_Fruit	Woodland	-0.019	-0.032	-0.006	<0.001	***
AF_Poplar	AF_Willow	0.032	0.019	0.046	<0.001	***
AF_Poplar	Hedgerow_Clus	0.015	0.001	0.028	0.020	*
AF_Poplar	Hedgerow_Dist	0.015	0.001	0.028	0.018	*
AF_Poplar	Woodland	0.020	0.007	0.034	<0.001	***
AF_Willow	Hedgerow_Clus	-0.018	-0.031	-0.005	0.001	**
AF_Willow	Hedgerow_Dist	-0.018	-0.031	-0.005	0.002	**
AF_Willow	Woodland	-0.012	-0.025	0.001	0.102	ns
Hedgerow_Clus	Hedgerow_Dist	0.000	-0.013	0.013	1.000	ns
Hedgerow_Clus	Woodland	0.006	-0.007	0.019	0.846	ns
Hedgerow_Dist	Woodland	0.006	-0.007	0.019	0.858	ns

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.24: Post-hoc Tukey test for relative change in tree-nesting bumblebee visitation rate (V – total number of visits as a fraction of the visitation with no AES interventions or tree planting present) between tree planting scenarios and baseline to OSR at high planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.130	0.109	0.152	<0.001	***
Baseline	AF_Poplar	0.004	-0.017	0.026	0.997	ns
Baseline	AF_Willow	0.107	0.085	0.128	<0.001	***
Baseline	Hedgerow_Clus	0.041	0.020	0.063	<0.001	***
Baseline	Hedgerow_Dist	0.046	0.025	0.067	<0.001	***
Baseline	Woodland	0.060	0.038	0.081	<0.001	***
AF_Fruit	AF_Poplar	-0.126	-0.148	-0.105	<0.001	***
AF_Fruit	AF_Willow	-0.023	-0.045	-0.002	0.022	*
AF_Fruit	Hedgerow_Clus	-0.089	-0.111	-0.068	<0.001	***
AF_Fruit	Hedgerow_Dist	-0.084	-0.106	-0.063	<0.001	***
AF_Fruit	Woodland	-0.070	-0.092	-0.049	<0.001	***
AF_Poplar	AF_Willow	0.103	0.081	0.124	<0.001	***
AF_Poplar	Hedgerow_Clus	0.037	0.015	0.058	<0.001	***
AF_Poplar	Hedgerow_Dist	0.042	0.020	0.063	<0.001	***
AF_Poplar	Woodland	0.056	0.034	0.077	<0.001	***
AF_Willow	Hedgerow_Clus	-0.066	-0.087	-0.044	<0.001	***
AF_Willow	Hedgerow_Dist	-0.061	-0.082	-0.040	<0.001	***
AF_Willow	Woodland	-0.047	-0.069	-0.026	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.005	-0.017	0.026	0.995	ns
Hedgerow_Clus	Woodland	0.019	-0.003	0.040	0.135	ns
Hedgerow_Dist	Woodland	0.014	-0.008	0.035	0.472	ns

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.25: Post-hoc Tukey test for relative change in ground-nesting bumblebee visitation rate (V – total number of visits as a fraction of the visitation with no AES interventions or tree planting present) between tree planting scenarios and baseline to field beans at low planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.090	0.058	0.123	<0.001	***
Baseline	AF_Poplar	0.028	-0.005	0.061	0.145	ns
Baseline	AF_Willow	0.095	0.062	0.128	<0.001	***
Baseline	Hedgerow_Clus	0.046	0.013	0.079	<0.001	***
Baseline	Hedgerow_Dist	0.050	0.017	0.083	<0.001	***
Baseline	Woodland	0.021	-0.012	0.054	0.482	ns
AF_Fruit	AF_Poplar	-0.062	-0.095	-0.029	<0.001	***
AF_Fruit	AF_Willow	0.004	-0.029	0.037	1.000	ns
AF_Fruit	Hedgerow_Clus	-0.045	-0.078	-0.012	0.001	**
AF_Fruit	Hedgerow_Dist	-0.040	-0.073	-0.007	0.006	**
AF_Fruit	Woodland	-0.069	-0.102	-0.036	<0.001	***
AF_Poplar	AF_Willow	0.066	0.034	0.099	<0.001	***
AF_Poplar	Hedgerow_Clus	0.018	-0.015	0.050	0.699	ns
AF_Poplar	Hedgerow_Dist	0.022	-0.011	0.055	0.446	ns
AF_Poplar	Woodland	-0.007	-0.040	0.026	0.995	ns
AF_Willow	Hedgerow_Clus	-0.049	-0.082	-0.016	<0.001	***
AF_Willow	Hedgerow_Dist	-0.045	-0.078	-0.012	0.001	**
AF_Willow	Woodland	-0.074	-0.107	-0.041	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.004	-0.029	0.037	1.000	ns
Hedgerow_Clus	Woodland	-0.025	-0.058	0.008	0.286	ns
Hedgerow_Dist	Woodland	-0.029	-0.062	0.004	0.128	ns

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.26: Post-hoc Tukey test for relative change in ground-nesting bumblebee visitation rate (V – total number of visits as a fraction of the visitation with no AES interventions or tree planting present) between tree planting scenarios and baseline to field beans at high planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.292	0.228	0.356	<0.001	***
Baseline	AF_Poplar	0.090	0.026	0.154	<0.001	***
Baseline	AF_Willow	0.306	0.242	0.370	<0.001	***
Baseline	Hedgerow_Clus	0.121	0.057	0.185	<0.001	***
Baseline	Hedgerow_Dist	0.141	0.077	0.205	<0.001	***
Baseline	Woodland	0.046	-0.018	0.110	0.332	ns
AF_Fruit	AF_Poplar	-0.202	-0.266	-0.138	<0.001	***
AF_Fruit	AF_Willow	0.014	-0.050	0.078	0.995	ns
AF_Fruit	Hedgerow_Clus	-0.171	-0.235	-0.107	<0.001	***
AF_Fruit	Hedgerow_Dist	-0.151	-0.215	-0.087	<0.001	***
AF_Fruit	Woodland	-0.246	-0.310	-0.182	<0.001	***
AF_Poplar	AF_Willow	0.216	0.152	0.280	<0.001	***
AF_Poplar	Hedgerow_Clus	0.031	-0.033	0.094	0.796	ns
AF_Poplar	Hedgerow_Dist	0.050	-0.014	0.114	0.232	ns
AF_Poplar	Woodland	-0.044	-0.108	0.020	0.393	ns
AF_Willow	Hedgerow_Clus	-0.185	-0.249	-0.121	<0.001	***
AF_Willow	Hedgerow_Dist	-0.165	-0.229	-0.101	<0.001	***
AF_Willow	Woodland	-0.260	-0.324	-0.196	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.020	-0.044	0.084	0.970	ns
Hedgerow_Clus	Woodland	-0.075	-0.138	-0.011	0.011	*
Hedgerow_Dist	Woodland	-0.094	-0.158	-0.030	<0.001	***

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.27: Post-hoc Tukey test for relative change in tree-nesting bumblebee visitation rate (V – total number of visits as a fraction of the visitation with no AES interventions or tree planting present) between tree planting scenarios and baseline to field beans at low planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.077	0.056	0.098	<0.001	***
Baseline	AF_Poplar	0.000	-0.020	0.021	1.000	ns
Baseline	AF_Willow	0.066	0.045	0.086	<0.001	***
Baseline	Hedgerow_Clus	0.026	0.005	0.047	0.004	**
Baseline	Hedgerow_Dist	0.028	0.008	0.049	0.001	**
Baseline	Woodland	0.033	0.013	0.054	<0.001	***
AF_Fruit	AF_Poplar	-0.076	-0.097	-0.056	<0.001	***
AF_Fruit	AF_Willow	-0.011	-0.032	0.009	0.680	ns
AF_Fruit	Hedgerow_Clus	-0.051	-0.072	-0.030	<0.001	***
AF_Fruit	Hedgerow_Dist	-0.049	-0.069	-0.028	<0.001	***
AF_Fruit	Woodland	-0.044	-0.064	-0.023	<0.001	***
AF_Poplar	AF_Willow	0.065	0.045	0.086	<0.001	***
AF_Poplar	Hedgerow_Clus	0.025	0.005	0.046	0.006	**
AF_Poplar	Hedgerow_Dist	0.028	0.007	0.049	0.001	**
AF_Poplar	Woodland	0.033	0.012	0.053	<0.001	***
AF_Willow	Hedgerow_Clus	-0.040	-0.061	-0.019	<0.001	***
AF_Willow	Hedgerow_Dist	-0.037	-0.058	-0.017	<0.001	***
AF_Willow	Woodland	-0.032	-0.053	-0.012	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.003	-0.018	0.023	1.000	ns
Hedgerow_Clus	Woodland	0.007	-0.013	0.028	0.937	ns
Hedgerow_Dist	Woodland	0.005	-0.016	0.026	0.993	ns

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table A3.28: Post-hoc Tukey test for relative change in tree-nesting bumblebee visitation rate (V – total number of visits as a fraction of the visitation with no AES interventions or tree planting present) between tree planting scenarios and baseline to field beans at high planting intensity.

Scenario 1	Scenario 2	Estimate	Conf.Low	Conf.High	P.Adj	Signif.
Baseline	AF_Fruit	0.249	0.206	0.291	<0.001	***
Baseline	AF_Poplar	0.002	-0.040	0.044	1.000	ns
Baseline	AF_Willow	0.207	0.165	0.249	<0.001	***
Baseline	Hedgerow_Clus	0.066	0.023	0.108	<0.001	***
Baseline	Hedgerow_Dist	0.078	0.035	0.120	<0.001	***
Baseline	Woodland	0.072	0.030	0.114	<0.001	***
AF_Fruit	AF_Poplar	-0.246	-0.289	-0.204	<0.001	***
AF_Fruit	AF_Willow	-0.042	-0.084	0.001	0.056	ns
AF_Fruit	Hedgerow_Clus	-0.183	-0.225	-0.141	<0.001	***
AF_Fruit	Hedgerow_Dist	-0.171	-0.213	-0.129	<0.001	***
AF_Fruit	Woodland	-0.176	-0.219	-0.134	<0.001	***
AF_Poplar	AF_Willow	0.205	0.163	0.247	<0.001	***
AF_Poplar	Hedgerow_Clus	0.064	0.021	0.106	<0.001	***
AF_Poplar	Hedgerow_Dist	0.075	0.033	0.118	<0.001	***
AF_Poplar	Woodland	0.070	0.028	0.112	<0.001	***
AF_Willow	Hedgerow_Clus	-0.141	-0.183	-0.099	<0.001	***
AF_Willow	Hedgerow_Dist	-0.129	-0.172	-0.087	<0.001	***
AF_Willow	Woodland	-0.135	-0.177	-0.092	<0.001	***
Hedgerow_Clus	Hedgerow_Dist	0.012	-0.031	0.054	0.983	ns
Hedgerow_Clus	Woodland	0.006	-0.036	0.049	0.999	ns
Hedgerow_Dist	Woodland	-0.005	-0.048	0.037	1.000	ns

*** p < 0.001; ** p < 0.01; * p < 0.05.

3.3 Additional Map Outputs

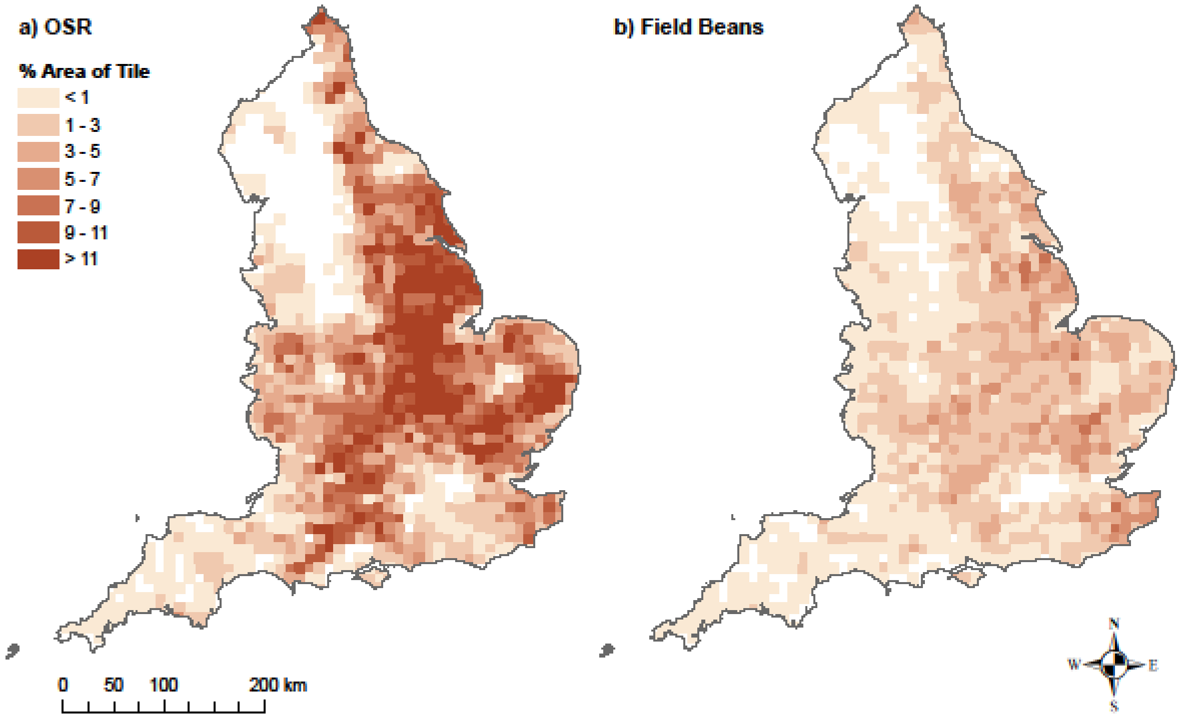

Figure A3.1: Coverage of a) OSR, b) Field Beans land cover by 10 km tile for England in 2016.

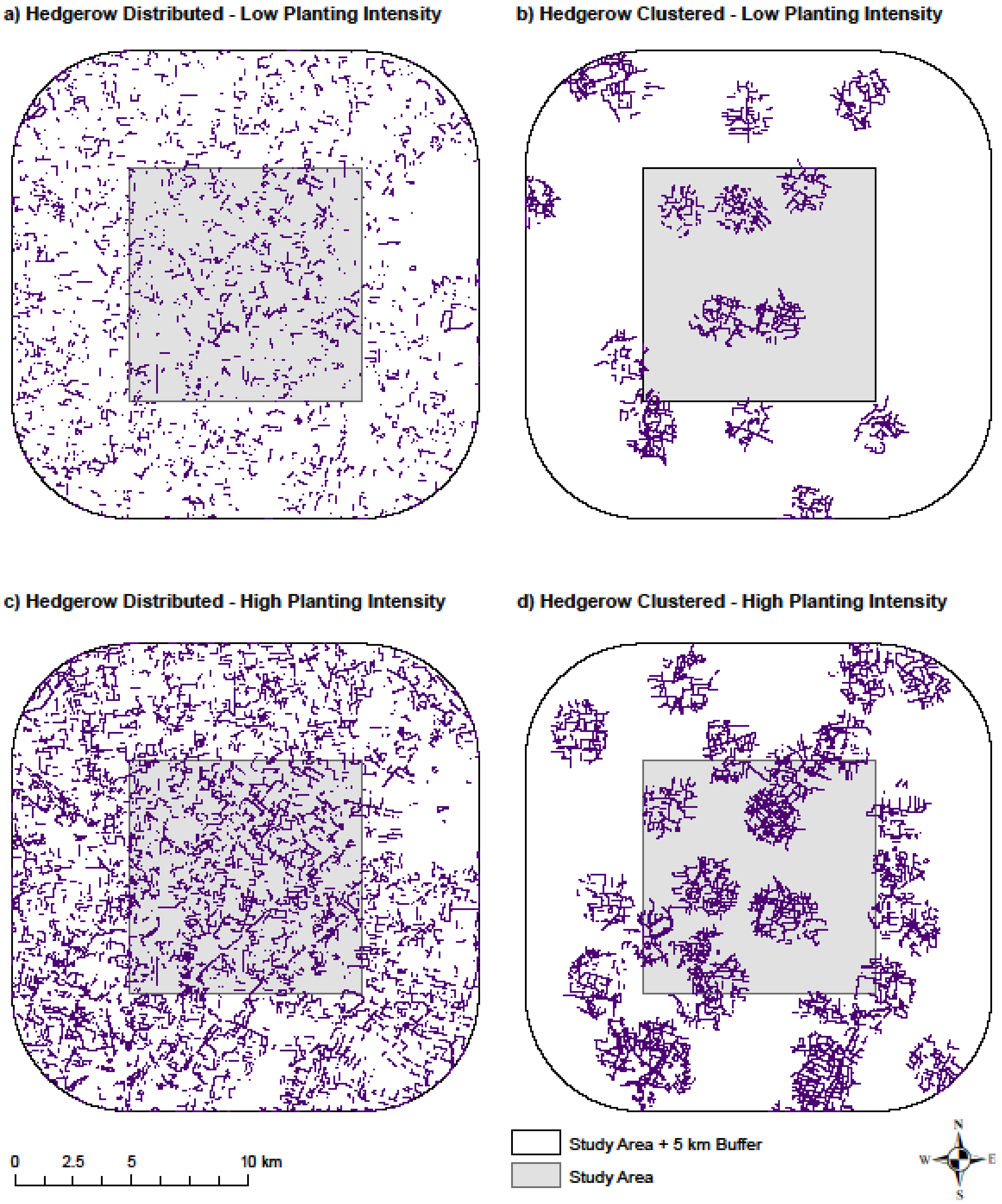

Figure A3.2: Example map outputs showing difference between hedgerow distributed and hedgerow clustered scenarios. The distributed scenarios a), c) are generated by random allocation of hedgerow to any eligible field boundary (i.e., agricultural field boundary without an existing hedgerow). The clustered scenarios b), d) are generated by preferential allocation to eligible field boundaries within spatial zones of ~100 ha - ~700 ha that represent hypothetical farms or farm clusters. Low planting intensity represents 3.4% increase in tree cover, equivalent to maintaining current tree-planting rates to 2035. High planting intensity represents 10.2% increase in tree cover, equivalent to a trebled rate over the same period that matches UK Government targets. See Section A3.1 for details.

Figure A3.3: Typical spatial distributions for the change in relative tree-nesting bumblebee Late Spring visitation rate for each tree planting scenario, expressed as a fraction of the baseline scenario visitation rate (VScenario / VBaseline), where the additional tree cover corresponds to the low intensity planting 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.

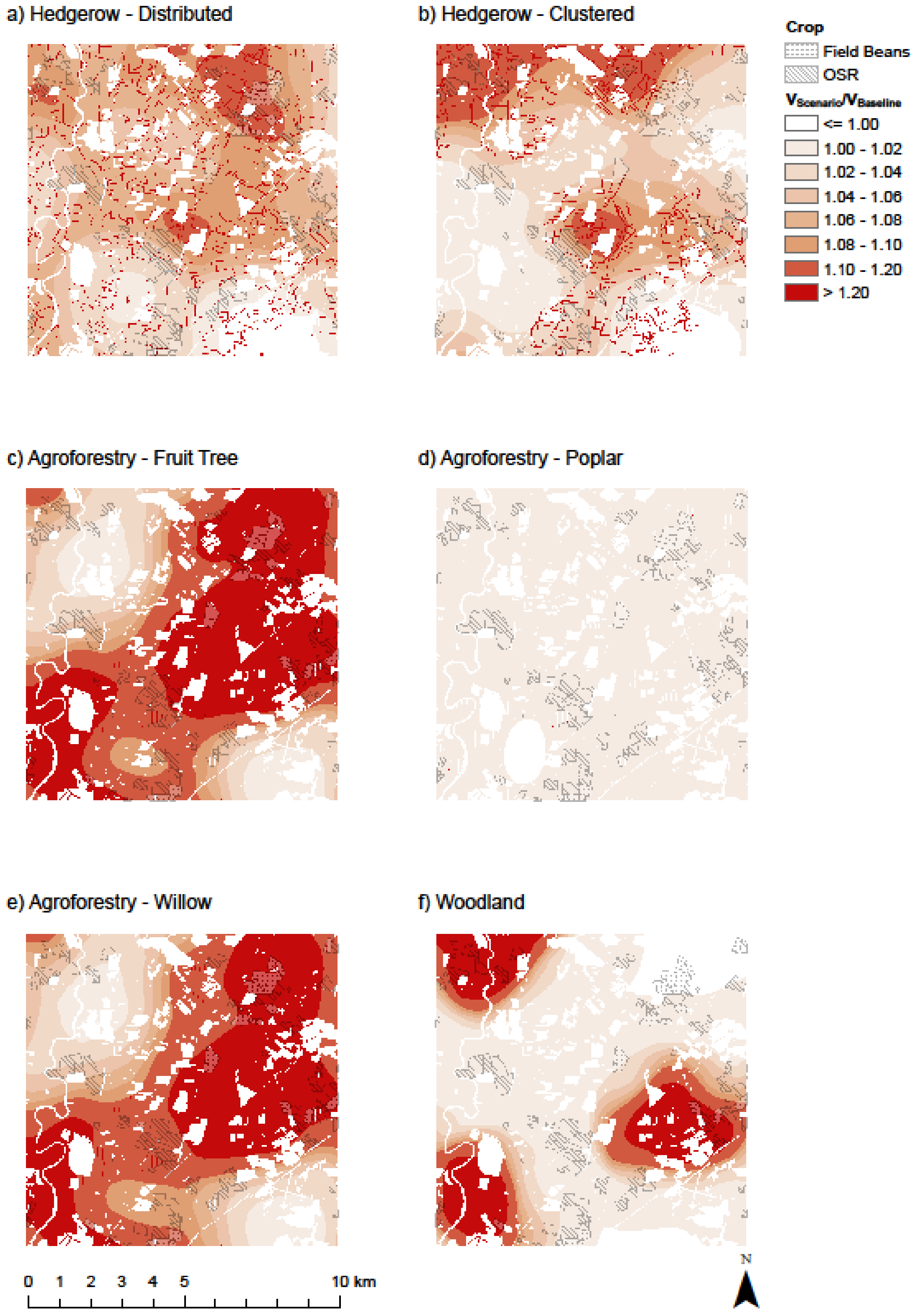

Figure A3.4: Typical spatial distributions for the change in relative tree-nesting bumblebee Late Spring visitation rate for each tree planting scenario, expressed as a fraction of the baseline scenario visitation rate (VScenario / VBaseline), where the additional tree cover corresponds to the high intensity planting 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.