Rothamsted Repository Download

F - Theses

Jowett, K. 2022. *Carabids for Natural-Enemy Pest Control: combining ecology and knowledge exchange to bridge the gaps.* F - Theses

Carabids for Natural-Enemy Pest Control: combining ecology and knowledge exchange to bridge the gaps

Kelly Jowett

December 2021

A thesis submitted to the University of Reading in fulfilment of the requirements for the degree

of Doctor of Philosophy

Supervisory team:

Jonathan Storkey, Alice Milne, Deepa Senapathi, and Simon Potts

Abstract

Carabid beetles are proven predators of crop pests and weed seeds. Agri-environmental measures, such as grass margins and beetle banks, are beneficial to the abundance and diversity of carabids. However, there is a lack of consensus over which measures are most effective in terms of Natural enemy Pest Control (NPC) by carabids, and interactions with the surrounding landscape.

This thesis aimed to improve the efficacy and applicability of farm management interventions that increase the abundance and diversity of carabid species that contribute to NPC. I analysed data from the Farm Scale Evaluation experiment to determine the effects of landscape features and crop management on species abundance and diversity. To investigate further, I undertook trapping campaigns on a plot-scale and a farm-scale experiment. For this I used novel subterranean traps and standard pitfall traps to capture both above and below ground activity. Data were analysed with Linear Mixed Models, Generalised Linear Mixed Models, multivariate and spatial statistical methods. Central to my findings was that the response of key species varied differentially according to crop type, distance from field edge, adjacent habitat, and boundary feature. By incorporating below-ground sampling, I was able to deliver new understanding of the distribution of soil-dwelling carabid larvae relative to adults, and argue for the inclusion of predatory larvae in the estimation of ecosystem services provided by carabids.

To incentivise farm management for NPC it is essential to understand the key motivations of farmers. To that end, I surveyed farmers to discover awareness, attitudes, and behavioural intent towards carabid beetles. Knowledge exchange interventions were also deployed. Farmer attitudes to carabids were positive, and experimental knowledge exchange treatments had a significant effect on behavioural intent. By drawing experimental and behaviour findings together, I was able to recommend specific actions favourable to farmers that were likely to boost NPC.

Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.
All illustrations, unless otherwise stated, are also my own work.

Kelly Jowett

Covid impact statement

This PhD project was affected by the Covid-19 outbreak, whereby access to laboratories was limited and face-to-face meetings were not possible.
The original project plan included workshops to engage farmers with an experimental approach, including testing of ID materials. This was altered to online events and communication materials, which took extra time to organise and administer, and also necessitated a simpler experimental design.
Sample processing was severely delayed by having no access to laboratories at the start of the outbreak. Subsequent access to samples was also limited in duration. The original plan was to analyse all four runs of the margin experiment, however, this was reduced to two runs due to setbacks. It was also intended to identify carabid larvae to species level, but this was not possible within time limitations.

Acknowledgements

Dion. I probably owe him my life, if not, my sanity.

Alice and Jon. Above and beyond the call of duty doesn't really cover it, especially considering the state of some of the pitfall traps…

Deepa and Simon, always there when I needed them with brilliant critique and enthusiastic encouragement.

Chris for leading me down the rabbit hole of subterranean trapping. Mark and Ian for kindly sharing their experience with the novel subterranean trapping.

Dan for the margins, and fieldwork, and completely turning around my sample processing problem

My mum. For oracular wisdom. My Granma and grandad for support even though I study horrible 'crawlies'. Dawn, Fox and Jack, for always cheering me up.

Lyzzy for financial support and for the example of a successful and powerful woman.

Sarah for academic commiserations, and brain twinning. Ary for spiritual camaraderie and screaming into the wind.

Donna, Alice, and Dana, for variously having my back.

Soil modelling group for giving me free reign with the tree.

Kirsty, for explaining stats in a way I understand easily.

Will for survey advice and contacts.

Gary for super animation skills.

Tom and Jack for sample sorting under difficult circumstances.

Helen for modelling expertise and fieldwork help.

Hannah, Timo, Jonah, and Todd, for digging lots of holes. Dion again for digging the most holes.

Farmer organisations: Linking the Environment and Farming (LEAF), Agricology, Biodiversity Agriculture Soil and Environment (BASE), Championing the Farmed Environment (CFE), The Farming and Wildlife Advisory Group (FWAG), Agri-Tech- east, The Agriculture and Horticulture Development Board (ADHB), and the National Farmers Union (NFU), for all their help promoting the beneficial beetles survey and talks. Mandy (Wellies and Labcoats), and Farmers weekly, for cutting the interviews so I sounded professional.

And the fantastically altruistic farmers who participated, and particularly those who contacted me afterwards. I never fail to be humbled by the spirit and tenacity of British farmers. This is why I do what I do.

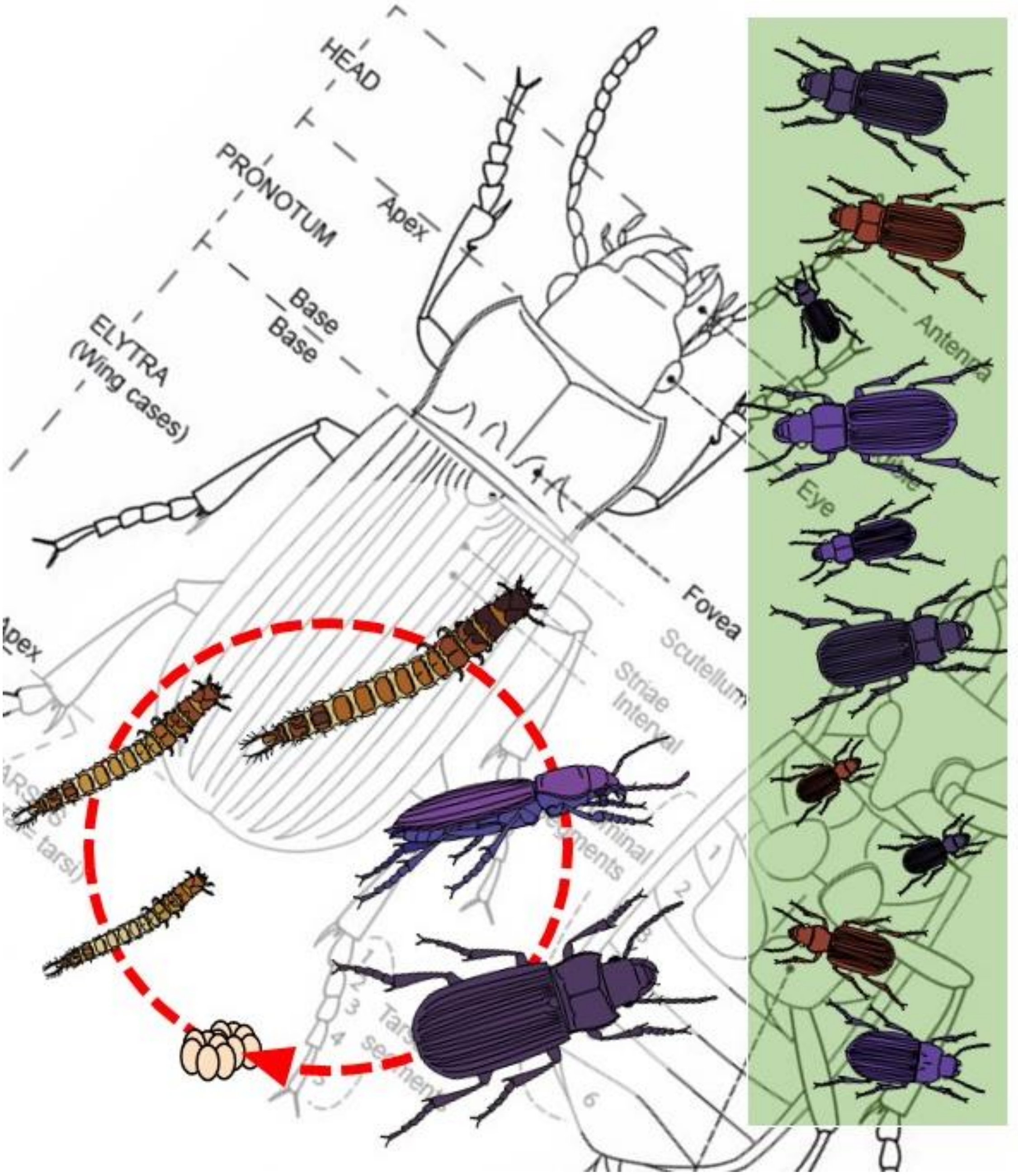
"I like to see my animals and crops are healthy as a result of a healthy farm. I would like to see a decrease in chemical inputs with plants forming resistance diseases through a healthy soil system. The healthy soil system is result of holistic management approaches which includes beetles. If the cows are happy, the stream flows clear, the wheat is golden, the birds are singing, bees are buzzing and I have made a profit then I'll be happy."

-Response to question about how farmers judge the success of Agri-environmental measures.

And last but not least, all the beetles I killed. I’ve tried my absolute hardest to make sure your sacrifice wasn’t in vain.

Table of Contents

Chapter 1


HEAD
PRONOTUM
ELYTRA
(Wing cases)
Apex
Base
Base
Apex
Antenna
Eye
Fovea
Scutellum
Striae
Interval
Tarsi
segments
1
2
3
4
5
6

Introduction

1.1 Ecosystem services and agriculture

Agricultural systems are under pressure to produce more food, from less land, and to do so more sustainably. The expansion of farmed land has greatly decreased the area of semi-natural habitats, and fragmented these areas spatially, disturbing the movements of wild animals and plants; this has led to catastrophic biodiversity loss (IPBES 2019). Added to this, the intensification of agricultural systems, with nutrient inputs, decreased fallow periods, and larger field sizes has simplified agricultural ecosystems to the point where there is less potential for cohabitation of wild species on farmland (Bianchi, Booij, and Tscharntke, 2006; Hayhow et al., 2019). This project focusses on the agricultural systems of the UK, however the research problems and potential solutions have applicability in many agricultural contexts worldwide.

Ecosystem services describe the benefits humans derive from natural systems. These services can be considered under four main categories: provisioning, regulating, supporting, and cultural. Provisioning describes the ability of ecosystems to produce goods, such as crops, livestock and timber, for human use. Regulating encompasses the services that support functioning of ecosystems, such as water quality and pest and disease regulation, whilst supporting overlaps somewhat, describing services such as soil formation and nutrient cycling that underlie ecosystem processes. Cultural services derive human values such as aesthetics and recreational use (Carpenter et al., 2009). Whilst intended to optimise productivity, the expansion and intensification of agriculture has actually negatively impacted the capability of natural systems to provide regulating services that support food production; one of the key areas of impact is reduced natural enemy pest control (NPC) (Power, 2010). The addition of chemical fertilisers and particularly pesticides impacts disproportionally on natural enemies of crop pests compared with herbivorous pest species. This is due to bioaccumulation of toxins, and the general autecological capability of pest species to relocate easily and reproduce exponentially in the optimum conditions that crops constitute, compared to the relatively resident status of generalist predatory species, reliant on resources over longer timescales (Bianchi, Booij, and Tscharntke, 2006; Wilby and Thomas, 2002).

Globally, insect consumption of crops accounts for 5 to 20% of global yield loss in major grain crops, a proportion which is predicted to increase under climate change (Deutsch et al., 2018). Invertebrate pests also affect all other crops, from root crops to soft fruits, and impact livestock systems; reducing milk yields and live weight gain (Beynon et al., 2015). Invertebrate pests are also major vectors of crop and livestock disease, further impacting yields (Prather et al., 2013). Historically the main response has been to develop pesticides, both specific and general in targeting crop pests. However, this approach, along with inappropriate and sometimes injudicious usage, has led to problems with negative externalities in ecosystems, resistance build-up in pest species, and increasing public concern about food safety and impacts on non-target taxa (Barzman et al,. 2015; Bommarco, Vico, and Hallin, 2018).

Weeds are another driver of agricultural adjustment of ecosystems. Weeds can be defined as a plant in the wrong place- in this case wild plant species adapted to disturbed environments, that compete with crops for resources (Bridges, 1994; Vila et al., 2021). These are often currently controlled with chemicals, creating similar problems of negative externalities such as pollution of water courses and resistance build-up accumulating (Holt, 1994).

Agri-environment schemes (AES) were designed to redress the impacts of agricultural expansion and intensification, as governmental schemes have evolved, this has increasingly involved the incorporation of natural areas and sustainable practices into farming management. AES options include, subsiding farmers for creation and maintenance of habitats beneficial to farmland agro-ecology such as hedgerows and field margins. Scheme options also include in-field measures such as reduced tillage and cover cropping that benefit the soil microbiome. Such options may also benefit the productivity of agricultural land, by reducing erosion, aiding nutrient cycling, supporting crop pollination, and creating areas of shelter for livestock (Gaba and Bretagnolle, 2020; Kremen and Chaplin-Kramer 2007; Pywell et al., 2015; Wezel et al., 2014; Woodcock et al., 2007).

AES can also potentially benefit farming and ecosystem health through Natural-enemy Pest Control. Natural-enemy Pest Control (NPC) describes the control of crop pests by promoting the occurrence of organisms that are adapted to predate on them in natural ecosystems. This approach is one key aspect of Integrated Pest Management (IPM) approaches, increasing the use of which is embedded in policy at the UK and European level to improve the sustainability of agriculture (EU 2009; UKGOV 2018). Whilst much research has shown NPC to have an effect on pest and weed control (Barzman et al 2015; Bianchi, Booij, and Tscharntke, 2006; Petit, Bohan, and Dijon, 2018; Redlich, Martin, and Steffan-Dewenter, 2018) the effectiveness of AES measures in promoting NPC is variable (Karp et al., 2018; Kleijn and Sutherland, 2003). Many agents are responsible for NPC, including spiders, parasitic wasps, predatory flies, and beetles. Interventions aimed at increasing their abundance seek to provide what they need to feed, breed and shelter (Bianchi, Booij, and Tscharntke, 2006; Dennis and Fry, 1992). However, ecological requirements vary tremendously by species, as does their capacity to provide pest control in crop areas (Harterreiten-Souza et al., 2021; Martin et al., 2013; Mestre et al., 2018;;

Schirmel et al., 2018). The limitations seen in effectiveness of interventions may therefore be due to ecological knowledge gaps (Campbell et al., 2017; De Heij, and Willenborg, 2020; Ouyang et al., 2020; Thomson and Hoffmann, 2010). However, a major factor is also the application of knowledge in practice, and so the uptake and implementation of interventions by farmers may also be responsible for insufficient results (Amoabeng et al., 2017; Loos et al., 2019; Maas et al., 2021).

1.2 Carabids as agents of Natural enemy pest control

Beetles of the family *Carabidae* exist on every continent and in nearly every ecosystem from rainforest to desert. The latest catalogue lists more than 35 000 species worldwide. These species vary widely in both morphology (size, shape, flight ability, running and digging abilities) and behaviour (nocturnal or diurnal activity, breeding times, breeding habits, feeding behaviours) (Kotze et al., 2011; Thiele, 1977). Due to their widespread presence, and relative ease of trapping, carabids are one of the insect families most studied by entomologists. Carabids are sensitive to environmental change, relatively mobile, ubiquitous across habitats, and are primary and secondary consumers in the food web; and so they can be useful indicator species of environmental change, habitat condition, and are studied as a model for ecological processes (Adamski et al., 2019; Holland, 2002; Kotze et al., 2011). However, most studies of carabids in agricultural land have focussed on their utility as natural enemies of crop pests rather than as indicators. Though some species are specialist feeders, the majority are polyphagous predators. In the UK there are around 350 species of carabid, about 30 of which are well adapted to disturbance and are considered as resident of farmland habitats. These species consume major crop pests, and have been proven to have significant impacts on pest outbreak, and regulation of pest populations (Sunderland, 2002).

A plethora of studies exist detailing carabid mediated predation of crop invertebrate pests, notably aphids, slugs and snails, moths and butterflies, weevils, flea beetles, and pest flies— this is dominated by studies from the UK (Bohan et al., 2000; Sunderland and Vickerman 1980; Symondson, 1989; Williams et al., 2010), North America (Floate, Doane and Gillott, 1990; Russel et al., 2017) and Europe (Ferrante, Cacciato, and Lövei, 2014; Kamenova et al., 2018; Staudacher, Jonsson and Traugott, 2016), but work is accelerating in other countries worldwide (Akhil, and Thomas, 2018; Cividanes, 2021; Imboma et al., 2020). The effects of predation on pest suppression has also been variously proven to be significant, for example carabid beetles were shown to cause an 81% decrease in emerging adults of orange wheat blossom midge (*Sitodiplosis mosellana*) (Kromp, 1999); it was demonstrated that eggs and first-instar larvae of the cabbage root fly (*Delia radicum*) may be reduced by 90% by such carabids as *Bembidion lampros* and *Trechus quadristriatus* (Finch and Elliott, 1992); and the population of Colorado potato beetles (*Leptinotara decemlineata*) were shown to be reduced by up to 30% in presence of such Carabidae species as *Carabus auratus* or *Pterostichus melanarius* (Kromp, 1999). Moreover, carabids have been shown to aggregate following the occurrence of crop pests spatially (Bohan et al., 2000; Sunderland and Vickerman 1980; Winder et al., 2001), this ability to seek out food resources means that their presence in the farm landscape may contribute to pest control in adjacent productive areas.

Many carabid species are omnivorous, eating plant matter, notably weed seeds, in addition to invertebrate prey. Some species are specialist granivores, notably *Harpalus rufipes*, the fecundity of which is dependent on a diet of seeds, and has been shown to preferentially feed on weed seeds (Holland, 2002; Petit, Boursalt and Bohan, 2014; Saska, Honek and Martinkova, 2019). The potential for contribution to weed control has been studied increasingly in recent years (Petit and Bohan, 2018), demonstrating impressive results for weed control in crop areas. For example, it has been shown that *Harpalus rufipes, Harpalus affinis*, and *Amara aenea* can help to reduce seed stock of a weed species in the range of 65 to 90% (Honek et al., 2003).

Based on the literature evidence described above, throughout this thesis it is assumed that increasing the abundance and diversity of carabid beetles will correlate to increased NPC through both the suppression of pest or weed populations, and control of pest outbreaks in crops.

The potential contribution of carabids to crop health and yield is therefore substantial, and therefore a well justified aim of agri-environmental interventions in farmland is to increase their abundance and diversity. However, the agricultural expansion and intensification has impacted the distribution of carabid species in farmland, with potential detrimental effects on their suppression of pests (Brooks et al., 2012; Kotze and O'Hara, 2003). In order to understand the factors influencing carabid populations in farmland, and design interventions to effectively boost their associated pest control, it is necessary to understand both their ecology, and the ways in which this may be affected by human utility.

1.3 Carabids in agro-ecosystems

In order to design models and/or management to examine or boost populations, it is crucial to consider the needs of carabid beetles, at a biological and behavioural level. This may be broken down into simple categories of feeding, breeding, and shelter.

1.3.1 Areas to feed

Crop pests and weed seeds are a major part of farmland carabid diets, however, this resource varies from season to season in part driven by crop rotation. Carabids of agroecosystems are generally polyphagous opportunists; by virtue of the transient nature of their niche. This benefits their utility in pest control in that more carnivorous species will follow pest outbreaks (Bohan et al., 2000; Reich et al., 2020; Winder et al., 2001), and more herbivorous or specialist (weed) seed feeders reside near food resources (Petit and Bohan 2018). However, this also means that if the resource is not available over time, carabids will migrate or perish. The availability of alternative food resources, such as non-pest arthropods, is one of the main benefits of permanent semi-natural habitats in farm landscapes. Retaining and creating semi-natural habitats on farms such as hedges, field margins, ditches, and beetle banks, provides food resources in both the presence of invertebrates and plant materials such as seeds and pollen, which sustain carabids when crop habitats are barren (Sunderland 2002; Thomas Holland and Brown 2002).

1.3.2 Areas to breed

Carabids, like all coleoptera, grow from eggs, to larvae (in stages or ‘instars’ with moulting), before pupating and emerging as adult beetles. Carabids may be generalised broadly into autumn (hibernating as larvae) or spring breeders (hibernating as adults), though much variation exists on a spectrum through this categorisation and even within it due to climate and resources. Figure 1 shows the lifecycle of a typical autumn breeder, *Pterostichus melanarius*, in the UK. Eggs are laid in the autumn, hatching to larvae which go through three stages, or instars, before pupation. Both previous generation adults and new generation larvae emerge from hibernation in the spring, the larvae pupating to adulthood in the summer, and both generations contributing to eggs laid in the autumn, as the cycle begins again (in some climatic and hydrological cycles *P. melanarius* may digress from this pattern) (Matalin, 2007; Trushitsyna, and Matalin, 2016). Carabids of agro-ecosystems largely lay their eggs in the soil, and larvae are predominantly carnivorous (even when adults are ominivorous), therefore assumed active in crop areas where soil arthropods are plentiful. Larvae, being soft bodied and subject to intense resource need for growth, are the most vulnerable and therefore, crucial, life-stage to consider in boosting populations (Thiele, 1977; Kotze et al., 2011). The timing of farm operations, particularly soil tillage, may impact breeding in egg laying and survivorship of larvae, and these impacts will be variable by species (Traugott, 1998). However, this has not been widely studied due to the difficulty in both trapping and identification of larvae (Luff and Larsson,1993).

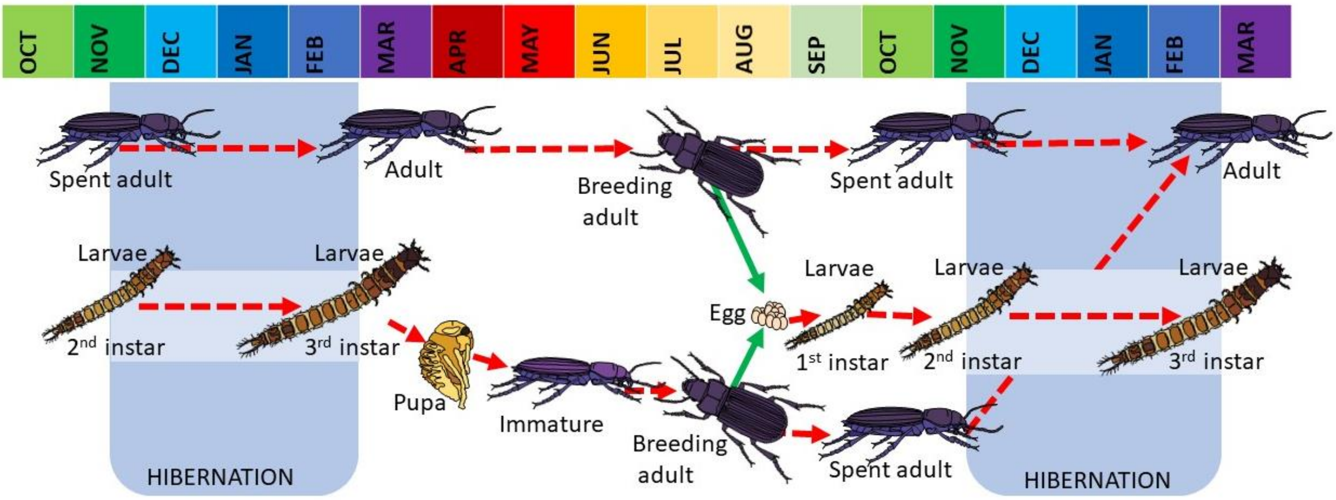


Figure 1- Lifecycle of *Pterostichus melanarius*, typical of autumn breeding carabids in the UK.

1.3.3 Areas to shelter

Providing multiple resources over time to boost the persistence and abundance of populations of natural enemies adjacent to crops is the reasoning behind many agri-environmental measures, such as flower rich margins, beetle banks, and buffer strips (Bianchi, Booij, and Tscharntke, 2006; Dennis and Fry, 1992). Adult carabids move daily and seasonally from these habitats into crop areas, providing services. However, since there are over 350 species of carabid in the UK, and their needs and actualised niches vary considerably, more accuracy is desirable to model community occurrence towards useful application (De Heij, and Willenborg, 2020; Kotze et al., 2011; Kromp, 1999; Tscharntke et al., 2007).

Shelter for carabids encompasses daily cycles, as well as hibernation and aestivation (mid-summer rests connected with resource availability, development, and breeding). In peak activity periods (spring and autumn) carabids of agricultural areas will make daily movements to feed (section 1.2.1). Species differ in their behavioural traits in this respect, some are nocturnal, whilst some diurnal species require ground cover to escape predation, and yet others prefer open areas, escaping predation by fast movement or metallic camouflage (Thiele, 1977). In the rest periods, hibernation and aestivation, carabids require permanent habitat with a stable microclimate, such as dense vegetation. This is the main reason for the recommendation of planting tussocky grasses in field margins or in ‘beetle banks’ (Holland, 2002; Honek et al., 2003; Woodcock et al., 2007). Behaviour again varies in this regard, with different species resting singly, in aggregations, and with different cues and timings according to their breeding cycle (Thiele, 1977).

More generally, different species of carabid have a variety of tolerances for a range of environments. This may be based on diet and availability of food resources, or ability to cope with microclimates such as aridity or humidity (Holland, 2002). More likely these are interlinked, as carabids have adapted to prey inhabiting their niche. For example, *Pterostichis niger* is tolerant of damp conditions, and is a major predator of slugs (Luff, 1998). In-field habitats vary in structure, and associated invertebrates, and therefore one of the key influences on carabid species present in productive area is the crop plant composition (Dennis, Shreeve and Sheppard, 2007; Seidl et al., 2020; Thomas, Holland and Brown, 2002). Farm management such as under-sowing and companion cropping raise the diversity of vegetation and structure, and so may support increased diversity and abundance of carabids in crop areas (Armstrong, and McKinlay, 1997; Theunissen, 1994; Theunissen, and Schelling, 2000). In livestock areas, a variation of grass species and sward length support carabids (Haysom et al., 2004; Toupet et al., 2020). Though the variability of carabid responses to environmental factors at a species level is well documented, this is not accounted for in agri-environmental interventions aimed at NPC (Kotze et al., 2011). More research is needed to elucidate the potential for management to act differently on the occurrence of particular beneficial species.

In summary, Carabids, as is the case with many invertebrates, need multiple habitats in close proximity. The need for complementary habitats to provide resources to forage, shelter, and breed is an essential consideration in farm management planning for NPC. However, simply providing for the needs of carabids in one area is not enough to ensure the presence of carabids, particularly those species that would be particularly useful in a given crop. Healthy populations need habitats to be connected at a wider scale. In order to ensure species movement and gene flow, it is also important to consider how carabids move in farm habitats and landscapes, in order to design interventions for a diverse and abundant assemblage of species (Eisenhauer et al., 2019).

1.3.4 Dispersal

In agricultural landscapes with high disturbance and species turnover, the ability to reach and colonise a habitat is a vital determinate of species presence or absence. In terms of carabid provision of pest control services, their presence in productive areas at the field level is key. This presence is determined by metapopulation dynamics at a larger, farm to landscape scale, as populations inhabiting patches linked by migration, are governed by processes of extinction and recolonization. In agricultural ecosystems the connectivity of patches is vital, as disturbances such as harvest and pesticide application can cause local extinctions. Areas of semi-natural habitats provide refuge for migrating individuals, and sources for recolonization (Cardona-Rivera et al., 2021; Hanski and Poyri, 2007). Recent research has suggested that not just the presence of these habitats, but the proportional size and juxtaposition for connectivity is vital in agricultural landscapes (Benjamin, Cedric, and Pablo, 2008; Feng et al., 2021; Kinnunen and Tiainen, 1999). Due to the divergence of traits and autecological needs, however, the particular effects of landscape composition vary by species (Aviron et al., 2018; Purtauf, Dauber, and Wolters, 2005)

Carabid species’ life histories, dispersal abilities, and responses to disturbances vary dramatically, and so landscape factors may act differently on species according to morphological and behavioural traits. Hedgerows are generally considered to act as connective corridors to a range of wildlife (Montgomery, Caruso, and Reid, 2020), however Thomas Holland and Brown (2002) find little empirical evidence of corridor effects for carabids, whilst Mauremooto et al. (1995) found movements of carabids to be slowed by passage through hedges, and Holland et al. (2004) report differential boundary movements in species of Carabidae.

Around 80% of Carabidae are capable of flight, but are thought to be more actively ground dispersive, as such roads, and even footpaths have been found to act as a barrier (Thomas Holland and Brown 2002). However, recent work by Chapman et al. (2005) has shown that swarms of *Notiophilus biguttatus* migrate seasonally at altitudes up to 1km, the authors assert that this dispersal is currently underestimated, notably by overreliance on pitfall trapping for sampling. Even amongst carabids capable of flight, this ability can be variable, by season with some species disabling flight muscles (autolysis) over periods, or shedding them entirely to allocate resources to breeding, whilst others display variable wing morphology (wing dimorphism, in short brachypterous wings and long macropterous wings) which may be affected by genetics or physical condition depending on species (Desender, 2000; Thiele, 1977).

Even within those species that primarily disperse across the ground there is a variety of locomotive ability. Forsythe (1983; 1987) identified a dichotomy of morphological locomotion among carabids, with runners (long slender tarsi, or legs) or pushers (thick strong tarsi adapted for digging). Behavioural cues also affect dispersal, with some species using open ground to hunt, and others actively moving towards shade for cover (Gruttke, 2000; Thiele, 1977).

The effects of dispersal can also be seen at a field level, whereby edge effects from semi-natural habitats create a spill-over zone of dispersal (Knapp et al., 2019; Rand, Tylianakis, and Tscharntke, 2006). Much research has shown that for many species there is a distance decay effect from greater abundance and diversity of carabids near boundary habitats, decreasing towards the centre of fields. Boezl et al. (2018) found that activity density and species richness declined from the field edge (1m), towards traps in the centre of fields (from 10m to 45m). Whilst Gayer et al. (2019) found larger, more carnivorous, and less flight dispersive species at field centres (12m to 15m in centre of small fields) than at field edges. Similarly, Pecheur et al. (2020) found increasing distances from the crop border to favour larger carabid species (crop edge 2m and centre 30m). The authors also found less granivorous species in crop centres. Therefore edge effects are variable by species, due to dispersal capabilities and diet, for example granivores are less likely to disperse large distances due to seed resources at field edges (Galle et al., 2018; Holland et al., 2005; Saska et al., 2007).

Presence in a habitat does not always equal persistence. The primary factors influencing the ability of carabids to thrive over time, feeding breeding and shelter as above, are also subject to wider constraints in the agricultural ecosystem, including food web processes, climate, physical attributes of a habitat, and human interventions (Dennis, Shreeve, and Sheppard 2007; Hanski and Poyri, 2007).

The factors above combine to characterise a species' functional niche- this is the range of parameters in which a species can inhabit a given environment (Davies, Krebs, and West, 2012). Whilst this can inform what species could potentially inhabit a habitat, the picture is more complex. Competition, predation, and the carrying capacity of the environment also play a role (De Heij, and Willenborg, 2020; Davies, Krebs, and West, 2012).

1.3.5 Niches, competition and predation

Competition over evolutionary time is the major theory explaining the diversity of carabid species, within the broad niche of ground active predatory and scavenging beetles there is, as covered above, a vast variety of strategies and specialisms to refine this niche to species level (Baulechner et al., 2020). Even species ostensibly similar, such as *Pterostichus melanarius*, and *Pterostichus niger*- with similar size, morphology, and predatory capacity, exhibit different tolerances and preferences to environmental factors (*P. melanarius* prefers open ground, whilst *P. niger* tolerates wet areas) (Luff, 1987). In this way, though carabid species may overlap, niche differentiation means direct competition is minimal. Scientific literature has yet to show conclusively that competition occurs interspecifically. Niemela's (1993) overview suggest that methodological flaws, particularly in laboratory-based diet studies, cast doubt on conclusions of competition where it was proposed. There is more evidence that carabid larvae can be cannibalistic, however most work on larvae, especially behaviour, also suffers from bias under laboratory conditions (Luff and Larrson, 1993; Suenaga, and Hamamura, 1998; Thiele, 1977). Gunther and Assmann (2000) in a study of four *Carabus* species at field sites with and without overlap of those species, found species had adjusted activity and phenology to counter reduced prey availability when species cooccurred. Thus, complementarity is more common for ecosystem service provision, as an effect of biodiversity, even within similar functional groups. In fact, some species are known to aggregate in hibernation or aestivation area, it is suggested that this behaviour is in some cases for a multiplicative effect of chemical defences (such as *Brachinus* spp.), and in others as a collective for quick breeding following rest periods (such as *Nebria brevicollis and Agonum dorsale*) (Thiele, 1977). In a recent study Tsafack et al. (2021) examined the spatial niche overlap and cooccurrence scores of carabids in different habitats. The authors found that competition was more evident in stable habitats (steppe and meadow), than disturbed habitats (desert steppe). This may translate to the disturbed agricultural ecosystem, whereby species are sorted by differential tolerances under high turnover.

Similar processes of niche segregation may be observed in various families of spiders (Araneae) competing for resources, as these are an order of invertebrates with similar predation yet divergent foraging strategies (Brown, 1981; Opatovsky et al., 2016; Riechert and Cady, 1983). Likewise, rove beetles (Staphylinidae) are a family of predators with many generalist foraging species overlapping in niche space, with a likelihood of niche segregation (Betz, Wichai, and Volker, 2020; Topp, 1983). Indeed, Staudacher et al. (2018) found that similar processes of habitat heterogeneity acted on communities of Aranae, Stapylinidae and Carabidae in crop areas, prompting relaxation of diet specialisation.

Competition of carabids with other arthropods within the niche of ground predators is potentially significant in spiders (Aranae), rove beetles (Staphilidae) and ants (Formicoidae). There are few studies quantifying their predatory relationship, but it is likely that competition is limited to prey availability, especially between carabids and spiders and ants, as their structural and environmental needs and tolerances are different. Larger rove beetles are able to attack carabids, and vice versa, but the effects of this are estimated to be negligible (Ekschmitt, Wolters, and Weber, 1997; Thiele, 1977; Vehviläinen, Koricheva, and Ruohomäki, 2008)

Carabids are attacked by pathogens and parasites, most frequently in the first life stages. However, in the few studies that exist on this topic, the effects of this have been proven negligible (Holland, 2002; Thiele, 1977). The effects of predation by animals are also not significant in terms of carabid persistence in habitats. Predation on carabids of agricultural areas is mainly by rodents, with lesser predation by farmland birds. Whilst they are capable of regulating carabid populations (Blubaugh, Widick, and Kaplan, 2017; Churchfield Hollier, and Brown, 1991; Rytkönen et al., 2019; Wilson et al., 1999) this has not been proven significant in agricultural areas (Holland 2002). Whilst the effects of predation may not significantly impact carabid populations or the pest regulating services they provide, the place of carabids in the food web supports many animals in agricultural environment. Notable in this respect is the place of carabids as a food resource for the young of threatened farmland birds such as the yellowhammer and grey partridge (Bowler et al., 2019; Larochelle, 1980; Potts and Abischer, 1991).

1.3.6 Farm habitat management

From the above it is apparent that complex biotic interactions determine the carrying capacity of a given environment, in the resources available and turnover in mortality of individuals. These effects are often relatively small when compared with the larger impacts of human alterations of habitats (Holland, 2002). Another, more vital aspect of carabid persistence in farm habitats is the impacts of farm management, such mechanical operations as tillage and harvest alter the physical environment in a catastrophic way for carabids- which, apart from direct mortality, vastly alters the resources and microclimate of the in-field environment (Thomas, Holland and Brown 2002). One of the key concepts supporting retention of semi-natural habitats adjacent to fields is to provide shelter to a proportion of carabids in crop areas, allowing them to persist in the farm landscape, and recolonise crop areas following management disturbance (Kremen and Chaplin-Kramer 2007). However, the science underpinning recommendations, and therefore recommendations in practice, are considered at a field scale. There is little work covering the farm scale effects of management and guidance for spatial placement of measures for natural-enemy pest control by carabids (Kotze, 1999; Heard et al., 2012; Holland, Birkett and Southway, 2009).

Use of chemicals in farm management likewise impacts on carabid beetles in treated areas, but with chemicals there can also be spray drift and runoff that affects semi-natural areas and has wider environmental impacts (De Heij and Willenborg, 2020). Pesticides impact beetles both directly though mortality from chemical effects on carabids as non-target organisms, and indirectly, through affecting mobility and physical abilities to move and feed, their ability to process food, fecundity running on to survivorship of young, and the removal of food resources (Giglio et al., 2011; Heimbach and Baloch, 1994; Holland and Luff, 2000; Leslie et al., 2009; Tooming, 2017). These effects are more marked in the case of insecticide use but are also seen with herbicide use too; particularly secondary effects on granivores (De Heij and Willenborg, 2020; Powell, Dean, and Dewar, 1985). Effects vary by specific chemicals and application, and furthermore vary in impact on different species. This is mainly by activity, for example, diurnal species active on vegetation or open ground will be more frequently hit by topical application (Critchley, 1972a; 1972b; Huusela-Viestola, 1996; Navntoft, Esbjerg, and Riedel, 2006). With seed treatments such as neonicotinoids, effects can be seen by transmission in consumption of prey (Douglas, Rohr and Tooker, 2015; Tooming et al., 2017). Natural enemies of crop pests are more likely to persist as residents in farm habitats, when appropriate shelter is provided, however crop pests have a greater tendency to disperse and populations undergo exponential growth in favourable conditions, meaning they can bounce back from population crashes prompted by farm management more quickly (Kremen and Chaplin-Kramer, 2007; Pisa et al., 2015).

1.3.7 Abiotic factors

Apart from the biotic and human factors, wider abiotic environmental conditions influence the distribution of carabids. The physical properties of the soil are frequently cited as the most influential on carabid persistence in an environment (Luff, 1996). The physical and chemical composition of soils combine, along with topography and climate, to determine the soil moisture, and thus impact on the soil biota. Since the eggs, larvae, and pupae of carabids are soil dwelling, less mobile, and more weakly sclerotised so vulnerable to microclimatic variation, the soil conditions have a great impact on survivorship. The availability of food in the soil for larval stages is determinate of the adult size, and linked to the fecundity of adults in many species. The adults too, use the soil environment to hunt and shelter, and are impacted by conditions and prey availability (Holland, 2002).

As covered above, carabids have a variety of preferences and tolerances for microclimates. At a small spatial scale this can impact breeding, with a higher egg production and longer reproductive period are associated with higher temperatures (within the species' tolerance range), as energy demands for activity are lower (Van Dijk, 1983). Thus at local scales, field aspect and exposure can influence survivorship. At larger scales the occurrence of species is seen in the UK to be variable by north to south temperature gradients (Luff, 1998), and east to west, which may be attributed by farming intensity (Brooks et al., 2008).

The abiotic and biotic factors outlined here are, therefore, operating in a system subject to additional, large scale drivers, with land use change and increasing fragmentation limiting species' movements, and the effects of climate change. The potential for negative impacts on ecosystem services is multiplicatory, especially in environments already degraded by effects of modern agriculture. Given this, there are general recommendations of diverse cropping and landscape to increase biodiversity, and provide the most species possible to fill required niches under a range of scenarios (Bommarco, Vico, and Hallin, 2018). However, interventions aimed at increasing the abundance and diversity of carabids for IPM need to be shown to be effective to balance the time and monetary cost of implementation, in order to boost uptake by farmers.

1.4 Pathways to application

Agri-environmental measures encompass farm management practices aiming to integrate environmental objectives within productive agricultural systems. This covers a wide range of practices, from diversified cropping, through habitat creation in set-aside and crop boundary features; reduced tillage, to decreased chemical inputs and IPM (Power, 2010; Defra, 2014). Encouraging and supporting agri-environmental decisions is one of the routes to securing conservation outcomes (Kelly et al., 2015; Maas et al., 2021; Wilson and Hart 2000). Agri-environmental policy in the UK delivers this in three ways: regulation, incentives, and voluntary action.

Regulation imposes minimum standards farm conditions. Under the European common agricultural policy (CAP) this is currently enforced with greening requirements in the basic payments scheme (Defra, 2014). The current agri-environment schemes (AES) utilise market-based incentives. These programs compensate farmers for loss of income (reduced productivity and capital costs) associated with environmentally friendly farming methods. In the UK, AES are currently delivered under the CAP in environmental stewardship (ES) (Defra, 2016a; 2016b; 2014), however schemes are currently undergoing redesign due to Britain exiting the EU. The new Environmental Land Management schemes (ELMs) are shifting focus from species conservation and general biodiversity, towards ecosystem service provision (Defra, 2020; Hurley et al., 2020). Amongst many novel elements, Defra intends the new ELMs to address previous shortfalls in the information needs of farmers and are reviewing the role of advice and guidance. They are also exploring the potential for innovative delivery mechanisms, including targeting of scheme outcomes, collaborative approaches and utilising the valuation of environmental outcomes to support payments (Defra, 2020). Going forward, the support for building agri-environmental management around organisms such as carabids that provide NPC, and support for better communication with farmers around the principles of agri-environmental intervention for IPM will increase, and research addressing these issues is needed to inform scheme design.

Agri-environmental measures are also implemented voluntarily outside of AES, due to farmer's inherent beliefs and values about the environment and/or perceived economic value (Ahnström et al., 2013). Measures such as the action-threshold spraying strategy have been shown to enhance the economic benefits provided by natural enemies in crops, yet this method, and indeed similar IPM schemes are little practiced in the UK (LEAF, 2015; Zhang et al., 2018). Criticisms have been levelled at scheme structure in commodifying environmental actions, resulting in the necessity for ongoing payments to ensure continued efforts, with some farmers abandoning environmental actions in the absence of reimbursement (Burton and Paragahawewa, 2011; de Snoo et al., 2013). Voluntary action is more likely to result in sustained environmental actions as it is based on enduring beliefs and values, rather than immediate productive or monetary outcomes (Cocklin, Mautner, and Dibden, 2007; Landon, Woosnam, and Boley, 2018; Lockie, 2013; Steg et al., 2014). Research suggests that if farmers are educated in ecosystem services and their utility to production, they are more likely to take-up, and more effectively implement, management targeted to environmental outcomes (Holland et al., 2014; Mills et al., 2017; Pike, 2008). Therefore, to increase both AES and voluntary uptake, more needs to be understood about the socio-economic factors surrounding farmer decision making for NPC.

1.4.1 Farmer decision making

The factors influencing farmer uptake of sustainable practices been extensively studied. Research has shown three major categories governing farmers' environmental decision making, i) *engagement* with environmental advice (awareness and knowledge), ii) *ability* to adopt (external factors), and iii) *willingness* to adopt (internal factors). External factors describe the physical and economic capabilities of farmers to implement, such as the availability of technology, labour and associated costs. Internal factors describe the influences acting upon farmer's thoughts around a behaviour (Mills et al., 2017; Prokopy et al., 2008). Increasing farmers' ability to adopt through addressing external factors have been the focus of early interventions to boost uptake (such as supplying financial support and technical advice) (EC, 2013). Though slow to follow social science advances, policy in the agricultural sector is increasingly incorporating the promise of psychological approaches in 'nudging' decisions and actions (Brook-Lyndhurst 2006). Recent studies have explored social and cultural aspects, recognising the potential for encouraging environmental actions by influencing beliefs and values (Baumgart-Getz, Prokopy, and Floress, 2012; Pike, 2008; Wilson and Hart, 2001).

In this regard, AES uptake can be conceptualised as a *behaviour* (action). Theoretical approaches can identify the factors governing behaviour, and guide intervention design. Though there is considerable diversity in agricultural behavioural research, the framework of the Theory of Planned Behaviour (TPB) (Azjen, 1991) is most widely used in the agricultural sector due to the conceptual fit with outside influences (in the concept of actual behavioural control), and therefore can be modified to explore different agricultural knowledge and information systems (Emery and Franks, 2012; Garforth and Rehman, 2006; Mills et al., 2017; Sutherland, 2010; Terry, Hogg and White, 1999).

Ajzen's (1991) TPB describes the concept of behaviour as a product of intention, based on experience and information accessed by a person. Behavioural intention is formed by a combination of three influencing factors (Figure 2). Attitudes are conceptualised as a product of beliefs about the behaviour (salient beliefs) and evaluations of these beliefs. Subjective norms (SN) are described as social and moral normative influences. Perceived behavioural control (PBC) is the ease or difficulty expected in carrying out a behaviour. PBC acts as a proxy measure of the actual control a subject has over their behaviour, as the perception of this is the critical psychological determinant.

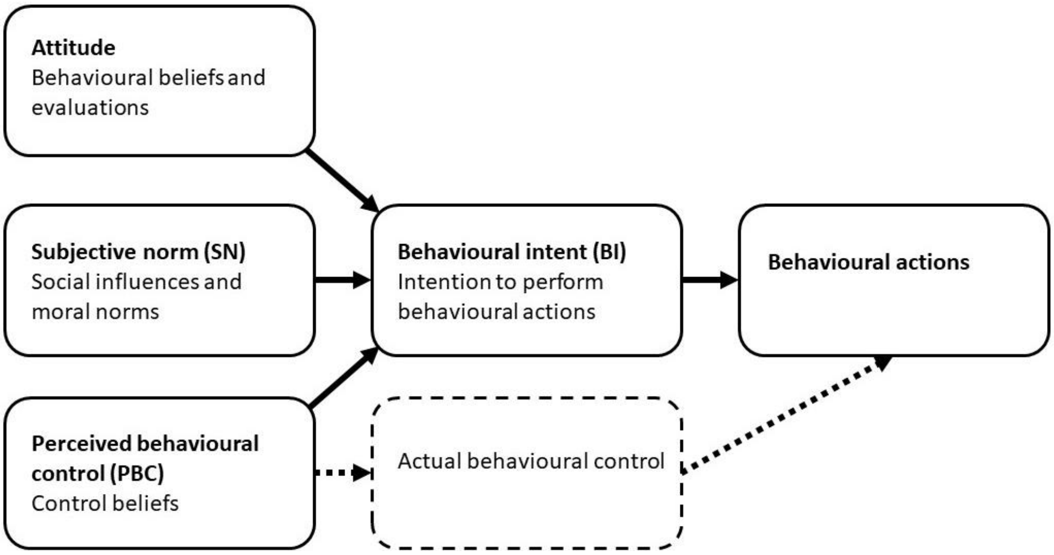


Figure 2- The components of behavioural intention leading to action according to Ajzens' 1991 Theory of Planned Behaviour (TPB)

Pike's (2008) policy framework for Defra draws from the TPB to identify four key interconnected components determining farmer behavioural intentions: attitudes, social norms, habits, and external factors. Social norms (the influence of peer opinions) and habits (continuing with previous behaviours) are influenced capaciously at multiple scales from individual history to wider societal factors. These are difficult to change directly, and in the short term. The approach of AES to address external factors has been inadequate to deliver sufficient attitude change towards uptake for sustainable agriculture, yet attitudes may be changed more directly by increasing awareness and knowledge. Education may therefore be a key focus for interventions (Stiff and Mongeau, 2003).

1.4.2 Agri-environmental education and advisory services

Since the privatisation of state advisory services in 1997, environmental advice and education to farmers in the UK (on regulations, schemes, and voluntary action) is undertaken by a multitude of agencies. Formally, and ubiquitously, in governmental departments such as Natural England (NE); to more specific organisations, such as conservation initiatives, industry enterprises, and businesses such as agronomists. The availability of these services varies spatially. Also, their messages and independent advisory capacities vary by organisation, which may create conflicts of interest such as sustainable and regenerative principles versus technological and biochemical interventions (Blackstock et al., 2010; Dwyer et al., 2007; Ingram, 2008; Klerkx and Proctor, 2013; Morris, 2006; Winter et al., 1996).

It has been shown that when agents understand the premise and benefits of a course of action, they are more likely to implement it effectively (Mills et al., 2018; McCracken et al., 2015), yet educational publications within AES largely comprises generic advice, with more specific and detailed information limited to higher tier agreements. Particularly lacking in these materials is contextual information on how and why management interventions support ecosystem services which underpin production (Winter et al., 1996, Defra, 2016a; 2016b). Particularly, there is no mention in the AES programme design, or documents given to farmers of the value of carabids as agents of pest and weed seed regulation (Defra, 2016a; 2016b; 2020). This may be due to ecological knowledge gaps in scientific literature not supporting the evidence base for interventions, or the lack of utilisation of journal published science in intervention design and extension. However, ‘natural enemies’, and ‘beneficial insects’ are included as umbrella terms, and whilst carabids are included within this remit, the supporting evidence is not in the public domain, and inaccessible to farmers. Different organisations distribute publications covering their respective objectives within their operational areas, such as conservation of farmland wildlife by regional branches of NGOs. Variable availability, and inapplicability to addressing barriers to implementation (in awareness, knowledge, and internal factors affecting willingness to adopt), have limited the impact of such materials to increase uptake (Slee, Gibbon, and Taylor, 2006). The content and context of publications may be also unsuitable for *changing* attitudes, as information alone may not engage and persuade individuals (Rogers, 2010).

Whilst top-down *knowledge transfer* has its place in raising awareness and supporting implementation, a growing body of literature supports *knowledge exchange* as a way forward in building attitudes conducive to uptake of agri-environmental measures acting on perceptions of self-efficacy and PBC (Burton and Paragahawewa, 2011; Ingram, 2008; Morris, 2006.). The multi-directional exchange of data and knowledge between stakeholders both builds trust and provides useful data to guide fully practicable solutions for all parties. In the agricultural sphere, this may comprise schemes for farmer education, farmer groups inputting on local agendas, and co-design of tools and schemes (Defra, 2020; Franks and Emery, , 2013; Lacombe, Couix, and Hazard, 2018; Oliver et al., 2017; Price, 2001; Reed et al.,2014). However, as yet, practical application of this is piecemeal, and there are issues particularly with engaging all farmer groups (Hurley et al., 2020). However, knowledge exchange with farmers has the potential to increase understanding of the benefits of agro-ecological approaches, whilst drawing in expertise to refine the application of these principles.

A major factor influencing farmer perceptions of importance and efficacy of management interventions is evidence that their undertaking is having an effect (Barnes and Toma, 2012; Price, 2001), and that the effect is relevant to the farmer (Dawoe et al., 2012; Ridley et al., 2007). Added to the above problems of access to scientific information, there is often a lack of direct contact, and even some misunderstanding and mistrust of scientific findings (Maas et al., 2021; Sutherland et al., 2013). Farmers are sometimes more likely to trust their own practical experience (Blackstock et al., 2010; Pike, 2008). Monitoring is undertaken as a measure of efficacy of agri-environmental interventions, yet past appraisal of ecological impacts has mainly been undertaken by contracted surveyors and researchers and employed as a site-based proof of concept to guide policy (Boatman et al., 2010; Heard et al., 2012; Oatway, 2018) Some self-assessment has been successful for assurance schemes, such as the Linking Environment and Farming (LEAF) marque scheme, however uptake of these is still low in the context of UK agriculture (LEAF 2015). Individual indicators of success at a farm level are predominantly based on quality standards with little correlation to the ecological improvement afforded by interventions and are undertaken by external agents such as agronomists (Cole, 2019; MacDonald et al., 2019; Waylen et al., 2019). Voluntary monitoring schemes have been successful in farmland—returning valuable data, and engaging farmers in conservation (Gillings et al., 2005; Gregory, Noble, and Custance, 2004; Ridley et al., 2007), yet these schemes have focused on charismatic species and not those that more directly impact production. Some recent studies have focused on monitoring species that have a more direct impact on crop yield, such as pollinators and earthworms (Cole, 2019; Breeze et al., 2020; Gaba and Bretagnolle, 2020; Garratt et al., 2019; Stroud, 2019). Other farmer self-monitoring studies and trials have benefitted from a focus on environmental and yield applicable outcomes (Billaud, Vermeersch, and Porcher, 2020; Matzdorf and Lorenz, 2010; Schroeder et al., 2013). These studies demonstrate the benefits of engaging farmers with conservation outcomes, from building positive attitudes, demonstrating impacts, and producing datasets to feed into further research. Moving forward it is likely that monitoring will become a requirement for results-based payments in the new ELMS (Defra, 2020). Therefore, monitoring is important both in terms of reinforcing that actions have positive affect and to make quantitative measures to refine practice.

1.5 Key areas of knowledge arising from literature review

The introduction has demonstrated the rationale of studying carabids, as a key provider of pest regulation services in farmland which are impacted by land use decisions. This project builds on the understanding gleaned from previous work and attempts to bridge the knowledge gaps, towards both ecological understanding, and behavioural change in farmers for carabid-mediated NPC.

1.5.1 The importance of scale for understanding carabid communities

From the literature reviewed above we can start to build a picture of the influences governing the presence of carabids in crop areas. It is useful to break this down into three spatial scales: the field scale (the crop or crops in question and boundary features), the farm scale (the crops across a farm unit, and adjacent habitats), and a landscape scale (across farm sites regional to national).

At a field scale we see the autecology of species daily needs, particularly granivorous species which cluster on spatially static food resources. The nature of the field environment will govern which particular species find the conditions suitable to persist, with some influence of predation, competition, and survivorship from farm management processes. The temporal aspect becomes more important at the farm level, where other farm habitats are necessary, with shifting resources in the farm cycle (particularly for predatory species), and to provide for lifecycle needs such as hibernation. At the broadest scale, greater temporal aspects of population dynamics in environmental tolerances and species movements become evident. At this landscape scale, the arrangement (juxtaposition) of habitats becomes important, as stepping-stones or corridors for species dispersal, along with the predominant climate and topography (including human architecture) and the fit with species tolerances and dispersal abilities.

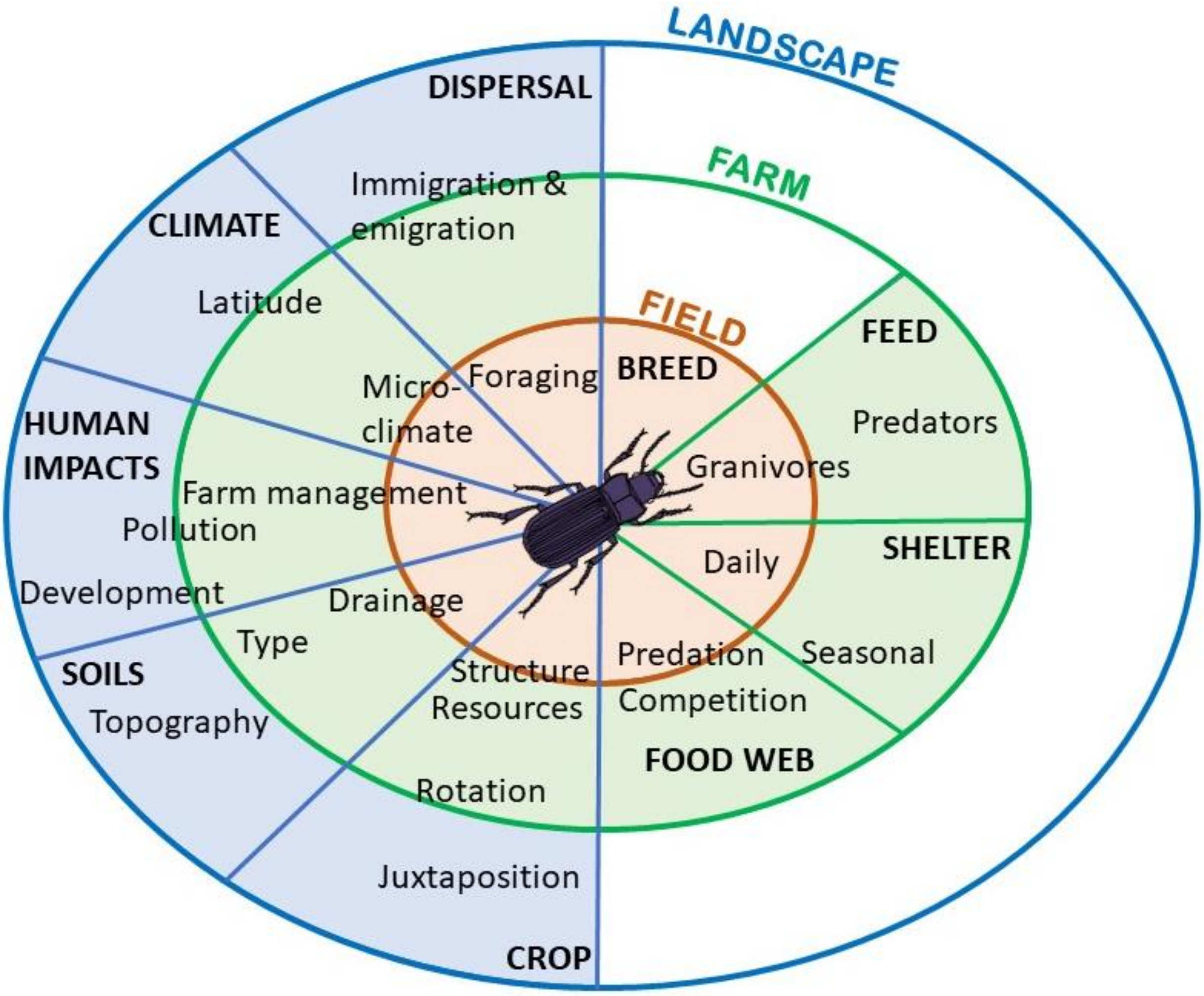


Figure 3- Conceptual diagram of key influences on carabids in agro-ecosystems, by scale

1.5.2 Management options beneficial to carabids

From this picture we can start to see which farm management practices may deliver necessary resources for carabids. Beetle banks were designed for the persistence and movement of beetles at a field scale. These banked structures run through the centre of fields (particularly large fields), connected to one boundary side, and are planted with tussocky grasses and/or wildflower mixes. This is designed to create a range of microclimates with the banked structure and vegetation, supporting a range of invertebrates as alternate food, and so providing resources over time for persistence. This is thought to promote spill-over of beneficial invertebrates into crop areas, based on the idea that centres of large fields will not support many invertebrates for such services as pest control due to distance-decay of dispersal from edge environments. Whilst beetle banks have proved effective in raising abundance of carabids within the bank area, evidence of ecosystem services arising from this is less well documented in the literature (Holland and Luff, 2000; Kromp, 1999; Thomas, Holland, and Brown, 2002; Thomas, Mitchell, and Wratten, 1992).

Hedgerows are commonly stated in the literature as beneficial to carabids. This is mainly based on their characteristic as a stable semi-natural habitat in the agricultural landscape, typically with associated dense grasses and wildflowers at the base, which provides shelter and food resources (Holland and Luff, 2000; Kotze et al., 2011; Kromp, 1999; Thiele, 1977; Thomas, Holland, and Brown, 2002). These are deemed valuable at a field level, however the role of hedges at a farm level is more questionable, with some authors asserting that (particularly dense) hedgerows can act as a barrier to carabids moving between fields, and hence potentially affecting assemblages (Mauremooto et al., 1995). The effects of penetrability are likely to be variable, even within ground dispersing carabids, since certain species are known to move towards the darkness of perceived shelter, whilst others do not (Thiele, 1977). Therefore, whilst hedgerows are valuable, more research into their placement and adjoining habitats is needed.

Field margins are another habitat stated in the literature as vital to the persistence of carabids in agro-ecosystems, with studies finding up to 90% of the catch for some species from field margins alone compared to in-crop and ley habitats (Thomas, Holland, and Brown, 2002). The value of this habitat is in the stability of shelter and alternative prey and seed resources over time, close to crop areas (Eyre, Luff, and Leifert, 2013; Holland, Birkett, and Southway, 2009). The general recommendation is to seed field margins with tussocky grasses, this appears to originate in literature finding that tussocky grasses support overwintering of a few key crop predators, such as cereal aphid predators *Agonum dorsale* and *Demetrias atricapillus* (Desender, 1982; Sotherton, 1984). However, other studies indicate that mat forming grasses, and florally diverse margins provide key resources that may be favoured by certain carabid species, over tussocky grasses at other times of the year (Dennis, Thomas, and Sotherton, 1994; Lagerlöf and Wallin, 1993). Since the effects of grass margins of different types is variable by species, and their seasonal needs may not ensure their utility for pest control in crops simply from spill-over effects, more detail on species specific use of various margins over time would be beneficial. Whilst field margins, as detailed here, are primarily of use at a field scale, there is also potential farm scale utility as corridors of relatively stable habitat linking fields, with a lesser barrier effect than hedgerows, which may better enable certain species to move between fields to pest outbreaks.

The wet areas around ponds and other waterbodies host particular species of carabids. Since these species are tolerant of wet conditions, encouraging them could be beneficial in farmland prone to flooding (Kotze et al., 2011; Thiele, 1977; Thomas, Holland, and Brown, 2002). Ditches in particular are of value to carabids, as these habitats typically host dense vegetation, as shelter in the landscape, and comprise corridors along the edges of fields. Their structure also affords a range of microclimates, similar to beetle banks (Holland and Luff, 2000; Kromp, 1999; Thiele, 1977; Thomas, Holland, and Brown, 2002).

Other semi-natural areas, such as grassland, scrub, and woodland, are valuable for carabids in the farm landscape. Grassland and scrub have been shown as vital source areas for breeding of carabids that move into agricultural areas (Bianchi, Booij, and Tscharntke, 2006; Boetzl et al., 2018; French and Elliott, 1999; Labruyere et al., 2016). Woodland specialist carabid species, whilst important to wider diversity goals, do not generally move out of their habitat, so woodland is not beneficial to crop protection in of itself. However, the edge habitat surrounding farm woodlands can be important to generalist species that inhabit farmland (Thiele, 1977; Thomas, Holland, and Brown, 2002).

The provision of stable semi-natural habitats of farms provides vital habitat for population processes and supports the colonisation of fields for NPC. Yet in-field habitats are more vital to ensure presence and persistence in crop areas (Butler et al., 2009; Butler, Vickery, and Norris, 2006; Kromp, 1999). One of the most beneficial in-field measures for carabids is reduced tillage. Reducing the disturbance that inversion tillage causes to both adults and larvae of carabids in field environments has been shown to boost abundance and diversity. This is added to my the presence of ground cover in surface chaff in some low tillage systems, which can shelter carabids and provides a warmer microclimate (Baguette, and Hance, 1997; Blubaugh and Kaplan, 2015; Eyre, Luff, and Leifert, 2013; Gareau, Voortman, and Barbercheck, 2019; Hatten et al., 2007; Lami et al., 2020; Shearin, Reberg-Horton, and Gallandt, 2014). Measures such as leaving fallow land for periods of time (Kromp, 1999; Thomas, Holland, and Brown, 2002) and cover cropping for periods within rotation cycles (Carmona and Landis, 1999; Gareau, Voortman, and Barbercheck, 2019; Holland and Luff, 2000; Kromp, 1999) are also beneficial to carabids in reducing disturbance and allowing lifecycle processes in field areas. In-crop measures of companion cropping, and under-sowing provide additional cover and food resources by diversifying crop structure at the ground and below-ground level, which has been shown to increase the abundance of carabids (Armstrong and McKinlay, 1997; Kromp, 1999; Theunissen, 1994; Theunissen, and Schelling, 2000). Likewise, extensive grazing diversifies the structure of grazed land, creating tussocks and variety of sward that supports a greater quantity and diversity of carabids (Kotze et al., 2011; McFerran, et al., 1994; Woodcock, et al., 2007). More broadly, a diversity of crops at a farm scale within rotations, and at a landscape scale supports a range of carabid species, comprising a range of conditions and resources within dispersal distances for carabids (particularly flight capable species) promoting species movements and population viability (Eyre, Luff, and Leifert, 2013; Holland and Luff, 2000; Kinnunen and Tiainen, 1999; Kromp, 1999; Redlich, Martin, and Steffan-Dewenter, 2018).

Low pesticide and herbicide use as part of IPM benefits carabids in reducing direct and indirect mortality (section 1.2.6), and maintaining alternative food resources (Brust, 1990; Chiverton, 1984; Holland and Luff, 2000; Kotze et al., 2011). However, the use of artificial fertilisers can impact carabids by modifying the soil environment compared to organic fertiliser, reducing the soil biota and compressing the soil structure (Clapperton and Clapperton 2003; Eyre, Luff, and Leifert, 2013; Holland and Luff, 2000; Kromp, 1999; Thiele, 1977).

Though we can build this broad picture from the literature on the effects of land use on carabids, in some areas the evidence is lacking, fragmented or indirect (De Heij and Willenborg, 2020; Kotze et al., 2011). If we can fill some of these gaps, we can start to get the details necessary to build more efficient interventions and raise uptake of farm measures towards better NPC. In all of the above interventions, effects on carabids are likely to be variable by species. Studies have shown that generalised management recommendations, such as to introduce more non-crop habitats, has inconsistent results across natural enemy taxa, and resultant pest numbers. The effects of interventions are highly context dependant, and subject to complex interactions as covered above (Eisenhauer et al., 2019; Karp et al., 2018; Martin et al., 2019; Tschumi et al., 2018). Carabids, as a group of highly variable species, are a useful taxon to explore the effectiveness of land use and configuration on pest regulation service providers. If we can determine the taxonomic level at which management interactions act, we can make more evidence-based recommendations of what measures to use, and where, for an agriculturally beneficial assemblage.

Whilst some of the influences here depicted are outside of a farmers control, the majority of influence on carabids is reliant of farmer decisions around management. Therefore, the attitudes and behavioural intent of farmers towards carabids is important to creating practicable solutions towards NPC. The gaps in research surrounding knowledge exchange with farmers are therefore also a key issue to address.

1.6 Key questions arising from literature review

a) Does the response of carabids to landscape and farm management significantly vary by species?

Though carabids of agricultural areas are classified as 'generalists' able to cope with a variety of environmental conditions, there is in fact substantial variation between species, in morphology, dispersal power, life histories, behaviours, and predation. This means that species are likely to respond differently to farm management, for instance in direct mortality: different tillage regimes may affect spring and autumn breeders differentially (Hatten et al., 2007; Shearin, Reburg-Hatton and Gallandt, 2014), or recolonisation of field areas: flight dispersive species may recolonise field centres more quickly (Desender, 2000; Thomas, Holland, and Brown, 2003). Since these species also vary in predatory preferences, from dietary preferences (granivores, omnivores or predators) to biomass consumed (by size or activity), management also has the capacity to alter the natural enemy pest control potential of the carabid species assemblage.

Since many studies use pooled carabid abundances, it follows that findings are averaged over potentially divergent species responses. This may be responsible for the lack of consensus over efficacy of measures to increase carabid abundance and diversity in the literature. Thus, it is important to discern whether differential species responses exist towards landscape and farm management, and how significant these would be in dictating the predatory potential of the assemblage.

b) How does larvae service provision differ to adult carabids?

Carabid larvae are mostly soil-dwelling, especially those species inhabiting agro-ecosystems. Though some species may move metres down into the soil, most live near the surface feeding on the biota of the topmost soil horizons. Larvae are predominantly carnivorous, even when the adults are herbivorous (Sasakawa, Ikeda, and Kubota, 2010); and have even been observed climbing up crop plants to feed on invertebrate pests (Suenaga and Hamamura, 1998). Some species such as *Harpalus rufipes* however, specialise in weed seed predation, collecting seeds in burrows for consumption (Traugott, 1998). Because adults move around the crop area following resource need (see section 1.2.1), it is assumed larvae inhabit this area for the duration of this life-stage, and therefore they occur differentially to adults spatially. They are also active in this area at different times to the adults, in particular, some species' larvae are more active than adults in the winter months (Paill, 2000; Traugott

1998). Added to their predacious diet this may mean that they provide a considerable addition to estimates of pest predation; that has previously not been considered.

Carabid larvae, despite attention to the taxa generally and adults in particular, have been scarcely studied. This is due primarily to difficulty of capture (as mostly soil dwelling). A large factor is also taxonomic intractability; identification is difficult, and few guides exist (Luff and Larsson, 1996). Many studies have trapped larvae in standard pitfall traps, yet few attempts to identify to a species level have been undertaken (Kotze et al., 2011). Studies have shown predation of key crop pests by larvae (Paill, 2000; Symondson, 2004), yet most studies on larvae are laboratory based, and suffer from the bias inherent in artificial environments when considering actualised predation and preferences (Suenaga and Hamamura, 1998; Thomas et al., 2009). Much work on larvae is based on assumptions from morphology and analogous organisms, and extended from limited data (Kotze et al., 2011).

This project adds to the knowledge of the distribution of carabid larvae relative to adults, in field scenarios. Coupled with information on their predatory capacity this would enable a holistic, and more accurate picture of carabid predation.

c) Which farm management interventions are most beneficial?

The beneficial effects of agri-environmental interventions on natural enemy pest control have been variable across the literature. This may be due to the very general recommendations, such as tussocky grass margins (Holland, 2002). Carabids of agricultural areas vary in diet, phenology, dispersal, and environmental tolerances (such as moisture levels and recovery from disturbances) (Thiele, 1977). Therefore, management interventions may act differentially on carabids to either boost specific species or connect particular populations. Of particular interest is the effect of different vegetation in margins and buffer strips, as tussocky grass mixes do not benefit all species, or particular species at all times (Dennis, Thomas, and Sotherton, 1994; Lagerlöf and Wallin, 1993). Another area of interest is the action of hedges as corridors or barriers to different species, particularly where hedges exist between crops (Mauremooto et al., 1995)

Not all species provide the services needed, in space and time, and species may be present that do not feed on particular crop pests when outbreaks occur. Though much data exists on the most prevalent species in agro-ecosystems, further knowledge of the impacts of management on specific species, linked with information on pest consumption, could inform targeted management towards more beneficial and efficient provision of services.

This project addresses this shortfall by contributing to the knowledge base by elucidating which species are linked to specific farm management actions. This could inform more specifically which interventions should be used, and where.

d) Can increasing farmers’ positive beliefs about carabids increase uptake of measures for natural-enemy pest control?

Communication and innovation theory points towards targeting beliefs and attitudes to increase the uptake of farm practices (Azjen, 1991). Whilst studies support the theoretical basis for sustainable agriculture (Cole, 2019; Breeze et al., 2020; Gaba and Bretagnolle, 2020; Stroud, 2019), little work has been done to explore the psychological factors surrounding farmer uptake of measures for natural enemy pest control. If an intervention is particularly beneficial for carabids, this needs to be communicated to farmers, or it will not be implemented for natural-enemy pest control. Engaging and educating farmers on the ecology of natural-enemy species has the potential to build positive beliefs and attitudes which will support effective decision making for pest management— and give farmers the understanding that can guide effective implementation of various beneficial management options within their farm system.

This project provides ecological insights into the perceptions of farmers around specific farm management interventions, and guide strategies to increase uptake. Current engagement promoting natural enemy pest control is limited in ecological educatory content, and there is potential for knowledge exchange to provide data for both research and application. The potential for engagement and education by inclusion in experimental work could be explored to develop pathways of knowledge exchange.

e) What are the factors influencing beneficial assemblages at the farm scale?

Though the range of studies involving carabid beetles in an agricultural context is capacious, most of these are either at a small scale (such as plot scale distributions and movements); or in complete contrast, a landscape scale (distributions and populations) (Kotze, 1999). Whilst these are ecologically informative in different respects, the missing intermediate level of farm scale movements presents a critical gap in spatially relevant information for application of practical management interventions. The understanding of movement of carabids in a farm scale landscape is crucial to decisions such as placement of field margins and hedgerows; in connecting populations and boosting resources in ways that accentuate utility to pest control in crop areas (Woodcock et al., 2007).

It is therefore important to determine the most important factors acting at a farm scale, and how farmers might use this information in practice to spatially arrange farm management interventions to boost carabid presence in crops.

1.7 Project aim and objectives

This project aims to improve the efficacy and applicability of farm management interventions that increase the abundance and diversity of carabid species that contribute to natural-enemy pest control. In order to do this, the project addresses three objectives:

1. **Identify factors influencing populations and develop statistical model of carabid distributions**

This incorporates key questions a) and e), by identifying factors from the literature, and examining these within past datasets to identify key factors to feed into data collection. Models statistically determine the relative importance of landscape features and management interventions.

2. **Fieldwork for validation and exploration**

This incorporates key questions a), b), c) and e). This was done by collecting data on species distributions across life-stages. Techniques for efficient sampling of adults, and particularly larvae, were developed. Data were then collected across habitat and management variables (identified in objective 1) at field to landscape scales. This was then related to predation identified in the literature for each species.

3. **Engagement and knowledge exchange with farmers**

This encompasses key question d) by first developing methods for engagement incorporating data collection, then employing this to engage farmers with carabid beetles. Data were collected on the socio-economic and psychological factors surrounding farmer uptake of management beneficial to carabids (identified in objectives 1 and 2). The opportunities and barriers to building ongoing knowledge exchange with farmers was investigated.

1.8 References

Adamski, Z., Bufo, S.A., Chowański, S., Falabella, P., Lubawy, J., Marciniak, P., Pacholska-Bogalska, J., Salvia, R., Scrano, L., Słocińska, M. and Spochacz, M., 2019. Beetles as model organisms in physiological, biomedical and environmental studies—a review. *Frontiers in Physiology*, 10, p.319.

Ahnström, J., Bengtsson, J., Berg, Å., Hallgren, L., Boonstra, W.J. and Björklund, J., 2013. Farmers' interest in nature and its relation to biodiversity in arable fields. *International Journal of Ecology*, 2013.

Akhil, S.V. and Thomas, S.K., 2018. Bombardier beetles (Coleoptera: Carabidae: Brachininae) of India–notes on habit, taxonomy and use as natural bio-control agents. *Frontiers in biological research*, pp.1-25.

Amoabeng, B.W., Asare, K.P., Asare, O.P., Mochiah, M.B., Adama, I., Fening, K.O. and Gurr, G.M., 2017. Pesticides use and misuse in cabbage Brassica oleracea var. capitata L.(Cruciferae) production in Ghana: The influence of farmer education and training. *Journal of Agriculture and Ecology Research International*, pp.1-9.

Ajzen, I., 1991. The theory of planned behavior. *Organizational behavior and human decision processes*, 50(2), pp.179-211.

Armstrong, G. and McKinlay, R.G., 1997. The effect of undersowing cabbages with clover on the activity of carabid beetles. *Biological agriculture & horticulture*, 15(1-4), pp.269-277.

Aviron, S., Lalechère, E., Duflot, R., Parisey, N. and Poggi, S., 2018. Connectivity of cropped vs. semi-natural habitats mediates biodiversity: a case study of carabid beetles communities. *Agriculture, Ecosystems & Environment*, 268, pp.34-43.

Baguette, M. and Hance, T.H., 1997. Carabid beetles and agricultural practices: influence of soil ploughing. *Biological Agriculture & Horticulture*, 15(1-4), pp.185-190.

Barnes, A.P. and Toma, L., 2012. A typology of dairy farmer perceptions towards climate change. *Climatic Change*, 112(2), pp.507-522.

Barney, R.J. and Pass, B.C., 2017. Pitfall trap collections of ground beetle larvae (Coleoptera: Carabidae) in Kentucky alfalfa fields. *The Great Lakes Entomologist*, 19(3), p.2.

Barzman, M., Barberi, P., Birch, A.N.E., Boonekamp, P., Dachbrodt-Saaydeh, S., Graf, B., Hommel, B., Jensen, J.E., Kiss, J., Kudsk, P., Lamichhane, J.R., Messean, A., Moonen, A.C., Ratnadass, A., Ricci, P., Sarah, J.L., Sattin, M., 2015. Eight principles of integrated pest management. *Agronomy for Sustainable Development* 35, 1199-1215.

Baulechner, D., Jauker, F., Neubauer, T.A. and Wolters, V., 2020. Convergent evolution of specialized generalists: Implications for phylogenetic and functional diversity of carabid feeding groups. *Ecology and evolution*, 10(20), pp.11100-11110.

Baumgart-Getz, A., Prokopy, L.S. and Floress, K., 2012. Why farmers adopt best management practice in the United States: a meta-analysis of the adoption literature. *Journal of environmental management*, 96(1), pp.17-25.

Bianchi, F.J., Booij, C.J.H. and Tscharntke, T., 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proceedings of the Royal Society of London B: Biological Sciences*, 273(1595), pp.1715-1727.

Billaud, O., Vermeersch, R.L. and Porcher, E., 2020. Citizen science involving farmers as a means to document temporal trends in farmland biodiversity and relate them to agricultural practices. *Journal of Applied Ecology*.

Benjamin, R., Cédric, G. and Pablo, I., 2008. Modeling spatially explicit population dynamics of Pterostichus melanarius I11.(Coleoptera: Carabidae) in response to changes in the composition and configuration of agricultural landscapes. *Landscape and Urban Planning*, 84(3), pp.191-199.

Beynon, S.A., Warwick, A., Wainright, W.A., Cristie, M., 2015. The application of an ecosystem services framework to estimate the economic value of dung beetles to the U.K. cattle industry. *Ecological Entomology* (2015), 40. Insects and Ecosystem services special issue (Suppl. 1). pp 124–135

Betz, O., Wichai, S. and Volker, P., 2020. Elevational gradients of species richness, community structure, and niche occupation of tropical rove beetles (Coleoptera: Staphylinidae: Steninae) across mountain slopes in Northern Thailand. *Evolutionary Ecology*, 34(2), pp.193-216.

Blackstock, K.L., Ingram, J., Burton, R., Brown, K.M. and Slee, B., 2010. Understanding and influencing behaviour change by farmers to improve water quality. *Science of the Total Environment*, 408(23), pp.5631-5638.

Blubaugh, C.K. and Kaplan, I., 2015. Tillage compromises weed seed predator activity across developmental stages. *Biological Control*, 81, pp.76-82.

Blubaugh, C.K., Widick, I.V. and Kaplan, I., 2017. Does fear beget fear? Risk-mediated habitat selection triggers predator avoidance at lower trophic levels. *Oecologia*, 185(1), pp.1-11.

Boatman, N.D., Jones, N.E., Gaskell, P. and Dwyer, J.C., 2010. Monitoring of agri-environment schemes in the UK. *Aspects of Applied Biology*, (100), pp.9-18.

Boetzl, F.A., Krimmer, E., Krauss, J. and Steffan-Dewenter, I., 2018. Agri-environmental schemes promote ground-dwelling predators in adjacent oilseed rape fields: Diversity, species traits and distance-decay functions. *Journal of Applied Ecology*.

Bohan, D.A., Bohan, A.C., Glen, D.M., Symondson, W.O., Wiltshire, C.W. and Hughes, L., 2000. Spatial dynamics of predation by carabid beetles on slugs. *Journal of Animal Ecology*, 69(3), pp.367-379.

Bommarco, R., Vico, G. and Hallin, S., 2018. Exploiting ecosystem services in agriculture for increased food security. *Global Food Security*, 17, pp.57-63.

Bowler, D. E., Heldbjerg, H., Fox, A. D., de Jong, M. and Böhning-Gaese, K., 2019. Long-term declines of European insectivorous bird populations and potential causes. *Conservation Biology* 33: 1120-1130

Breeze, T.D., Bailey, A.P., Balcombe, K.G., Brereton, T., Comont, R., Edwards, M., Garratt, M.P., Harvey, M., Hawes, C., Isaac, N. and Jitlal, M., 2020. Pollinator monitoring more than pays for itself. *Journal of Applied Ecology*.

Bridges, D.C., 1994. Impact of weeds on human endeavors. *Weed Technology*, pp.392-395.

Brook-Lyndhurst, 2006. Innovative Methods for Influencing Behaviours & Assessing Success: Triggering widespread adoption of sustainable behaviour. *Final Report for Defra*. March 2006

Brooks, D.R., Bater, J.E., Clark, S.J., Monteith, D.T., Andrews, C., Corbett, S.J., Beaumont, D.A. & Chapman, J.W., 2012. Large carabid beetle declines in a United Kingdom monitoring network increases evidence for a widespread loss in insect biodiversity. *Journal of Applied Ecology*, 49, 1009–1019.

Brooks, D.R., Perry, J.N., Clark, S.J., Heard, M.S., Firbank, L.G., Holdgate, R., Shortall, C.R., Skellern, M.P. & Woiwod, I.P., 2008. National-scale metacommunity dynamics of carabid beetles in UK farmland. *Journal of Animal Ecology*,77,265–274.

Brown, K.M., 1981. Foraging ecology and niche partitioning in orb-weaving spiders. *Oecologia*, 50(3), pp.380-385.

Brust, G.E., 1990. Direct and indirect effects of four herbicides on the activity of carabid beetles (Coleoptera: Carabidae). *Pesticide Science*, 30(3), pp.309-320.

Burton, R.J. and Paragahawewa, U.H., 2011. Creating culturally sustainable agri-environmental schemes. *Journal of Rural Studies*, 27(1), pp.95-104.

Butler, S.J., Vickery, J.A. & Norris, K., 2007. A risk assessment framework for evaluating progress towards sustainability targets. *Aspects of Applied Biology*, 81, 317–323.

Butler, S.J., Brooks, D., Feber, R.E., Storkey, J., Vickery, J.A. and Norris, K., 2009. A cross-taxonomic index for quantifying the health of farmland biodiversity. *Journal of Applied Ecology*, 46(6), pp.1154-1162.

Campbell, A.J., Wilby, A., Sutton, P. and Wäckers, F., 2017. Getting more power from your flowers: Multi-functional flower strips enhance pollinators and pest control agents in apple orchards. *Insects*, 8(3), p.101.

Cardona-Rivera, G.A., Clark, B., McHugh, J.V., Bush, B. and Batzer, D.P., 2021. Wetlands Provide a Source of Arthropods Beneficial to Agriculture: A Case Study from Central Georgia, USA. *Journal of Entomological Science*, 56(3), pp.424-440.

Carmona, D.M. and Landis, D.A., 1999. Influence of refuge habitats and cover crops on seasonal activity-density of ground beetles (Coleoptera: Carabidae) in field crops. *Environmental Entomology*, 28(6), pp.1145-1153.

Carpenter, S.R., Mooney, H.A., Agard, J., Capistrano, D., DeFries, R.S., Díaz, S., Dietz, T., Duraiappah, A.K., Oteng-Yeboah, A., Pereira, H.M. and Perrings, C., 2009. Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proceedings of the National Academy of Sciences*, 106(5), pp.1305-1312.

Chapman, J.W., Reynolds, D.R., Smith, A.D., Riley, J.R., Telfer, M.G. and Woiwod, I.P., 2005. Mass aerial migration in the carabid beetle Notiophilus biguttatus. *Ecological Entomology*, 30(3), pp.264-272.

Chiverton, P.A., 1984. Pitfall-trap catches of the carabid beetle Pterostichus melanarius, in relation to gut contents and prey densities, in insecticide treated and untreated spring barley. *Entomologia experimentalis et applicata*, 36(1), pp.23-30.

Churchfield, S., Hollier, J. and Brown, V.K., 1991. The effects of small mammal predators on grassland invertebrates, investigated by field exclosure experiment. *Oikos*, pp.283-290.

Cividanes, F.J., 2021. Carabid beetles (Coleoptera: Carabidae) and biological control of agricultural pests in Latin America. *Annals of the Entomological Society of America*, 114(2), pp.175-191.

Clapperton, M.J. and Clapperton, M.J., 2003. Increasing soil biodiversity through conservation agriculture: managing the soil as a habitat. *Proc. Second World Cong. on Conservation Agriculture: producing in harmony with nature*, Iguassu Falls, Parana-Brazil, pp.11-15.

Critchley, B.R., 1972a. A laboratory study of the effects of some soil-applied organophosphorus pesticides on Carabidae (Coleoptera). *Bulletin of Entomological research*, 62(2), pp.229-242.

Critchley, B.R., 1972b. Field investigations on the effects of an organophosphorus pesticide, thionazin, on predacious Carabidae (Coleoptera). *Bulletin of Entomological Research*, 62(2), pp.327-342. DOI: https://doi.org/10.1017/S0007485300047751

Cocklin, C., Mautner, N. and Dibden, J., 2007. Public policy, private landholders: perspectives on policy mechanisms for sustainable land management. *Journal of environmental management*, 85(4), pp.986-998.

Cole, A., 2019. Agri-Environment Monitoring and Evaluation Programme Annual Report 2017/18: A summary of findings from recently published projects. *Natural England Research Reports, Number 079*.

Cole, L., Pollock, M., Robertson, D., Holland, J. and McCracken, D., 2006. Carabid (Coleoptera) assemblages in the Scottish uplands: the influence of sheep grazing on ecological structure. *Entomologica Fennica*, 17(3), pp.229-240.

Davies, N.B., Krebs, J.R. and West, S.A., 2012. *An introduction to behavioural ecology*. John Wiley & Sons.

Dawoe, E.K., Quashie-Sam, J., Isaac, M.E. and Oppong, S.K., 2012. Exploring farmers' local knowledge and perceptions of soil fertility and management in the Ashanti Region of Ghana. *Geoderma*, 179, pp.96-103.

Defra, 2020. *Environmental Land Management Policy discussion document February 2020*. Available online at [https://consult.defra.gov.uk/elm/elmpolicyconsultation/supporting_documents/elmdiscussiondocument20200225a%20002.pdf] accessed 09.03.20

Defra 2016a. *Countryside Stewardship: Mid Tier Manual*. Published 14 March 2016. London: HMGOV

Defra 2016b. *Countryside Stewardship: Higher Tier Manual*. Published 14 March 2016. London: HMGOV

Defra, 2014. *An introduction to the new Common Agricultural Policy schemes in England*. April 2014

De Heij, S.E. and Willenborg, C.J., 2020. Connected Carabids: Network Interactions and Their Impact on Biocontrol by Carabid Beetles. *BioScience*, 70(6), pp.490-500.

Dennis, P. and Fry, G.L., 1992. Field margins: can they enhance natural enemy population densities and general arthropod diversity on farmland?. *Agriculture, Ecosystems & Environment*, 40(1-4), pp.95-115.

Dennis, R.L.H., Shreeve, T.G. and Sheppard, D.A., 2007. Species conservation and Landscape Management- A Habitat Perspective. In- Stewart A.J.A, New, T.R. and Lewis, O.T., 2007. Insect Conservation Biology. *Proceedings of the Royal Entomological Societies 23rd symposium.* Oxford: CABI. Pp 92-126.

Dennis, P., Thomas, M.B. and Sotherton, N.W., 1994. Structural features of field boundaries which influence the overwintering densities of beneficial arthropod predators. *Journal of Applied Ecology* 31, 361–370.

Desender, K., 1982. Ecological and faunal studies on Coleoptera in agricultural land. II. Hibernation of Carabidae in agro-ecosystems. *Pedobiologia* 23, 295–303.

Desender, K., 2000. Flight muscle development and dispersal in the life cycle of carabid beetles: patterns and processes. *Entomologie*, 70, pp.13-31.

De Snoo, G.R., Herzon, I., Staats, H., Burton, R.J., Schindler, S., van Dijk, J., Lokhorst, A.M., Bullock, J.M., Lobley, M., Wrbka, T. and Schwarz, G., 2013. Toward effective nature conservation on farmland: making farmers matter. *Conservation Letters*, 6(1), pp.66-72.

Deutsch, C.A., Tewksbury, J.J., Tigchelaar, M., Battisti, D.S., Merrill, S.C., Huey, R.B. and Naylor, R.L., 2018. Increase in crop losses to insect pests in a warming climate. *Science*, 361(6405), pp.916-919.

Drmić, Z., Čačija, M., Gašparić, H.V., Lemić, D. and Bažok, R., 2016. Endogaeic ground beetles fauna in oilseed rape field in Croatia*. Journal of central European agriculture*.

Douglas, M.R., Rohr, J.R. and Tooker, J.F., 2015. EDITOR'S CHOICE: Neonicotinoid insecticide travels through a soil food chain, disrupting biological control of non-target pests and decreasing soya bean yield. *Journal of Applied Ecology*, 52(1), pp.250-260.

Duflot, R., Ernoult, A., Aviron, S., Fahrig, L. and Burel, F., 2017. Relative effects of landscape composition and configuration on multi-habitat gamma diversity in agricultural landscapes. *Agriculture, Ecosystems & Environment*, 241, pp.62-69. https://doi.org/10.1016/j.agee.2017.02.035

Dwyer, J., Mills, J., Ingram, J., Taylor, J., Burton, R., Blackstock, K., Slee, B., Brown, K., Schwarz, G., Matthews, K. and Dilley, R., 2007. *Understanding and influencing positive behaviour change in farmers and land managers*. CCRI, Macaulay Institute.

EC, 2013. *Agricultural Policy Perspectives Brief N°5** / December 2013 Overview of CAP Reform 2014-2020.

Eisenhauer, N., Schielzeth, H., Barnes, A.D., Barry, K., Bonn, A., Brose, U., Bruelheide, H., Buchmann, N., Buscot, F., Ebeling, A. and Ferlian, O., 2019. A multitrophic perspective on biodiversity–ecosystem functioning research. *Adv. Ecol. Res*, 61, pp.1-54.

Ekschmitt, K., Wolters, V., and Weber, M., 1997. Spiders, carabids, and staphylinids: the ecological potential of predatory macroarthropods. *Fauna in soil ecosystems*. Recycling processes, nutrient fluxes, and agricultural production, pp.307-362.

Emery, S.B. and Franks, J.R., 2012. The potential for collaborative agri-environment schemes in England: Can a well-designed collaborative approach address farmers' concerns with current schemes? *Journal of Rural Studies*, 28(3), pp.218-231.

EU, 2009. *Directive 2009/128/EC of the European parliament and of the council of 21 October 2009*. establishing a framework for community action to achieve the sustainable use of pesticides. Off J Eur Union 52:71–86, Available at: http://eur-lex.europa.eu/legal-content/EN/ TXT/?uri=OJ:L:2009:309:TOC [Accessed 13/01/21]

Eyre, M.D., Luff, M.L. and Leifert, C., 2013. Crop, field boundary, productivity and disturbance influences on ground beetles (Coleoptera, Carabidae) in the agroecosystem. *Agriculture, ecosystems & environment*, 165, pp.60-67.

Ferrante, M., Cacciato, A.L. and Lövei, G.L., 2014. Quantifying predation pressure along an urbanisation gradient in Denmark using artificial caterpillars. *European Journal of Entomology*, 111(5), p.649.

Feng, L., Arvidsson, F., Smith, H.G. and Birkhofer, K., 2021. Fallows and permanent grasslands conserve the species composition and functional diversity of carabid beetles and linyphiid spiders in agricultural landscapes. *Insect Conservation and Diversity*.

Floate, K.D., Doane, J.F. and Gillott, C., 1990. Carabid predators of the wheat midge (Diptera: Cecidomyiidae) in Saskatchewan. *Environmental Entomology*, 19(5), pp.1503-1511.

Finch, S. and Elliott, M.S., 1992. Predation of cabbage root fly eggs by Carabidae. *Predation of cabbage root fly eggs by Carabidae*., 15(4), pp.176-183.

Forsythe, T.G., 1983. Locomotion in ground beetles (Coleoptera Carabidae): an interpretation of leg structure in functional terms. *Journal of Zoology*, 200(4), pp.493-507.

Forsythe, T.G., 1987. The relationship between body form and habit in some Carabidae (Coleoptera). *Journal of Zoology*, 211(4), pp.643-666.

Franks, J.R. and Emery, S.B., 2013. Incentivising collaborative conservation: Lessons from existing environmental Stewardship Scheme options. *Land Use Policy*, 30(1), pp.847-862.

French, B.W. and Elliott, N.C., 1999. Temporal and spatial distribution of ground beetle (Coleoptera: Carabidae) assemblages in grasslands and adjacent wheat fields. *Pedobiologia*, 43(1), pp.73-84.

Gaba, S., and Bretagnolle, V., 2020 Designing multifunctional and resilient agricultural landscapes: lessons from long-term monitoring of biodiversity and land use. In: The Changing Status of Arable Habitats in Europe (Eds. Hurford C, Wilson, P. & Storkey J.). *Springer Nature Publishing*. In press

Gallé, R., Happe, A.K., Baillod, A.B., Tscharntke, T. and Batáry, P., 2018. Landscape configuration, organic management, and within-field position drive functional diversity of spiders and carabids. *Journal of Applied Ecology*. https://doi.org/10.1111/1365-2664.13257

Gareau, T.P., Voortman, C. and Barbercheck, M., 2019. Carabid beetles (Coleoptera: Carabidae) differentially respond to soil management practices in feed and forage systems in transition to organic management. *Renewable Agriculture and Food Systems*, pp.1-18.

Garforth, C. and Rehman, T., 2006. Research to understand and model the behaviour and motivations of farmers in responding to policy changes (England). *Department for Environment, Food and Rural Affairs Research project EPES 0405/17*

Garratt, M.P.D., Potts, S.G., Banks, G., Hawes, C., Breeze, T.D., O'Connor, R.S. and Carvell, C., 2019. Capacity and willingness of farmers and citizen scientists to monitor crop pollinators and pollination services. *Global Ecology and Conservation,* 20, p.e00781.

Gayer, C., Lövei, G.L., Magura, T., Dieterich, M. and Batáry, P., 2019. Carabid functional diversity is enhanced by conventional flowering fields, organic winter cereals and edge habitats. *Agriculture, Ecosystems & Environment*, 284, p.106579.

Giglio, A., Giulianini, P.G., Zetto, T. and Talarico, F., 2011. Effects of the pesticide dimethoate on a non-target generalist carabid, Pterostichus melas italicus (Dejean, 1828)(Coleoptera: Carabidae). *Italian Journal of Zoology*, 78(4), pp.471-477.

Gillings, S., Newson, S.E., Noble, D.G. and Vickery, J.A., 2005. Winter availability of cereal stubbles attracts declining farmland birds and positively influences breeding population trends. *Proceedings of the Royal Society B: Biological Sciences*, 272(1564), pp.733-739.

Gregory, R.D., Noble, D, and Custance, J., 2004. *The state of play of farmland birds: population trends and conservation status of lowland farmland birds in the United Kingdom*. Ibis, 146, pp.1-13.

Gruttke, H., 2000. Experiments on orientation and habitat choice of Laemostenus terricola (Col., Carabidae). *Natural history and applied ecology of Carabid beetles*. Moscow: Pensoft, pp.123-131.

Günther, J.M. and Assmann, T., 2000. Competition in the woodland? Phenology, body mass and body length of coexisting Carabus species–preliminary results (Coleoptera, Carabidae). *Natural history and applied ecology of carabid beetles*. Pensoft, Sofia, pp.185-195.

Hanski, I., and Poyry, J., 2007. Insect populations in Fragmented Habitats. In- Stewart A.J.A, New, T.R. and Lewis, O.T., 2007. Insect Conservation Biology. *Proceedings of the Royal Entomological Societies 23rd symposium*. Oxford: CABI. Pp 175-202.

Harterreiten-Souza, É.S., Togni, P.H., Capellari, R.S., Bickel, D., Pujol-Luz, J.R. and Sujii, E.R., 2021. Spatiotemporal dynamics of active flying Diptera predators among different farmland habitats. *Agricultural and Forest Entomology*.

Hatten, T.D., Bosque-Pérez, N.A., Labonte, J.R., Guy, S.O. and Eigenbrode, S.D., 2007. Effects of tillage on the activity density and biological diversity of carabid beetles in spring and winter crops. *Environmental entomology*, 36(2), pp.356-368.

Hayhow D.B., Eaton, M.A., Stanbury, A.J., Burns, F., Kirby, W.B., Bailey, N., Beckmann, B., Bedford, J., Boersch-Supan P.H., Coomber, F., Dennis, E.B., Dolman, S.J., Dunn, E., Hall, J., Harrower, C., Hatfield, J.H., Hawley, J., Haysom, K., Hughes J., Johns, D.G., Mathews, F., McQuatters-Gollop A., Noble, D.G., Outhwaite, C.L., Pearce-Higgins, J.W., Pescott, O.L,, Powney, G.D. and Symes, N., 2019. *The State of Nature 2019*. The State of Nature partnership.

Haysom K.A., McCracken D.I., Foster G.N and Sotherton N.W. 2004. Developing grassland conservation headlands: response of carabid assemblage to different cutting regimes in a silage field edge. *Agriculture, Ecosystems and Environment* 102 (2004) 263–277

Heard, M.S., Botham, M., Broughton, R., Carvell, C., Hinsley, S., Woodcock, B. and Pywell, R.F., 2012. *Quantifying the effects of entry level stewardship (ELS) on biodiversity at the farm scale: the Hillesden experiment*. NERC

Heimbach, U. and Baloch, A.A., 1994. Effects of three pesticides on Poecilus cupreus (coleoptera: carabidae) at different post-treatment temperatures. *Environmental Toxicology and Chemistry: An International Journal*, 13(2), pp.317-324.

Holland, J.M., 2002. *The agroecology of carabid beetles*. Intercept Limited.

Holland, J.M., Begbie, M., Birkett, T., Southway, S., Thomas, S.R., Alexander, C.J. and Thomas, C.F.G., 2004. The spatial dynamics and movement of Pterostichus melanarius and P. madidus (Carabidae) between and within arable fields in the UK. *International Journal of Ecology and Environmental Sciences.* 30, pp.35-50.

Holland, J.M., Frampton, G.K. and Van den Brink, P.J., 2002. Carabids as indicators within temperate arable farming systems: implications from SCARAB and LINK integrated farming systems projects. *The agroecology of carabid beetles*. Intercept, Andover, UK.

Holland, J.M. and Luff, M.L., 2000. The effects of agricultural practices on Carabidae in temperate agroecosystems. *Integrated pest management reviews*, 5(2), pp.109-129.

Holland, J.M., Storkey, J., Lutman, P.J.W., Birkett, T.C., Simper, J. and Aebischer, N.J., 2014. Utilisation of agri-environment scheme habitats to enhance invertebrate ecosystem service providers. *Agriculture, ecosystems & environment*, 183, pp.103-109.

Holland, J.M., Thomas, C.F.G., Birkett, T., Southway, S. & Oaten, H., 2005. Farm-scale spatiotemporal dynamics of predatory beetles in arable crops. *Journal of Applied Ecology*, 42, 1140–1152.

Holland, J.M., Birkett, T. and Southway, S., 2009. Contrasting the farm-scale spatio-temporal dynamics of boundary and field overwintering predatory beetles in arable crops. *Biocontrol*, 54(1), pp.19-33. https://doi.org/10.1007/s10526-008-9152-2

Holland, J.M. and Luff, M.L., 2000. The effects of agricultural practices on Carabidae in temperate agroecosystems. *Integrated pest management reviews*, 5(2), pp.109-129.

Holt, J.S., 1994. Impact of weed control on weeds: New problems and research needs. *Weed Technology*, pp.400-402.

Honek et al., 2003 *In*: Kotze, D.J., et al 2011. Forty years of carabid beetle research in Europe–from taxonomy, biology, ecology and population studies to bioindication, habitat assessment and conservation. *ZooKeys,* (100), p.55.

Hurley, P., Lyon, J., Hall, J., Little, R., Tsouvalis, J. and Rose, D., 2020. *Co-designing the Environmental Land Management Scheme in England: the why, who, and how of engaging 'harder to reach' stakeholders*. HMGOV

Huusela-Veistola, E., 1996, January. Effects of pesticide use and cultivation techniques on ground beetles (Col., Carabidae) in cereal fields. In *Annales Zoologici Fennici* (pp. 197-205). Finnish Zoological and Botanical Publishing Board.

Imboma, T.S., Gao, D.P., You, M.S., You, S. and Lövei, G.L., 2020. Predation Pressure in Tea (Camellia sinensis) Plantations in Southeastern China Measured by the Sentinel Prey Method. *Insects*, 11(4), p.212.

Ingram, J., 2008. Agronomist–farmer knowledge encounters: an analysis of knowledge exchange in the context of best management practices in England. *Agriculture and Human Values*, 25(3), pp.405-418.

IPBES, 2019. *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. S. Díaz, J. et al. (eds.). IPBES secretariat, Bonn, Germany. https://www.ipbes.net/global-assessment

Karp, D.S., Chaplin-Kramer, R., Meehan, T.D., Martin, E.A., DeClerck, F., Grab, H., Gratton, C., Hunt, L., Larsen, A.E., Martínez-Salinas, A. and O'Rourke, M.E., 2018. Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. *Proceedings of the National Academy of Sciences*, p.201800042.

Kamenova, S., Bretagnolle, V., Plantegenest, M. and Canard, E., 2018. DNA metabarcoding diet analysis reveals dynamic feeding behaviour and biological control potential of carabid farmland communities. *BioRxiv*, p.332312.

Kelly, E., Heanue, K., Buckley, C. and O'Gorman, C., 2015, August. Proven science versus farmer perception. In 2015 Conference International Association of Agricultural Economists, Milan, Italy, 9-14 August 2015. *International Conference of Agricultural Economists.*

Kinnunen, H. and Tiainen, J., 1999. Carabid distribution in a farmland mosaic: the effect of patch type and location. *In Annales Zoologici Fennici* (pp. 149-158). Finnish Zoological and Botanical Publishing Board.

Kleijn. D., and Sutherland, W.J., 2003. How effective are European agri-environment schemes in conserving and promoting biodiversity? *Journal of Applied Ecology*. 2003 40. Pp 947–969

Klerkx, L. and Proctor, A., 2013. Beyond fragmentation and disconnect: networks for knowledge exchange in the English land management advisory system. *Land Use Policy*, 30(1), pp.13-24.

Knapp, M., Seidl, M., Knappová, J., Macek, M. and Saska, P., 2019. Temporal changes in the spatial distribution of carabid beetles around arable field-woodlot boundaries. *Scientific reports*, 9(1), pp.1-11.

Kos, T., Bažok, R., Drmić, Z., Graša, Ž. (2013) Ground beetles (Coleoptera: Carabidae) in sugar beet fields as the base for conservation biological control. In: Jehle, J. A., Bažok, R., Crickmore, N., López-Ferber, M., Glazer, I., Quesada-Moraga, E., Traugott, M., eds. (2013) *Proceedings of the 14th Meeting of the IOBC/wprs Working Group "Insect Pathogens and Entomoparasitic Nematodes".* Zagreb, Croatia, 16-20 June 2013. IOBC/wprs Bulletin, 90, 353-357.

Kotze, D.J. & O'Hara, R.B., 2003. Species decline – but why? Explanations of carabid beetle (Coleoptera, Carabidae) declines in Europe. *Oecologia*, 135, 138–148.

Kotze, D.J., Brandmayr, P., Casale, A., Dauffy-Richard, E., Dekoninck, W., Koivula, M.J., Lövei, G.L., Mossakowski, D., Noordijk, J., Paarmann, W. and Pizzolotto, R., 2011. Forty years of carabid beetle research in Europe–from taxonomy, biology, ecology and population studies to bioindication, habitat assessment and conservation. *ZooKeys,* (100), p.55.

Kremen, C., and Chaplin-Kramer, R., 2007. Insects as Providers of Ecosystem Services: Crop pollination and pest control. *In-* Stewart A.J.A, New, T.R. and Lewis, O.T., 2007. I*nsect Conservation Biology. Proceedings of the Royal Entomological Societies 23rd symposium*. Oxford: CABI. Pp 349-382

Kromp, B., 1999. Carabid beetles in sustainable agriculture: a review on pest control efficacy, cultivation impacts and enhancement. *Agriculture, Ecosystems & Environment*. Volume 74, Issues 1–3, June 1999, Pp 187–228

Labruyere, S., Bohan, D.A., Biju-Duval, L., Ricci, B. and Petit, S., 2016. Local, neighbor and landscape effects on the abundance of weed seed-eating carabids in arable fields: A nationwide analysis. *Basic and applied ecology*, 17(3), pp.230-239. https://doi.org/10.1016/j.baae.2015.10.008

Lacombe, C., Couix, N. and Hazard, L., 2018. Designing agroecological farming systems with farmers: A review. *Agricultural systems*, 165, pp.208-220.

Lagerlöf, J. and Wallin, H., 1993. The abundance of arthropods along two field margins with different types of vegetation composition: an experimental study. *Agriculture, Ecosystems & Environment* 43, 141–154.

Lami, F., Boscutti, F., Masin, R., Sigura, M. and Marini, L., 2020. Seed predation intensity and stability in agro-ecosystems: Role of predator diversity and soil disturbance. *Agriculture, Ecosystems & Environment*, 288, p.106720.

Landon, A.C., Woosnam, K.M. and Boley, B.B., 2018. Modeling the psychological antecedents to tourists' pro-sustainable behaviors: An application of the value-belief-norm model. *Journal of sustainable tourism*, 26(6), pp.957-972.

Larochelle, A., 1980. A list of birds of Europe and Asia as predators of carabid beetles including Cicindelini (Coleoptera: Carabidae). *Cordulia*, 6, pp.1-19.

LEAF, 2015. *A review of our 2014 global impacts*. Linking Environment and Farming. Stoneleigh Park, Warwickshire.

Leslie, T.W., Biddinger, D.J., Mullin, C.A. and Fleischer, S.J., 2009. Carabidae population dynamics and temporal partitioning: response to coupled neonicotinoid-transgenic technologies in maize. *Environmental entomology*, 38(3), pp.935-943.

Lockie, S., 2013. Market instruments, ecosystem services, and property rights: assumptions and conditions for sustained social and ecological benefits. *Land use policy*, 31, pp.90-98.

Loos, J., Batáry, P., Grass, I., Westphal, C., Bänsch, S., Baillod, A.B., Hass, A.L., Rosa, J. and Tscharntke, T., 2019. Vulnerability of ecosystem services in farmland depends on landscape management. *In Atlas of Ecosystem Services* (pp. 91-96). Springer, Cham.

Lövei, G.L. and Sunderland, K.D., 1996. Ecology and behavior of ground beetles (Coleoptera: Carabidae). *Annual review of entomology*, 41(1), pp.231-256.

Luff, M.L., 1998. Provisional Atlas of the Ground Beetles (Coleoptera, Carabidae) of Britain. *Biological Records Centre Institute of Terrestrial Ecology*

Luff, M.L., 1987. Biology of polyphagous ground beetles in agriculture. *Agricultural Zoology Reviews*, 2, pp.237-278.

Luff, M.L. and Larsson, S.G., 1993. *The Carabidae (Coleoptera) Larvae of of Fennoscandia and Denmark* (Vol. 27). Brill.

Maas, B., Fabian, Y., Kross, S.M. and Richter, A., 2021. Divergent farmer and scientist perceptions of agricultural biodiversity, ecosystem services and decision-making. *Biological Conservation*, 256, p.109065.

MacDonald, M.A., Angell, R., Dines, T.D., Dodd, S., Haysom, K.A., Hobson, R., Johnstone, I.G., Matthews, V., Morris, A.J., Parry, R. and Shellswell, C.H., 2019. Have Welsh agri-environment schemes delivered for focal species? Results from a comprehensive monitoring programme. *Journal of Applied Ecology*, 56(4), pp.812-823.

Marrec, R., Badenhausser, I., Bretagnolle, V., Börger, L., Roncoroni, M., Guillon, N. and Gauffre, B., 2015. Crop succession and habitat preferences drive the distribution and abundance of carabid beetles in an agricultural landscape. *Agriculture, Ecosystems & Environment*, 199, pp.282-289.

Martin, E.A., Dainese, M., Clough, Y., Báldi, A., Bommarco, R., Gagic, V., Garratt, M.P., Holzschuh, A., Kleijn, D., Kovács-Hostyánszki, A. and Marini, L., 2019. The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe. *Ecology letters*.

Martin, E.A., Reineking, B., Seo, B. and Steffan-Dewenter, I., 2013. Natural enemy interactions constrain pest control in complex agricultural landscapes. *Proceedings of the National Academy of Sciences*, 110(14), pp.5534-5539.

Matalin, A.V., 2007. Typology of life cycles of ground beetles (Coleoptera, Carabidae) in Western Palaearctic. *Entomological Review*, 87(8), pp.947-972.

Matzdorf, B. and Lorenz, J., 2010. How cost-effective are result-oriented agri-environmental measures?An empirical analysis in Germany. *Land use policy*, 27(2), pp.535-544.

Mauremooto, J.R., Wratten, S.D., Worner, S.P., and Fry, G.L.A., 1995. Permeability of hedgerows to predatory carabid beetles. *Agriculture, Ecosystems and Environment*. 52 (1995) pp 141-148

Mestre, L., Schirmel, J., Hetz, J., Kolb, S., Pfister, S.C., Amato, M., Sutter, L., Jeanneret, P., Albrecht, M. and Entling, M.H., 2018. Both woody and herbaceous semi-natural habitats are essential for spider overwintering in European farmland. *Agriculture, Ecosystems & Environment*, 267, pp.141-146.

McCracken, M.E., Woodcock, B.A., Lobley, M., Pywell, R.F., Saratsi, E., Swetnam, R.D., Mortimer, S.R., Harris, S.J., Winter, M., Hinsley, S. and Bullock, J.M., 2015. Social and ecological drivers of success in agri-environment schemes: the roles of farmers and environmental context. *Journal of Applied Ecology*, 52(3), pp.696-705.

McFerran, D.M., Meharg, M.J., Montgomery, W.I. and McAdam, J.H., 1994. The impact of grazing on communities of ground-dwelling beetles (Coleoptera: Carabidae) in upland vegetation in north-east Ireland. In *Carabid beetles: ecology and evolution* (pp. 325-330). Springer, Dordrecht.

Mills, J., Gaskell, P., Ingram, J., Dwyer, J., Reed, M. and Short, C., 2017. Engaging farmers in environmental management through a better understanding of behaviour. *Agriculture and Human Values*, 34(2), pp.283-299.

Mitchell, B., 1963. Ecology of two carabid beetles, Bembidion lampros (Herbst) and Trechus quadristriatus (Schrank). *The Journal of Animal Ecology*, pp.377-392.

Montgomery, I., Caruso, T. and Reid, N., 2020. Hedgerows as ecosystems: service delivery, management, and restoration. *Annual Review of Ecology, Evolution, and Systematics*, 51, pp.81-102.

Morris, C., 2006. Negotiating the boundary between state-led and farmer approaches to knowing nature: an analysis of UK agri-environment schemes. *Geoforum*, 37(1), pp.113-127.

Navntoft, S., Esbjerg, P. and Riedel, W., 2006. Effects of reduced pesticide dosages on carabids (Coleoptera: Carabidae) in winter wheat. *Agricultural and Forest Entomology*, 8(1), pp.57-62.

Niemelä, J., 1993. Interspecific competition in ground-beetle assemblages (Carabidae): what have we learned?. *Oikos*, pp.325-335.

Oatway, R., 2018. Agri-Environment Monitoring and Evaluation Programme Annual Report 2016/17- A summary of findings from recently published projects. *Natural England Research Reports, Number NERR074*.

Oliver, D.M., Bartie, P.J., Heathwaite, A.L., Pschetz, L. and Quilliam, R.S., 2017. Design of a decision support tool for visualising E. coli risk on agricultural land using a stakeholder-driven approach. *Land Use Policy*, 66, pp.227-234.

Opatovsky, I., Gavish-Regev, E., Weintraub, P.G. and Lubin, Y., 2016. Various competitive interactions explain niche separation in crop-dwelling web spiders. *Oikos*, 125(11), pp.1586-1596.

Ostman, R., Ekbom, B., Bengtsson, J., Weibull, C., 2001. Landscape complexity and farming practice influence the condition of polyphagous carabid beetles. *Ecological Applications*. 11(2), 2001, pp. 480–488

Ouyang, F., Su, W., Zhang, Y., Liu, X., Su, J., Zhang, Q., Men, X., Ju, Q. and Ge, F., 2020. Ecological control service of the predatory natural enemy and its maintaining mechanism in rotation-intercropping ecosystem via wheat-maize-cotton. *Agriculture, Ecosystems & Environment*, 301, p.107024.

Pacheco, R. and Vasconcelos, H.L., 2012. Subterranean pitfall traps: is it worth including them in your ant sampling protocol?. *Psyche: A Journal of Entomology*, 2012.

Paill, W., 2000. Slugs as prey for larvae and imagines of Carabus violaceus (Coleoptera: Carabidae). In: Brandmayr, P. ed., 2000. *Natural History and Applied Ecology of Carabid Beetles: Proceedings of the IXth European Carabidologists' Meeting* (26-31 July 1998, Camigliatello, Cosenza, Italy) (No. 19). Pensoft Publishers. Pp 221-227

Payne, R.W. ed., 1993. *Genstat 5 release 3 reference manual*. Oxford University Press.

Pecheur, E., Piqueray, J., Monty, A., Dufrêne, M. and Mahy, G., 2020. The influence of ecological infrastructures adjacent to crops on their carabid assemblages in intensive agroecosystems. *PeerJ*, 8, p.e8094.

Petit, S., and Bohan, D.A., 2018. The use of insects in integrated weed management. In: Zimdahl, R.L., 2018. *Integrated weed management for sustainable agriculture*. Burleigh Dodds Science Publishing Limited.

Petit, S., Boursault, A. and Bohan, D.A., 2014. Weed seed choice by carabid beetles (Coleoptera: Carabidae): Linking field measurements with laboratory diet assessments. *European Journal of Entomology*, 111(5).

Petit, S., Bohan, D.A. and Dijon, A., 2018. The use of insects in integrated weed management. In *Integrated weed management for sustainable agriculture* (pp. 453-468). Burleigh dodds Science publishing. DOI: 10.19103/AS.2017.0025.23

Pike, T., 2008. *Understanding Behaviours in a Farming Context: Bringing theoretical and applied evidence together from across Defra and highlighting policy relevance and implications for future research*. Defra Agricultural Change and Environment Observatory Discussion Paper. HMGOV

Pisa, L.W., Amaral-Rogers, V., Belzunces, L.P., Bonmatin, J.M., Downs, C.A., Goulson, D., Kreutzweiser, D.P., Krupke, C., Liess, M., McField, M. and Morrissey, C.A., 2015. Effects of neonicotinoids and fipronil on non-target invertebrates. *Environmental Science and Pollution Research*, 22(1), pp.68-102.

Plantegenest, M., Aviron, S. and Pétillon, J., 2019. Local vs. landscape characteristics differentially shape emerging and circulating assemblages of carabid beetles in agroecosystems. *Agriculture, Ecosystems & Environment*, 270, pp.149-158.

Potts, G.R. and Aebischer, N.J., 1991. Modelling the population dynamics of the grey partridge: conservation and management. Bird Population Studies. *Relevance to Conservation and Management*, pp.373-390.

Powell, W., Dean, G.J. and Dewar, A., 1985. The influence of weeds on polyphagous arthropod predators in winter wheat. *Crop Protection*, 4(3), pp.298-312.

Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. *Philosophical Transactions of the Royal Society B,* 2010, 365. Pp 2959–2971

Prager, K., Reed, M. and Scott, A., 2012. Encouraging collaboration for the provision of ecosystem services at a landscape scale—Rethinking agri-environmental payments. *Land use policy*, 29(1), pp.244-249.

Prather, C.M., Pelini, S.L., Laws, A., Rivest, E., Woltz, M., Bloch, C.P., Del Toro, I., Ho, C.K., Kominoski, J., Newbold, T.S. and Parsons, S., 2013. Invertebrates, ecosystem services and climate change. *Biological Reviews*, 88(2), pp.327-348.

Price, L.L., 2001. Demystifying farmers' entomological and pest management knowledge: a methodology for assessing the impacts on knowledge from IPM-FFS and NES interventions. *Agriculture and human values*, 18(2), pp.153-176.

Prokopy, L.S., Floress, K., Klotthor-Weinkauf, D. and Baumgart-Getz, A., 2008. Determinants of agricultural best management practice adoption: Evidence from the literature. *Journal of Soil and Water Conservation*, 63(5), pp.300-311.

Purtauf, T., Dauber, J., and Wolters, V., 2005. The response of carabids to landscape simplification differs between trophic groups. *Oecologia*, 142, 458-464.

Purvis, G. and Fadl, A., 1996, January. Emergence of Carabidae (Coleoptera) from pupation: A technique for studying the'productivity'of carabid habitats. In Annales Zoologici Fennici (pp. 215-223). *Finnish Zoological and Botanical Publishing Board.*

Pywell, R.F., Heard, M.S., Woodcock, B.A., Hinsley, S., Ridding, L., Nowakowski, M., Bullock, J.M., 2015. Wildlife-friendly farming increases crop yield: evidence for ecological intensification. *Proceedings of the Royal Society B-Biological Sciences* 2015, 282, 8, doi:10.1098/rspb.2015.1740.

Rand, T. A., Tylianakis, J. M., & Tscharntke, T., 2006. Spillover edge effects: The dispersal of agriculturally subsidized insect natural enemies into adjacent natural habitats. *Ecology Letters*, 9, 603–614. https://doi.org/10.1111/j.1461-0248.2006.00911.x

Redlich, S., Martin, E.A. and Steffan-Dewenter, I., 2018. Landscape-level crop diversity benefits biological pest control. *Journal of Applied Ecology*.

Reed, M.S., Moxey, A., Prager, K., Hanley, N., Skates, J., Bonn, A., Evans, C.D., Glenk, K. and Thomson, K., 2014. Improving the link between payments and the provision of ecosystem services in agri-environment schemes. *Ecosystem Services*, 9, pp.44-53.

Riechert, S.E. and Cady, A.B., 1983. Patterns of resource use and tests for competitive release in a spider community. *Ecology,* 64(4), pp.899-913.

Reich, I., Jessie, C., Ahn, S.J., Choi, M.Y., Williams, C., Gormally, M. and Mc Donnell, R., 2020. Assessment of the biological control potential of common carabid beetle species for autumn-and winter-active pests (Gastropoda, Lepidoptera, Diptera: Tipulidae) in annual ryegrass in western Oregon. *Insects*, 11(11), p.722.

Ridley, A.M., Seymour, E.J., Huhn, K.J. and Park, G., 2007. Priority environmental issues for monitoring–mismatch between farmers and catchment management perspectives. *Australian Journal of Experimental Agriculture*, 47(3), pp.356-366.

Riley, M., 2016. How does longer term participation in agri-environment schemes [re] shape farmers' environmental dispositions and identities?. *Land Use Policy*, 52, pp.62-75.

Rogers, E.M., 2010. *Diffusion of innovations* (5th edition). Simon and Schuster.

Russell, M.C., Lambrinos, J., Records, E. and Ellen, G., 2017. Seasonal shifts in ground beetle (Coleoptera: Carabidae) species and functional composition maintain prey consumption in Western Oregon agricultural landscapes. *Biological Control*, 106, pp.54-63.

Rytkönen, S., Vesterinen, E. J., Westerduin, C., Leviäkangas, T., Vatka, E., Mutanen, M., Välimäki, P., Hukkanen, M., Suokas, M. and Orell, M., 2019. From feces to data: A metabarcoding method for analyzing consumed and available prey in a bird-insect food web. *Ecology and Evolution* 9: 631-639.

Sasakawa, K., Ikeda, H. and Kubota, T., 2010. Feeding ecology of granivorous carabid larvae: a stable isotope analysis. *Journal of applied entomology*, 134(2), pp.116-122.

Saska, P., Honěk, A. and Martinková, Z., 2019. Preferences of carabid beetles (Coleoptera: Carabidae) for herbaceous seeds. *Acta Zool. Acad. Sci. Hung*, 65, pp.57-76.

Saska, P., Vodde, M., Heijerman, T., Westerman, P. & van der Werf, W., 2007. The significance of a grassy field boundary for the spatial distribution of carabids within two cereal fields. *Agriculture, Ecosystems and Environment*, 122, 427–434.

Schirmel, J., Albrecht, M., Bauer, P.M., Sutter, L., Pfister, S.C. and Entling, M.H., 2018. Landscape complexity promotes hoverflies across different types of semi-natural habitats in farmland. *Journal of Applied Ecology*, 55(4), pp.1747-1758.

Schroeder, L.A., Isselstein, J., Chaplin, S. and Peel, S., 2013. Agri-environment schemes: Farmers' acceptance and perception of potential 'Payment by Results' in grassland—A case study in England. *Land Use Policy*, 32, pp.134-144.

Seidl, M., Gonzalez, E., Kadlec, T., Saska, P. and Knapp, M., 2020. Temporary non-crop habitats within arable fields: The effects of field defects on carabid beetle assemblages. *Agriculture, Ecosystems & Environment*, 293, p.106856.

Shearin, A.F., Reberg-Horton, S.C. and Gallandt, E.R., 2014. Direct effects of tillage on the activity density of ground beetle (Coleoptera: Carabidae) weed seed predators. *Environmental entomology*, 36(5), pp.1140-1146.

Sims, I., Cole, J. and Verdon, P., 2016. Hypogean pitfall trapping: a novel technique for assessing soil biodiversity in agroecosystems. *British Journal of Entomology and Natural History*, 29(4), pp.211-229.

Slee, B., Gibbon, D. and Taylor, J., 2006. Habitus and style of farming in explaining the adoption of environmental sustainability-enhancing behaviour. *Final Report, Countryside and Community Research Unit, University of Gloucestershire*

Smith, J., Potts, S. and Eggleton, P., 2008. Evaluating the efficiency of sampling methods in assessing soil macrofauna communities in arable systems. *European Journal of Soil Biology*, 44(3), pp.271-276.

Staudacher, K., Jonsson, M. and Traugott, M., 2016. Diagnostic PCR assays to unravel food web interactions in cereal crops with focus on biological control of aphids. *Journal of pest science*, 89(1), pp.281-293.

Staudacher, K., Rennstam Rubbmark, O., Birkhofer, K., Malsher, G., Sint, D., Jonsson, M. and Traugott, M., 2018. Habitat heterogeneity induces rapid changes in the feeding behaviour of generalist arthropod predators. *Functional ecology*, 32(3), pp.809-819.

Steg, L., Bolderdijk, J.W., Keizer, K. and Perlaviciute, G., 2014. An integrated framework for encouraging pro-environmental behaviour: The role of values, situational factors and goals. *Journal of Environmental psychology*, 38, pp.104-115.

Stiff, J.B. and Mongeau, P.A., 2003. *Persuasive communication*. Guilford press.

Stroud, J.L., 2019. Soil health pilot study in England: Outcomes from an on-farm earthworm survey. *PloS one*, 14(2), p.e0203909.

Suenaga, H. and Hamamura, T., 1998. Laboratory evaluation of carabid beetles (Coleoptera: Carabidae) as predators of diamondback moth (Lepidoptera: Plutellidae) larvae. *Environmental entomology*, 27(3), pp.767-772.

Sutherland, L.A., Mills, J., Ingram, J., Burton, R.J., Dwyer, J. and Blackstock, K., 2013. Considering the source: Commercialisation and trust in agri-environmental information and advisory services in England. *Journal of environmental management,* 118, pp.96-105.

Sutherland L.A., 2010. Environmental grants and regulations in strategic farm business decision-making: a case study of attitudinal behaviour in Scotland. *Land Use Policy* 27:415–423.

Sunderland, K., 2002. Invertebrate pest control by carabids. *In*: Holland, J.M. *The Agroecology of Carabid Beetles*. Andover: Intercept

Sunderland, K.,1995. Density estimation for beneficial predators in agroecosystems. *Acta Jutlandica* 70, 133–164

Sunderland, K.D. and Vickerman, G.P., 1980. Aphid feeding by some polyphagous predators in relation to aphid density in cereal fields. *Journal of Applied Ecology*, pp.389-396.

Symondson, W.O.C., 2004. *Coleoptera (Carabidae, Drilidae, Lampyridae and Staphylinidae) as predators of terrestrial gastropods. Natural Enemies of Terrestrial Molluscs* (ed. by G. M.Barker), pp. 37–84. CAB International, Oxford, U.K.

Symondson, W.O.C., 1989. Biological control of slugs by carabids. *Biological control of slugs by carabids*., (41), pp.295-300.

Terry, D.J., M.A. Hogg, and K.M. White. 1999. The theory of planned behaviour: Self-identity, social identity and group norms. *British Journal of Social Psychology* 38(3): 225–244.

Theunissen, J., 1994. Intercropping in field vegetable crops: pest management by agrosystem diversification—an overview. *Pesticide Science*, 42(1), pp.65-68.

Theunissen, J. and Schelling, G., 2000. Undersowing carrots with clover: suppression of carrot rust fly (Psila rosae) and cavity spot (Pythium spp.) infestation. *Biological agriculture & horticulture*, 18(1), pp.67-76.

Thiele, H.U., 1977. *Carabid beetles in their environments: a study on habitat selection by adaptations in physiology and behaviour* (Vol. 10). Springer Science & Business Media.

Thomas, C.G., Holland, J.M. and Brown, N.J., 2002. The spatial distribution of carabid beetles in agricultural landscapes. *The agroecology of carabid beetles*. Andover: Intercept, pp.305-344.

Thomas, M.B., Mitchell, H.J. and Wratten, S.D., 1992. Abiotic and biotic factors influencing the winter distribution of predatory insects. *Oecologia*, 89(1), pp.78-84.

Thomson, L.J. and Hoffmann, A.A., 2010. Natural enemy responses and pest control: importance of local vegetation. *Biological Control*, 52(2), pp.160-166.

Traugott M., 1998. Larval and adult species composition, phenology and life cycles of carabid beetles (Coleoptera: Carabidae) in an organic potato field. *European Journal of Soil Biology* 34, 189-197.

Trushitsyna, O.S. and Matalin, A.V., 2016. Specific features of the life cycle of Pterostichus melanarius (Coleoptera, Carabidae) in mosaic floodplain meadows. *Entomological Review*, 96(2), pp.144-159.

Tooming, E., Merivee, E., Must, A., Merivee, M.I., Sibul, I., Nurme, K. and Williams, I.H., 2017. Behavioural effects of the neonicotinoid insecticide thiamethoxam on the predatory insect Platynus assimilis. *Ecotoxicology*, 26(7), pp.902-913.

Tooming, E., 2017. *The sublethal effects of neurotoxic insecticides on the basic behaviours of agriculturally important carabid beetles* (Doctoral dissertation, Eesti Maaülikool).

Topp, W., 1983. Limiting Similarity in Rove Beetles (Col. Staphylinidae) of a Habitat Inland. *In Adaptations to terrestrial environments* (pp. 3-11). Springer, Boston, MA.

Toupet, R., Gibbons, A.T., Goodacre, S.L. and Bell, M.J., 2020. Effect of herbage density, height and age on nutrient and invertebrate generalist predator abundance in permanent and temporary pastures. *Land*, 9(5), p.164.

Tsafack, N., Wang, X., Xie, Y. and Fattorini, S., 2021. Niche overlap and species co-occurrence patterns in carabid communities of the northern Chinese steppes. *ZooKeys*, 1044, p.929.

Tscharntke, T., Tylianakis, J.M., Wade, M.R., Wratter, S.D., Bengtsson, J. and Kleijn, D., 2007. Insect Conservation in Agricultural Landscapes. *In*- Stewart A.J.A, New, T.R. and Lewis, O.T., 2007. Insect Conservation Biology. *Proceedings of the Royal Entomological Societies 23rd symposium*. Oxford: CABI. Pp 383-404.

Tschumi, M., Ekroos, J., Hjort, C., Smith, H.G. and Birkhofer, K., 2018. Predation-mediated ecosystem services and disservices in agricultural landscapes. *Ecological applications*, 28(8), pp.2109-2118.

UK Government, 2018. *A green future: our 25 year environment plan to improve the environment*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf [Accessed 13/01/21]

Van Dijk, T.S., 1983. The influence of food and temperature on the amount of reproduction in carabid beetles. In The Synthesis of Field Study and Laboratory Experiment. *Report of the Fourth Meeting of European Carabidologists* (pp. 105-123).

Van Dijk, T.S., 1994. On the relationship between food, reproduction and survival of two carabid beetles: Calathus melanocephalus and Pterostichus versicolor. *Ecological Entomology*, 19(3), pp.263-270.

Vehviläinen, H., Koricheva, J. and Ruohomäki, K., 2008. Effects of stand tree species composition and diversity on abundance of predatory arthropods. *Oikos*, 117(6), pp.935-943.

Vilà, M., Beaury, E.M., Blumenthal, D.M., Bradley, B.A., Early, R., Laginhas, B.B., Trillo, A., Dukes, J.S., Sorte, C.J. and Ibáñez, I., 2021. Understanding the combined impacts of weeds and climate change on crops. *Environmental Research Letters*, 16(3), p.034043.

Waylen, K.A., Blackstock, K.L., Van Hulst, F.J., Damian, C., Horváth, F., Johnson, R.K., Kanka, R., Külvik, M., Macleod, C.J., Meissner, K. and Oprina-Pavelescu, M.M., 2019. Policy-driven monitoring and evaluation: Does it support adaptive management of socio-ecological systems?. *Science of the Total Environment*, 662, pp.373-384.

Wezel, A., Casagrande, M., Celette, F., Vian, J.F., Ferrer, A. and Peigné, J., 2014. Agroecological practices for sustainable agriculture. A review. *Agronomy for sustainable development*, 34(1), pp.1-20.

Wheater, C.P., Bell, J.R. and Cook, P.A., 2020. *Practical field ecology: a project guide*. John Wiley & Sons.

Wilby, A. and Thomas, M.B., 2002. Natural enemy diversity and pest control: patterns of pest emergence with agricultural intensification. *Ecology Letters*, 5(3), pp.353-360.

Williams, I.H., Ferguson, A.W., Kruus, M., Veromann, E. and Warner, D.J., 2010. Ground beetles as predators of oilseed rape pests: incidence, spatio-temporal distributions and feeding. In *Biocontrol-based integrated management of oilseed rape pests* (pp. 115-149). Springer, Dordrecht.

Wilson, G.A. and Hart, K., 2000. Financial imperative or conservation concern? EU farmers' motivations for participation in voluntary agri-environmental schemes. *Environment and planning A*, 32(12), pp.2161-2185.

Wilson, J. D., Morris, A. J., Arroyo, B. E., Clark, S. C. and Bradbury, R. B., 1999. A review of the abundance and diversity of invertebrate and plant foods of granivorous birds in northern Europe in relation to agricultural change. *Agriculture, Ecosystems & Environment* 75: 13-30.

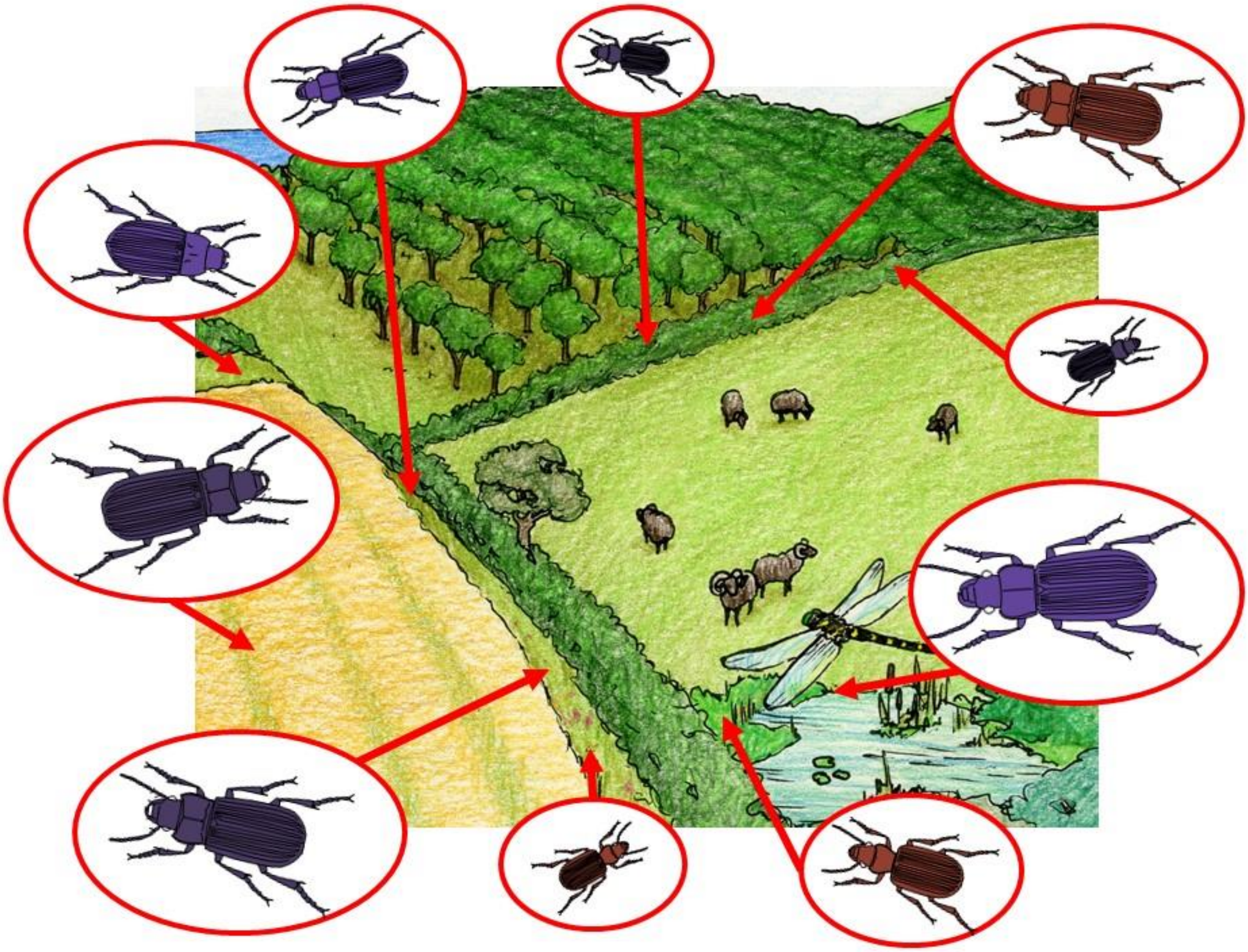
Winder, L., Alexander, C.J., Holland, J.M., Woolley, C. and Perry, J.N., 2001. Modelling the dynamic spatio-temporal response of predators to transient prey patches in the field. *Ecology Letters*, 4(6), pp.568-576.

Winter, M., Gasson, R., Curry, N., Selman, P. and Short, C., 1996. *Socio-economic Evaluation of Free Conservation Advice Provided to Farmers in England by ADAS and FWAG.* Cheltenham: Countryside and Community Press.

Woodcock, B.A., Potts, S.G., Westbury, D.B., Ramsay, A.J., Lambert, M., Harris, S.J. and Brown, V.K., 2007. The importance of sward architectural complexity in structuring predatory and phytophagous invertebrate assemblages. *Ecological Entomology*, 32(3), pp.302-311.

Zhang H., Garratt M., Bailey A., Potts S.G., Breeze T., 2018. Economic valuation of natural pest control of the summer grain aphid in wheat in South East England. *Ecosystem Services* 30: 149-157

Chapter 2



Old data for new inferences

This chapter comprises the groundwork for the project, initiating work on the first objective of identifying the factors influencing carabid populations and developing statistical modelling of distributions. The experimental designs of subsequent chapters are underpinned by the factors identified as significant, and warranting further investigation, in this large dataset.

Species matter when considering landscape effects on carabid distributions

Kelly Jowett[a,b,*], Alice E. Milne[a], Helen Metcalfe[a], Kirsty L. Hassall[a], Simon G. Potts[b], Deepa Senapathi[b], Jonathan Storkey[a]
[a]*Sustainable Agricultural Sciences, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK*
[b]*Centre for Agri-Environmental Research, School of Agriculture Policy and Development, University of Reading, Reading, Berkshire RG6 6AR, UK*

Abstract

Increasing the abundance and diversity of carabid beetles is a common objective of farm habitat management to deliver sustainable pest control. Carabid spatial distributions in relation to crop areas are important to the delivery of this ecosystem service. We used pitfall count data at distances from edge habitats into crop centres, from farm sites across the UK, to determine the effects of in-field and adjacent environmental features on carabid abundance and diversity. Overall carabid abundance increased towards the crop centre, whilst species richness and diversity decreased. The analyses of carabid abundance based on all the species pooled together strongly reflected the behaviour of the most abundant species. Species preferences varied by crop, soil type, and environmental features. For instance, some species were positively associated with habitats such as margins, while others responded negatively. This contrast in individual species models highlights the limitations on pooled models in elucidating responses. Studies informing farm-habitat design should consider individual species' preferences for effective enhancement of pest control services. Diverse cropping and landscape heterogeneity at the farm scale can benefit the varied preferences of individual species, help build diverse communities and, potentially increase service resilience and stability over time.

This chapter is published as:

Jowett, K., Milne, A.E., Metcalfe, H., Hassall, K.L., Potts, S.G., Senapathi, D. and Storkey, J., 2019. Species matter when considering landscape effects on carabid distributions. *Agriculture, Ecosystems & Environment*, 285, p.106631.

2.1 | INTRODUCTION

Carabid beetles, as ubiquitous polyphagous predators, are much studied in agro-ecosystems. Research has shown their potential to control pest arthropods and weed seeds in crop areas, leading to the inclusion of management measures to boost carabid abundances on farms (Kromp, 1999). Landscape features such as hedgerows and field margins are presumed to provide refuge, breeding and hibernation habitats, and food resource stability; therefore, ensuring viable populations in proximity to crop areas (Thomas et al., 2002). The European Commission and member states have made policy commitments towards the sustainable use of pesticides (EC 2009 Directive 2009/128/EC, and National Action Plans: EC 2018) to support more efficient food production and reduce negative environmental impacts. To help deliver on this, effective management solutions to enhance natural pest regulation need to be developed (Petit et al., 2018).

Approximately 350 species of carabid reside in the UK, with widely differing characteristics, environmental needs and preferences. Carabids inhabiting agro-ecosystems are polyphagous generalists, exploiting the range of disturbed agroecosystems (Thielle, 1977). Previous work has focussed on within field factors that drive carabid community structure, for example agricultural inputs (Garratt et al., 2011) and the presence of field margins (Woodcock et al. 2007). Since a common justification of many agricultural studies is the delivery of ecosystem services by carabids, the literature has focussed on the metrics this utility is dependent on: overall abundance, diversity, and spatial distribution. Overall abundance is a major focus, as it affects the quantity of service provision (Kotze 2011; Pennekamp et al. 2018). Diversity is thought to affect the quality, stability, and resilience of provision, by the differential predation, environmental tolerances and complementarity of species (Petit et al., 2018). Distribution impacts the provision in relation to service requirements spatially (Holland et al 2005; Weibull, Östman and Granqvist 2003).

As well as in-field factors, boundary habitats and adjacent environments also significantly impact carabid abundance and community composition (Fahrig and Jonsen, 1998; Holland et al. 2004). Yet a key aspect for the delivery of pest-control services is the role these landscape features play in determining the carabid species that are found in the crop determined by the degree of spill over (Holland Birkett and Southway 2009; Petit et al., 2018). For instance, the presence of certain types of carabids at the field edge may not be strongly associated with the species distribution and abundance of those foraging within crop areas (Crowder and Jabbourb 2014, Holland et al 2005). Carabid abundance by distance from the crop edge has been extensively studied to explore ecological edge effects (Koivula et al. 2004), yet until recently literature focussed on the plot-scale effects of management, irrespective of landscape composition (Booij 1994; Petit et al., 2018). Recent work, linking landscape composition to in-crop community structure (Boetzl et al. 2018; Gallé et al. 2018), lacks replication over multiple crops and sites. Meta-analyses have drawn general ecological conclusions at a landscape scale (Karp et al. 2018; Lichtenberg et al. 2017), but these fail to capture fine-scale nuances and interactions. The grouping of ecologically dissimilar species and methodologies into broad categories potentially loses the distinctions and details necessary for farm-scale specific interpretations. For example, Bianchi et al (2006) found that complex landscapes enhanced natural enemy pest control in 74% of studies across multiple arthropod groups but, for carabids, landscape composition had no apparent effect. This is likely due to the loss of power to separate out the influence of other landscape factors, such as the relative importance of landscape configuration on carabid distribution and infield management (Fusser et al 2018, Winqvist, et al. 2011). Therefore, to determine whether complex landscapes enhance natural enemy pest control for such diverse taxa, the retention of site specifics could disentangle complex interactions to enable more informative conclusions to be drawn.

In attempting to disentangle these complex landscape effects on carabids, studies tend to focus at either the narrow or broad end of the study spectrum, such as the plot to field scale, or landscape to regional scale, respectively. Brooks et al. (2008) studied national scale distributions; finding carabid meta-communities structured by dynamics operating at two spatial scales: at a local scale, along a resource gradient determined by crop type; and at a landscape scale along a longitudinal gradient. Woodcock et al. (2014) considered national patterns of functional diversity, highlighting correlations between carabids and landscape cover of semi-natural habitats and linking this to extinctions ordered by body size and dispersal ability.

There remain relatively few studies covering the distribution of carabids at the mid-scale (field to landscape), which we define as the *farm-scale* integrating both cropped areas and semi-natural features (Kotze et al 2011). This scale is important when considering how to manage better the population dynamics and community composition of carabids (Brooks et al. 2008; Kotze et al. 2011). Within the context of this knowledge gap, Labruyere et al. (2016) found that crop type and management intensity affected carabid community composition at the plot scale, whilst neighbouring habitat (grassland or oilseed rape (OSR)) had an effect at the farm-scale, and landscape scale. However, additional evidence is required to inform management decisions at the farm-scale to improve the efficacy of habitat management to deliver ecosystem services from carabids. For example, the optimal arrangement of semi-natural habitat in relation to different crop types, enabling carabids to follow crop rotations; towards greater service delivery and resilient communities.

Here, we make novel use of the UK Farm-Scale Evaluation (FSE) of Genetically Modified Herbicide Tolerant (GMHT) crops (Firbank et al., 2003; Brooks et al., 2003). The study gathered extensive and detailed survey data on farm habitats, within and adjacent to GMHT and conventional crops. This is the largest dataset on farm-scale distribution of carabids over multiple UK farm sites; and within various crops. In relation to carabids, the FSE data have previously been analysed in five studies (Brooks et al., 2003; Brooks et al., 2008; Brooks et al., 2012; Woodcock et al., 2014; Labruyere et al., 2016). Here we consider the data from a new perspective and focus on the effect of, previously unpublished, data on neighbouring environmental features on carabid abundance and diversity in cropped fields. In line with more recent understanding and work, we argue that considering processes at this farm-scale is the most relevant for management decisions aimed at manipulating in-field service delivery (Kotze et al 2011; Holland Birkett and Southway 2009; Weibull, Östman and Granqvist 2003)

We analysed the data to determine how environmental and management factors interact to affect the in-field abundance and diversity of carabid species, addressing three hypotheses on the relationships between carabids and land use to help inform habitat management and to develop recommendations for carabid mediated pest control.

- H1: Carabid abundance, species richness, and diversity decrease with distance from the boundary habitat towards the crop centre.
- H2: The relationship of carabid abundance, species richness, and diversity with distance into the field will be contingent on the neighbouring field boundary and habitat. For example: abundance, species richness, and diversity in the crop area are expected to be higher closer to and in the presence of a field margin.
- H3: Responses to environmental and management factors will vary by individual carabid species. For example: species associated with woodland habitats are expected to occur more frequently in the presence of a hedge boundary.

2.2 MATERIALS AND METHODS

2.2.1 Data

The FSE dataset quantifies weed and invertebrate populations in conventional and GMHT crops and the ecological characteristics of habitats adjacent to these crops in a network of 251 fields in lowland farms across Great Britain from 2000 to 2002 (Firbank et al. 2003). The crops included in the study were spring-sown sugar beet (*Beta vulgaris L.*), maize (*Zea mays L.*), spring OSR (*Brassica napus L.*) and winter OSR (*Brassica napus L.*). The experiment comprised random blocks where each field was a block with treatments (conventional or GMHT) replicated once on half-field units. Each field-crop combination was sampled in a single growing season. Here we use a subset of data from conventional crops, focussing on variables that we expect to affect carabid abundance.

Pitfall trapping was conducted according to the FSE protocol (Brooks et al., 2003) on four transect lines per field at 3 distances: 2, 8, and 32 metres into the crop (Fig. 1). Traps were run for 14-

day periods three times in 2000, 2001 and 2002 respectively; May to August in spring crops, and September to early July for winter OSR. For each event, carabids were identified to species level and counted.

Environmental factors were grouped to reflect differences in the biology of carabid species, accounting for similar habitat structures and resources in carabid niche space (Thomas et al., 2002). These were: *Adjacent habitat* (Fig. 1), with six levels: crop, ploughed, grassland, semi-natural (including scrub and heath), woodland, and urban; *Hedge*; *Margin*; *Water* (pond or streams); *Road or track*; and *Ditch*; with levels of present or absent. Other in-field factors were *Soil type*- categorised as either Heavy, Medium, Light, or Organic; *Crop type* (with 4 levels as listed above); and *Distance* into crop, with levels categorised as 2, 8 and 32m.

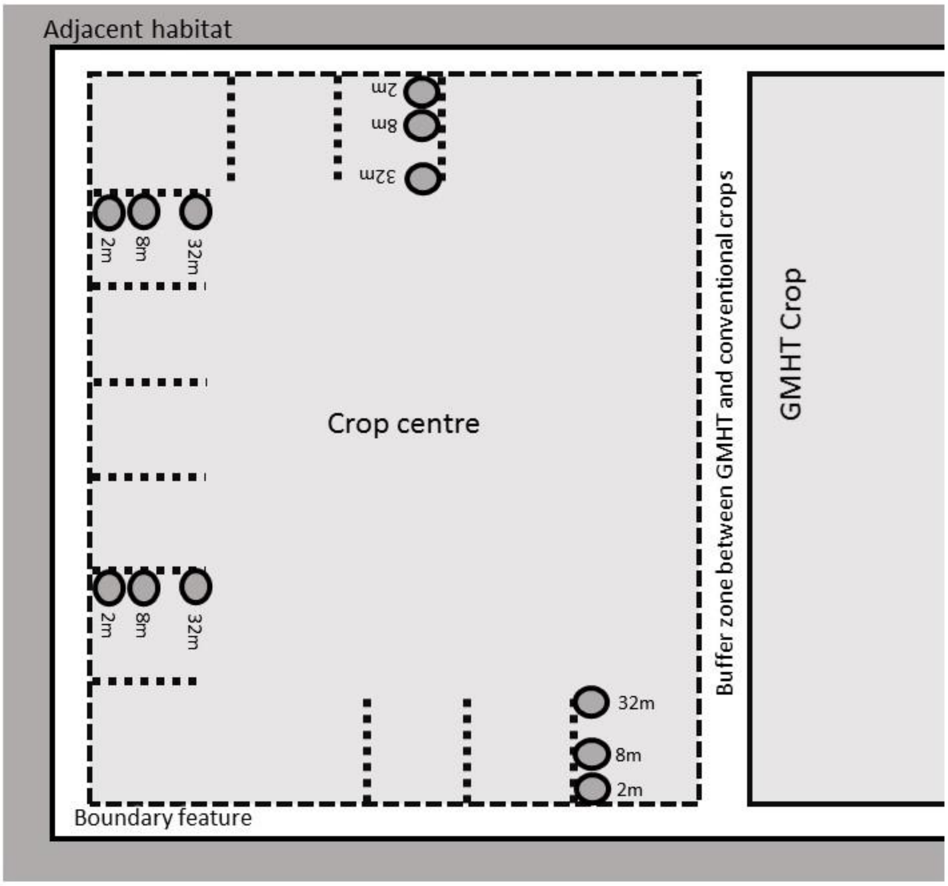


Figure 1- The experimental layout of the Farm Scale Evaluation. The circles denote trap locations, on dashed transect lines, from boundary feature to crop centre. Adapted from Firbank et al., (2003).

2.3 | Statistical analysis

2.3.1 | Pooled-carabid abundance, species richness, and diversity

We analysed only the count data from complete records with information recorded for all environmental factors, leaving 3,469 trap occasions, from 992 transects. For each trap occasion we calculated, what we refer to as 'pooled-carabid abundance' (N), i.e. the total number of carabids of any species, and species richness (S), i.e. the number of different species. We fitted the log series model (Equation 1) to the data by maximum likelihood to give estimates of Fisher's log-series alpha ($\hat{\alpha}$), a robust and widely used diversity metric (Beck and Schwanghart, 2010; Magurran, 2004)

$$S = \hat{\alpha} \log\left(1 + \frac{N}{\hat{\alpha}}\right)$$

(eqn 1)

We fitted Generalized Linear Mixed effects Models (GLMMs) using the GenStat statistical software package (Payne, 1993) to determine the effect of environmental factors on pooled-carabid abundance (N), richness (S) and species diversity (quantified as $\hat{\alpha}$). We considered the environmental factors *Soil type, Crop type, Adjacent habitat, Hedge*, *Margin*, *Water*, *Road or track*, *Ditch,* and *Distance* into the crop as fixed effects with all two-way interactions. The full random model was defined as *Site,* and nested within each site, *Transect* and nested within each transect, *Visit* (i.e. *Site/Transect/Visit*). We assumed a Poisson distribution for pooled-carabid abundance, species richness and diversity and used a log link function. We estimated the dispersion parameter to account for over dispersion, and set this to one where under dispersion was detected to avoid inflating the significance of hypothesis tests (see Welham et al. 2014). We selected terms using backwards elimination according to the largest P-value given by the Kenward-Roger approximate F-tests, in some cases it is not possible for the software to estimate the F-value so we report the associated Wald test, which is approximate under a large sample approximation. The final predictive model was chosen when all remaining terms gave significant values ($P \leq 0.05$) when dropped from the model.

2.3.2 Frequency and abundance of individual species

Preliminary analysis showed the counts were dominated by a single species, therefore to separate species responses and further investigate the effect of environmental factors and management on abundance we also considered the effect of the explanatory variables at the level of individual species. There were 92 species in the dataset in total, but many were observed extremely infrequently. Therefore, we restricted this analysis to ten species. These were selected to represent the most abundant and frequently trapped species, to account for bias towards aggregative species (Table 1). We fitted separate GLMMs to the data for each of these species, to identify differential responses. We first modelled the presence/absence of each species using a binomial GLMM to understand the characteristics contributing to the probability that each species was present (assuming a logit link function). Conditional on species presence, we then modelled the abundance using a Poisson GLMM (assuming a log link function).

The structure of the models was similar to that described above (see Section 2.2.1). As before, the dispersion parameter was estimated to account for over-dispersion or fixed to 1 for under dispersion. Terms were selected using backwards elimination as described above.

2.4 Results

The ten species selected as the most abundant and frequently trapped accounted for nearly 94% of the total counts (Table 1). The order of species ranks between count and trapping frequency was different, reflecting aggregative species: those that occur in fewer locations but with higher abundances where trapped. The catch was heavily dominated by *Pterostichus melanarius* (54% of total carabids counted and identified in 85% of traps).

Table 1- Summary statistics for the ten most common species of carabid in the FSE. These ten species were selected for further analysis based on abundance and frequency of trapping.

species	**count**	**% of total**	**Occasions trapped**	**% of traps**	**Mean per trap**	**Std Dev**	**Variance**	**Skew**
Pterostichus melanarius	106,589	53.8	2,933	84.6	30.40	52.38	2744	3.04
Pterostichus madidus	38,353	19.4	1,542	44.5	11.02	37.25	1388	6.51
Harpalus rufipes	7,799	3.9	1,160	33.4	2.23	6.98	48.65	6.63
Bembidion lampros	4,788	2.4	973	28.0	1.37	5.66	32.08	10.05
Pterostichus niger	8,165	4.1	961	27.7	2.27	7.63	58.14	6.05
Agonum dorsale	2,121	1.0	805	23.2	0.602	1.81	3.29	5.84
Trechus quadristriatus	2,517	1.3	739	21.3	0.70	2.61	6.80	7.78
Calathus fuscipes	3,894	2.0	700	20.2	1.09	4.442	19.73	8.34
Nebria brevicollis	6,630	3.3	643	18.5	1.83	12.91	166.80	16.97
Bembidion tetracolum	5,531	2.8	466	13.4	1.58	10.76	115.80	13.21
Total top ten	186,387	94.1	3,469					
Total overall	198,051							

2.4.1 Pooled-carabid abundance, species richness, and diversity

Table 2 GLMM final terms and significance (NS term included in model but not significant, * P≤0.05, **P≤0.01, ***P≤0.001) for species richness, and diversity.

	Main effects									Interactions			
	Hedge	Margin	Water	Adjacent habitat	Road or Track	Ditch	Crop	Distance	Soil category	Distance & Crop	Distance & Soil category	Distance & Road/ Track	Distance & Ditch
Pooled-carabid abundance							***	***	***	***	***		
Wald							23.07	45.24	11.56	17.39	19.32		
d.f							3	2	3	6	6		
Species richness		**						***	***				
Wald		5.60						39.74	16.44				
d.f		1						2	3				
Diversity (fishers α)					NS	NS	***	***		***		***	***
Wald					1.03	0.68	13.13	21.01		17.35		14.69	16.71
d.f						1	3	2		6		4	2

The fitted models for pooled-carabid abundance, species richness and diversity are presented in Table 2. Pooled-carabid abundance significantly increased with distance into the crop and varied significantly between crops with most carabids trapped in sugar beet, and least in winter OSR. There was a significant interaction between crop type and distance (Fig. 2a). The highest pooled-carabid abundance was found on light and medium soils, and lowest in organic (Fig. 2b). There were no significant effects of any boundary feature on the pooled carabid abundance.

Species richness decreased with distance into the crop and was significantly greater on soils classified as light or medium and least on organic soil (Fig. 3a). The presence of a margin had a significant effect with a greater number of species present when margins are absent (Fig. 3b).

Diversity, measured as Fisher's α, also decreased into the crop. Diversity varied by crop with the largest diversity in winter OSR and lowest in maize and sugar beet (Fig. 4a). There were interactions between Distance and the Road/Track factor and Ditch (Fig. 4b,c).

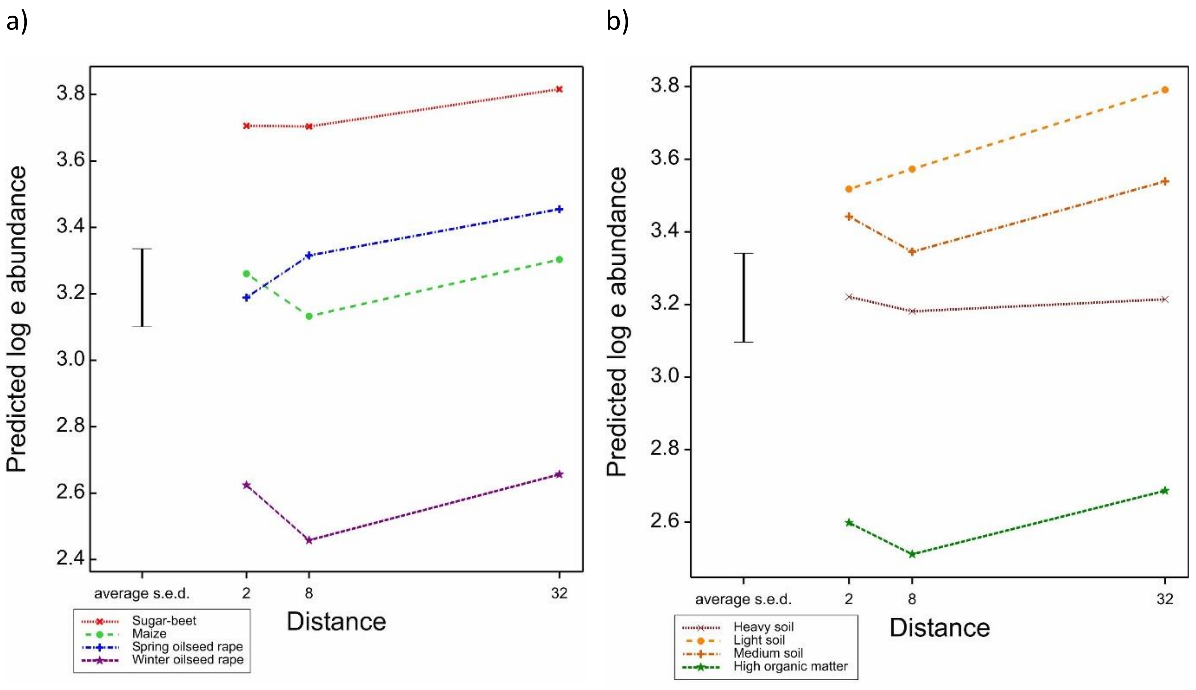


Figure 2- Pooled carabid abundance predictions plotted against distance into crop according to (a) crop type and (b) soil category. The vertical bar shows the average standard error of the difference.

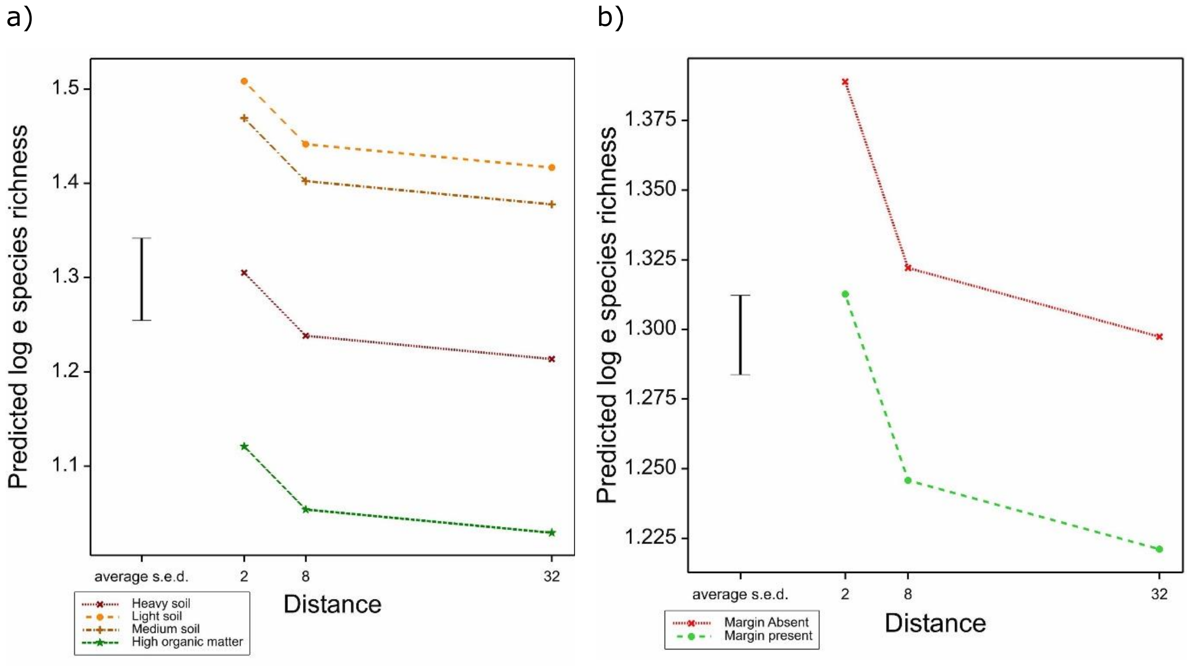


Figure 3- Species richness predictions plotted against distance into the crop according to (a) soil category, and (b) the presence of a margin. The vertical bar shows the average standard error of difference.

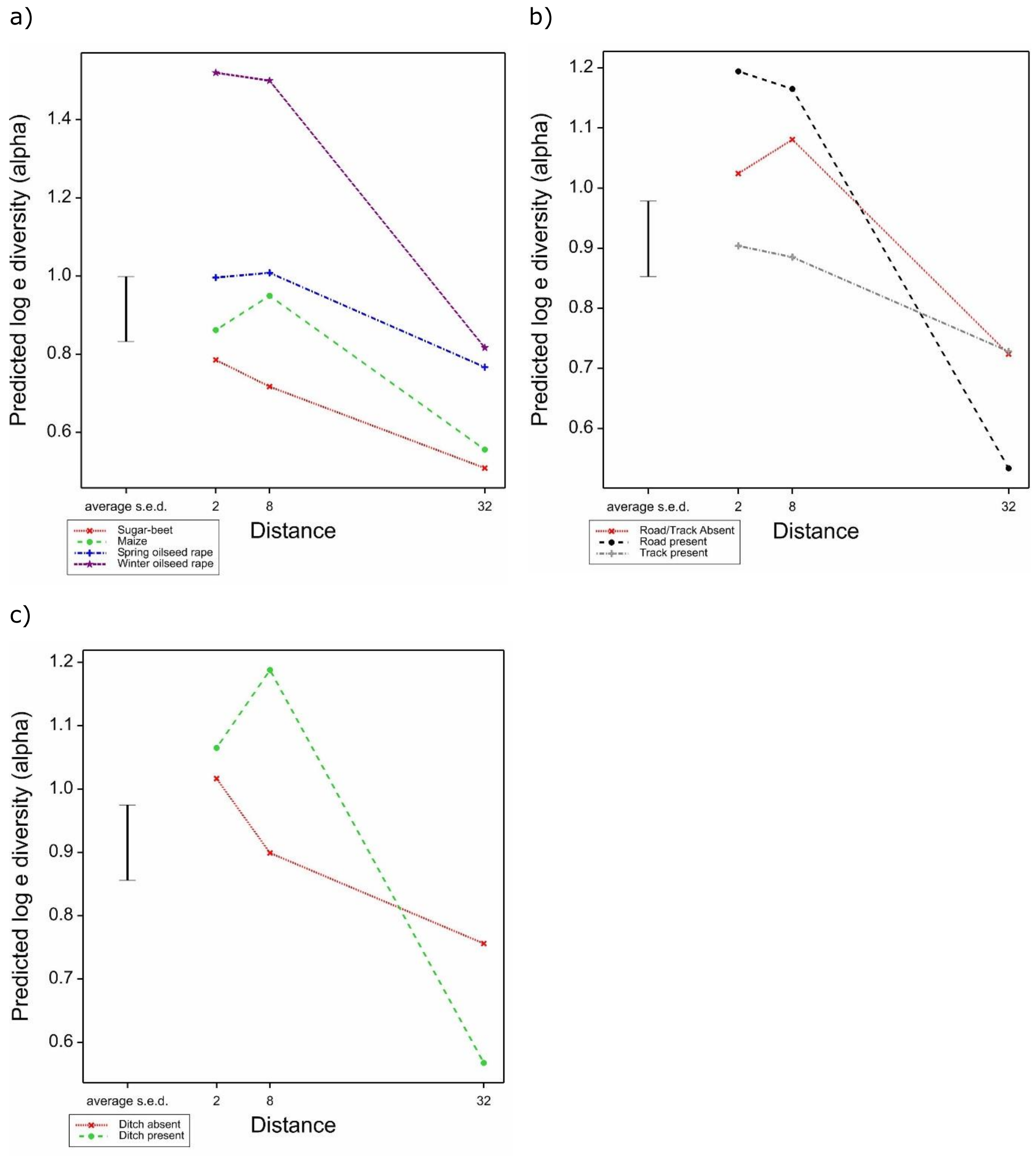


Figure 4 - Diversity (Fisher's alpha) predictions plotted against distance into crop according to (a) crop type and (b) the presence of roads or tracks (Road/Track factor) (c) the presence of a ditch. The vertical line shows the approximate average standard error of difference.

2.4.2 Abundance according to species

Table 3 - GLMM of factors upon presence/absence, by individual species (NS term included in model but not significant, * P≤0.05, **P≤0.01, ***P≤0.001).

	Main effects								
	Hedge	Margin	Water	Adjacent	Road or Track	Ditch	Crop	Distance	Soil category
P. melanarius	NS	NS	NS	NS	NS		***	NS	NS
P. madidus			*				NS	***	***
H. rufipes							***	***	
B. lampros		NS	NS	NS			*	***	**
P. niger	NS	NS	NS			*	***	NS	
A. dorsale		NS		NS			*	***	NS
T. quadristriatus		NS		NS	NS		NS	***	NS
C. fuscipes	NS	NS		NS	NS		*	***	
N. brevicollis						NS	***	***	
B tetracolum	NS			NS			*	**	NS

	Interactions														
	Distance & Crop	Distance & Soil cat.	Distance & Road/Track	Distance & Ditch	Distance & Adjacent	Distance & Margin	Distance & Hedge	Distance & Water	Crop & Adjacent	Crop & Soil category	Crop & Hedge	Crop & Margin	Adjacent & Soil cat.	Water & Adjacent	Water & Road/Track
P. melanarius										***				*	NS
P. madidus	**														
H. rufipes															
B. lampros	***					NS		**							
P. niger						*	NS	***							
A. dorsale		***			**	***						NS			
T. quadristriatus	**	***				***				*					
C. fuscipes			*		***	***	**								
N. brevicollis	*			**											
B tetracolum	**	**							**		**		*		

In the GLMMs of individual species presence/absence and abundance, the Crop, Distance, and Soil factors were often retained as significant terms (Tables 3 and4). Generally, more significant interactions and landscape variable terms were retained in the abundance models (Table 4).

The significant terms in the models for *P. melanarius* (Tables 3-4) largely correspond with those in the pooled carabid abundance model (Table 2). This reflects the dominance of *P. melanarius* in the total catch (Table 1). Fig. 5 illustrates the dominance of *P. melanarius* across crops and distances. It can be seen that by discounting *P. melanarius*, the highest pooled-carabid abundances would be less biased to 32 metres distances and the sugar beet crop.

Table 4- GLMM of factors upon abundance where present, by individual species (NS term included in model but not significant, * P≤0.05, **P≤0.01, ***P≤0.001). † site.transect random term was dropped due to zero variance component

Main effects

	Hedge	Margin	Water	Adjacent	Road or Track	Ditch	Crop	Distance	Soil category
P. melanarius				NS	NS		***	***	NS
P. madidus		NS		NS	NS		NS	NS	NS
H. rufipes	NS			*		NS	NS	**	NS
B. lampros	NS	NS	NS	NS				NS	***
P. niger †	NS		NS	*	NS		**	**	NS
A. dorsale			NS					***	
T. quadristriatus		NS		NS	NS			***	NS
C. fuscipes	NS	NS		NS			*	NS	NS
N. brevicollis		NS					NS	***	
B tetracolum	NS			NS	NS			NS	

Interactions

	Distance & Crop	Distance & Soil cat.	Distance & Road/Track	Distance & Adjacent	Distance & Margin	Distance & Hedge	Distance & Water	Hedge & Adjacent
P. melanarius	***	***	***	NS				
P. madidus	***	***	NS	***	**			
H. rufipes	***	***						**
B. lampros				***	**	***	***	
P. niger †	**	***				NS	NS	***
A. dorsale							***	
T. quadristriatus		***	***	***	***			
C. fuscipes	*	**		***	**	NS		
N. brevicollis	***				***			
B tetracolum				***		***		

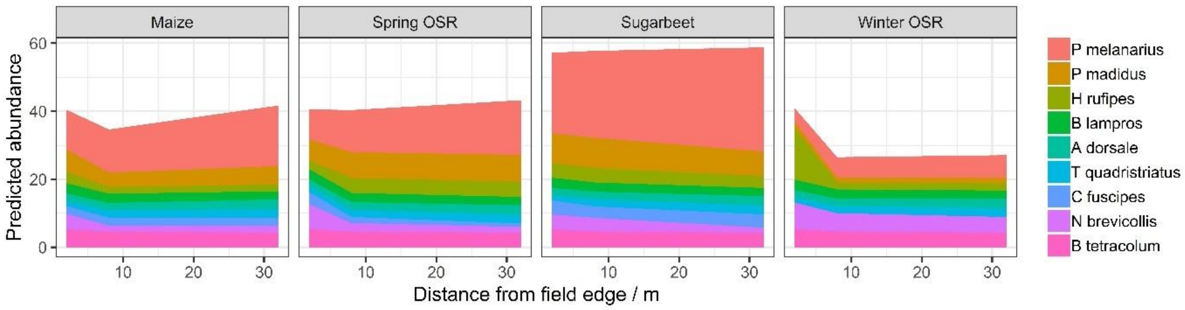


Figure 5- Overall abundance predictions from the individual GLMMs by Distance into crop, stacked by Species. Predictions are averaged over all levels of other terms included in the model (see Table 3).

The direction of response differed between species for factors identified as significant in the models (Figs 5–7). Most species showed a decrease in abundance and/or probability of occurrence from crop edge to centre (although for some species this was crop dependent), whilst some, notably *P. melanarius*, increased in abundance at the crop centre (Figs 5 and 6). The predictions from the individual species models demonstrate differences in response between species that are lost in the typical pooled analyses, whilst infield habitats are key to presence/absence and abundance, the specifics of responses vary. Responses are stronger in the presence/absence models, suggesting that the in-crop environment is most influential in the presence of species. Again, we note the effect of pooled counts in obscuring details of distributions: *Pterostichus melanarius* is most abundant in sugar beet, and least in Winter OSR; the pattern shown by the overall abundance (Fig. 5). This pattern does not hold true for all species (Fig. 6)

Species responses also varied by landscape features. For Margin, some species were predicted to have a greater abundance near the crop edge in the presence of a margin (*B. lampros, N. brevicollis*), whilst some were predicted to be less abundant (*T. quadristriatus*) (Fig. 7). In terms of the interaction of adjacent habitat with distance into the field, we observed different responses of individual carabid species to urban, ploughed, and woodland adjacent habitats; yet less marked differences in predicted abundances in response to adjacent crop and grassland habitats (Fig. 8). A high abundance close to the field edge with a steep negative gradient into the field is indicative of a strong preference to the adjacent habitat with spill over only to short distances into the field (for example *B. tetracolum* next to semi-natural habitat). In contrast, the consistently positive gradients for *P. melanarius* confirm its preference for the cropped field centre habitat with some evidence for an adjacent ploughed field reducing the local scale population size.

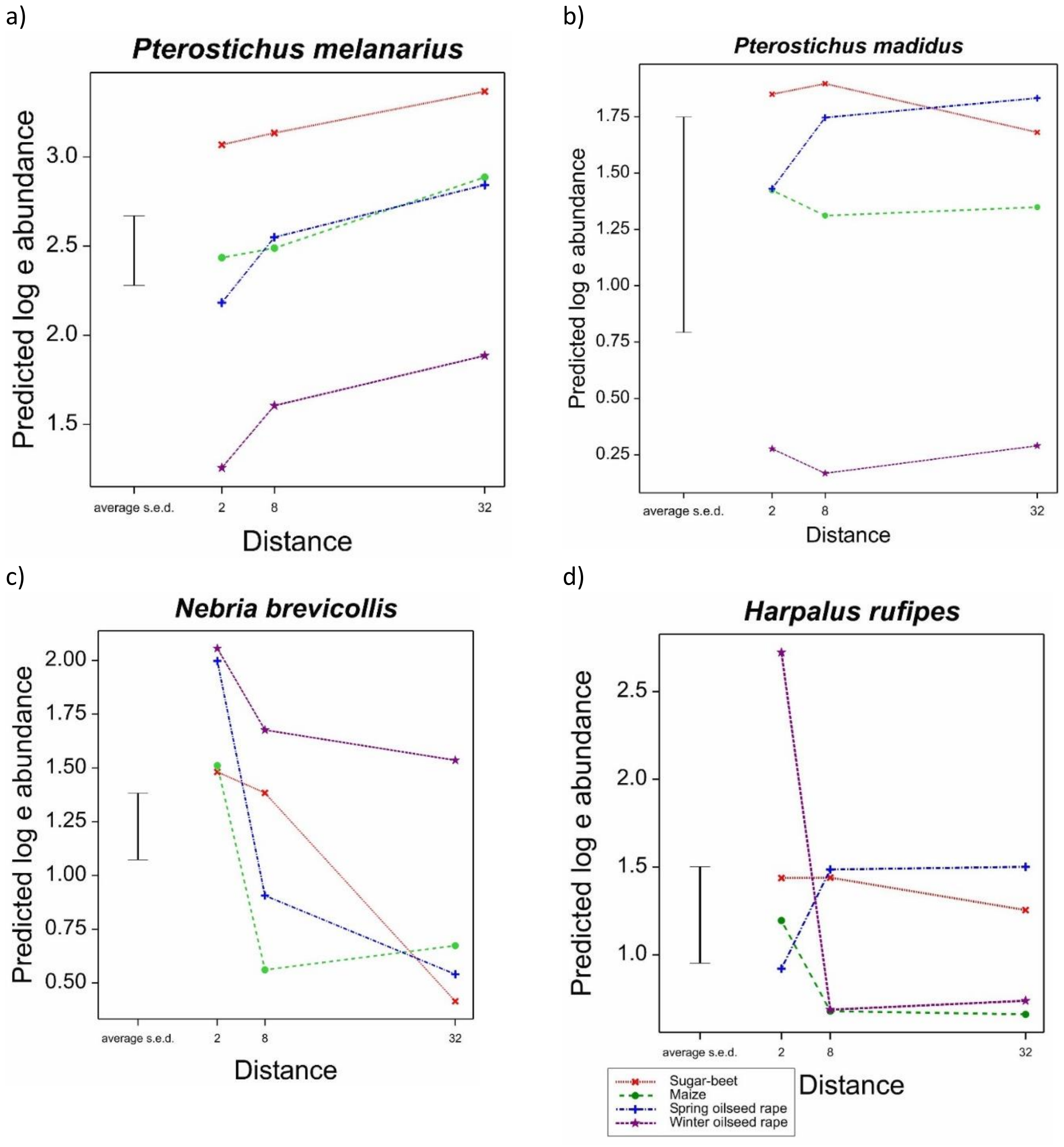


Figure 6- abundance predictions by distance according to crop type for species: (a) P. melanarius, (b) P. madidus, (c) N. brevicollis, (d) H. rufipes. The vertical line shows the approximate average standard error of difference.

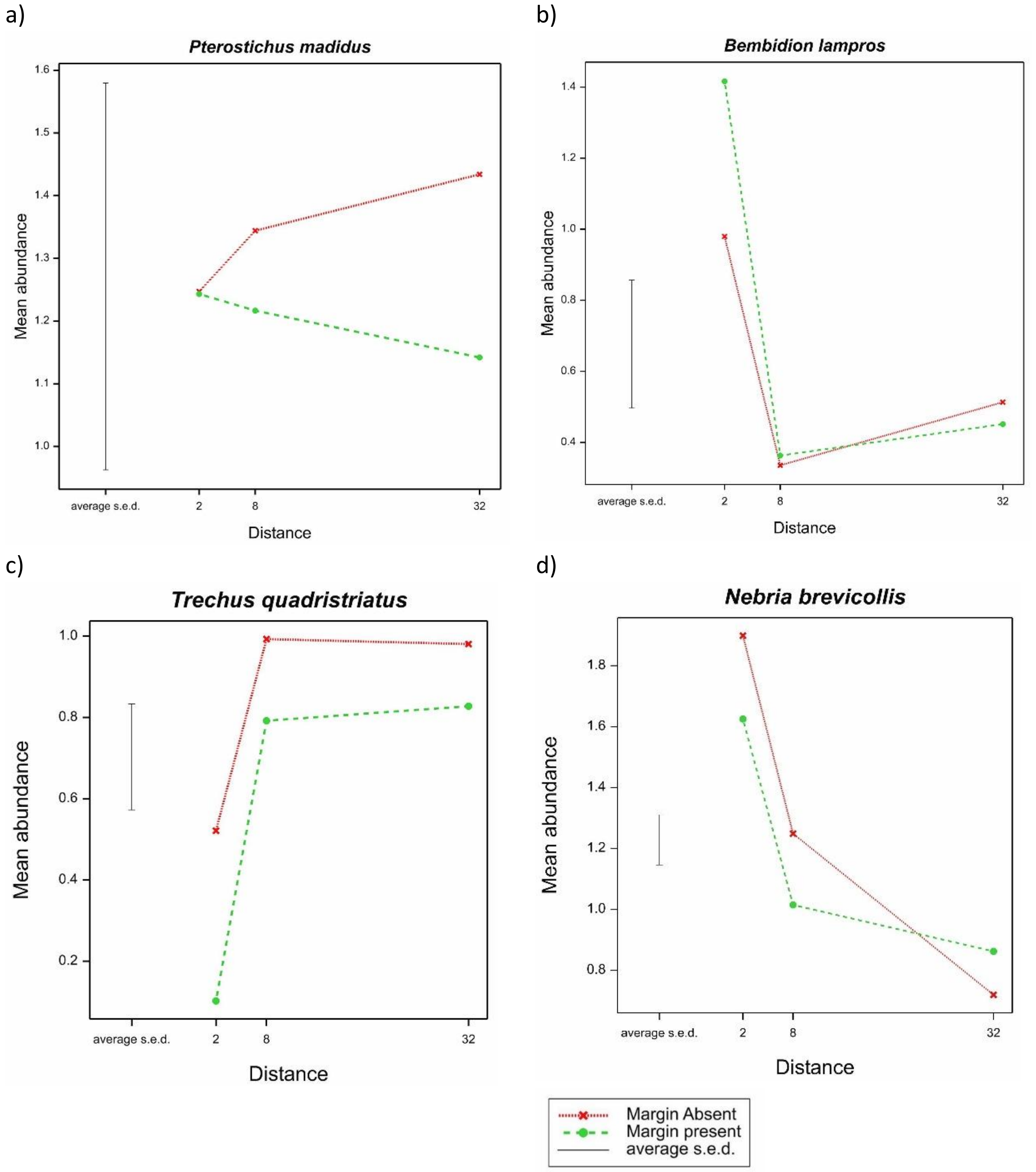


Figure 7- Abundance predictions by distance according to margin presence/absence, for species: (a) *P. madidus*, (b) *B. lampros*, (c) *T. quadristriatus* (d) *N. brevicollis*. The vertical line shows the approximate average standard error of difference.

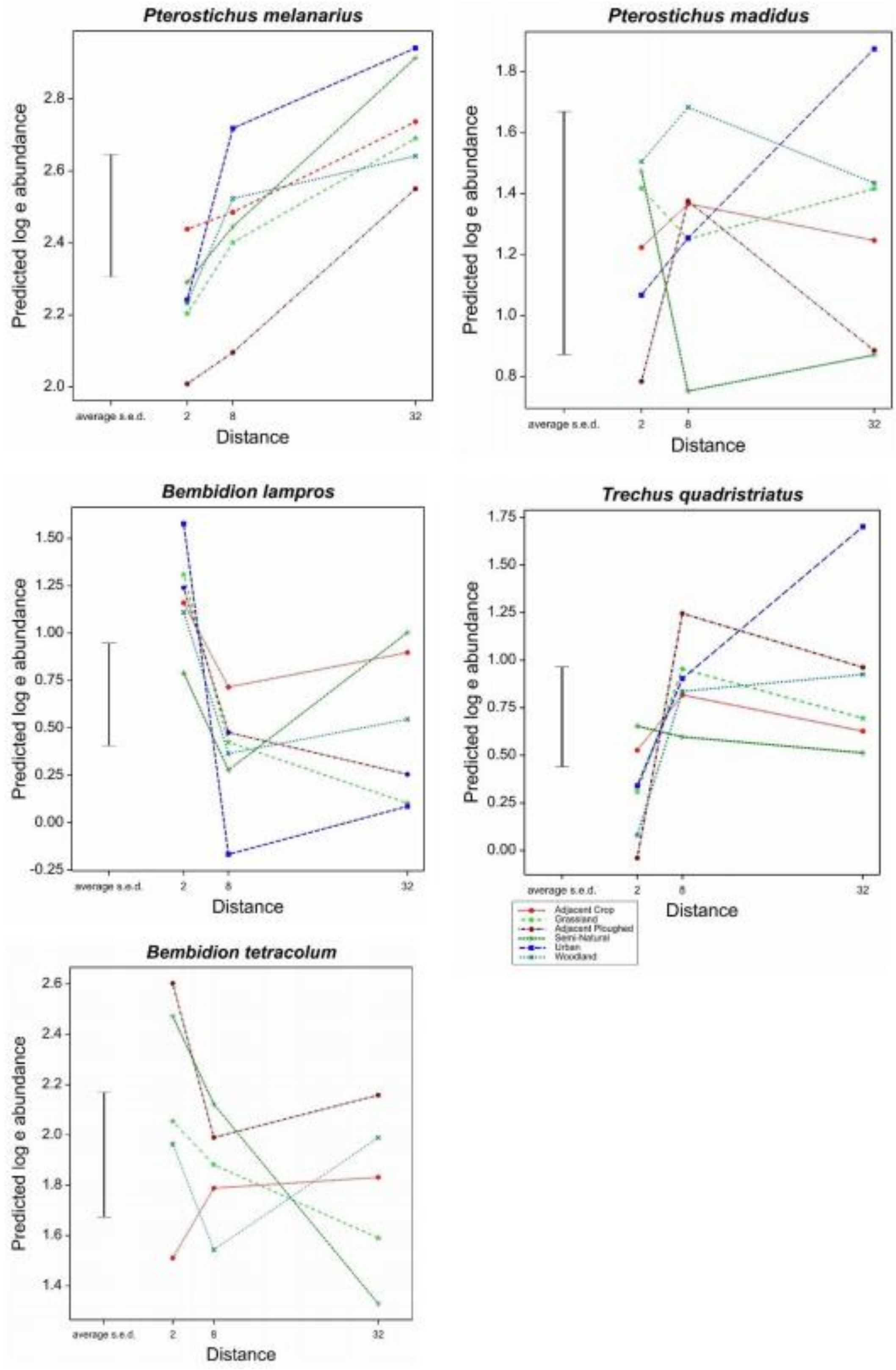


Figure 8- Abundance predictions for by distance into crop according to adjacent habitat, for species: (a) *P. melanarius*, (b) *P. madidus*, (c) *B. lampros* (d) *T. quadristriatus*, (e) *B. tetracolum*. The vertical line shows the approximate average standard error of difference.

2.5 DISCUSSION

H1: Carabid abundance, species richness, and diversity decrease with distance from the boundary habitat towards the crop centre.

We found that in contrast to Hypothesis 1, pooled-abundance of carabids increased towards the centre of the field. However, the overall picture is biased by the dominance of *P. melanarius* in catches. This species is predatory, aggregating in crop areas following pest distributions (Warner et al., 2008) and we would predict this would have a positive effect on the delivery of ecosystem services into field centres. However, if we consider predator diversity to be an important component of ecosystem services (Greenop et al. 2018), the increasing dominance of a single species away from field edges may compromise the resilience of service delivery; the abundance of most other major species reduced with distance into the crop. However, interactions between distance into crop and other factors such as soil category and crop type indicate that there is not a simple response to distance even within a species. For example *H. rufipes* is more abundant near the edge in Winter oilseed rape, yet more abundant towards the centre in Spring oilseed rape. Since these crops are similar in structure, this suggests temporal influence of management or resources is crucial (as trapping was carried out at different times in winter and spring crops) and species with differing habitat requirements may be delivering predation services at different times of the cropping season. For example, relative weed seed availability in crop areas (Petit et al., 2014).

The importance of species level differences in the response to distance into the crop is particularly important when considering the implementation of agri-environment options as not all species will respond in the same way. Boetzl et al (2018) investigated abundances by distance into crops and found evidence for distance decay, suggesting that carabid abundances were increased in fields of oilseed rape adjacent to agri-environent options. However, our results indicate that their approach of considering pooled carabid abundances may be obscuring underlying trends, particularly if the counts are dominated by one or two species. This highlights an advantage of using the FSE dataset that includes data from multiple crops and regions, capturing variability in responses between contrasting species pools and supporting Hypothesis 3 (see below). The most abundant species in their study were smaller, more flight dispersive species in contrast to *P. melanarius* which is predominantly ground dispersive. However, we also note that in our data the greatest distance into the crop was 32 m, which may not constitute crop centre: Boetzl et al. (2018) extended distance to around 60 m.

Species richness and species diversity were shown to decrease towards the centre of the crop supporting Hypothesis 1. These observations agree with the literature on edge effects: with species of both overlapping habitats co-occurring in the peripheral zones (Bianchi et al 2006; Saska et al 2007). This reflects the requirements of carabids in terms of providing habitats for aestivation and hibernation, and stable food and shelter, so dictating accumulations of species where these resources are most likely to co-occur (Thielle, 1977).

H2: The relationship of carabid abundance, species richness, and diversity with distance into the field will be contingent on the neighbouring field boundary and habitat.

We found no significant interactions between landscape features and distance in the models of pooled-carabid abundance and species richness indicating that the spillover of carabids from off-crop habitats into the field is limited. However, in the diversity model we did observe significant interactions between distance and landscape features that represent a barrier or corridor for many species. This supports the theory that the carabid community structure is driven by a combination of spatial mass effects from corridors, or the prevention of spatial mass effects across species specific barriers, from adjacent habitats. The lack of such effects in the species richness models may be accounted for by the nature of this measure showing only the total count of species, and not incorporating evenness, for example a habitat may be species rich but not diverse if dominated by certain species (Magurran 2013; Shmida and Wilson 1985).

The only environmental feature retained in the pooled-carabid models was margin, yet this did not interact with distance to support Hypothesis 2. Margins, with relatively diverse and stable resources, are generally thought to support more species and higher abundances (Weibull et al., 2003). However, we found species richness was lower in the presence of a margin. This may be due to the margin acting as a sink, providing stable resources for a greater range of species than the habitat afforded within the crop. Fusser et al. (2018) and Anjum-Zubair et al (2010) found carabid abundances to be higher in the field centre than near margins, but lacked comparative margin samples to make causal conclusions.

H3: Responses to environmental and management factors will vary by individual carabid species.

The limited interactions between environmental features and Distance into crop in the pooled-carabid abundance and species richness models suggest rejection of Hypothesis 2. This contrasts with the role of spatial mass effects described by Metcalfe et al (2018) for arable plants, indicating that the classic view of spillover from agro-ecological habitats cannot be extended from the passive dispersal of weeds to actively dispersing invertebrates. However, the individual species models show that all environmental features were important determinants of carabid presence and abundances and often interact with distance.

When we consider the predictions from the individual species models where there are interactions between Margin and Distance, an important general pattern emerges - responses are different for different species. For instance, in the presence of a margin, our models predicted that *B. lampros* would be more abundant at 2 metres (spillover zone), yet *Trechus quadristriatus* and *Nebria brevicollis* would be less abundant; with divergent patterns of distribution towards crop centres. When taken in context of management design, the utility of margins to ensure spillover of predation services into crop areas must be considered, especially given that different species may carry out desirable services in those areas.

Most notably in the consideration of Hypothesis 2, for many species there was an interaction between adjacent habitat and distance into crop, suggesting that landscape configuration should be taken into in management design. However, on examination of model predictions we see that species' differences mean that one size fits all recommendations cannot be made. For example, *P. melanarius* and *P. madidus*, although morphologically similar, display divergent responses to adjacent habitats, likely due to niche differentiation; *P. madidus* has a known preference for wooded habitats (Luff 1998). *B. lampros* and *T. quadristriatus*, are likewise similar in their small size and flight dispersal (Luff 1998), yet the patterns of abundance by distance are broadly reversed in interaction with most adjacent habitats. The pattern across these models appears to tell that for adjacent habitats with a similar vegetative structure to the crop environment (i.e. crop, and grassland), the response is less markedly divergent, representing a somewhat consistent matrix. Conversely, urban and woodland habitats, where the vegetative structure is very different to the cropped field are where we most often observe edge effect. This may be interpreted as landscape factors filtering the species pool.

Across the individual species models we found that there were significant interactions between distance and landscape features, particularly in the abundance models. For every species, at least one model related a landscape feature to the distance into the crop. This strongly supports Hypothesis 2, and underlines the importance of examining the effects of these variables when considering management. As active dispersers, carabids can search out resources for daily and seasonal needs- yet the parameters governing which resources guide their dispersal, and physically affect their dispersal, varies species to species (Luff 1998). The assumption of proximity effects on distribution has extended into management design (Marshall and Moonen 2002), backed by numerous studies correlating abundance of desirable species with semi-natural habitats (Bianchi, Booij, and Tscharntke, 2006). However, our results indicate more complex interactions of mass effects, niche differentiation, coexistence, and resource partitioning theories similar to those reported in Shmida and Wilson (1985) - this reportedly generic genus, in practice, demonstrating different actualised distributions than may be extended from their preferences when considered grouped as a whole (Holland, Birkett, and Southway, 2009).

The significance of the in-field habitat in our models, as represented by crop and soil factors, conformed to expectations from the literature of their importance to key carabid resource needs (Kotze et al 2011). Crop was a significant factor in the pooled abundance and diversity models, and across the majority of species models. This reflects the differential resources and structure of the crop habitats in question. General ecological theory supports increased species richness and diversity with diverse habitat structure and abundant food resources (Davies et al., 2012). Differing crops are also subject to differing management which can interact with the biological needs of resident species, for instance the timing of cultivation relative to presence of eggs and larvae in the soil can be important in determining whether the species can complete its life-cycle in that crop type. The significance of crop further emphasises the necessity to manage carabids with contrasting ecological requirements at the farm scale to deliver ecosystem services across the range of crops grown, as management may change areas from source to sink across the year, and if managed strategically, perhaps by staggering resource across space and time, populations may persist and repopulate effectively (Kromp 1999, Thorbeck and Bilde, 2004; Weibull, Östman, and Granqvist, 2003). Soil is known to impact greatly on carabids, due to food web and habitat effects, most crucially on (soil dwelling) larvae (Kotze et al., 2011). Our results show that Soil is significant in explaining species richness and abundance, but not diversity.

Particular distinctions are seen in abundance by distance in different crops. *Harpalus rufipes* is clearly more abundant near the edge of the crop in Winter OSR. Brooks et al. (2012) linked *H. rufipes* with larger seeded spring germinating weeds, which were shown to be less abundant than other weed functional groups in Winter oilseed rape. More generally the Brooks et al. study demonstrated preferences in different functional groups of carabids between invertebrate and weed food resources; shifting in omnivores over time due to resource availability. This supports our findings in relation to *H. rufipes* as foraging activity based on resources, not structure of crop; but does not account for those species distinctions we observe in our models, between such similar carabids as *P. melanarius* and *P. madidus.* Holland et al. (2004) examined the spatial dynamics of *P. melanarius* and *P. madidus*; finding both species were associated with margins early in the year, yet aggregated differentially in the crops over time. Furthermore, the authors found that *P. madidus* crossed boundaries 'more frequently' than *P. melanarius*. Clearly these *Pterostichus* species - assumed by much literature to have similar distributions based upon morphologies, respond differentially to landscape factors.

In the individual species abundance models, landscape variables are retained more often than when we consider presence/absence. This reflects the influence that these variables have upon breeding and survivorship. For example, Luff (1998) describes *Pterostichus niger'*s preference for damp grassland and woodland habitats, which is seen in the retention of hedge, water and adjacent habitat in the abundance model (Table 5). This clarifies the above lack of evidence for Hypothesis 2 under the pooled abundance model. Environmental features were associated with abundances, however this was varied greatly by species; an effect that is lost when considering only pooled carabid abundance.

The individual species models elucidate the influence of environmental features on the distribution of carabid species. *P. niger* was more likely to be observed in pitfalls with a ditch at the boundary, suggesting this species use ditches as a corridor. *Pterostichus melanarius* appears to associate with tracks which may be explained by its preference for hunting in open habitats (Holland et al 2004; Luff 1998); whilst it is less abundant near roads. When *P. melanarius* is considered in context with *B. lampros*, a primarily flight dispersive species (Luff 1998; Thielle 1977); the influence of running dispersal, seems to be indicated. *Bembidion lampros*'s higher abundance near the edge in association with urban adjacent habitats may represent colonisation where other species' lower abundances leave a gap in exploitation of resources. Flight dispersal may render the urban environment less of a barrier, and support quicker recolonization for this species after agricultural disturbances (Davies et al 2012).

We have shown that the configuration of environmental features at a farm-scale affects the species present and their abundances. This supports Hypothesis 3, and indicates that the picture afforded by pooled-carabid abundance loses accuracy due to the diverse preferences and tolerances of individual species where boundary and adjacent environmental features act by sorting the species pool found in the field. This is likely to impact functional diversity, and the traits of particular species assemblages may have considerable impact on the extent of ecosystem service delivery.

2.6 Management implications

Understanding the multiple effects of environmental and management factors upon overall abundance, and spatial distribution (e.g. spillover distances into the crop) are key to the design of effective management for pest control. Recent innovations in agri-environmental measures have worked on the assumption of spillover (Rand et al., 2006); however, the findings of this study are not consistent with this simplistic idea. We argue that managing landscape features crucial to carabid's daily (for example weed seed food resource) and seasonal needs (for example hibernation in hedgerows) (Thomas, Holland and Brown 2002) are the most important consideration when seeking to maintain ecosystem service delivery at the individual field scale. Our results suggest the importance of considering this at a farm scale, to account for the differing response of species (which may each be providing different ecosystem services) to environmental factors.

Our findings suggest that plot scale immediacy of these habitat and dispersal resources affects movements in the crop, but that species' responses vary markedly with landscape variables. Therefore fine-scale service delivery may not be determined solely by the proximity of refuge habitats; an argument supported by the limited benefit of margins on in-crop carabid abundance in the neighbouring field observed in this large dataset. The effect of species preferences is likely to have the effect of balancing out the benefits of measures such as margins and hedges - with some species responding positively, and some negatively. What is needed to transform our findings into practical applications of management interventions is the integration of species preferences with the service provision desired in space and time (i.e. matching supply and demand of pest regulation services). In the absence of rigorous data on this (Kotze et al 2010), a simple recommendation is that a diversity in habitat provision, relative to landscape features, can provide multiple habitats for individual species to thrive - in essence, maximising habitat diversity for carabid diversity.

With even a limited species pool of the ten species considered in this study, it is evident that in any combination of crop, soil and landscape attributes; one or more species is likely to thrive. Our analyses show that diversity and species richness are strongly linked to the boundary of the field, and more crucially to the crop - this suggests that multiple crop types at a farm scale can be most advantageous. Given the mobility of this group of ecosystem service providers, there may be potential to manipulate carabid distributions through the year by the placement of crops in relation to each other and the surrounding landscape. We suggest this would be most effective by avoiding block cropping and maximising the interfaces between crops to enable populations to move with favoured crops through the rotation.

There is scope from this work to tailor farm habitat management to enhance the abundance of specific desirable species in a given location; yet current understanding falls short of directly linking this to pest regulation services. Further knowledge on the actual levels of pest control service provision by individual species is needed, along with their specific lifecycle needs. Desirable species assemblages could be encouraged by providing appropriate resources in time as well as space; for example, weed seeds of preferred species set in margins at key times for population persistence of *H. rufipes*; in farms where weed seed predation is desirable.

We show that important relationships between carabids and habitats can be missed if a study only considers a limited number of scales, on single crops, and single species. The overwhelming influence of species identity as a factor modulating interactions with habitats challenges the applicability of previous recommendations on general management practices based on limited data.

For example Boetzl et al (2018) studied carabid beetle assemblages in OSR fields relative to four types of similar semi-natural adjacent habitats. The authors used the strong distance decay exhibited by the communities they sampled as a basis for a general recommendation for small field sizes or agri-environment scheme options inside fields based. This community (as discussed above), typical of the OSR in their region, and with limited inclusion of other landscape factors- may not be as widely applicable for recommendations, for example cropped wheat in a tree and scrub rich landscape.

Furthermore, this may explain the conflict of various studies on the effects of certain landscape factors. Even as polyphagous generalists, carabids display vastly variable realised niches over space and time. Though widely recognised in environmental scientific theory, the bias of carabid species differences appears to be inadequately accounted for. Though some efforts are made by measures of species richness and diversity- and some approaches attempt to disentangle species differences by use of traits and functional diversity (Magurran, 2004), we counter that such analyses may be missing vital distinctions. As discussed above, *P. melanarius* and *P. madidus* are morphologically similar and identical in many trait groupings, yet display different preferences. This can have a great impact on extensions- in fact the general assumption that tussocky grass margins benefit carabids in general may be inaccurate for many species of potential benefit in specific farming systems- such as *H. rufipes*; discussed above (Saska et al 2007; Weibull, Östman, and Granqvist, 2003; Woodcock et al, 2007).

We conclude that in any given study of carabids, dominant species and differing assemblages are likely to bias inferences and general conclusions, if data is pooled. Though this genus is extensively studied, more work still is needed particularly at the species level, to enable effective utilisation for natural enemy pest control.

- **Authors' Contributions**

KJ and JS conceived and designed the study. The research and analysis was performed by KJ with input from HM, AEM, and KLH. All authors contributed to interpretation of results and writing the manuscript.

Acknowledgements

KJ is grateful for funding from the Rothamsted-Reading Alliance. JS, AEM and HM are supported by research programmes NE/N018125/1 LTS-M ASSIST – Achieving Sustainable Agricultural Systems, funded by NERC and BBSRC (BBS/E/C/000I0140), and the Smart Crop Protection (SCP) strategic programme (BBS/OS/CP/000001) and the Soil to Nutrition (S2N) strategic programme (BBS/E/C/000I0330) both funded by the BBSRC. We thank Suzanne Clark for their advice on the analysis.

2.7 References

Anjum-Zubair, M., Schmidt-Entling, M.H., Querner, P. & Frank, T., 2010. Influence of within-field position and adjoining habitat on carabid beetle assemblages in winter wheat. *Agricultural and Forest Entomology,* 12, 301–306.

Beck, J. and Schwanghart, W., 2010. Comparing measures of species diversity from incomplete inventories: an update. *Methods in Ecology and Evolution*, 1(1), pp.38-44.

Bianchi, F.J., Booij, C.J.H. and Tscharntke, T., 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proceedings of the Royal Society B: Biological Sciences*, 273(1595), pp.1715-1727.

Brooks, D.R., Storkey, J., Clark, S.J., Firbank, L.G., Petit, S. and Woiwod, I.P., 2012. Trophic links between functional groups of arable plants and beetles are stable at a national scale. *Journal of Animal Ecology*, 81(1), pp.4-13. https://doi.org/10.1111/j.1365-2656.2011.01897.x

Brooks, D.R., Bohan, D.A., Champion, G.T., Haughton, A.J., Hawes, C., Heard, M.S., Clark, S.J., … Rothery, P., 2003. Invertebrate responses to the management of genetically modified herbicide–tolerant and conventional spring crops. I. Soil-surface-active invertebrates. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 358(1439), pp.1847-1862. DOI: 10.1098/rstb.2003.1407

Brooks, D.R., Perry, J.N., Clark, S.J., Heard, M.S., Firbank, L.G., Holdgate, R., Shortall, C.R., …. Woiwod, I.P. (2008) National-scale metacommunity dynamics of carabid beetles in UK farmland. *Journal of Animal Ecology*,77,265–274 https://doi.org/10.1111/j.1365-2656.2007.01331.x

Boetzl, F.A., Krimmer, E., Krauss, J. and Steffan-Dewenter, I., 2018. Agri-environmental schemes promote ground-dwelling predators in adjacent oilseed rape fields: Diversity, species traits and distance-decay functions. *Journal of Applied Ecology*. https://doi.org/10.1111/1365-2664.13162

Booij, K., 1994. Diversity patterns in carabid assemblages in relation to crops and farming systems. *In*: Desender, K., Dufrêne, M., Loreau, M., Luff, M.L. and Maelfait, J.P. eds., 2013. *Carabid beetles: ecology and evolution (Vol. 51).* Springer Science & Business Media. pp. 425-431 https://doi.org/10.1007/978-94-017-0968-2_64

Council Directive 2009/128/EC of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides

Crowder, D.W.,and Jabbourb, R., 2014. Relationships between biodiversity and biological control in agroecosystems: Current status and future challenges. *Biological Control*. Volume 75, August 2014, Pp 8–17 https://doi.org/10.1016/j.biocontrol.2013.10.010

Davies, N.B., Krebs, J.R. and West, S.A., 2012. *An introduction to behavioural ecology*. John Wiley & Sons.

EC 2018. *Pesticide National Action Plans* [19/10/18]. Available at: https://ec.europa.eu/food/plant/pesticides/sustainable_use_pesticides/nap_en.

Fahrig, L. and Jonsen, I., 1998. Effect of habitat patch characteristics on abundance and diversity of insects in an agricultural landscape. *Ecosystems*, 1(2), pp.197-205 https://doi.org/10.1007/s100219900015

Firbank, L.G., Heard, M.S., Woiwod, I.P., Hawes, C., Haughton, A.J., Champion, G.T., Scott, R.J., … May, M.J., 2003. An introduction to the Farm-Scale Evaluations of genetically modified herbicide-tolerant crops. *Journal of Applied Ecology*, 40(1), pp.2-16. https://doi.org/10.1046/j.1365-2664.2003.00787.x

Fusser, M.S., Holland, J.M., Jeanneret, P., Pfister, S.C., Entling, M.H. and Schirmel, J., 2018. Interactive effects of local and landscape factors on farmland carabids. *Agricultural and Forest Entomology*. https://doi.org/10.1111/afe.12288

Garratt, M.P.D., Wright, D.J. and Leather, S.R., 2011. The effects of farming system and fertilisers on pests and natural enemies: a synthesis of current research. *Agriculture, Ecosystems & Environment*, *141*(3-4), pp.261-270. https://doi.org/10.1016/j.agee.2011.03.014

Greenop, A., Woodcock, B.A., Wilby, A., Cook, S.M. and Pywell, R.F., 2018. Functional diversity positively affects prey suppression by invertebrate predators: a meta-analysis. *Ecology*, *99*(8), pp.1771-1782.

Holland, J.M., Begbie, M., Birkett, T., Southway, S., Thomas, S.R., Alexander, C.J. and Thomas, C.F.G., 2004. The spatial dynamics and movement of Pterostichus melanarius and P. madidus (Carabidae) between and within arable fields in the UK. *International Journal of Ecology and Environmental Sciences*. 30, pp.35-50.

Holland, J.M., Birkett, T. and Southway, S., 2009. Contrasting the farm-scale spatio-temporal dynamics of boundary and field overwintering predatory beetles in arable crops. *Biocontrol*, 54(1), pp.19-33. https://doi.org/10.1007/s10526-008-9152-2

Holland, J.M., Thomas, C.F.G., Birkett, T., Southway, S. & Oaten, H., 2005. Farm-scale spatiotemporal dynamics of predatory beetles in arable crops. *Journal of Applied Ecology*, 42, 1140–1152.

Karp, D.S., Chaplin-Kramer, R., Meehan, T.D., Martin, E.A., DeClerck, F., Grab, H., Gratton, C., … O'Rourke, M.E., 2018. Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. *Proceedings of the National Academy of Sciences*, *115*(33), pp.E7863-E7870. https://doi.org/10.1073/pnas.1800042115

Kenward, M.G. & Roger, J.H. (1997). Small sample inference for fixed effects from restricted maximum likelihood. *Biometrics*, 53, 983-997.

Koivula, M., Hyyryläinen, V. and Soininen, E., 2004. Carabid beetles (Coleoptera: Carabidae) at forest-farmland edges in southern Finland. *Journal of Insect Conservation*, *8*(4), pp.297-309. https://doi.org/10.1007/s10841-004-0296-9

Kotze, D.J., Brandmayr, P., Casale, A., Dauffy-Richard, E., Dekoninck, W., Koivula, M.J., Lövei, G.L., … Pizzolotto, R., 2011. Forty years of carabid beetle research in Europe–from taxonomy, biology, ecology and population studies to bioindication, habitat assessment and conservation. *ZooKeys*, (100), p.55. 10.3897/zookeys.100.1523

Kromp, B., 1999. Carabid beetles in sustainable agriculture: a review on pest control efficacy, cultivation impacts and enhancement**.** *Agriculture, Ecosystems & Environment***.** Volume 74, Issues 1–3, June 1999, Pp 187–228 https://doi.org/10.1016/B978-0-444-50019-9.50014-5

Labruyere, S., Bohan, D.A., Biju-Duval, L., Ricci, B. and Petit, S., 2016. Local, neighbor and landscape effects on the abundance of weed seed-eating carabids in arable fields: A nationwide analysis. *Basic and applied ecology*, *17*(3), pp.230-239. https://doi.org/10.1016/j.baae.2015.10.008

Lichtenberg, E.M., Kennedy, C.M., Kremen, C., Batáry, P., Berendse, F., Bommarco, R., Bosque-Pérez, N.A., …Winfree, R., 2017. A global synthesis of the effects of diversified farming systems on arthropod diversity within fields and across agricultural landscapes. *Global change biology*, *23*(11), pp.4946-4957. https://doi.org/10.1111/gcb.13714

Luff, M.L., 1998. *Provisional atlas of the ground beetles (Coleoptera, Carabidae) of Britain*. Biological Records Centre Institute of Terrestrial Ecology.

Magurran, A.E., 2013. *Measuring biological diversity*. John Wiley & Sons.

Marshall, E. J. P., & Moonen, A. C. (2002). Field margins in northern Europe: their functions and interactions with agriculture. *Agriculture, Ecosystems & Environment*, *89*(1-2), 5-21. https://doi.org/10.1016/S0167-8809(01)00315-2

Metcalfe, H., Hassall, K.L., Boinot, S. and Storkey, J., 2019. The contribution of spatial mass effects to plant diversity in arable fields. *Journal of Applied Ecology*.

Payne, R.W. ed., 1993. *Genstat 5 release 3 reference manual*. Oxford University Press.

Pennekamp, F., Pontarp, M., Tabi, A., Altermatt, F., Alther, R., Choffat, Y., Fronhofer, E.A., …Greene, S., 2018. Biodiversity increases and decreases ecosystem stability. *Nature*.

Petit, S., Bohan, D.A. and Dijon, A., 2018. The use of insects in integrated weed management. In *Integrated weed management for sustainable agriculture* (pp. 453-468). Burleigh dodds Science publishing. DOI: 10.19103/AS.2017.0025.23

Petit, S., Boursault, A. and Bohan, D.A., 2014. Weed seed choice by carabid beetles (Coleoptera: Carabidae): Linking field measurements with laboratory diet assessments. *European Journal of Entomology*, *111*(5). DOI: 10.14411/eje.2014.086

R Core Team, 2017. *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rand, T.A., Tylianakis, J.M. and Tscharntke, T., 2006. Spillover edge effects: the dispersal of agriculturally subsidized insect natural enemies into adjacent natural habitats. *Ecology letters*, *9*(5), pp.603-614. https://doi.org/10.1111/j.1461-0248.2006.00911.x

Saska, P., Vodde, M., Heijerman, T., Westerman, P. & van der Werf, W., 2007. The significance of a grassy field boundary for the spatial distribution of carabids within two cereal fields. Agriculture, Ecosystems and Environment, 122, 427–434.

Thiele, H.U., 1977. *Carabid Beetles in Their Environments: A Study on Habit Selection by Adaptations in Physiology and Behaviour.* Translated by Joy Wieser. Springer-Verlag.

Thomas, C.G., Holland, J.M. and Brown, N.J., 2002. The spatial distribution of carabid beetles in agricultural landscapes. *The agroecology of carabid beetles*. Andover: Intercept, pp.305-344.

UK Biodiversity Steering Group (1998) *Tranche 2 action plans 2*. Terrestrial and freshwater habitats, English Nature, Peterborough, UK.

Thorbek, P., and Bilde, T., 2004 Reduced numbers of generalist arthropod predators after crop management. *Journal of Applied Ecology*, 41, 526– 538.

Warner, D.J., Allen-Williams, L.J., Warrington, S., Ferguson, A.W. and Williams, I.H., 2008. Implications for conservation biocontrol of spatio-temporal relationships between carabid beetles and coleopterous pests in winter oilseed rape. *Agricultural and forest Entomology*, *10*(4), pp.375-387. https://doi.org/10.1111/j.1461-9563.2008.00391.x

Weibull, A.C., Östman, Ö. and Granqvist, Å., 2003. Species richness in agroecosystems: the effect of landscape, habitat and farm management. *Biodiversity & Conservation*, *12*(7), pp.1335-1355. https://doi.org/10.1023/A:1023617117780

Welham, S.J., Gezan, S.A., Clark, S.J. and Mead, A., 2014. *Statistical methods in biology: Design and analysis of experiments and regression*. Chapman and Hall/CRC.

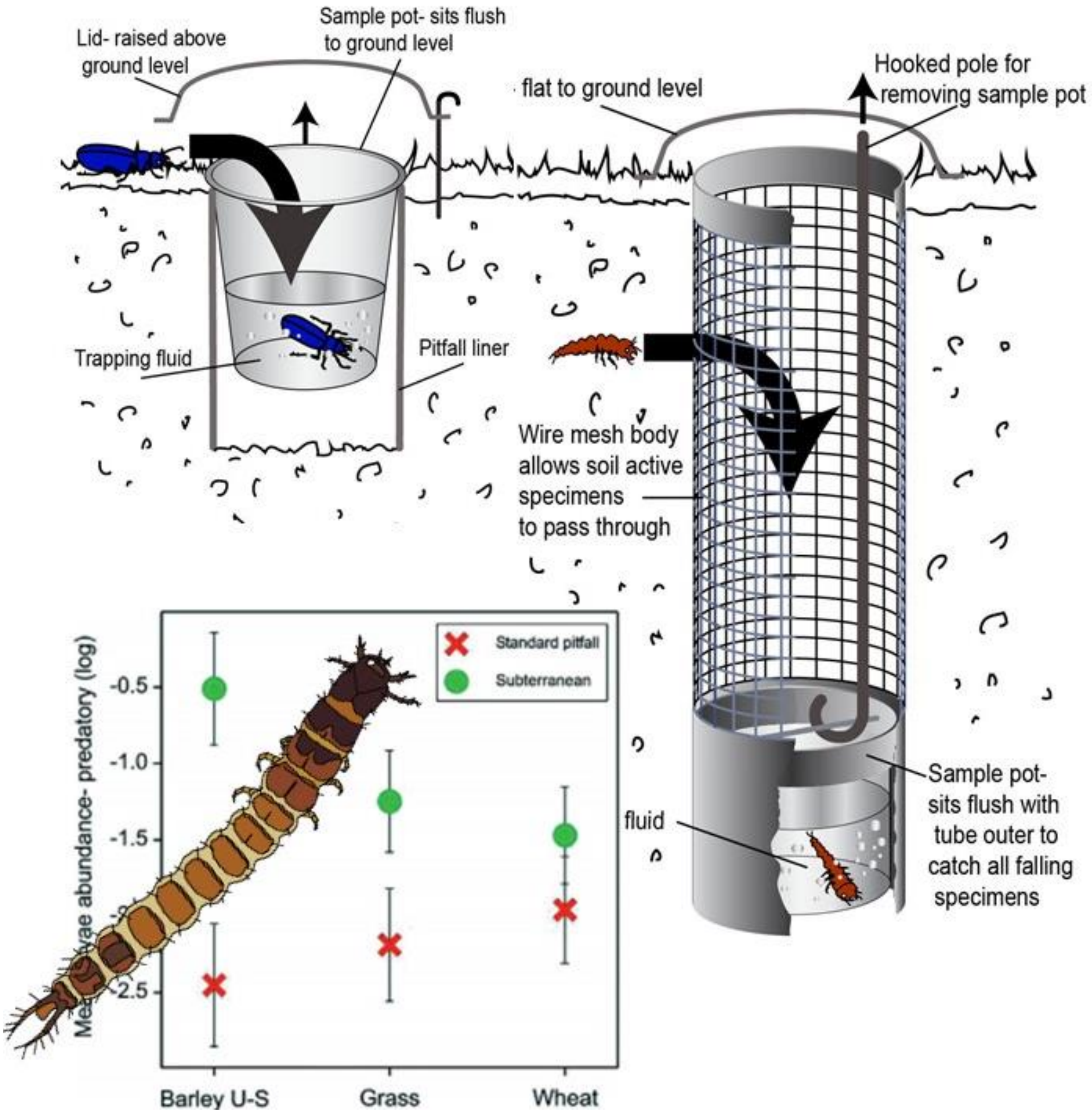
Weibull, A.C., Östman, Ö. and Granqvist, Å., 2003. Species richness in agroecosystems: the effect of landscape, habitat and farm management. Biodiversity & Conservation, 12(7), pp.1335-1355. https://doi.org/10.1023/A:1023617117780

Winqvist, C., Bengtsson, J., Aavik, T., Berendse, F., Clement, L.W., Eggers, S., Fischer, C., Flohre, A., Geiger, F., Liira, J. and Pärt, T., 2011. Mixed effects of organic farming and landscape complexity on farmland biodiversity and biological control potential across Europe. *Journal of applied ecology*, 48(3), pp.570-579. https://doi.org/10.1111/j.1365-2664.2010.01950.x

Woodcock B.A., Potts S.G., Westbury D.B., Ramsay A.J., Lambert M., Harris S.J., Brown V.K., 2007. The importance of sward architectural complexity in structuring predatory and phytophagous invertebrate assemblages. *Ecological Entomology* 32, 302-311 https://doi.org/10.1111/j.1365-2311.2007.00869.x

Woodcock, B.A., Harrower, C., Redhead, J., Edwards, M., Vanbergen, A.J., Heard, M.S., Roy, D.B. and Pywell, R.F., 2014. National patterns of functional diversity and redundancy in predatory ground beetles and bees associated with key UK arable crops. *Journal of Applied Ecology*, 51(1), pp.142-151. https://doi.org/10.1111/1365-2664.12171

Chapter 3



Carabids as study organisms

As detailed in the introduction, carabids as organisms have been extensively studied (Adamski et al., 2019; Holland and Luff, 2000; Kinnunen, and Tiainen; 1999; Thiele, 1977; Woodcock et al., 2007). Though much of their utility to science lies in the ubiquity of the genera over habitats and their sensitivity to environmental change, arguably the legacy of this capacious research originated in the ease of collecting specimens for study. Pitfall trapping was first described over 90 years ago (berber traps), and has been the standard technique for carabidologists ever since (Kotze et al., 2011). Though a variety of designs exist, the principle is a collecting cup buried in the ground with the rim level to the soil surface, collecting any invertebrates traversing the soil surface that fall into the trap. Generally, a scentless killing fluid preserves the specimens and prevents in-trap predation (Wheater, Bell, and Cook, 2020).

Pitfall trapping is a very useful method, easy and inexpensive to set up, and robust as a measurement allowing comparison of samples with different environmental variables. However, since the behaviour of carabids to run across the soil surface is variable both between species and individuals, this measure is not indicative of carabid abundance in a given area, it is actually a measure of surface *activity density*. This is recognised in the literature, yet unresolved. As Kotze et al. (2011) state, in their review of 40 years of carabid research "*most carabidologists tip their hat at the problem, then proceed to ignore it*". This is of concern when analysis based on pitfall trapping is used to draw conclusions on ecological quandaries. For example, pitfall trapping revealed that *Pterostichus melanarius* was more abundant in plots treated with insecticides, to which one might conclude that pesticides had little impact on abundance— however these were seen to be starved individuals responding to lack of invertebrate food by increasing their surface foraging (Chiverton, 1984). Added to this, the entire assemblage may not be sampled, particularly cryptic or soil active species (Blubaugh, and Kaplan, 2015; Holland, Frampton, and Van der Brink, 2002).

Whilst methodological biases of pitfall trapping can be somewhat ameliorated with analytical techniques, it may be more appropriate (particularly when considering ecological processes of carabid assemblages) to use different sampling methods. Modifications to basic pitfall traps design, such as radiating 'fences' to funnel invertebrates towards the trap, can improve the abundance trapped, particularly in cryptic species, these still exhibit the surface-active bias. Suction sampling, whereby vegetation is sampled with equipment that vacuums invertebrates into a collection bag, can be effective in capturing smaller species active in crop canopies (Sunderland, 1995). Emergence traps are designed to measure the invertebrates emerging for the soil, thereby giving a better estimate of origin. Emergence traps consist of a structure encompassing a certain area of soil surface, with either a collection cup at the top of a tented structure, or pitfalls on the ground, so that only specimens emerging from the soil in the delimitated are captured. This technique can inform well on carabids breeding and survivorship, but are time sensitive to match emergence of new adults- which is variable by species and conditions, and also relatively expensive (Plantegenest, Aviron, and Pétillon, 2019; Purvis and Fadl, 1996).

A key downside of all of these techniques is in capturing carabid larvae, which is desirable to inform on full predation by carabids, and to determine the effects of management on survivorship. Carabid larvae may be surface active in foraging behaviour, however, they are primarily active beneath the soil surface— therefore pitfall traps are inefficient for sampling. Most studies disregard larval catch due to low numbers and difficulty of identification, yet where elaborated, catches of larvae can be as little as 2.5% of the total carabids caught (Barney and Pass, 2017).

To capture a complete assemblage of invertebrate species active in the soil area, soil cores are the dominant technique, whereby certain areas of soil are dug out of a pit, and either hand sifted on site, or processed with laboratory equipment to separate specimens. These techniques are effective in giving a complete picture of species presence at one place and time, however, are time and labour intensive, or require specialist equipment (Smith, Potts, and Eggleton, 2008). Soil cores are rarely used for carabids, yet may be effective in the investigation of species such as *Trechus quadristriatus*, which is flight dispersive and soil active (Mitchell, 1963).

Hypogean, or subterranean pitfall traps work on the premise of pitfall traps, but are set underground, beneath a mesh or perforated tube, which soil active specimen fall through into the collecting dish. Subterranean pitfalls provide a similar time window trapping of activity to standard pitfalls, yet being a novel technique, traps are not available for purchase. This sampling technique is mainly used in the investigation of ants (where singular large traps are constructed and used near colonies) (Pacheco, and Vasconcelos, 2012), and is only documented in a few published studies of carabids. Drmić et al. (2016) and Kos et al. (2013) used commercially available traps (for insect pests in grain stores) of a meshed pipe design, to increase the estimation of below-ground predator communities in crops, however, both studies found that catches of larger species were excluded due to the small perforation size (4mm x 2mm). Sims, Cole, and Verdon (2016) constructed traps (mesh size 10mm^2), and found them effective for estimating soil biodiversity in field margins, including good catches of both carabid adults and larvae. Therefore, subterranean pitfalls would merit further investigation as a method to extend sampling and inform more accurately on occurrence of cryptic species and carabid larvae.

In order to gain a full picture of carabids in farmland, from ecology to utility, it would be beneficial to use a variety of methods. These methodological issues are addressed in my first empirical study, which meets the project's second objective of fieldwork for validation and exploration. The factors identified in Chapter 2 were built into the experimental design by testing for crop effects, and controlling for distance and edge effects. We also explored tillage, as a key factor identified in the literature review, yet not included in the FSE dataset.

References

Adamski, Z., Bufo, S.A., Chowański, S., Falabella, P., Lubawy, J., Marciniak, P., Pacholska-Bogalska, J., Salvia, R., Scrano, L., Słocińska, M. and Spochacz, M., 2019. Beetles as model organisms in physiological, biomedical and environmental studies—a review. *Frontiers in Physiology*, 10, p.319.

Barney, R.J. and Pass, B.C., 2017. Pitfall trap collections of ground beetle larvae (Coleoptera: Carabidae) in Kentucky alfalfa fields. *The Great Lakes Entomologist*, 19(3), p.2.

Blubaugh, C.K. and Kaplan, I., 2015. Tillage compromises weed seed predator activity across developmental stages. *Biological Control*, 81, pp.76-82.

Chiverton, P.A., 1984. Pitfall-trap catches of the carabid beetle Pterostichus melanarius, in relation to gut contents and prey densities, in insecticide treated and untreated spring barley. *Entomologia experimentalis et applicata*, 36(1), pp.23-30.

Drmić, Z., Čačija, M., Gašparić, H.V., Lemić, D. and Bažok, R., 2016. Endogaeic ground beetles fauna in oilseed rape field in Croatia. *Journal of central European agriculture.*

Holland, J.M., Frampton, G.K. and Van den Brink, P.J., 2002. Carabids as indicators within temperate arable farming systems: implications from SCARAB and LINK integrated farming systems projects. *The agroecology of carabid beetles*. Intercept, Andover, UK.

Holland, J.M. and Luff, M.L., 2000. The effects of agricultural practices on Carabidae in temperate agroecosystems. *Integrated pest management reviews*, 5(2), pp.109-129.

Kinnunen, H. and Tiainen, J., 1999. Carabid distribution in a farmland mosaic: the effect of patch type and location. *In Annales Zoologici Fennici* (pp. 149-158). Finnish Zoological and Botanical Publishing Board.

Kos, T., Bažok, R., Drmić, Z., Graša, Ž. (2013) Ground beetles (Coleoptera: Carabidae) in sugar beet fields as the base for conservation biological control. In: Jehle, J. A., Bažok, R., Crickmore, N., López-Ferber, M., Glazer, I., Quesada-Moraga, E., Traugott, M., eds. (2013) *Proceedings of the 14th Meeting of the IOBC/wprs Working Group "Insect Pathogens and Entomoparasitic Nematodes"*. Zagreb, Croatia, 16-20 June 2013. IOBC/wprs Bulletin, 90, 353-357.

Kotze, D.J., Brandmayr, P., Casale, A., Dauffy-Richard, E., Dekoninck, W., Koivula, M.J., Lövei, G.L., Mossakowski, D., Noordijk, J., Paarmann, W. and Pizzolotto, R., 2011. Forty years of carabid beetle research in Europe–from taxonomy, biology, ecology and population studies to bioindication, habitat assessment and conservation. *ZooKeys*, (100), p.55.

Mitchell, B., 1963. Ecology of two carabid beetles, Bembidion lampros (Herbst) and Trechus quadristriatus (Schrank). *The Journal of Animal Ecology*, pp.377-392.

Pacheco, R. and Vasconcelos, H.L., 2012. Subterranean pitfall traps: is it worth including them in your ant sampling protocol?. *Psyche: A Journal of Entomology*, 2012.

Plantegenest, M., Aviron, S. and Pétillon, J., 2019. Local vs. landscape characteristics differentially shape emerging and circulating assemblages of carabid beetles in agroecosystems. *Agriculture, Ecosystems & Environment*, 270, pp.149-158.

Purvis, G. and Fadl, A., 1996, January. Emergence of Carabidae (Coleoptera) from pupation: A technique for studying the'productivity'of carabid habitats. *In Annales Zoologici Fennici* (pp. 215-223). Finnish Zoological and Botanical Publishing Board.

Sims, I., Cole, J. and Verdon, P., 2016. Hypogean pitfall trapping: a novel technique for assessing soil biodiversity in agroecosystems. *British Journal of Entomology and Natural History*, 29(4), pp.211-229.

Smith, J., Potts, S. and Eggleton, P., 2008. Evaluating the efficiency of sampling methods in assessing soil macrofauna communities in arable systems. *European Journal of Soil Biology*, 44(3), pp.271-276.

Sunderland, K., 1995. Density estimation for beneficial predators in agroecosystems. *Acta Jutlandica* 70, 133–164

Thiele, H.U., 1977. *Carabid beetles in their environments: a study on habitat selection by adaptations in physiology and behaviour* (Vol. 10). Springer Science & Business Media.

Wheater, C.P., Bell, J.R. and Cook, P.A., 2020. *Practical field ecology: a project guide.* John Wiley & Sons.

Woodcock, B.A., Potts, S.G., Westbury, D.B., Ramsay, A.J., Lambert, M., Harris, S.J. and Brown, V.K., 2007. The importance of sward architectural complexity in structuring predatory and phytophagous invertebrate assemblages. *Ecological Entomology*, 32(3), pp.302-311.

Above- and below-ground assessment of carabid community responses to crop type and tillage

Kelly Jowett[1,2], Alice E Milne[1], Dion Garrett[1,2], Simon G. Potts[3], Deepa Senapathi[3], Jonathan Storkey[1]
[1]Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK
[2]University of Warwick, Coventry, CV4 7AL, UK
[3]Centre for Agri-Environmental Research, School of Agriculture Policy and Development, University of Reading, Reading, RG6 6AR, UK
Corresponding Author: Kelly Jowett, Sustainable Agricultural Sciences, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK, Kelly.jowett@rothamsted.ac.uk

Abstract

1) Carabid beetles are major predators in agro-ecosystems. The composition of their communities within crop environments governs the pest control services they provide. An understudied aspect is the distribution of predacious carabid larvae in the soil.
2) We used novel subterranean trapping with standard pitfall trapping, within a multi-crop rotation experiment, to assess the responses of above- and below-ground carabid communities to management practices
3) Crop and trap type significantly affected pooled carabid abundance with an interaction of the two, the highest numbers of carabids were caught in subterranean traps in barley under sown with grass.
4) Trap type accounted for the most variance observed in carabid community composition, followed by crop.
5) Tillage responses were only apparent at the species level for three of the eight species modelled.
6) Responses to crop type varied by species. Most species had higher abundance in under-sown barley, than grass, wheat and barley. Crop differences were greater in the subterranean trap data. For predaceous larvae standard pitfalls showed lowest abundances in under-sown barley, yet subterranean traps revealed actual abundances to be highest in this crop.
7) Comprehensive estimation of ecosystem services should incorporate both above- and below ground community appraisal, towards appropriate management.

This chapter is published as:

Jowett, K., Milne, A.E., Garrett, D., Potts, S.G., Senapathi, D. and Storkey, J., 2021. Above-and below-ground assessment of carabid community responses to crop type and tillage. Agricultural and Forest Entomology, 23(1), pp.1-12.

3.1 Introduction

Carabid beetles, as ubiquitous and generally polyphagous predators, are much studied in agro-ecosystems. Research has shown their potential utility to control pest arthropods and weed seeds in crop areas, leading to the development of management measures to boost carabid abundance in farm habitats (Kromp, 1999; Tscharntke et al., 2007; Petit et al., 2018a). Furthermore, there is a general consensus that a diverse carabid community will provide more stable and increased natural pest regulation in agricultural crops (Bianchi et al., 2006; Bommarco et al., 2018). The presence of carabids in crop areas largely depends on the resources available in these areas, which is modified by farm management practices (Thomas et al., 2002). This may vary considerably by species; therefore, to design models and management to boost populations or increase biodiversity, it is important to understand the needs of carabid beetles, at a biological and behavioural level (Kleijn & Sutherland, 2003; Petit et al., 2018b; Jowett et al., 2019).

One large biological, and indeed behavioural, knowledge gap exists around the immature life-stages of carabids. Carabid larvae are principally soil-dwelling, especially those species inhabiting agro-ecosystems (Luff & Larsson, 1993). Though some species may move metres down into the soil, most live near the surface (top 50 cm) feeding on the biota of the top soil horizons. Larvae are predominantly carnivorous, even when the adults are granivorous (Sasakawa et al., 2010); and have even been observed climbing up crop plants to feed on invertebrate pests (Suenaga & Hamamura, 1998). Some species such as Harpalus rufipes (De Geer, 1778), however, specialise in weed seed predation, collecting seeds in burrows for consumption (Traugott, 1998). Since a large proportion of crop pests have at least one life-stage inhabiting topsoil layers (Ratnadass et al., 2006), and weed seeds cycle in this soil level (Petit et al., 2018a), carabid larvae comprise a large proportion of natural enemy pest-control in crops.

Some studies have shown predation of key crop pests by carabid larvae (e.g. Symondson, 2004), yet most studies on larvae are laboratory based, and suffer from the bias inherent in artificial environments when considering actualised predation and preferences (Suenaga & Hamamura, 1998; Thomas et al., 2009). Much work on larvae is based on assumptions from morphology and analogous organisms, and extended from limited data (Kotze et al., 2011). To gain a fuller, and more accurate picture of carabid predation we must incorporate data on the relative abundance and occurrence of carabids at all life stages within arable fields.

There are around 350 species of carabid in the UK. Though much data exist on the most prevalent carabid species in agro-ecosystems, further knowledge of their occurrence by site, habitat, and crop, would help inform targeted management to increase the efficient provision of services (Thiele, 1977; Kromp, 1999; Tscharntke et al., 2007; Kotze et al., 2011; Redlich et al., 2018). Crucial to these considerations is the community composition of carabids in a given agro-ecosystem. This will be a result of the filtering of species by environmental factors, management and biological interactions leading to large variation in the level of ecosystem services they provide spatially and temporally (Tylianakis & Romo, 2010; Eisenhauer et al., 2019).

The in-field factors that have the greatest influence on carabid communities across all life stages relate to the structure and resources in the habitat. Above-ground, the crop type determines the shelter, microclimate, and food resource availability. As such, this is a key determinate in the abundance and species richness of carabids present (Brooks et al., 2003, 2008; Woodcock et al., 2014). Where two or more crops are grown simultaneously (inter or companion cropping) this would be expected to lead to greater habitat complexity than if crops were grown in monocultures. One example is the practice of establishing grass leys by undersowing the grass into a cereal crop. This method of continuous cropping is thought to improve soil structure and function. Under-sowing may also benefit carabids by providing a greater variety of canopy structure and resources, and through associated reductions in pesticides and disturbance (Clapperton, 2003; Scopel et al., 2013). Grass is also of interest as it is suggested that tussocky grass margins and adjacent grass habitats can boost carabid populations (Holland, 2002; Woodcock et al., 2007; Boetzl et al., 2018). For below-ground structure and resources, crop type also affects rooting structure and associated resources, as well as determining cultivation timings and crucially tillage. Constituting a major disturbance event below-ground, and a reconfiguration of the upper soil level structure and resources, tillage is reported to have a great effect on carabid abundance- particularly to larvae (Baguette & Hance, 1997; Hatten et al., 2007; Lami et al., 2020). Cultivation timings of winter and spring cereals may constitute the largest management effect upon carabids due to the impacts on population processes between autumn and spring breeding (Holland & Luff, 2000; Marrec et al., 2015).

Though the literature on carabids documents the differential responses of carabids by crop, few studies consider the effect of crop on above- and below-ground communities. The majority of studies use pitfall trapping to collect carabids. These traps are level with the soil surface, so organisms that move across the soil surface will fall in. Fluid (typically a solution of alcohol) is placed in traps to preserve the catch for accurate species identification and to prevent in-trap predation (Wheater et al., 2011). The ease of setting these traps and their reliability have largely standardised reliance on this technique; despite some concerns over bias in species capture towards surface active and more activity-dense individuals (Holland, 2002). Pitfall traps do capture carabid larvae; but the numbers caught are relatively small compared to adults, typically less than 1% of the catch (McGavin, 1997; New, 1998; Hyvarinen et al., 2006). Soil cores are the standard approach for collecting soil-active invertebrates (Smith et al., 2008; Wheater et al., 2011) yet this method may be inefficient for surveying carabid larvae (Bell, personal communication), returning few specimens for much effort and/or cost.

Subterranean pitfall traps offer a third alternative and work on a similar premise of standard pitfalls. They catch active invertebrates in a trap solution, where the trap is set underground, with the trap area delimited by a mesh tube through which soil organisms pass and fall. This allows a catch over time (rather than the snapshot of soil cores); which may return more specimens of soil-active larvae moving to the surface to feed; and is more comparable to pitfall catches (Owen, 1995; Sims & Cole, 2016; Sims & Cole, 2017; Telfer, 2017). Furthermore, the subterranean element of the trap means that it will also capture adult carabids moving through the soil, constituting a differential activity-density measurement to standard pitfalls, and affording a more comprehensive appraisal of the species present and their movements in crop.

In this study, we deployed subterranean and pitfall traps across an existing agricultural experimental platform to assess the effect of crop type and cultivation method on carabid communities. Based on our previous findings (Jowett et al., 2019), we expected that there would be a difference in response to these factors according to species and life stage (larvae vs. adults). We aimed to (i) investigate the infield factors influencing carabid abundance, species richness, and diversity, (ii) relate this to individual carabid species and community composition between treatments, and (iii) quantify the differential response of carabid larvae to infield factors.

3.2 Methods

3.2.1 Brooms barn large-scale rotation experiment

To explore the impact of crop and tillage on carabid communities, we used a new field-scale experimental platform established on the Rothamsted Research farm at Brooms Barn (Suffolk, U.K.) that has been designed to quantify the impact of alternative cropping systems on a range of agronomic and environmental variables. The experimental platform, known as the large scale rotation experiment (LSRE), was set up in 2017 and has 63 plots each 24 × 24 m in size, set in a grid of 7 by 9 plots in a single field (Fig. 1). Each plot forms an experimental unit. The main treatments are three crop rotations (3, 5, or 7 years long) and two cultivation strategies (zero tillage vs. mouldboard ploughing). Each phase of every rotation is sown every year in both a zero till or ploughed plot and replicated twice in a fully randomised design (Fig. 1, appendix 2). The first crops were established in autumn 2017 following a preparation crop of winter oats. The main plots were divided into two sub-plots for the implementation of an organic amendment treatment in future years; this treatment is not relevant to the results reported in this paper as the trapping was done before the first application of compost but the traps were always positioned in the sub-plot designated as 'unamended'. Invertebrate sampling was not done on all plots of the platform, but the opportunity was taken in the first cropping year to quantify the effect of different crop types and tillage on carabid assemblages by selecting plots that had replicate treatments in the first year. Using an experimental platform in this way ensured that soil type, field history, and the local carabid species pool were all constant meaning any differences could be attributed to the plot treatments.

ZERO TILL Grass / clover	INVERSION Grass / clover	INVERSION Winter wheat	ZERO TILL Soybean	ZERO TILL Winter wheat	INVERSION Spring barley	ZERO TILL Winter wheat
INVERSION Oilseed rape	INVERSION Oilseed rape	ZERO TILL Winter wheat	ZERO TILL Winter wheat	INVERSION Winter wheat	INVERSION Winter wheat	INVERSION Winter wheat
INVERSION Winter wheat	ZERO TILL Oilseed rape	ZERO TILL Winter wheat	INVERSION Grass / clover	ZERO TILL Under-sown Spring barley	INVERSION Oilseed rape	ZERO TILL Oilseed rape
INVERSION Grass / clover	INVERSION Under-sown Spring barley	INVERSION Winter wheat	INVERSION Winter wheat	INVERSION Under-sown Spring barley	ZERO TILL Under-sown Spring barley	INVERSION Winter Wheat
INVERSION Winter wheat	ZERO TILL Grass / clover	INVERSION Soybean	INVERSION Field beans	INVERSION Sugar beet	INVERSION Soybean	ZERO TILL Linseed
ZERO TILL Winter wheat	ZERO TILL Winter wheat	ZERO TILL Winter wheat	INVERSION Spring barley	INVERSION Grass / clover	INVERSION Winter wheat	ZERO TILL Sugar beet
ZERO TILL Spring Barley	ZERO TILL Winter wheat	INVERSION Winter wheat	INVERSION Sugar beet	ZERO TILL Field beans	ZERO TILL Winter wheat	ZERO TILL Grass / clover
ZERO TILL Spring barley	ZERO TILL Grass / clover	ZERO TILL Winter wheat	ZERO TILL Winter wheat	INVERSION Winter wheat	ZERO TILL Field beans	ZERO TILL Oilseed rape
ZERO TILL Winter wheat	INVERSION Field beans	ZERO TILL Soybean	ZERO TILL Oilseed rape	ZERO TILL Sugar beet	INVERSION Oilseed rape	ZERO TILL Grass / clover

Figure 1- A plan and photograph of the Large Scale Rotation Experiment (LSRE) at Brooms Barn Experimental Farm, which is located Suffolk, UK. The plan shows the crops grown and associated tillage type for harvest year 2018. Each plot is 24 × 24 m. Plots with a dashed border were included in the invertebrate trapping Run 1 only, plots with a solid border in Run 2 only, and plots with a double border were included in both runs. The photograph was taken at the time of spring crop drilling.

3.2.2 Sampling design

The carabid sampling was done in the spring and summer of 2018. Because this was the first cropping year of the experiment, plots in the same crop type could be treated as true replicates (Fig. S1, Table 1). The crops chosen for sampling were selected on the basis of the functional differences we expected to have the biggest effects on carabid communities. We chose to sample carabids in (i) spring barley (Hordeum vulgare), (ii) spring barley (H. vulgare) under-sown with grass (Lolium perenne), (iii) winter wheat (Triticum aestivum), and (iv) grass (L. perenne) (Table 1). These were chosen to examine the effects of spring and winter crops, and the effects of cultivated grasses (under-sown and main crop) as identified above as having an impact on carabid distributions. For wheat and grass plots, there were six replicates in total, three had a zero till cultivation and three had inversion. For the barley and barley under-sown plots, there were two replicates of each crop by tillage treatment. To control for distance, where possible, plots were chosen for each set of treatment replicates at distances close to the experiment edge.

Table 1- LSRE treatments and runs in which treatments were included

Treatment codes	Crop	Included in:
WHEAT B1, B3, C5	Winter wheat	Run 1, Run 2
BARLEY B4	Spring barley	Run 1
BARLEY C2	Spring barley under-sown grass clover mix	Run 1, Run 2
GRASS C3, C4	Grass	Run 2

The experimental unit was therefore the selected plots, represented by the sub-plot of standard nutrition. Each 12 m × 24 m sub-plot was stratified into three 8 m × 12 m grids and one pitfall trap placed at random in each grid (three pseudo replicates). A subterranean trap was subsequently located randomly in each stratum, but at distance of at least a 5 m from any other trap. This made a total of 60 traps of each type across the experiment. These were installed on the fourth May 2018. With a two-month settling in period (Sims & Cole, 2017). We ran two 14-day trap runs (which we refer to as Run 1 and Run 2). Farm operations meant that the two runs did not have identical treatments. Run 1 was set 16th July and collected 30th July, grass plots were excluded from this run because of plot harvesting. Run 2 was set 30th August and collected 13th September. Grass plots were included in this second run but the Spring barley treatment was dropped due to harvest.

3.2.3 Trap design

The standard pitfall equipment used was 7.5 diameter 10 cm depth cups, set in space holding pipes, with lids raised 4 cm when set (Fig. 2a).

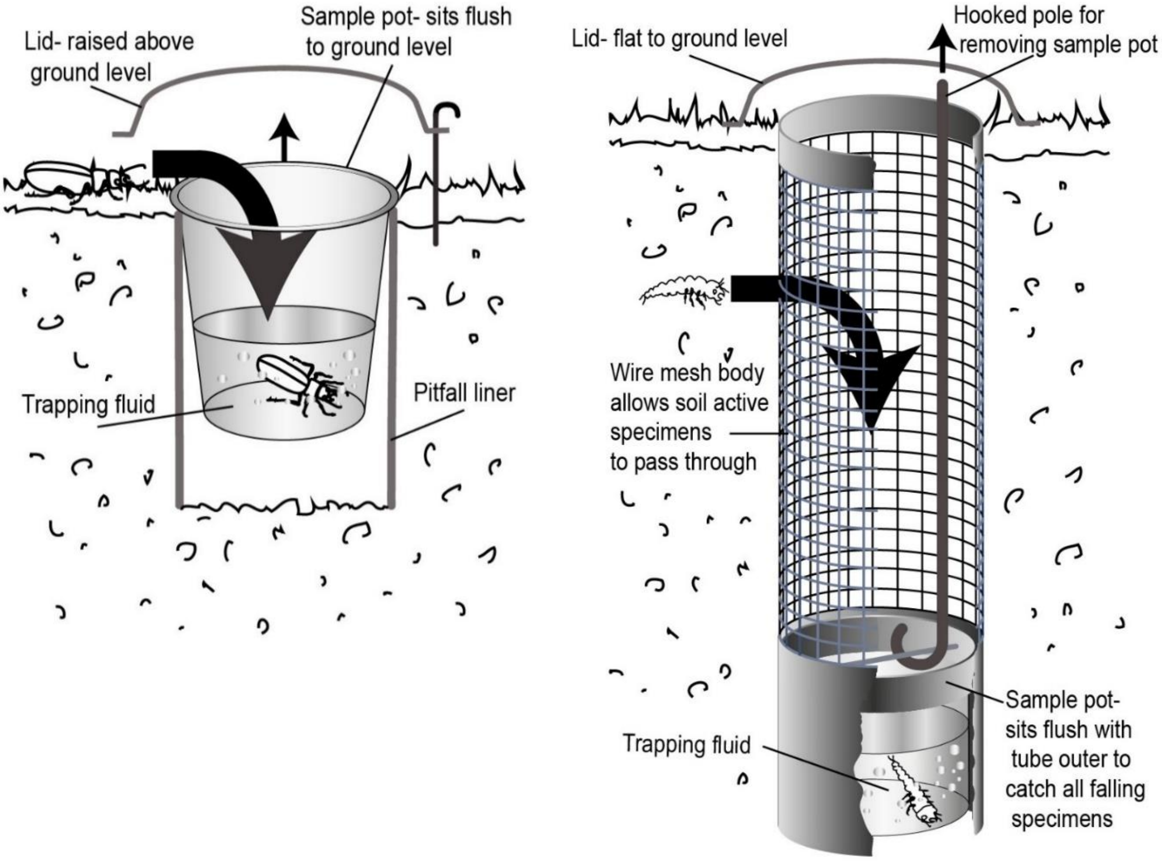


Figure 2- (a) Standard pitfall trap design and setup. Cup 7.5 diameter 10 cm depth. (b) Subterranean pitfall design and setup. Pipe 34 cm × 7 cm with 3 cut-out sections 20 cm × 4 cm, bordered by wire mesh of 1.2 cm grid.

The design of the subterranean trap was based on Owen (1995) (see also Sims & Cole, 2016, 2017; Telfer, 2017). The design is based on a 34 cm × 7 cm pipe with 3 cut-out sections 20 cm × 4 cm, bordered by wire mesh of 1.2 cm grid. A closely fitting sample collection pot sits at the base of the trap and collects soil active invertebrates falling through the wire mesh panels. The collection pot has a handle for collection and resetting with a hooked pole. A lid sits on the top, stopping surface active catch (to a depth of 3 cm), while allowing access to empty (Fig. 2b). When unset, a plastic film sleeve was used to block the mesh. This is a novel aspect that reduced setting in times and unintentional catch when not in use. When set, liquid is put in the collection cup. We chose to use a 70:30 ratio of ethanol and water because it preserves samples should we wish to carry out DNA analysis at a later date (Schmidt et al., 2006; Moreau et al., 2013). This liquid was also used in standard pitfalls.

3.3 Statistical analysis

3.3.1 Pooled-carabid abundance, species richness, and diversity

Carabid adults were identified to species level (Luff, 1997). Identifying carabid larvae to species level is notoriously difficult. Therefore larvae were classified by size, and predatory morphology classified as (i) seed-eaters or (ii) predatory/omnivorous. During Run 1, drought conditions and particularly high temperatures caused the pitfall trap fluid to dry out in nearly all of the standard pitfall traps, in some cases causing in-trap predation; therefore, we analysed the two runs separately. Although the results from Run 1 need to be interpreted with caution, where they are consistent with the observations in Run 2, they provide valuable supporting evidence.

Some traps (around 1%) were spoiled or data labels incomplete; therefore, we analysed only the count data from complete records with information recorded for all environmental factors, leaving 78 trap occasions in Run 1 and 75 in Run 2. We use the standard proxy measure of activity density to account for abundance. For each trap occasion, we calculated the 'pooled-carabid abundance' (N), i.e. the total number of carabids of any species, and species richness (S), i.e. the number of different species. We fitted the log series model (Eqn 1) to the data by maximum likelihood to give estimates of Fisher's log-series alpha (urn:x-wiley:14619555:media:afe12397:afe12397-math-0001), which is a robust and widely used diversity metric (Beck and Schwanghart, 2010; Magurran, 2013) that accounts for the effect of total numbers of individuals in a sample on diversity estimates.

$$S = \hat{\alpha} \log\left(1 + \frac{N}{\hat{\alpha}}\right) \tag{1}$$

We fitted linear mixed models (LMMs) using the Genstat statistical software package (Payne, 1993) to determine the effect of environmental factors on (i) pooled-carabid abundance (N), (ii) richness (S), (iii) species diversity (quantified as urn:x-wiley:14619555:media:afe12397:afe12397-math-0003), (iv) carabid larvae (pooled), and (v) abundance of carabids at species level (where sufficient numbers were present). We considered the environmental factors crop type, tillage type, and trap type (denoting hypogeal and epigeal movements) as fixed effects with three-way interactions. The random model was defined as plot, and nested within each plot, trap number (i.e. plot\trap replicate). We log transformed the pooled-abundance and alpha so that residuals conformed to normality. We selected terms using backward elimination according to the largest P-value given by the Kenward-Roger approximate F-tests. The final predictive model was chosen when all remaining terms gave significant values ($P \leq 0.05$) when dropped from the model.

The effect of crop type and cultivation on carabid community composition was analysed using redundancy analysis (RDA), a constrained principal components analysis using crop type, tillage, and trap type as explanatory variables. Analyses were carried out in Canoco (Smilauer & Leps, 2014) for each run separately using Monte Carlo methods to derive a measure of statistical significance. To avoid the analysis being biased by infrequent species, species were excluded if they were only recorded in a single trap in any given run. The partial effects of each explanatory variable were first quantified, including the other variables as co-variates. All variables with significant partial effects were then included in a combined analysis for each run.

3.4 Results

3.4.1 Summary of data

After data cleaning, a dataset of 4648 records was produced for Run 1 (Table S1). Trap drying under the drought conditions experienced during this run was notably more prevalent in standard pitfalls, with the majority containing little to no preservation fluid. Weather conditions were much more favourable during Run 2 and the trap preservation fluid did not evaporate. After data cleaning, a dataset comprising 1703 records was produced; less than half of the abundance seen in Run 1 (Table 1, appendix 2).

3.4.2 Carabid occurrence by treatment

For pooled carabid abundance, none of the factors in the LMM were found to be significant in Run 1. For species richness, only trap type was found to be significant, with greater numbers of species caught in subterranean traps, with a predicted mean of 4.42 while standard pitfalls had a predicted mean of 3.27 ($F_{1,66} = 13.36$, $P < 0.001$, LSD 0.6347). Since Fishers alpha relies on the combination of abundance and species richness, the unidentified damaged specimens and latent catch of eaten specimens rendered diversity analysis of this run unreliable.

For Run 2, we found crop ($F_{2,11} = 62.8$, $P < 0.001$), trap type ($F_{1,63} = 5.92$, $P = 0.018$), and their interaction ($F_{2,63} = 5.11$, $P = 0.009$) to be significant factors in the variation of pooled abundance. For barley under-sown with grass/clover, abundance was significantly greater in subterranean traps. In wheat and grass, trap types were comparable with lower abundance in grass compared to wheat and barley (Fig. 3). No significant effect of crop, trap, or tillage was detected for species richness and diversity.

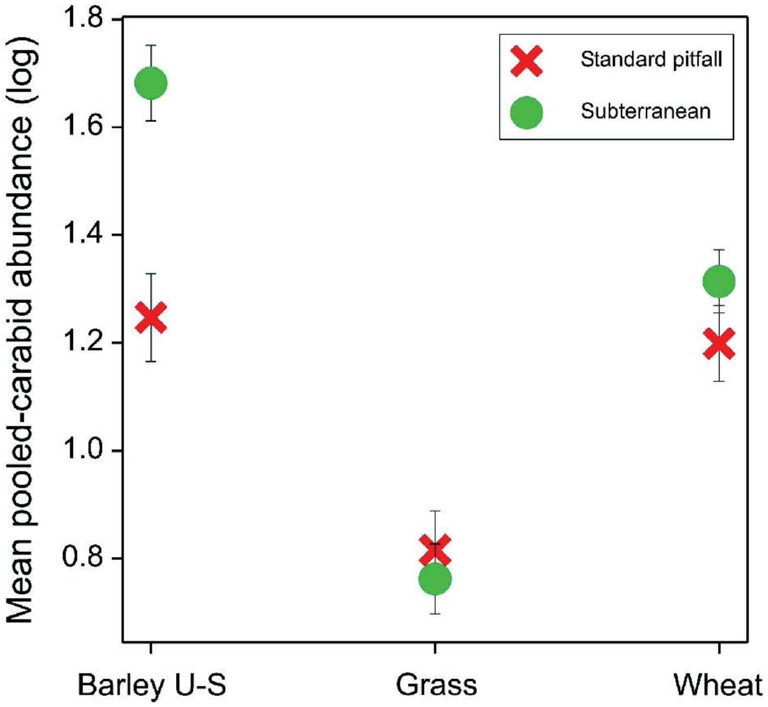


Figure 3- Run 2 fitted linear mixed model predictions for pooled-carabid abundance, predicted means with effective standard error bars. LSD for trap type 0.1215; LSD for crop type 0.1342.

3.4.3 Assemblage differences

Crop, tillage, and above-/below-ground movements

The primary axis of the RDA for Run 1 was determined by the contrast between the carabid communities caught either in the pitfall or subterranean traps with the second axis resulting from differences between winter wheat and spring barley. For most species, relative abundance was higher in barley under-sown with grass and in subterranean traps (compared to pitfalls) (Fig. 4). Notably, all larvae were associated with subterranean traps, along with the two Bembidion species. Pterostichus melanarius (Illiger, 1798) and Calathus fuscipes (Goeze, 1777) showed association with wheat crops, and Poecilus cupreus (Linnaeus, 1758) solely showed an association with standard pitfalls. No species showed an association with (non-under-sown) barley.

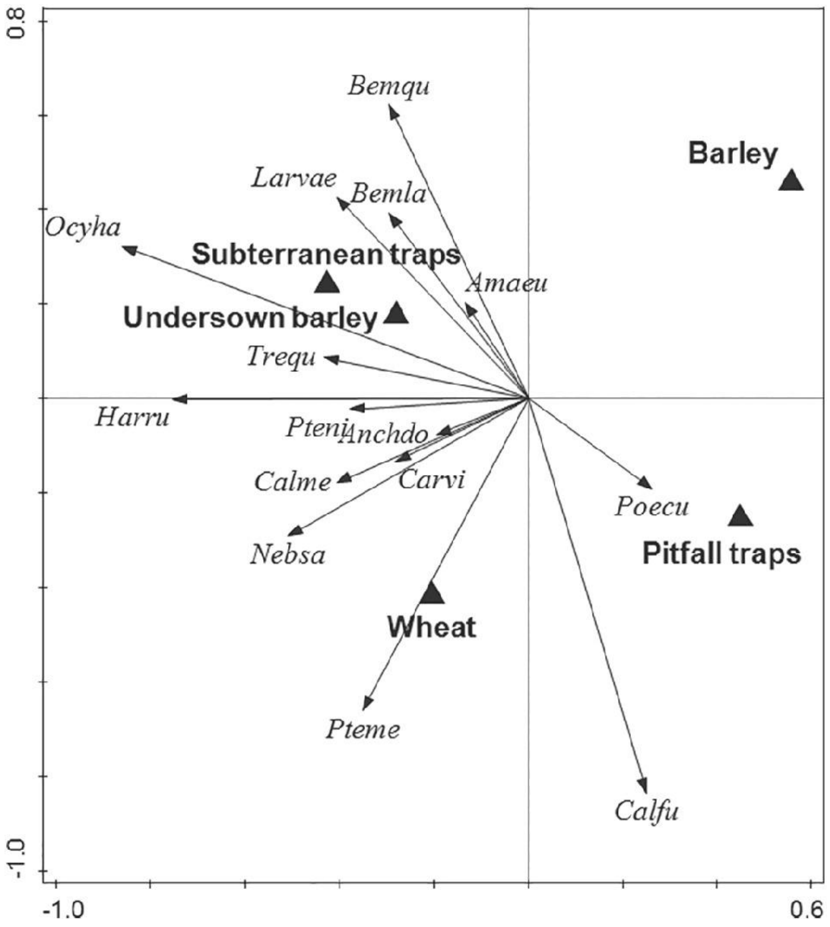


Figure 4- Redundancy analysis ordination of carabid species in run 1: with constrained axes of crop and trap type. Species names adult carabids: Bemqu = Bembidion quadrimaculatum; Bemla = Bembidion lampros; Ocyha = Ocys harpaloides; Amaeu = Amara eurynota; Trequ = Trechus quadristriatus; Harru = Harpalus rufipes; Pteni = Pterostichus niger; Anchdo = Anchomenus dorsalis; Calme = Calathus melanocephalus; Carvi = Carabus violaceus; Nebsa = Nebria salina; Poecu = Poecilius cupreus; Calfu = Calathus fuscipes; Pteme = Pterostichus melanarius. Larvae pooled.

Tillage did not explain any variance in carabid community composition in Run 1; including crop type and trap type accounted for 12.5% of the total variance in the RDA, with crop accounting for 5.9% and trap type 6.3% (pseudo-F = 4.7, P = 0.001, Fig. 4). While the community data from Run 1 provides useful supporting evidence of the effects of trap type and crop, the low variance explained may be partly due to the drought during the trapping period and individual species responses were, therefore, not analysed for this run.

For Run 2, the variation explained by RDAs was much greater. Crop accounted for 23.7% of variance, and trap type accounted for 13.1% of variance. Tillage was, again, found to be nonsignificant.

The final constrained ordination with explanatory variable terms crop and trap type accounted for 37.4% (pseudo-F = 15.8, P = 0.001, Fig. 5). The inclusion of grass crops resulted in the primary RDA axis being determined by the contrast between communities in the perennial grass and annual cereals with trap type driving the second axis.

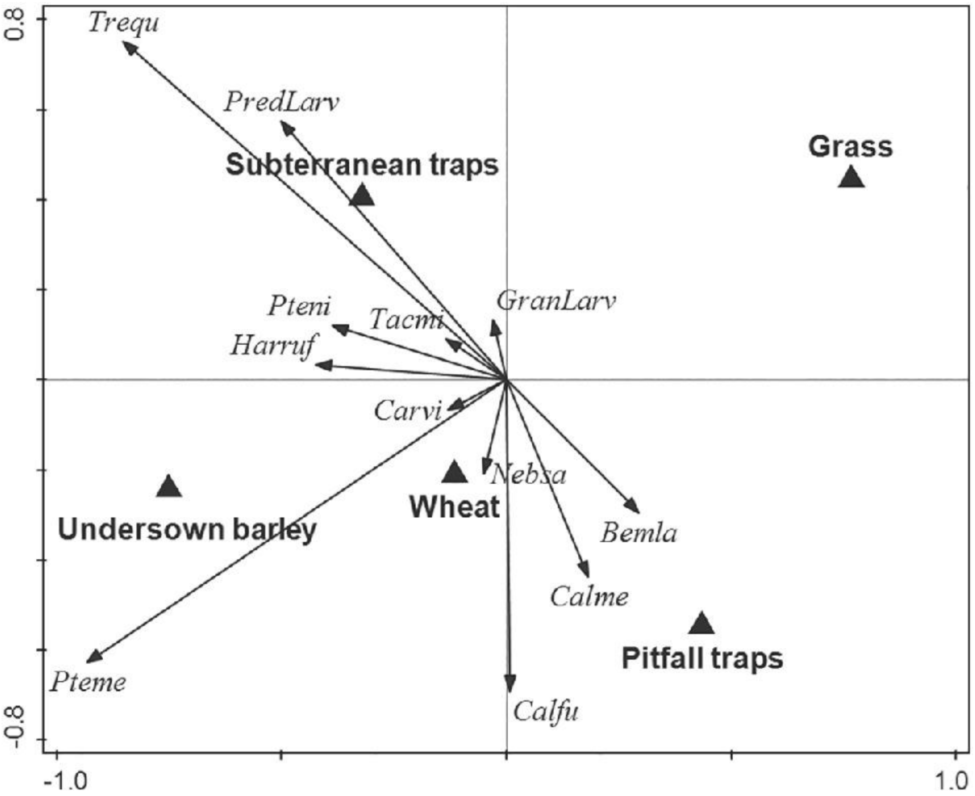


Figure 5- Redundancy analysis ordination of carabid species in run 2: with constrained axes of crop and trap type. Species names adult carabids: Trequ = Trechus quadristriatus; Pteni = Pterostichus niger; Tacmi = Tachys micros; Harruf = Harpalus rufipes; Carvi = Carabus violaceus; Nebsa = Nebria salina; Bemla = Bembidion lampros; Calme = Calathus melanocephalus; Calfu = Calathus fuscipes; Pteme = Pterostichus melanarius. Larvae divided between predatory/omnivorous (Predlarv) and granvory (Granlarv).

Species associations with management for Run 2 were stronger than in the Run 1 ordination (Fig. 5) but with some consistent effects. Predatory larvae and Trechus quadristriatus (Schrank, 1781) again showed a strong association with subterranean traps. Calathus melanocephalus (Linnaeus, 1758), C. fuscipes and, notably, Bembidion lampros (Herbst, 1784) showed an association with standard pitfall traps. P. melanarius showed a general association with cereal crops, and none between trap type. No carabid species showed an association with the grass crop.

Because of the stronger effects of crop and trap type observed in Run 2, additional univariate analyses were done on the abundance measures at the species level. The LMM predictions supported the association of P. melanarius with cereal crops in the ordination. There was also a significant interaction of trap type and crop (Table S2; Fig. 6a): in under-sown Barley, abundance was much higher in subterranean traps. Trechus quadristriatus showed a similar interaction to P. melanarius (Table S2; Fig. 6b), yet the abundance was consistently lower in standard pitfall traps across crop types. The abundance of Harpalus rufipes showed a significant response to crop, with the greatest abundances in barley under-sown, followed by grass, then wheat (Table S2; Fig. 6c). Pterostichus niger (Schaller, 1783) showed the same pattern of interaction as P. melanarius, yet with a lesser general abundance in standard pitfalls, apart from in the wheat crop (Table 2, appendix 2; Fig. 6d). In the fitted model for Calathus fuscipes, predictions showed higher abundances in pitfall traps (Table 2, appendix 2; Fig. 6e). In the fitted model for the abundance of B. lampros, tillage was shown to be significant along with trap type, whereby abundances were greater in standard pitfalls, and in zero till (Table 2, appendix 2; Fig. 6f). Tillage was also retained as a significant effect in the model for Calathus melanocephalus abundance; however, in an interaction with crop type (Table 2, appendix 2; Fig. 6g). Tillage alone was significant in the fitted model for Carabus violaceus (Linnaeus, 1758), with higher abundances in zero tillage (Table 2, appendix 2; Fig. 6h).

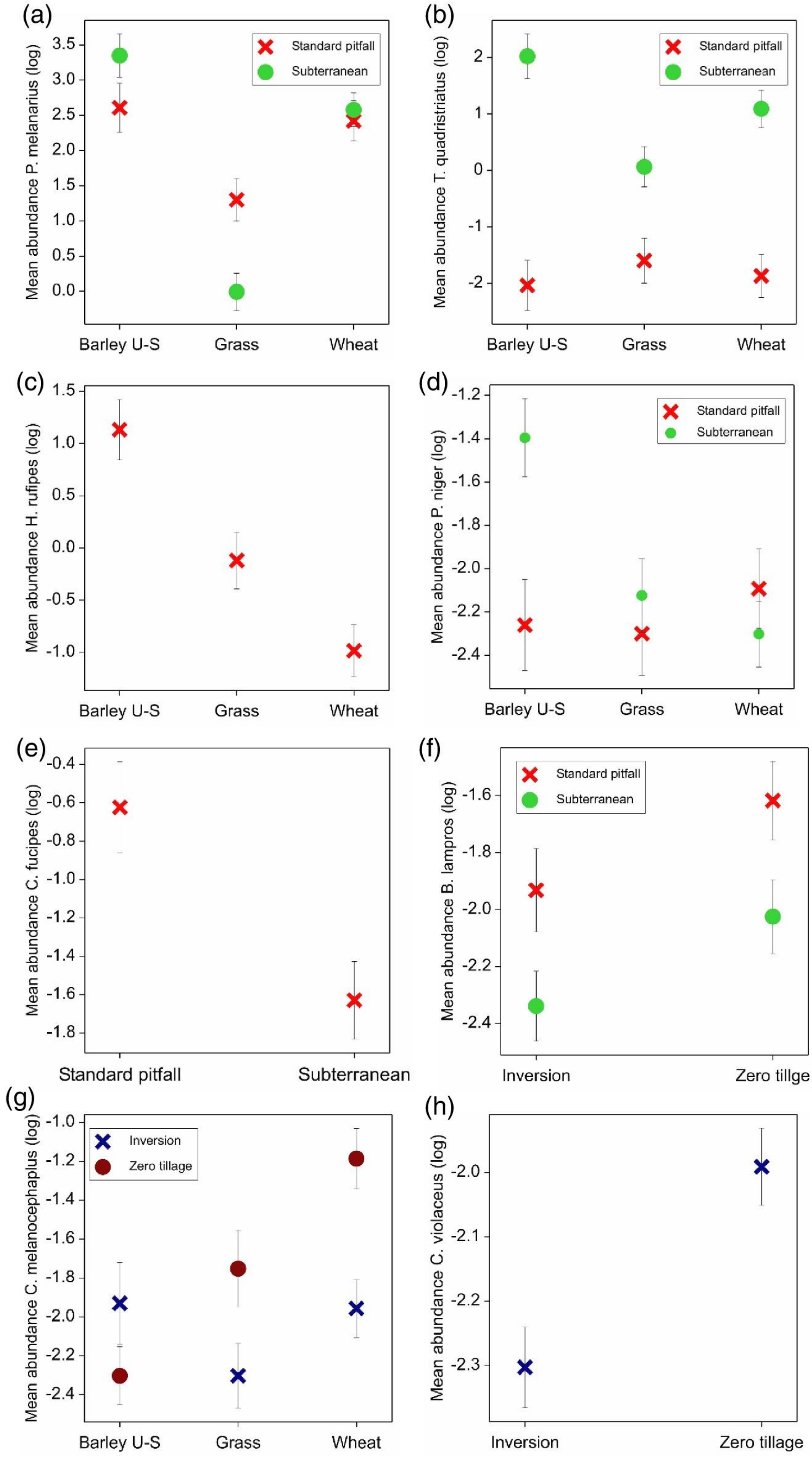


Figure 6- Linear mixed fitted model prediction means plots with effective standard error bars, for log abundance of adult carabids (a) Pterostichus melanarius LSD for trap type 0.4873; LSD for crop type 0.6769; (b) Trechus quadristriatus LSD for trap type 0.5450; LSD for crop type 0.9705; (c) Harpalus rufipes; LSD for crop type 0.8763; (d) Pterostichus niger LSD for trap type 0.3190; LSD for crop type 0.3821; (e) Calathus fuscipes; LSD for trap type 0.6636; (f) Bembidion lampros LSD for trap type 0.3599; LSD for tillage 0.3062; (g) Calathus melanocephalus LSD for crop type 0.4274; LSD for till 0.3273; and (h) Carabus violaceaus; LSD for till 0.1916.

3.4.4 Larvae occurrence

The larvae catch during Run 1 was very low, however, all larvae were found in subterranean pitfall traps (Table S1). This may have been due to the dry conditions reducing the movement of larvae at the soil surface. We were unable to analyse these low numbers statistically in LMMs. In the RDA analysis, larvae were strongly associated with subterranean traps in under-sown barley (Fig. 4).

Larvae were much more abundant in Run 2 (Table S1); therefore, statistical analysis of a division into granivorous and predatory species was possible. In the RDA analysis, granivorous larvae showed a weak association with subterranean traps, and predatory/omnivorous larvae showed a strong association with subterranean traps in under-sown barley (Fig. 5). The LMM for granivorous larvae failed to retain any significant terms. The fitted model for predatory/omnivorous larvae showed an interaction of crop and trap type (F2,58 = 4.00, P = 0.024) whereby abundances were higher in subterranean traps in all crops, yet highest in subterranean traps in barley under-sown, and lowest in pitfall traps in barley under-sown (Fig. 7).

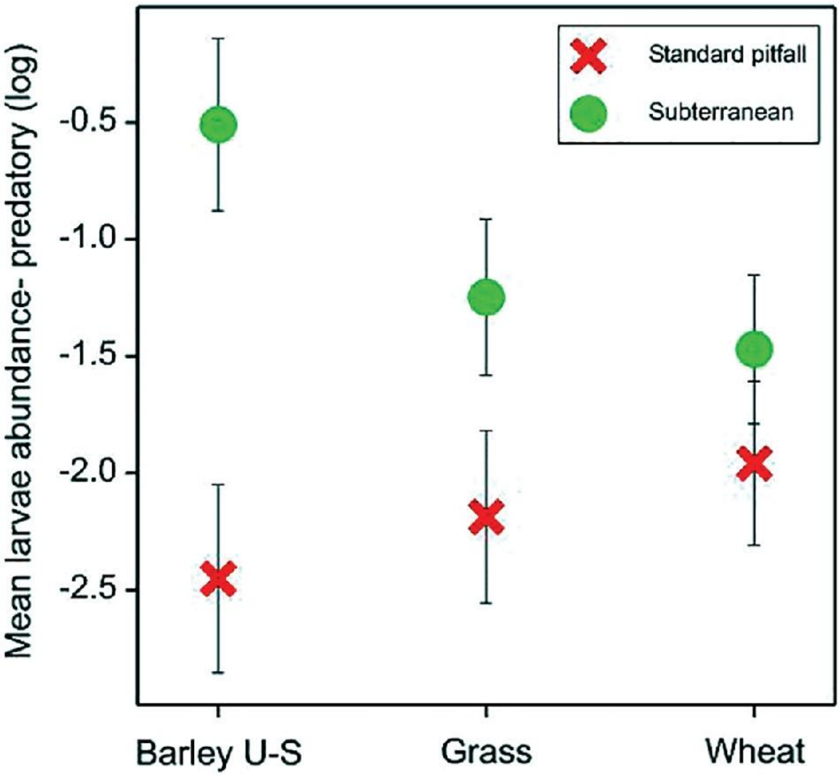


Figure 7- Linear mixed model fitted model prediction means plots with effective standard error bars, for predatory carabid larvae abundance by trap type in Run 2. LSD for trap type 0.4255; LSD for crop type 0.953.

3.5 Discussion

3.5.1 The infield factors influencing carabid abundance, species richness and diversity

Crop type and tillage were anticipated to have an effect on total species abundance. The results for Run 2 broadly conformed with the literature on crop effects with relatively high catches in cereals compared with lower catches in grass (Eyre et al., 2013). Variation was seen in abundance according to crop type, with an interaction with trap type. Notably higher abundance in subterranean traps in under-sown barley demonstrated the effects of above-ground structure, which is cited in the literature as crucial to the distribution of carabids (Thiele, 1977; Holland, 2002; Kotze et al., 2011). It is likely this also holds true for the mirrored below-ground environment. Increased structure and resources afforded by shallower grass and nitrogen fixing clover roots in among the longer barley cereal roots supports a richer micro and macrofauna environment, including altering soil structure and microclimatic properties (Clapperton, 2003; Scopel et al., 2013; Wezel et al., 2014). Our results suggest this supports increased abundance of carabids and their potential for predation in this below-ground crop area and indicate under-sowing cereals may enhance this ecosystem service.

The absence of significant tillage effects in pooled analyses was surprising. Inversion tillage changes the soil structure, inverting the soil surface to a lower level and burying organic matter in the form of previous crop chaff remaining on the soil surface. This constitutes a drastic change in microclimate and resources at the level of soil macrofauna, and also a physical disturbance potentially killing adults and larvae at the time of treatment (Baguette & Hance, 1997; Holland & Luff, 2000). Although we sampled several months after the soil had been cultivated (potentially reducing the observed effect), other studies (Hatten et al., 2007; Shearin et al., 2014) that included multiple sample points across crop rotations with contrasting tillage found all species to be affected by tillage, with species richness and diversity higher in zero tillage.

However, neither crop type nor tillage significantly explained any of the observed variation for Run 1. These results were biased by the drought conditions and should be interpreted with caution. The effect of trap type on species richness is likely due to a combination of in-trap predation and the traps changing from passive to active, as the trapping fluid evaporated, attracting other invertebrates to previously caught specimens (Kotze et al., 2011). The higher abundance and species richness observed in the desiccated standard pitfall traps is likely an artefact of these events.

The greater abundance observed in traps for Run 1 compared with Run 2 can be partially explained by the traps shifting from passive to active, altering trapping dynamics. However, it is more likely to be a measure of activity-density, which is largely influenced by species phenology, but is compounded here under drought conditions: carabids will move from an unsuitable habitat to find the resources they require. Consequently, the abundance in traps could have measured increased movement activity in searching behaviour (Chiverton, 1984; Wheater et al., 2011).

3.5.2 Carabid species and community composition between treatments

Species responded differently to crop type. In Run 1, though it must be interpreted with caution because of the effect of the drought, the higher number of individual carabid species associated with under-sown barley than standard barley supports the argument that the more complex structure (two canopy layers of vegetation) of this crop is beneficial for carabids as opposed to the fact that it was spring sown.

In Run 2, we saw less crop associations than Run 1 at species level, for example, P. melanarius abundances were associated with both cereal crops. However, the relatively low catches within the grass crop are surprising, given the recommendations in the literature that grass margins play an important role in survivorship and landscape level population dynamics. Though studies have found this to be beneficial to carabid abundance and survivorship (French & Elliott, 1999; Thomas et al., 2002; Saska et al., 2007; Holland et al., 2009), this could be attributed to the nature of the habitat as a structural resource in refuge area and food resources of noncrop vegetation. As opposed to the attribute of grass as a plant harbouring resources in attendant pests and producing pollen and seeds as food. Sample timing may, therefore, be important in understanding the role of this habitat. Grass margins and adjacent habitat may only be used at certain times by carabid beetles which needs to be considered when designing farm habitats to optimise ecosystem services. Eyre et al., (2013) also found no species to be strongly associated with grass crops in a study of a nine-crop rotation over 5 years, yet differences in community associations between organic and conventional cereal crops were noted.

The main split in community composition was by trap type. By examining the species captured moving in the top 30 cm of soil, we may draw conclusions about species not commonly trapped as surface active. Furthermore, subterranean traps may better reflect a species preference for a crop habitat, as below-ground movements suggest the area has ample resources. Surface measures of activity-density may give a false impression of abundance, for example Chiverton (1984), found increased catches in pitfall traps of insecticide treated plots were in fact of individuals that had low gut content. The author concluded that higher activity-density was a result of foraging behaviour in invertebrate denuded plots, and inferences should not be drawn from pitfall trapping alone. Juran et al. (2013) found that organic management supported greater abundance of carabids than conventional and integrated systems, with their subterranean sampling reflecting multiple management influences. Subterranean traps are therefore expected to provide a better indication of a species preference and assemblage within a given area, and the detrimental effects of such management as foliar insecticide applications would be dampened or removed. This is particularly important in obtaining an accurate and unbiased account of a species assemblage. For example, P. niger is a key predator of molluscs (Luff, 1998; Symondson, 2004), accurate estimation of hypogean movements of this species, especially in root crops for instance, could be implemented into management planning for crop pest problems.

Bembidion lampros showed an association with subterranean traps in the first run, but a converse link to pitfalls in Run 2. This could be attributed to climatic effects or phenological stage, but the LMM for this species suggests that it is more likely that in-trap predation is responsible for the disparity. Most likely due its smaller size, it was subject to higher predation by larger carabids, obscuring the observations. The predictions for P. melanarius show that species movements (surface and subterreanean) were significantly different only in under-sown barley. Since the abundances, denoted by activity-density at the surface as measured by pitfalls, are equal in wheat and barley, this should not be an attribute of niche spill-over through sheer abundance. Increased below-ground catch was also observed in the data for T. quadristriatus and P. niger, although their overall crop preference patterns in wheat and barley vary from P. melanarius. Trechus quadristriatus was also noted to be abundant in a study of below-ground carabid assemblages in oilseed rape (Drmić et al., 2016). It is evident that under-sown crop confers some advantage for carabid resources, yet this is not universal. Our previous work (Jowett et al., 2019) concluded that species preferences, even in the reportedly omni-preferential Carabidae family, resulted in quite specific actualised niches, potentially being obscured in pooled measure analysis. This work supports and extends this for the species highlighted above.

At the species level, tillage effects were shown for B. lampros, C. melanocephalus and C. violaceus. Kinnunen and Tiainen (1999) found community composition to be different between green set-aside and tilled fields, relating this to the colonisation of tilled fields in early spring by spring breeders, while set-aside supported a higher proportion of autumn breeders. The only spring breeder modelled separately in our study was B. lampros. This species had higher abundance in zero till and no effect of crop type. Armstrong and McKinlay (1997) found a range of carabid responses to four under-sowing treatments, relating this to species preferences to plant cover, noting a temporal aspect with the spring abundance of B. lampros connected with spring plant cover. Thus, the abundance of this species in our study is likely due to weed cover in zero-till. While C. violaceus is predominantly nocturnal, its predatory behaviour on molluscs may drive association with weedier crops and shelter in surface chaff (Luff, 1998). Calathus melanocephalus is defined as mainly nocturnal but varies from the other species trapped in its noted xerophilic (dry tolerance) and preference for light soils. This is interesting in the respect of the interaction with crop. In grass and wheat, the effect of tillage may have made the soil structure more water retentive, negatively affecting this xerophilic species (Breland, 1996).

The literature is divided on the species specifics of tolerance to tillage – Baguette and Hance (1997) found P. melanarius to increase in abundance with increasing frequency of tillage treatments, while Shearin et al. (2014) highlights P. melanarius to be reduced by all tillage treatments – more so than weed seed specialists. This may indicate in relation to our results, that complex interactions play on species differentially within the singular treatment of tillage.

3.5.3 Differential response of carabid larvae to infield factors

We found significant patterns of larvae distributions in both runs. The strong associations of carabid larvae with the under-sown barley is likely to be due to the benefits of the microbiome of a dual vegetative structure, and its associated resources (Theunissen, 1994; Theunissen & Schelling, 2000; Hance, 2002; Ratnadass et al., 2006). This is contrary to our expectation that larvae and adults would be most abundant in the same crop. We conclude that the resources and structure allow for the differential needs of both life stages.

The lack of effects observed from tillage treatments could be due to the short establishment period in respect of generational time and population processes as outlined above. However, Blubaugh and Kaplan (2015) used 1-year established similarly small plots to examine weed seed predatory adult and larval Harpalus spp. The authors found that both adults and larvae were substantially reduced in frequently tilled plots, but effects between no-till and strip till cover crops were insignificant. While we cannot conclude from our results that annual tillage events constitute a disturbance that is catastrophic to carabid populations, it will be valuable to monitor carabids in future years on the experiment following consecutive tillage events to study any long-term impacts.

The association of carabid larvae with subterranean traps is unsurprising given their inclusion primarily to reveal the distribution of larval life stages in this study. The clear dominance of the subterranean catch highlights the advantage of below-ground trapping to robustly assess the contribution of larvae to ecosystems services. Blubaugh and Kaplan (2015) used standard pitfall traps to assess the granivorous larvae of Harpalus spp., extending this to weed seed predation. This study was able to elucidate the movements of predatory species that are less surface active. Particularly, under the drought conditions of the first run, larvae were active in lower soil layers and present solely in subterranean traps. If the assessment of larval predation was merely on the pitfall traps as predictions showed, the barley under-sown would be assumed to have low abundances of predatory larvae and subsequently the pest regulation capacity would be underestimated.

3.6 Conclusions

Carabid distributions constitute a complex picture. We found that the above and below-ground assessments using standard and subterranean traps in tandem provided a more comprehensive and accurate understanding of carabid distributions. Our study saw that pitfall traps alone were insufficient to fully account for the contribution of carabids to sustainable pest control, particularly the vital contribution of carabid larvae. Specifically, the beneficial effects of under-sown barley would not have been apparent if only standard pitfall traps had been used without subterranean sampling. This may impact on the recommendation of appropriate management to boost service provision above- and below-ground. Future work should incorporate the accuracy of multiple trap types, along with estimates of predation for different life-stages and carabid species to accurately quantify the level of ecosystem services in farm habitats.

Acknowledgements

KJ is grateful for funding from the Rothamsted-Reading Alliance. JS and AEM are supported by research programmes NE/N018125/1 LTS-M ASSIST – Achieving Sustainable Agricultural Systems, funded by NERC and BBSRC (BBS/E/C/000I0140), and the Smart Crop Protection (SCP) strategic programme (BBS/OS/CP/000001) and the Soil to Nutrition (S2N) strategic programme (BBS/E/C/000I0330) both funded by the BBSRC. DG is funded by Waitrose Collaborative Training Partnership. We thank Suzanne Clark and Kirsty Hassall for their advice on the analysis.

Authors' contributions

KJ and JS conceived and designed the study. The research and analysis were performed by KJ and JS with input from AEM and DG. All authors contributed to interpretation of results and writing the manuscript.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

3.7 References

Armstrong, G. and McKinlay, R.G., 1997. The effect of undersowing cabbages with clover on the activity of carabid beetles. *Biological agriculture & horticulture*, 15(1-4), pp.269-277.

Baguette, M. and Hance, T.H., 1997. Carabid beetles and agricultural practices: influence of soil ploughing. *Biological Agriculture & Horticulture*, *15*(1-4), pp.185-190.

Bianchi, F.J., Booij, C.J.H. and Tscharntke, T., 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proceedings of the Royal Society of London B: Biological Sciences*, 273(1595), pp.1715-1727.

Beck, J. and Schwanghart, W., 2010. Comparing measures of species diversity from incomplete inventories: an update. *Methods in Ecology and Evolution*, 1(1), pp.38-44.

Blubaugh, C.K. and Kaplan, I., 2015. Tillage compromises weed seed predator activity across developmental stages. *Biological Control*, 81, pp.76-82.

Boetzl, F.A., Krimmer, E., Krauss, J. and Steffan-Dewenter, I., 2018. Agri-environmental schemes promote ground-dwelling predators in adjacent oilseed rape fields: Diversity, species traits and distance-decay functions. *Journal of Applied Ecology*.

Bommarco, R., Vico, G. and Hallin, S., 2018. Exploiting ecosystem services in agriculture for increased food security. *Global Food Security*, 17, pp.57-63.

Breland, T.A., 1996. Green manuring with clover and ryegrass catch crops undersown in small grains: Effects on soil mineral nitrogen in field and laboratory experiments. *Acta Agriculturae Scandinavica B-Plant Soil Sciences*, 46(3), pp.178-185.

Brooks, D.R., Bohan, D.A., Champion, G.T., Haughton, A.J., Hawes, C., Heard, M.S., Clark, S.J., Dewar, A.M., Firbank, L.G., Perry, J.N. and Rothery, P., 2003. Invertebrate responses to the management of genetically modified herbicide–tolerant and conventional spring crops. I. Soil-surface-active invertebrates. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 358(1439), pp.1847-1862

Brooks, D.R., Perry, J.N., Clark, S.J., Heard, M.S., Firbank, L.G., Holdgate, R., Shortall, C.R., Skellern, M.P. & Woiwod, I.P., 2008. National-scale metacommunity dynamics of carabid beetles in UK farmland. *Journal of AnimalEcology*,77,265–274.

Brooks, D.R., Storkey, J., Clark, S.J., Firbank, L.G., Petit, S. and Woiwod, I.P., 2012. Trophic links between functional groups of arable plants and beetles are stable at a national scale. *Journal of Animal Ecology*, 81(1), pp.4-13.

Clapperton, M.J. and Clapperton, M.J., 2003. Increasing soil biodiversity through conservation agriculture: managing the soil as a habitat. *Proc. Second World Cong. on Conservation Agriculture*: producing in harmony with nature, Iguassu Falls, Parana-Brazil, pp.11-15.

Chiverton, P.A., 1984. Pitfall-trap catches of the carabid beetle Pterostichus melanarius, in relation to gut contents and prey densities, in insecticide treated and untreated spring barley. *Entomologia experimentalis et applicata*, 36(1), pp.23-30.

Eisenhauer, N., Schielzeth, H., Barnes, A.D., Barry, K., Bonn, A., Brose, U., Bruelheide, H., Buchmann, N., Buscot, F., Ebeling, A. and Ferlian, O., 2019. A multitrophic perspective on biodiversity–ecosystem functioning research. *Adv. Ecol. Res*, 61, pp.1-54.

Eyre, M.D., Luff, M.L. and Leifert, C., 2013. Crop, field boundary, productivity and disturbance influences on ground beetles (Coleoptera, Carabidae) in the agroecosystem. *Agriculture, ecosystems & environment*, 165, pp.60-67.

Firbank, L.G., Heard, M.S., Woiwod, I.P., Hawes, C., Haughton, A.J., Champion, G.T., Scott, R.J., Hill, M.O., Dewar, A.M., Squire, G.R. and May, M.J., 2003. An introduction to the Farm-Scale Evaluations of genetically modified herbicide-tolerant crops. *Journal of Applied Ecology*, 40(1), pp.2-16.

French, B.W. and Elliott, N.C., 1999. Temporal and spatial distribution of ground beetle (Coleoptera: Carabidae) assemblages in grasslands and adjacent wheat fields. *Pedobiologia*, 43(1), pp.73-84.

Gareau, T.P., Voortman, C. and Barbercheck, M., 2019. Carabid beetles (Coleoptera: Carabidae) differentially respond to soil management practices in feed and forage systems in transition to organic management. *Renewable Agriculture and Food Systems*, pp.1-18.

Hatten, T.D., Bosque-Pérez, N.A., Labonte, J.R., Guy, S.O. and Eigenbrode, S.D., 2007. Effects of tillage on the activity density and biological diversity of carabid beetles in spring and winter crops. *Environmental entomology*, *36*(2), pp.356-368.

Holland, J.M., 2002. *The agroecology of carabid beetles.* Intercept Limited.

Holland, J.M., Birkett, T. and Southway, S., 2009. Contrasting the farm-scale spatio-temporal dynamics of boundary and field overwintering predatory beetles in arable crops. *Biocontrol*, 54(1), pp.19-33. https://doi.org/10.1007/s10526-008-9152-2

Holland, J.M. and Luff, M.L., 2000. The effects of agricultural practices on Carabidae in temperate agroecosystems. *Integrated pest management reviews*, 5(2), pp.109-129.

Honek et al., *2003 In:* Kotze, D.J., et al 2011. Forty years of carabid beetle research in Europe–from taxonomy, biology, ecology and population studies to bioindication, habitat assessment and conservation. *ZooKeys, (100), p.55.*

Hyvarinen, E., Kouki, J., and Martikainen, P., 2006. A comparison of three trapping methods used to survey forest-dwelling Coleoptera. European *Jounal of Entomology*. 103: pp 397–407

Jowett, K., Milne, A.E., Metcalfe, H., Hassall, K.L., Potts, S.G., Senapathi, D. and Storkey, J., 2019. Species matter when considering landscape effects on carabid distributions. *Agriculture, Ecosystems & Environment*, 285, p.106631.

Kinnunen, H. and Tiainen, J., 1999, January. Carabid distribution in a farmland mosaic: the effect of patch type and location. In Annales Zoologici Fennici (pp. 149-158). *Finnish Zoological and Botanical Publishing Board.*

Kleijn. D., and Sutherland, W.J., 2003. How effective are European agri-environment schemes in conserving and promoting biodiversity? *Journal of Applied Ecology*. 2003 40. Pp 947–969

Kotze, D.J., et al 2011 Forty years of carabid beetle research in Europe–from taxonomy, biology, ecology and population studies to bioindication, habitat assessment and conservation. *ZooKeys*, (100), p.55.

Koivula, M., Hyyryläinen, V. and Soininen, E., 2004. Carabid beetles (Coleoptera: Carabidae) at forest-farmland edges in southern Finland. *Journal of Insect Conservation*, 8(4), pp.297-309. https://doi.org/10.1007/s10841-004-0296-9

Kromp, B., 1999. Carabid beetles in sustainable agriculture: a review on pest control efficacy, cultivation impacts and enhancement. *Agriculture, Ecosystems & Environment*. Volume 74, Issues 1–3, June 1999, Pp 187–228

Labruyere, S., Bohan, D.A., Biju-Duval, L., Ricci, B. and Petit, S., 2016. Local, neighbor and landscape effects on the abundance of weed seed-eating carabids in arable fields: A nationwide analysis. *Basic and applied ecology*, *17*(3), pp.230-239. https://doi.org/10.1016/j.baae.2015.10.008

Lami, F., Boscutti, F., Masin, R., Sigura, M. and Marini, L., 2020. Seed predation intensity and stability in agro-ecosystems: Role of predator diversity and soil disturbance. *Agriculture, Ecosystems & Environment*, 288, p.106720.

Lövei, G.L. and Sunderland, K.D., 1996. Ecology and behavior of ground beetles (Coleoptera: Carabidae). *Annual review of entomology*, 41(1), pp.231-256.

Luff, M.L., 1998. *Provisional atlas of the ground beetles (Coleoptera, Carabidae) of Britain*. Biological records Centre Institute of Terrestrial Ecology.

Luff, M.L. and Larsson, S.G., 1993. *The Carabidae (Coleoptera) Larvae of of Fennoscandia and Denmark* (Vol. 27). Brill.

Magurran, A.E., 2013. *Measuring biological diversity*. John Wiley & Sons.

Marrec, R., Badenhausser, I., Bretagnolle, V., Börger, L., Roncoroni, M., Guillon, N. and Gauffre, B., 2015. Crop succession and habitat preferences drive the distribution and abundance of carabid beetles in an agricultural landscape. *Agriculture, Ecosystems & Environment*, 199, pp.282-289.

McGavin, G., 1997. *Expedition Field Techniques. Insects :and other terrestrial arthropods*. London: Royal Geographical Society.

New, T. R. 1998. *Invertebrate surveys for conservation*. Oxford: Oxford University Press

Noriega, J.A., Hortal, J., Azcárate, F.M., Berg, M.P., Bonada, N., Briones, M.J., Del Toro, I., Goulson, D., Ibanez, S., Landis, D.A. and Moretti, M., 2017. Research trends in ecosystem services provided by insects. *Basic and Applied Ecology*.

Owen, J.A., 1995. A pitfall trap for repetitive sampling of hypogean arthropod faunas. *Entomologist's record and journal of variation*, 107, 225 – 228.

Payne, R.W. ed., 1993. *Genstat 5 release 3 reference manual*. Oxford University Press.

Perry, J.N., Rothery, P., Clark, S.J., Heard, M.S. & Hawes, C., 2003. Design, analysis and statistical power of the FarmScale Evaluations of genetically modified herbicide-tolerant crops. *Journal of Applied Ecology*, 40, 17–31

Petit, S., Bohan, D.A. and Dijon, A., 2018. The use of insects in integrated weed management. In *Integrated weed management for sustainable agriculture* (pp. 453-468). Burleigh dodds Science publishing. DOI: 10.19103/AS.2017.0025.23

Petit, S., Cordeau, S., Chauvel, B., Bohan, D., Guillemin, J.P. and Steinberg, C., 2018. Biodiversity-based options for arable weed management. A review. *Agronomy for Sustainable Development*, 38(5), p.48.

Petit, S., Trichard, A., Biju-Duval, L., McLaughlin, Ó.B. and Bohan, D.A., 2017. Interactions between conservation agricultural practice and landscape composition promote weed seed predation by invertebrates. Agriculture, ecosystems & environment, 240, pp.45-53.

Redlich, S., Martin, E.A. and Steffan-Dewenter, I., 2018. Landscape-level crop diversity benefits biological pest control. *Journal of Applied Ecology*.

Saska, P., Vodde, M., Heijerman, T., Westerman, P. & van der Werf, W., 2007. The significance of a grassy field boundary for the spatial distribution of carabids within two cereal fields. *Agriculture, Ecosystems and Environment*, 122, 427–434.

Scopel, E., Triomphe, B., Affholder, F., Da Silva, F.A.M., Corbeels, M., Xavier, J.H.V., Lahmar, R., Recous, S., Bernoux, M., Blanchart, E. and de Carvalho Mendes, I., 2013. Conservation agriculture cropping systems in temperate and tropical conditions, performances and impacts. A review. *Agronomy for Sustainable Development*, 33(1), pp.113-130.

Shearin, A.F., Reberg-Horton, S.C. and Gallandt, E.R., 2014. Direct effects of tillage on the activity density of ground beetle (Coleoptera: Carabidae) weed seed predators. *Environmental entomology*, *36*(5), pp.1140-1146.

Sims, I., and Cole, J. 2016. Hypogean Pitfall Trapping: A Novel Teqnique for Assessing Soil Biodiversity in Agroecosystems. *BR. J. ENT. NAT. HIST.*, 29: 2016

Sims, I., and Cole, J. 2017. Baeus seminulum (hymenoptera:scelionidae) new to Berkshire and a review of records from the British Isles. *BR. J. ENT. NAT. HIST*., 30: 2017

Smilauer, P. & Leps, J. (2014). *Multivariate analysis of ecological data using Canoco 5*. Cambridge University Press

Smith, J., Potts, S. and Eggleton, P., 2008. Evaluating the efficiency of sampling methods in assessing soil macrofauna communities in arable systems. *European Journal of Soil Biology*, 44(3), pp.271-276.

Suenaga, H. and Hamamura, T., 1998. Laboratory evaluation of carabid beetles (Coleoptera: Carabidae) as predators of diamondback moth (Lepidoptera: Plutellidae) larvae. *Environmental entomology*, 27(3), pp.767-772.

Sunderland, K., 2002. Invertebrate pest control by carabids. *In:* Holland, J.M. *The Agroecology of Carabid Beetles.* Andover: Intercept

Sunderland, K.D. and Vickerman, G.P., 1980. Aphid feeding by some polyphagous predators in relation to aphid density in cereal fields. *Journal of Applied Ecology*, pp.389-396.

Symondson, W.O.C. (2004) Coleoptera (Carabidae, Drilidae, Lampyridae and Staphylinidae) as predators of terrestrial gastropods. *Natural Enemies of Terrestrial Molluscs* (ed. by G. M.Barker), pp. 37–84. CAB International, Oxford, U.K.

Telfer, M. 2017. *Subterranean pitfall traps for beetles* [online blog] Available at: http://www.markgtelfer.co.uk/beetles/techniques-for-studying-beetles/subterranean-pitfall-traps-for-beetles/ [accessed 20/11/2017]

Theunissen, J., 1994. Intercropping in field vegetable crops: pest management by agrosystem diversification—an overview. *Pesticide Science*, 42(1), pp.65-68.

Theunissen, J. and Schelling, G., 2000. Undersowing carrots with clover: suppression of carrot rust fly (Psila rosae) and cavity spot (Pythium spp.) infestation. *Biological agriculture & horticulture,* 18(1), pp.67-76.

Thiele, H.U., 1977. *Carabid beetles in their environments: a study on habitat selection by adaptations in physiology and behaviour* (Vol. 10). Springer Science & Business Media.

Thomas, R.S., Harwood, J.D., Glen, D.M. and Symondson, W.O.C., 2009. Tracking predator density dependence and subterranean predation by carabid larvae on slugs using monoclonal antibodies. *Ecological Entomology,* 34(5), pp.569-579.

Thomas, C.G., Holland, J.M. and Brown, N.J., 2002. The spatial distribution of carabid beetles in agricultural landscapes. *The agroecology of carabid beetles*. Andover: Intercept, pp.305-344.

Traugott M. (1998): Larval and adult species composition, phenology and life cycles of carabid beetles (Coleoptera: Carabidae) in an organic potato field. *European Journal of Soil Biology* 34, 189-197. Abstract

Tylianakis, J.M., Romo, C.M., 2010. Natural enemy diversity and biological control: making sense of the context-dependency. *Basic Appl. Ecol*. 11, 657–668. http://dx. doi.org/10.1016/j.baae.2010.08.005.

Tscharntke, T., Tylianakis, J.M., Wade, M.R., Wratter, S.D., Bengtsson, J. and Kleijn, D., 2007. Insect Conservation in Agricultural Landscapes. . In- Stewart A.J.A, New, T.R. and Lewis, O.T., 2007. *Insect Conservation Biology.* Proceedings of the Royal Entomological Societies 23rd symposium. Oxford: CABI. Pp 383-404.

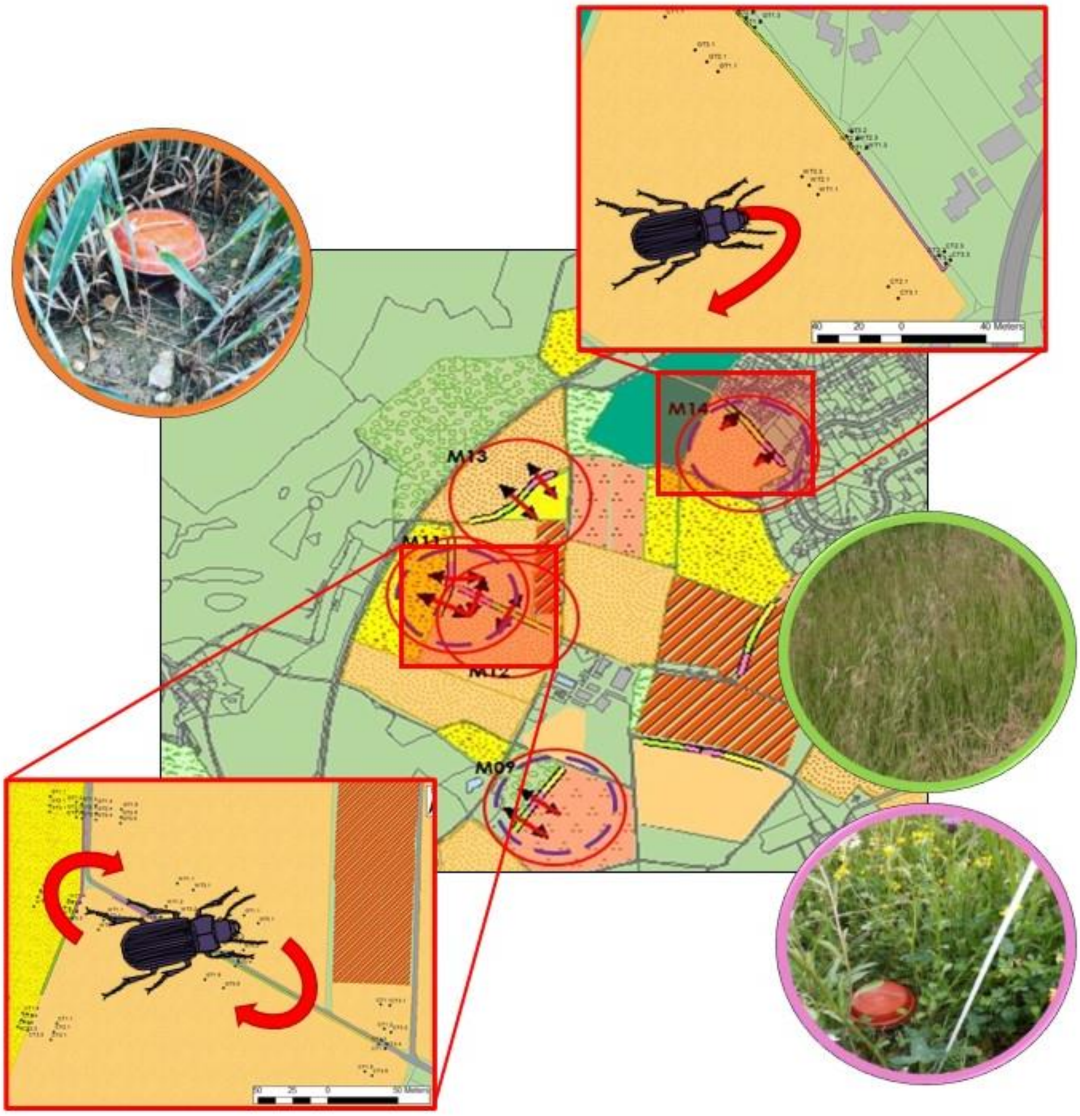
Wheater, C.P., Bell, J.R. and Cook, P.A., 2011. *Practical field ecology: a project guide*. John Wiley & Sons.

Wezel, A., Casagrande, M., Celette, F., Vian, J.F., Ferrer, A. and Peigné, J., 2014. Agroecological practices for sustainable agriculture. A review. *Agronomy for sustainable development*, 34(1), pp.1-20.

Woodcock, B.A., Harrower, C., Redhead, J., Edwards, M., Vanbergen, A.J., Heard, M.S., Roy, D.B. and Pywell, R.F., 2014. National patterns of functional diversity and redundancy in predatory ground beetles and bees associated with key UK arable crops. *Journal of Applied Ecology*, 51(1), pp.142-151.

Woodcock, B.A., Potts, S.G., Westbury, D.B., Ramsay, A.J., Lambert, M., Harris, S.J. and Brown, V.K., 2007. The importance of sward architectural complexity in structuring predatory and phytophagous invertebrate assemblages. *Ecological Entomology*, *32*(3), pp.302-311.

Chapter 4



Multiple factors at a farm scale

This chapter builds on the former chapters to complete the first and second objectives. Taking the factors identified as significant and of interest with the FSE dataset, we tested for crop, adjacent habitat, and margins, and controlled for boundary features. This builds on chapter 2, validating the effects of margins and adjacent with measurements in these areas, and sampling in different crop types. Addition of spatial data exploration in this chapter elucidates the scales acting on carabid communities. We also use the methodology verified in chapter 3 to elucidate further the distinctions in hypogean activity, and the distributions of larvae. This chapter is written in the paper style, as it is intended for publication with the addition of data from a third run, following thesis completion.

Using a farm-scale approach to examine the effects of field margins and landscape features on predatory carabid communities

4.1 Introduction

Carabid beetles, as voracious predators of both weed seeds and invertebrate crop pests, have been the subject of much research in the agro-ecological literature (Kotze et al., 2011; Kromp, 1999; Holland 2003). This body of research has helped inform the development of farm measures such as beetle banks, buffer strips and headlands, and tussocky grass margins aimed at boosting the abundance of carabids adjacent to crop areas. The literature on the success of these measures in promoting in-crop predation is, however, more divided, with the effects of agro-ecological interventions being highly variable between studies (Begg et al., 2017; Berendse et al., 2004; Kleijn et al., 2006; Kleijn and Sutherland, 2003, Segre et al., 2020).

The breadth of studies on agricultural carabids have gleaned broad insight into the factors affecting their abundance and population dynamics. Crop type, soil type, soil moisture, cultivations, pesticides, and landscape including non-crop habitats have been widely proven to have significant effect on carabid abundance and diversity (Holland and Luff, 2000; Jowett et al., 2019; 2021; Labruyere, Petit, and Ricci, 2018; Thiele, 1977; Thomas, Holland, and Brown, 2003). In order to understand the key influences and make effective recommendations to practitioners we need to understand the relative importance of these factors individually and in combination.

A key knowledge gap in this respect is understanding the factors affecting carabid abundance and community composition in crop areas at a *farm scale*. Most studies are undertaken at either small-scale: in laboratory or plot studies, or large: in landscape scale analyses (Aguilera et al., 2020; Brooks et al., 2008; Kinnunen, Tiainen, and Tukia, 2001; Kotze et al., 2011). What is lacking is the knowledge of where, in a farm-landscape, interventions should be placed. Our previous work (Jowett et al., 2019) indicates the placement of such boundary measures as margins, in juxtaposition with crops and landscape, can contribute to effective community composition and abundance of key species for pest control. In order to spatially prioritise management options, the interactions of field scale impacts with landscape processes must be understood.

Added to this, the influence of landscape features is recognised, yet in some cases debated. There is scientific consensus on the importance of adjacent habitat, particularly grassland, in influencing carabid community composition, yet the extension of this to the utility of the community in question to efficient control of pests in the crop area has not been comprehensively investigated (Aguilera et al,. 2020; Boetzl et al., 2019, Ricci et al., 2019). In our previous work (Jowett et al., 2019) examining carabid abundance in crop areas across the UK relative to multiple boundary features and adjacent habitats, we discovered that the presence of margins did not universally encourage carabid abundance in central crop areas.

The recommendation for grass margins, specifically seeded with tussock forming grass species originates in carabid literature from the 80s where certain species of carabid were found to overwinter in abundance within tussocks of grasses, these areas comprising relatively permanent habitat of favourable microclimatic conditions (Dennis, Thomas, and Sotherton, 1994; Desender 1982; Sotherton 1984; 1985). The value of these habitats is therefore as providing hibernation and aestivation (summer diapause) habitats to promote persistence in farm habitats (Thomas, Holland, and Brown, 2003; Thomas and Marshall 1999). However, the provision of these small-scale grass habitats does not necessarily translate to carabid spill-over and predation in crop areas (Rand, Tylianakis, and Tscharntke, 2006). Moreover, the value of tussocky grass margins may not hold true for all carabid species of value to agricultural pest and weed seed control (Jowett et al 2019; Lagerloff and Wallin 1993). The design of management to boost carabid pest control, therefore, needs to be underpinned by an understanding of the ecology of key predatory species.

The biological needs, and behavioural aspects of carabid beetles are highly divergent (Den Boer, Thiele, and Weber, 1979; Kotze et al., 2011; Luff, 2002), and as such, recommendations from specific species studied may not be applied wholesale to the management of whole communities. Previous work (Jowett et al., 2019), detailed in chapter 2, shows that factors affecting presence and abundance of carabids varied by species even when morphologically similar. The habitat preference of carabid species acts as a filter to species occupying farm habitats, so that despite their polyphagous opportunistic nature, this results in actualised niches avoiding interspecific competition (Holland, 2002; Loreau, 1990; Niemelä, 1993). Different species were found to be abundant in margin and boundary areas to varying degrees, and in interaction with different crop types. It follows that the resources necessary to promote their presence may be supplied differentially in margin habitats, and this governs their movements into crop areas.

Another large knowledge gap surrounds the role of carabid larvae in agro-ecosystems. As soil living organisms, carabid larvae inhabit the crop area. Due to nutritional needs larvae are more carnivorous and voracious then adults, and due to their phenology are active at different times— notably as more surface active than adults in the winter (Lövei and Sunderland, 1996; Paill, 2000; Traugott, 1998). Thus, they have the potential to contribute significantly to pest control and will respond differently to management. However, due to difficulty of capture and identification, larvae are poorly studied, and consequently seldom considered in estimations of carabid ecosystem service delivery, and the promotion of this with farm management interventions. This is a particular oversight, since larvae are the most vulnerable life stage for mortality (Van Dijk, 1994), also the nutritional status of larvae affect the morphology of adults in size and dispersal ability (Holland 2002; Noordhuis, Thomas, and Goulson, 2001; Thiele, 1977; Van Dijk, 1994). It would therefore be desirable to feed into the elucidation of key factors influencing carabids at a farm scale, to explore the effect of crop and landscape influences on carabid abundances at the larval stage. This has implications for trapping methodologies.

Subterranean pitfalls work on a similar premise of standard pitfalls. They catch falling invertebrates in a trap solution, yet the trap is set underground, with the trap area delimited by a mesh tube through which soil organisms pass and fall. This allows a catch over time (rather than the snapshot of soil cores), which may return more specimens of soil active larvae moving to the surface to feed, and be comparable to pitfall catches. (Owen, 1995; Sims and Cole, 2016; 2017; Telfer, 2017; and personal communication with authors). Furthermore, the nature of belowground movements means that subterranean traps capture a differential activity density to standard pitfalls, that is more indicative of carabids resident in the habitat (Fornier and Loreau, 2001). Our previous study (Jowett et al., 2021) found that subterranean trapping revealed differential distribution data to standard pitfall trapping, that built a fuller picture of both adult and larval movement in crops.

This study utilised a network of experimental field margins across a UK farm site of 330 ha to sample adult and larval carabid beetles with standard and subterranean pitfall traps. In order to connect this with management at a farm scale, we studied the effects of different field margin interventions over multiple farm habitats and crop combinations across the farm site. By trapping with standard and subterranean pitfalls, we sampled the whole communities of carabid beetles, in various crops, experimental margins, and adjacent landscape features, across a farm landscape. We used this data to explore three aspects of carabid occurrence in the landscape:

1) What are the key factors influencing carabid abundance, species richness, and diversity in crop areas? What place does different types of margin treatment occupy within this?
2) How does differential species responses to landscape factors influence the community composition relative to the above factors?
3) Do these processes vary at a farm scale irrespective of field level differences?

4.2 Methods

We used 10 experimental margins established across the Rothamsted farm estate, UK, in 2017. Each margin was 210 m length in total, split into three sections of 70 m x 3 m each section randomly allocated to either 'grass mix', 'wildflower mix' or Lepidoptera 'moth mix' (Blumgart, 2020) (Fig. 1). We used only the grass and wildflower margins both of which were planted with standardised mixes commercially produced for field margin and were relevant to carabid-management interventions. The *grass* margin contains four species of non-competitive grasses (*Agrostis capillaris, Cynosurus cristatus, Festuca rubra* and *Phleum bertolonii*), and the *wildflower* margin contains the same four grasses plus 13 species of perennial wildflower widely used in agri-environment scheme margins (Table S1). We also included a control as an additional level in the treatment with no sown margin (just with a cultivated field edge or natural-grass border).

Figure 1- Rothamsted farm map with field margin experiment locations and treatments, showing crop type and adjacent habitats. Selected margins labelled M01-M14 with standard (red) and subterranean trap (purple) locations circled. Arrows denote one-way and two-way transect lines.

For each set of margins, we sampled along transects perpendicular to the field edge (as far as possible as dictated by field shapes). Each field was split into three zones (i) Margin or field edge (in the case of the control treatment), (ii) crop edge (2–3m from Margin or field edge), (iii) crop centre (defined as a representative central point of the field over 20 m from the field edge). Six transect groups included an additional two zones that extended back into the adjacent habitat (two-way transects), similarly measuring (ii) adjacent habitat edge and (iii) adjacent habitat centre (Fig. 2). All transect groups ran parallel to field side boundaries in blocking, to minimise the effect from these.

We had access to 16 sets of margins (known as M01 – M16). We selected the 10 margins that allowed multiple comparisons of features of interest. Features were selected that are shown in the literature to have impacts on carabid distribution in agricultural areas, these were: crop type, and adjacent habitats of grassland, scrub and urban. Margins selected for inclusion were balanced in repetitions between boundaries of hedgerow, trees, fences, and tracks (identified in literature to have an impact on carabid distribution), in order that effects across the experiment would be relatively uniform (Holland, 2002; Jowett et al., 2019; 2021; Kotze et al., 2011; Thiele, 1977) (Table 1).

The 10 margins comprised six sets with two-way transects and four with one-way (Table 1). Where transects were two-way, the adjacent habitat was sampled, making a line of 5 points for each transect. Where transects were one-way, transect lines comprised 3 points, and adjacent habitat was only noted as a factor. Urban habitats could not be sampled as they were not part of the farm site.

Table 1- Selected margins for standard pitfall transects, with infield, boundary and adjacent habitat variables. Margins with subterranean traps are indicated by *. Areas/factors not sampled indicated in italics. OSR= Oilseed rape.

Margin		Infield crop	Sowing time	Adjacent habitat	Boundary	Previous crop
One-way margins	M1 w	Wheat	Winter	*Hedge*	*Urban*	*Winter oats*
	M1 g	Wheat	Winter	*Hedge*	*Urban*	*Winter oats*
	M2 w *	Oats	Spring	*Gappy trees*	*Urban*	*Spring beans*
	M2 g *	Oats	Spring	*Gappy trees*	*Urban*	*Spring beans*
	M7 w	Barley	Winter	*Hedge*	*Urban*	*Spring wheat*
	M7 g	Barley	Winter	*Hedge*	*Urban*	*Spring wheat*
	M14 w *	Wheat	Winter	*Hedge*	*Urban*	*Spring barley*
	M14 g *	Wheat	Winter	*Hedge*	*Urban*	*Spring barley*
Two-way margins	M3 w	Oats	Spring	*Gappy trees*	Oilseed rape	*Spring beans*
	M3 g	Oats	Spring	*Gappy trees*	Oilseed rape	*Spring beans*
	M4 w *	Oilseed rape	Winter	*Hedge*	Grass/scrub	*Winter barley*
	M4 g *	Oilseed rape	Winter	*Fence*	Grass /scrub	*Winter barley*
	M9 w *	Barley	Spring	*none*	Grass/scrub	*Winter wheat*
	M9 g *	Barley	Spring	*none*	Grass/scrub	*Winter wheat*
	M11 w *	Wheat	Winter	*track*	Wheat	*Winter OSR*
	M11 g *	Wheat	Winter	*track*	Wheat	*Winter OSR*
	M12 w	Wheat	Winter	*Track*	Wheat	*Winter OSR*
	M12 g	Wheat	Winter	*Track*	Wheat	*Winter OSR*
	M13 w	Oilseed rape	Spring	*Hedge*	Wheat	*Winter wheat*
	M13 g	Oilseed rape	Spring	*Hedge*	Wheat	*Winter wheat*

Standard pitfalls were used on all transect groups, with a subterranean pitfall traps used on a subset of five fields, three of which were two-way (Table 1). For standard pitfalls there were two lines for each margin/control- located 10 m apart; and for subterranean traps a single line was set, this was located between transect lines (5 m distant to standard pitfalls). For control lines, where possible, these were fit alongside experimental margins avoiding field edges areas to minimise edge effects. Often circumstances did not allow avoidance of edges due to field size or shape, so where practicable, control treatment was then split either end of margin treatments to balance impacts (Fig.2).

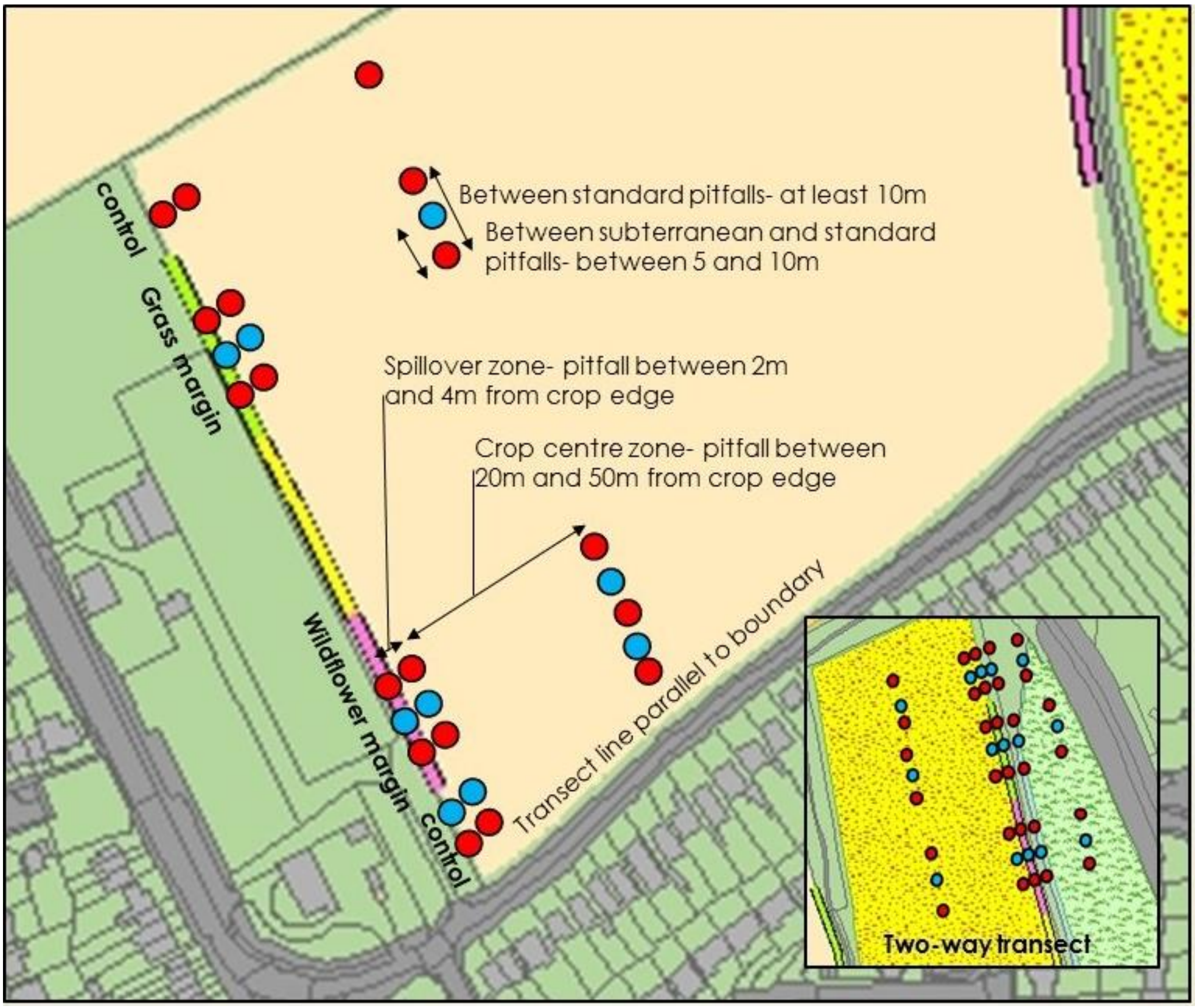


Figure 2- example of typical transect layout for one way (Margin 02), and (insert) two way transects (Margin 04)

4.2.1 Trapping

The standard pitfall equipment used comprised cups of diameter 7.5cm and depth 10cm, set in space holding pipes, with rain covers (Fig. 3a). The design of the subterranean trapping was based on Owens (1995) (see also Sims and Cole, 2016; 2017; Telfer, 2017). The design was based on a 34cm x 7cm pipe with 3 cut-out sections 20cm x 4cm, bordered by wire mesh of 1.2cm grid. A sliding section with attached sample collection cup sits inside the pipe, allowing a hooked collection from the base. A hat sits on the top, stopping surface active catch, whilst allowing access to empty (Fig. 3b). When unset, stiff plastic film sits, blocking the mesh. This is a novel aspect that reduced setting-in times and unintentional catch in our pilots. When set, liquid is put in the collection cup. Liquid used was a 70% ethanol 30% water mix, filled to 1/3 of the standard (200ml) pitfall cup, and ¼ of the subterranean (150ml) pot.

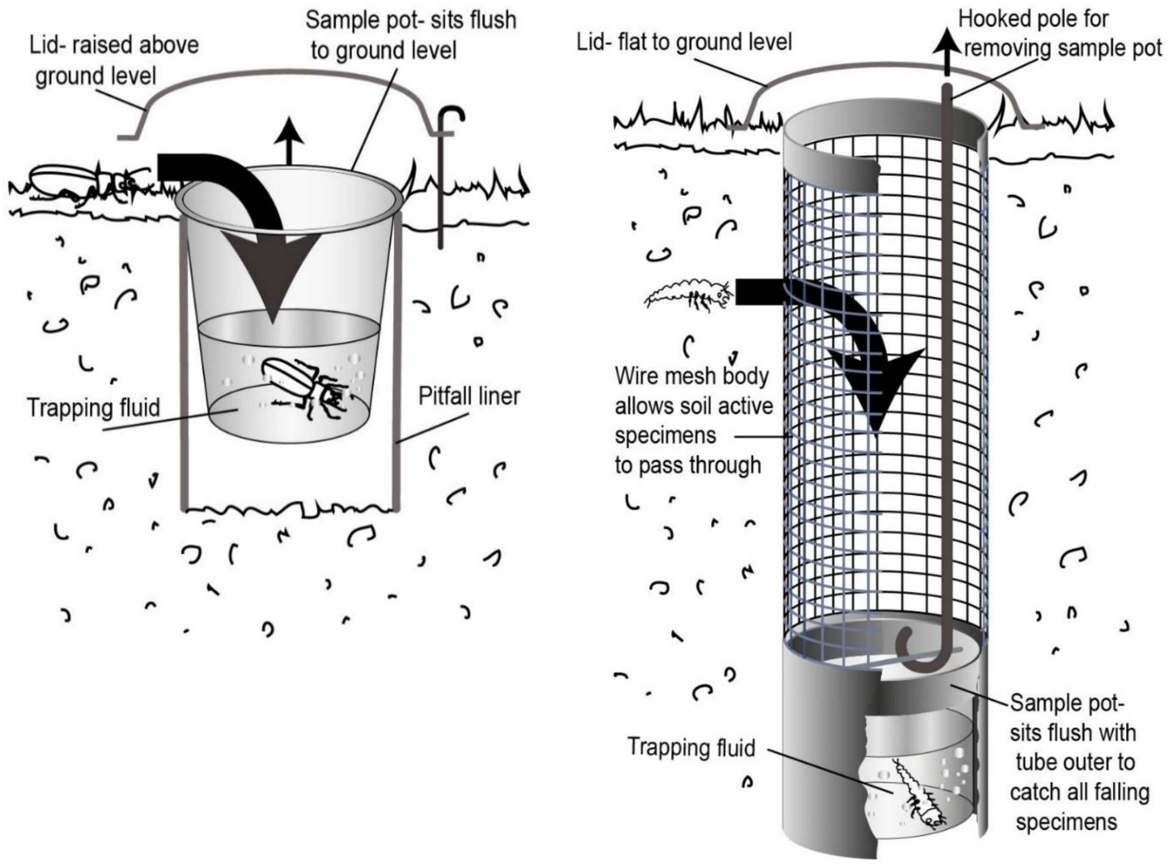


Figure 3- a) Standard pitfall trap design and setup; b) Subterranean pitfall design and setup

Traps were run from the 20th June to 25th July 2017, in 2 runs; each run consisted of a seven-day period with traps reset at first emptying. For practical reasons field locations were grouped in proximity and set on sequential days.

4.2.2 Statistical analysis

Carabid adults were identified to species level (Luff, 2007). Identifying carabid larvae to species level is notoriously difficult. Therefore, larvae were pooled across all species. Both runs of the experiment were subject to similar climatic conditions and constituted the same lifecycle period in terms of community assemblages, and as such were pooled for analyses.

Some traps (around 10%) were spoiled or data labels incomplete (spread across treatments), therefore these were discarded, and we analysed only the count data from complete records. This left 224 trap occasions in Run 1 and 269 in Run 2. We use the standard proxy measure of activity density to account for abundance. For each trap occasion we calculated the ‘pooled-carabid abundance’ (N), i.e. the total number of carabids of any species, and species richness (S), i.e. the number of different species. We fitted the log series model (Equation 1) to the data by maximum likelihood to give estimates of Fisher's log-series alpha ($\hat{\alpha}$), which is a robust and widely used diversity metric (Beck & Schwanghart, 2010; Magurran, 2013) that accounts for the effect of total numbers of individuals in a sample on diversity estimates.

$$S = \hat{\alpha} \log\left(1 + \frac{N}{\hat{\alpha}}\right)$$

(eqn 1)

We fitted Linear Mixed Models (LMMs) using the Genstat statistical software package (Payne, 1993) to determine the effect of environmental factors on (i) pooled-carabid abundance (N), (ii) richness (S), (iii) species diversity (quantified as $\hat{\alpha}$). We chose to use a LMM on logged abundance over a GLMM with poisson distribution, because the model fit often proved more stable for complex data sets such as the one described here.

4.2.3 Carabid abundance and diversity in crop areas

For our first aim, exploring the effect of management and landscape factors on carabid abundance and diversity in crop areas, we subset the data to include only samples from the crop area (*crop edge* and *crop centre)*, and further to pitfall traps only, as each trap type represents a different measure of activity density, and the reduced factor repetition in subterranean trap data resulted in insufficient power to draw statistical conclusions with linear models.

We considered the factors *in-field crop* (winter wheat, spring barley, winter barley, spring OSR, winter OSR, and spring oats), *position* (transect point crop centre or crop edge), *margin type* (grass, wildflower or control), and *adjacent habitat* (pooled to categories of crop, grass/scrub, or urban) as fixed effects with two-way interactions. The random model was defined as *run* (to examine time as a block and average temporal effects over locations), and nested within each *run*, *field* (i.e. experimental margin number), *transect*, and *location* on the transect (i.e. plot/trap replicate). We log transformed the pooled-abundance, species richness, and alpha so that residuals conformed to normality. We selected terms using backwards elimination according to the largest P-value given by the Kenward-Roger approximate F -tests. The final predictive model was chosen when all remaining terms gave significant values ($P \leq 0.05$) when dropped from the model.

To explore the effects of margins, we extended the dataset to include margin transect points, so *position* is expanded to include *margin, crop edge*, and *crop centre*. LMMs were repeated, as above, to examine the effects of margin type on relative abundance and diversity compared to crop areas.

4.2.4 Carabid communities across habitats

For our second aim, to look at community differences, we carried out Principal Components Analyses (PCAs) on the count data for both runs pooled. We ran a separate PCA for each trap type, as activity differs between trap types, and so abundances are not directly comparable. We used a subset of the data to only include species with over 10 observations and excluded any occasions with no observations under this restriction. In this analysis, we also included data from the adjacent transect positions (adjacent edge and adjacent centre, Figure 2) from the two way transects, using *vegetation* as a factor, that included crops and semi-natural habitats, with the categories *winter wheat, spring barley, winter barley, spring OSR, winter OSR, spring oats*, *grass/scrub*, and *field edge* (comprising experimental margins or control). The data were log transformed.

To further examine the species preferences driving community differences, we fitted LMMs to the data on abundance of (i) carabids at species level for the five most abundant species (to ensure enough data for model terms) and (ii) carabid larvae (pooled). Both trap types were included, in order to model every recorded occasion of species occurrence. The proportion of pitfall and subterranean traps was balanced across crops and adjacent habitats in the experimental design. Therefore, species could be analysed by the activity (*trap type* denoting above ground or subterranean movements) in each habitat type. Random terms remained the same as pooled LMMs above, and we included the factors *vegetation* (winter wheat, spring barley, winter barley, spring OSR, winter OSR, spring oats, and grass/scrub), *transect point* (centre, edge, or margin), and *trap type* (pitfall or subterranean) in the fixed effects.

4.2.5 Spatial dynamics of carabids

For our third aim, to Investigate the spatial dependence in carabid abundances, we first plotted the total abundance of all carabid species, the abundance of the top five most abundant species, and the pooled larvae according to location to examine any visible spatial trends.

To explore the spatial dependence in carabid abundance a Linear Mixed Model (LMM) framework was used in which the log abundance was modelled for the pooled standard pitfalls and subterranean pitfalls (since these comprise differential activity-density). We also modelled the top five most common species, with the pitfall trap data alone. In this instance, our interest was on the spatial covariance in the data, which we capture as a correlated random effect of the model along with an independent and identically distributed (iid) random error (known in spatial statistics as the nugget effect). In this case, *Run* was included as a fixed affect to avoid issues related to the co-location of measurements made at the two time points. As before the environmental factors expected to affect the abundance of carabids (*Vegetation* and *adjacent*) were tested as potential fixed effects as well as the spatial coordinates *eastings* and *northings* in order to account for large scale trend effects. The random effects model describes the spatial covariance in the data and is described by a suitable variogram model for which the parameters are estimated. Initial exploration showed that the exponential variogram model gave the best fit for the total abundance model and so we chose to use this functional form in all of our fitted models. The exponential model is given by

$$\gamma(h) = c_0 + c_1\left\{1 - \exp(-\frac{h}{a})\right\} \quad \text{for } h > 0$$

$$= 0 \quad \text{for } h = 0$$

where c_0 is the nugget c_1 is the spatially correlated random component and a is the distance parameter. The quantity 3a is the effective range of the spatial correlation (Webster and Oliver, 2007).

Models were fitted by sequentially adding fixed effects to the "null" model which in this case was the model with only the Run factor as a fixed effect. Model fitting was done using the `likfit` function in the `geoR` package for the R platform (Diggle and Ribeiro, 2007; R Core Team, 2021). This method has options to fit by maximum likelihood (ML) or by residual maximum likelihood (REML). The ML method is appropriate to use when comparing different fixed effects structures and the REML when forming the final model because it reduces bias in the estimated random effects. Therefore we use ML for the sequential fitting process to determine the relevant fixed effects and then refitted the final model using REML. The sequential fitting was done by fitting the factors in perceived order or importance, that was first *vegetation,* second *eastings, northings* and an interaction of the two, and third *adjacent*. *Vegetation*, as in the species models, denotes the actual vegetation at the transect point, whether crop, grass/scrub, or experimental margin. *Eastings* and *northings* capture the large-scale spatial trend across a landscape level, as opposed to the autocorrelation between points which is assumed to be a stationary process. *Adjacent* denotes the habitat adjacent to the transect. Terms were retained if there was evidence that adding fixed effects to a simpler model achieved a significant improvement by computing the log-ratio statistic:

$$L = 2(\ell_1 - \ell_0)$$

where ℓ_1 and ℓ_0 denote, respectively the maximised log-likelihoods from fitting the model with the additional fixed effects, and the simpler model without them. Under the null hypothesis, where the additional fixed effects are not related to the dependent variable, this statistic is asymptotically distributed as chi-square with degrees of freedom equal to the number of additional fixed effects. Here we assumed a significance threshold of $p = 0.05$.

The final fitted models were inspected to determine whether there was any longer-range trend in abundance across the farm and to characterise any spatial dependence in carabid populations, and specific species.

4.3 Results

4.3.1 Summary of data

After data cleaning, a dataset of 493 trap occasions (Run 1: 224, Run 2: 269), comprising 10,087 individual records of 56 carabid species, and 641 carabid larvae was produced. Species ranking in terms of abundance was similar for both runs, but differed between trap types (Table 2).

Table 2- Summary Table of carabids tapped, by runs and trap type. Colour scale denotes abundance ranking per column.

	both runs	**run 1**	**run 2**	**pitfall**	**ST**
total carabids	10,087	4,553	5,534	7,990	2,097
total carabid larvae	641	450	191	293	348
Pterostichus melanarius	2,891	1,374	1,517	2,456	435
Harpalus rufipes	2,835	1,039	1,796	1,996	839
Pterostichus madidus	2,031	800	1,231	1,772	259
Amara eurynota	448	154	294	231	217
Poecilius cupreus	411	265	146	385	26
Harpalus affinis	316	179	137	238	78
Trechus quadristriatus	179	92	87	135	44
Amara ovata	171	149	22	155	16
Anchomenus dorsalis	149	104	45	80	69
Calathus fuscipes	96	27	69	91	5
Amara similata	95	46	49	67	28
Amara plebeja	63	47	16	51	12
Nebria salina	56	43	13	37	19
Bembidion lampros	54	48	4	49	3
Carabus violaceus	45	17	28	45	0
Loricera pilicornis	43	23	20	41	2
Pterostichus niger	34	18	16	32	2
Nebria brevicollis	34	25	9	17	17
Amara lunicollis	18	13	5	18	0
Notiophilus biggutatus	17	12	5	14	3
Amara aenea	13	13	0	12	1

Abax paralelipedus	11	6	5	10	1
Pterostichus aethiops	10	10	0	8	2
Pterostichus cristatus	10	10	0	6	4
	both runs	**run 1**	**run 2**	**pitfall**	**ST**
Poecilius versicolor	9	7	2	7	2
Amara tibialis	6	6	0	6	0
Pterostichus vernalis	5	2	3	5	0
Ophonus ardosiacus	4	2	2	1	3
Calathus melanocephalus	3	2	1	3	0
Badister bullatus	3	2	1	1	2
Agonum muelleri	2	0	2	2	0
Amara praeterrmissa	2	2	0	2	0
Pterostichus strenuus	2	2	0	1	1
Pterostichus nigrita	2	1	1	2	0
Bembidion lunulatum	2	2	0	1	1
Microlestes minutulus	2	2	0	2	0
Ophonus rufibarbis	2	0	2	2	0
Curtonotus aulicus	2	0	2	2	0
Bembidion obtusum	2	0	2	0	2
Demetrius atricaillus	1	1	0	1	0
Acupalpus meridiaius	1	1	0	1	0
Acupalpus dubius	1	0	1	1	0
Amara nitida	1	1	0	1	0
Amara convexior	1	1	0	1	0
Notiophilus rufipes	1	1	0	1	0
Pterostichus quadrifovealatus	1	1	0	0	1
Stomis pumicatus	1	1	0	0	1
Bembidion aeneum	1	1	0	0	1
Bembidion iricolor	1	1	0	0	1
Anisodactylus binotatus	1	1	0	1	0
Demetrias atricapillus	1	1	0	1	0
Ocys quinquestriatus	1	1	0	1	0
Brachinus crepitans	1	1	0	1	0
Ocys harpaloides	1	1	0	1	0
Leistus spinibarbis	1	0	1	1	0

4.3.2 Aim 1- crop area influences

The LMM of crop area abundance of carabids showed a highly significant interaction between crop and transect position ($F_{5,74}$=4.91,p=<0.001), and a significant interaction between transect position and adjacent habitat ($F_{1,72}$=9.37,p=0.003). Margin type was not retained in the model. Abundances at the crop centre were similar for the same crop type next to different habitats, but abundances at the crop edge were lower next to urban compared to being next to crops. Abundances were greatest in spring barley adjacent to grass (Fig 4). There was a near significant interaction of transect position and margin type ($F_{2,74}$=2.72,p=0.072).

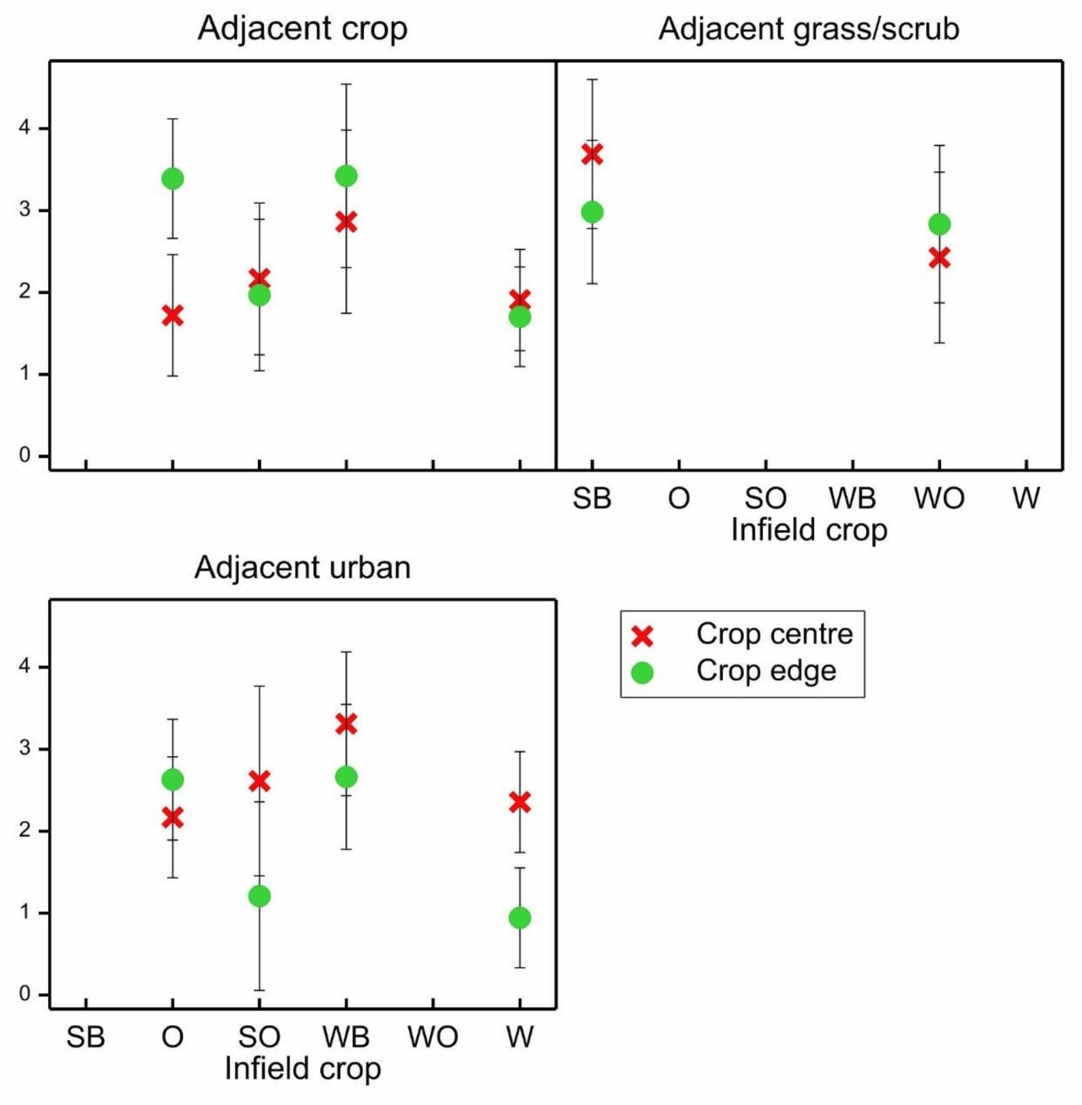


Figure 4- Fitted linear mixed model predictions for pooled-carabid abundance in the crop area by adjacent habitat, predicted means with effective standard error bars. Crop centre= between 20m and 50m from edge, Crop edge = between 2m and 4m from field boundary, SB= spring barley, O=oats, SO= spring oilseed rape, WO= winter oilseed rape, W=wheat.

The LMM for species richness in crop areas showed a significant interaction between crop and transect position ($F_{5,78.9}$=5.40,p<0.001), and a significant interaction between transect position and adjacent habitat ($F_{1,71.7}$=8.54,p=0.005). Margin type was not retained in the model. Species richness at the crop centre was similar for the same crop type next to different habitats, but richness at the crop edge was lower next to urban compared to being next to crops (Fig 5). There was a near significant interaction of transect position and margin type ($F_{2,73.4}$=2.50, p=0.089).

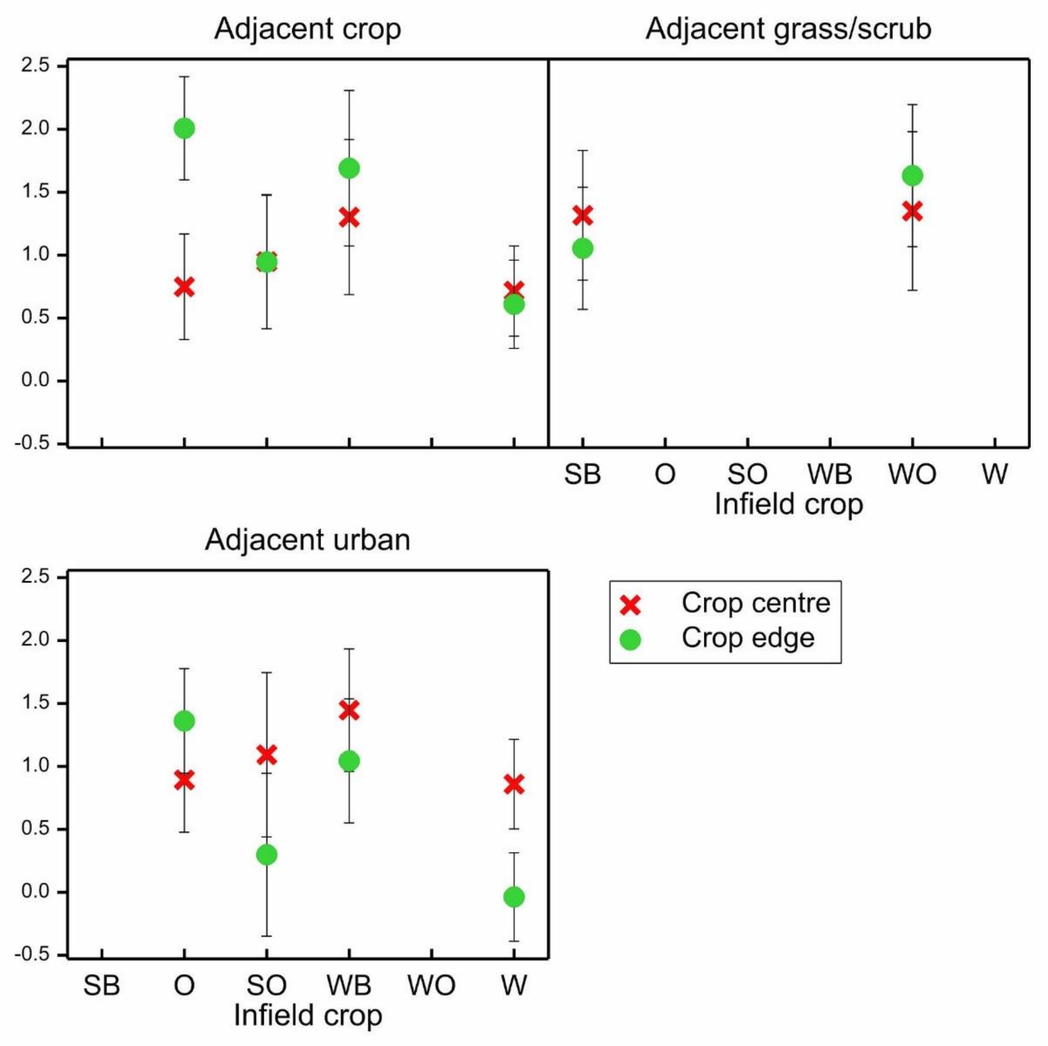


Figure 5- Fitted linear mixed model predictions for carabid species richness in the crop area by adjacent habitat, predicted means with effective standard error bars. Crop centre= between 20m and 50m from edge, Crop edge = between 2m and 4m from field boundary, SB= spring barley, O=oats, SO= spring oilseed rape, WO= winter oilseed rape, W=wheat.

The LMM for fisher's alpha retained only a significant term of crop ($F_{5,2.29}$=11.46, p=0.043) and an interaction of crop and transect position ($F_{5,3.41}$=17.07, p=0.004). Diversity varied by crop and position on the transect within the crop. In wheat, diversity was generally low compared to other crops, but was higher in the crop centre. In winter oilseed rape, spring oats, and spring oilseed rape, diversity was generally higher, and was higher at crop edges than the crop centre (Fig 6).

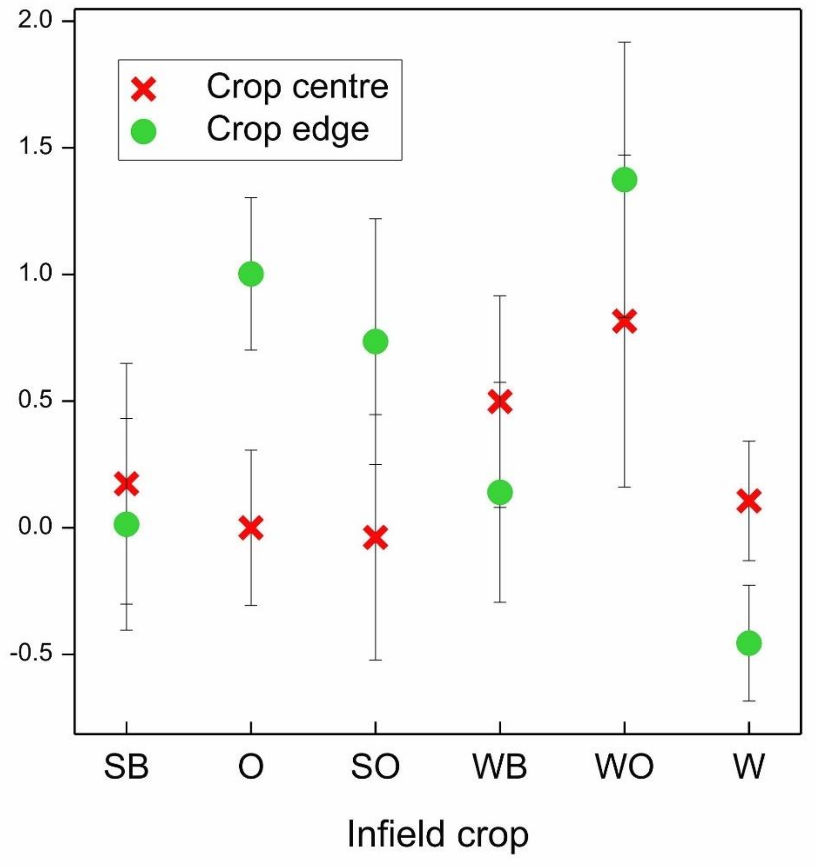


Figure 6- Fitted linear mixed model predictions for carabid diversity in the crop area, predicted means with effective standard error bars. Crop centre= between 20m and 50m from edge, Crop edge = between 2m and 4m from field boundary, SB= spring barley, O=oats, SO= spring oilseed rape, WO= winter oilseed rape, W=wheat.

When we included the transect position from within the experimental margin in the LMMs, significant model terms were similar, but margin type was now retained as a significant term in the model. For abundance, the LMM showed a significant effect of transect position ($F_{2,8.96}$=17.91,p=<0.001), transect position showed a significant interaction with crop ($F_{10,2.94}$=29.42,p=0.001), margin type ($F_{4,4.14}$=16.47,p=0.002), and adjacent habitat ($F_{2,4.21}$=8.42,p=0.015). Though standard error bars overlap, crop edge positions showed generally less abundance when next to a grass margin, and more abundance when next to a control area or wildflower margin. There was a clearly lower abundance in the margin transect position when this was in a wildflower margin (Fig 7).

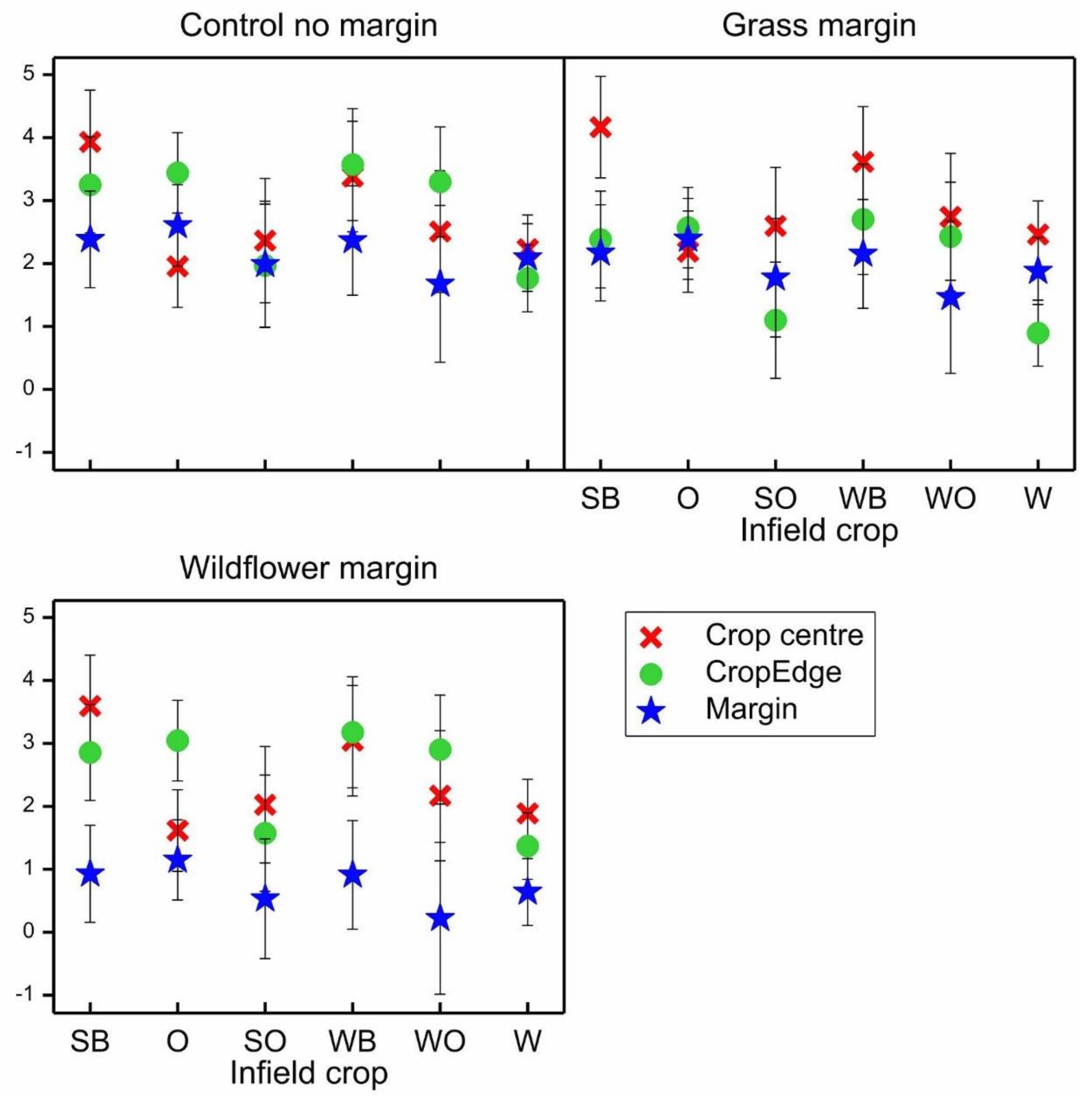


Figure 7- Fitted linear mixed model predictions for pooled-carabid abundance in the crop area and experimental margins by margin type, predicted means with effective standard error bars. Crop centre= between 20m and 50m from edge, Crop edge = between 2m and 4m from field boundary, SB= spring barley, O=oats, SO= spring oilseed rape, WO= winter oilseed rape, W=wheat.

For species richness with a margin transect position, LMMs showed significant interactions of transect position, with terms of crop ($F_{10,2.37}$=23.66,p=0.009), margin type ($F_{4,3.46}$=13.83,p=0.008), and adjacent habitat ($F_{2,4.07}$=8.14,p=0.017). The same patterns are evident as abundance, particularly that species richness is reduced in margin transect positions, where that occurs within a wildflower margin (Fig 8).

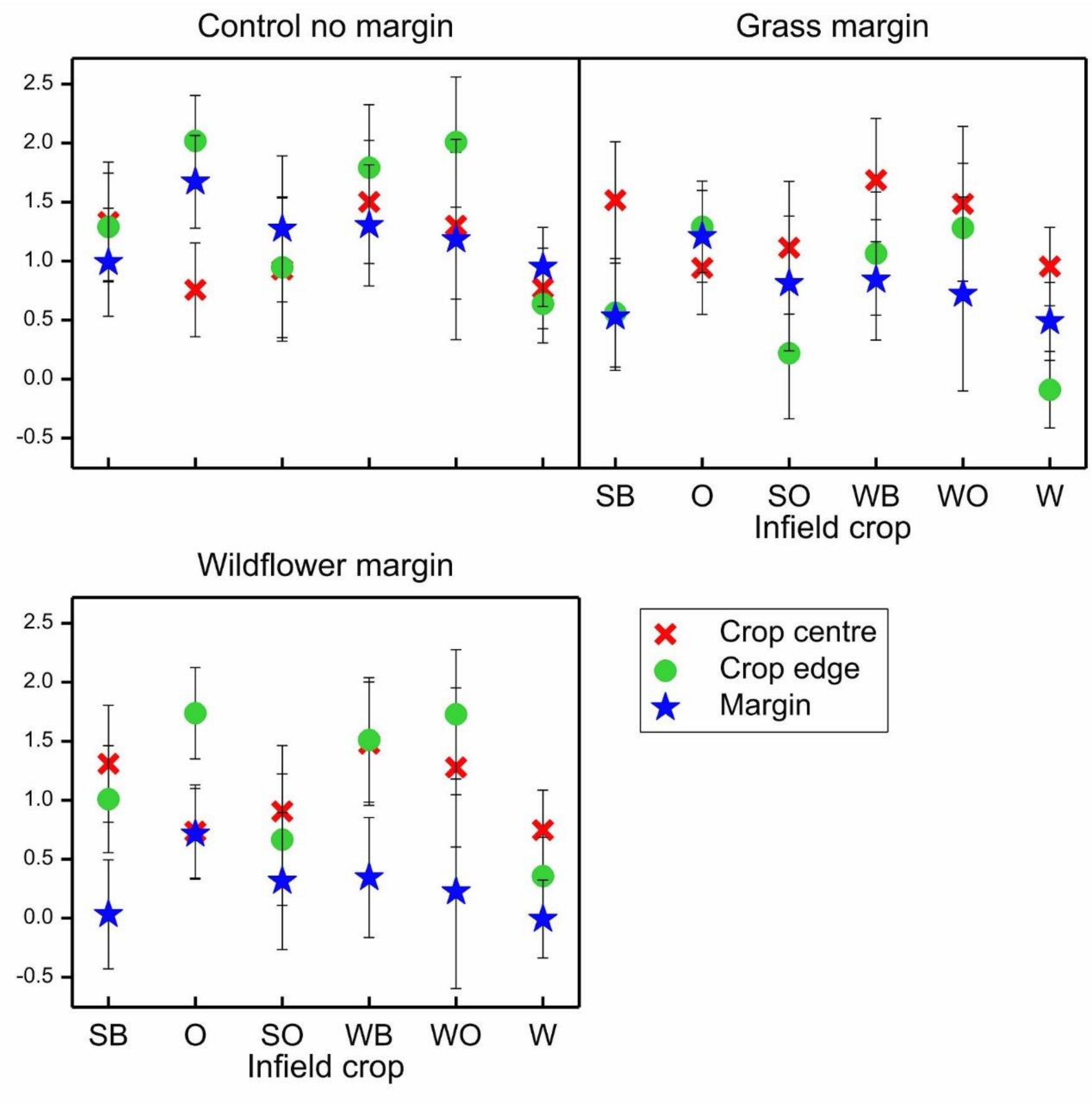


Figure 8- Fitted linear mixed model predictions for species richness in the crop area and experimental margins by margin type, predicted means with effective standard error bars. Crop centre= between 20m and 50m from edge, Crop edge = between 2m and 4m from field boundary, SB= spring barley, O=oats, SO= spring oilseed rape, WO= winter oilseed rape, W=wheat.

For fisher's alpha with margin transect points included, the LMM terms for crop ($F_{5,2.65}$=13.26,p=0.021) and adjacent habitat ($F_{1,6.40}$=6.40,p=0.011) were significant, with an interaction of crop and transect position ($F_{10,2.18}$=21.81,p=0.016). Generally, diversity was similar in crop edge and margin transect points, and lower in crop centre points. When adjacent to crops, diversity was greater in all positions, than when adjacent to urban. In winter oilseed rape adjacent to grassland diversity is much lower in margin positions, however this result should be interpreted with caution due to low factor repetition (Fig 9).

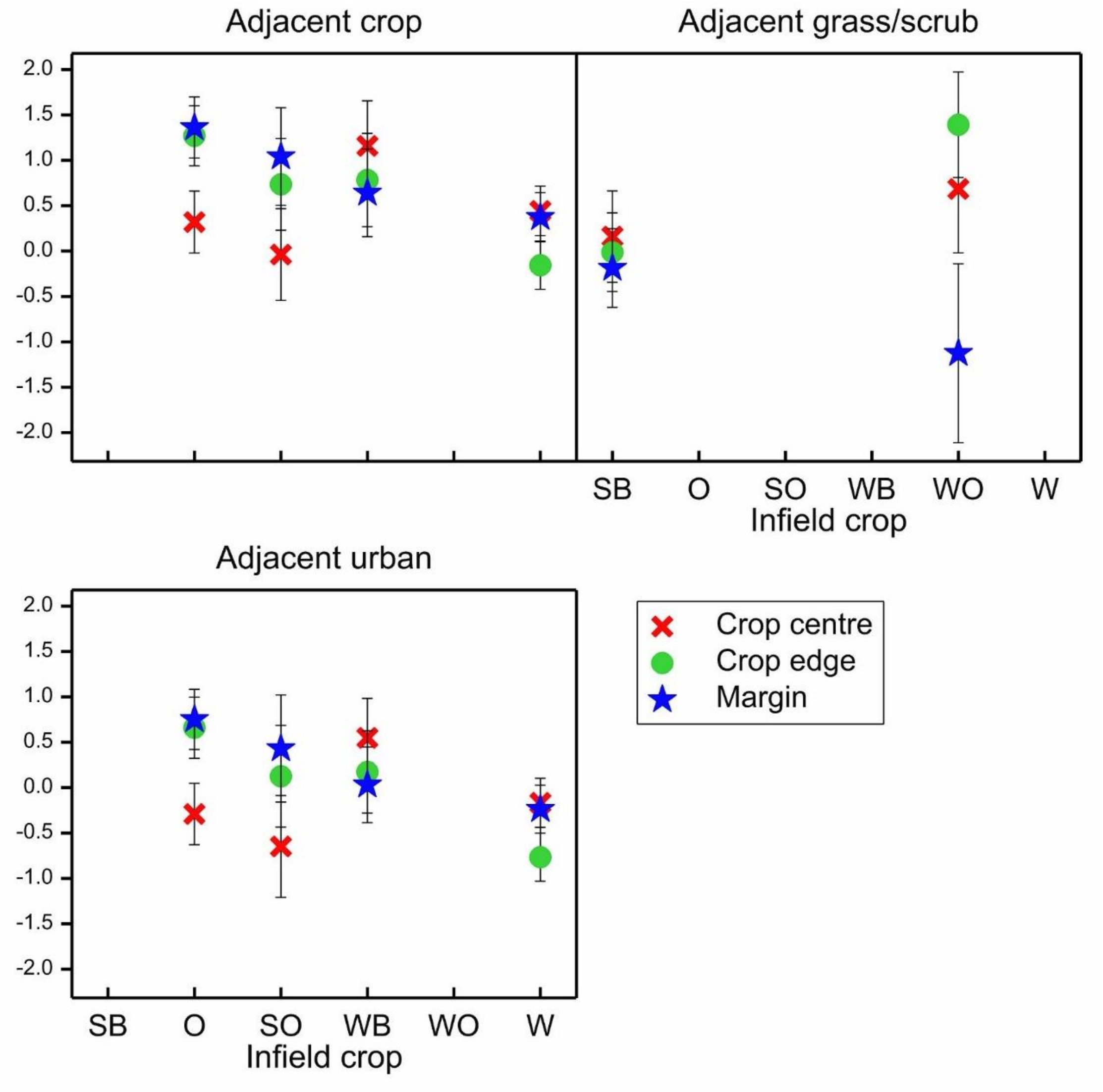


Figure 9- Fitted linear mixed model predictions for diversity in the crop area and experimental margins by adjacent habitat, predicted means with effective standard error bars. Crop centre= between 20m and 50m from edge, Crop edge = between 2m and 4m from field boundary, SB= spring barley, O=oats, SO= spring oilseed rape, WO= winter oilseed rape, W=wheat.

4.3.3 Aim 2- Species and community responses to key factors

The PCA analysis for standard pitfalls was performed on 367 observations of 21 species and pooled larvae, after restricting data to species with over 10 observations. The first two axes accounted for 11% and 9.3% of the variance respectively, and visible patterns could be seen in grouping the data points by factors. There were distinct clusters visible when grouped by *vegetation*, particularly for *spring barley*, *spring oats*, and *winter oilseed rape*. *Spring oats* was clearly driving the first axis, with other vegetation ranged more along the second axis. *Field Edge* habitats (including the experimental margins) and *grass/scrub* were more scattered than crop vegetation, with much overlap (Fig. 109). Grouping by margin type displayed no visible trends.

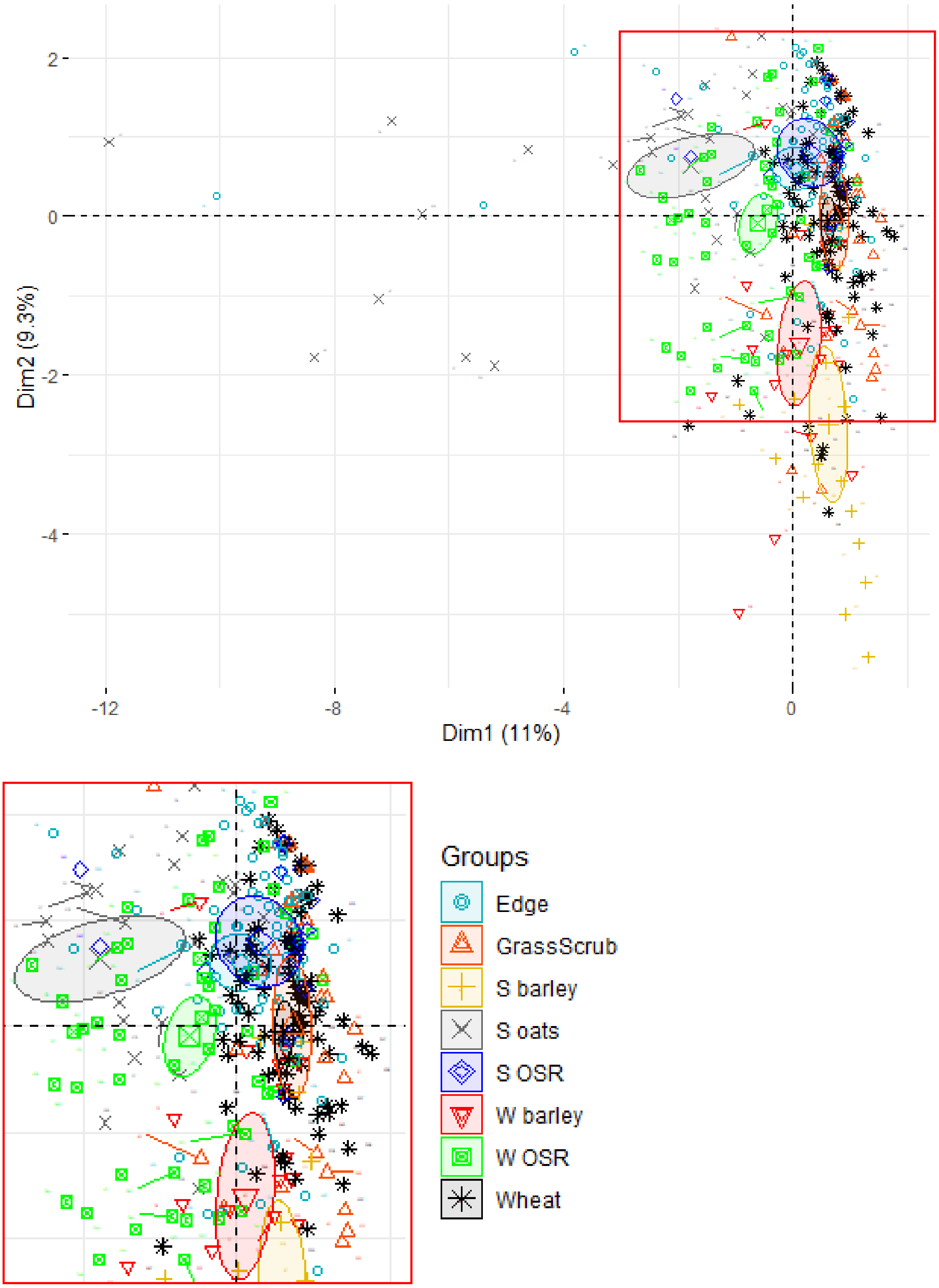


Figure 10- Standard pitfalls PCA plot of data points grouped by vegetation type. Top right-hand corner expanded to show detail. Edge= all experimental margin areas, S=spring, W= winter, OSR= oil seed rape.

The PCA analysis for subterranean pitfalls was performed on 96 observations of 13 species and pooled larvae, after restricting data to species with over 10 observations. The first two axes accounted for a greater proportion of variance than in the pitfalls (22.1% and 13.7%). Since subterranean traps were run on a subset of margins, there are less crops. *Spring barley*, *spring oats* and *winter oilseed rape* were again very distinctly grouped, with more scatter showing for *field edge* habitats and overlap for *grass/scrub* vegetation. The first axis is more driven by *winter oilseed rape*, and the weighting of *spring barley* appears reduced, compared to the pitfall data (Fig. 11). Grouping by margin type showed no visible trends.

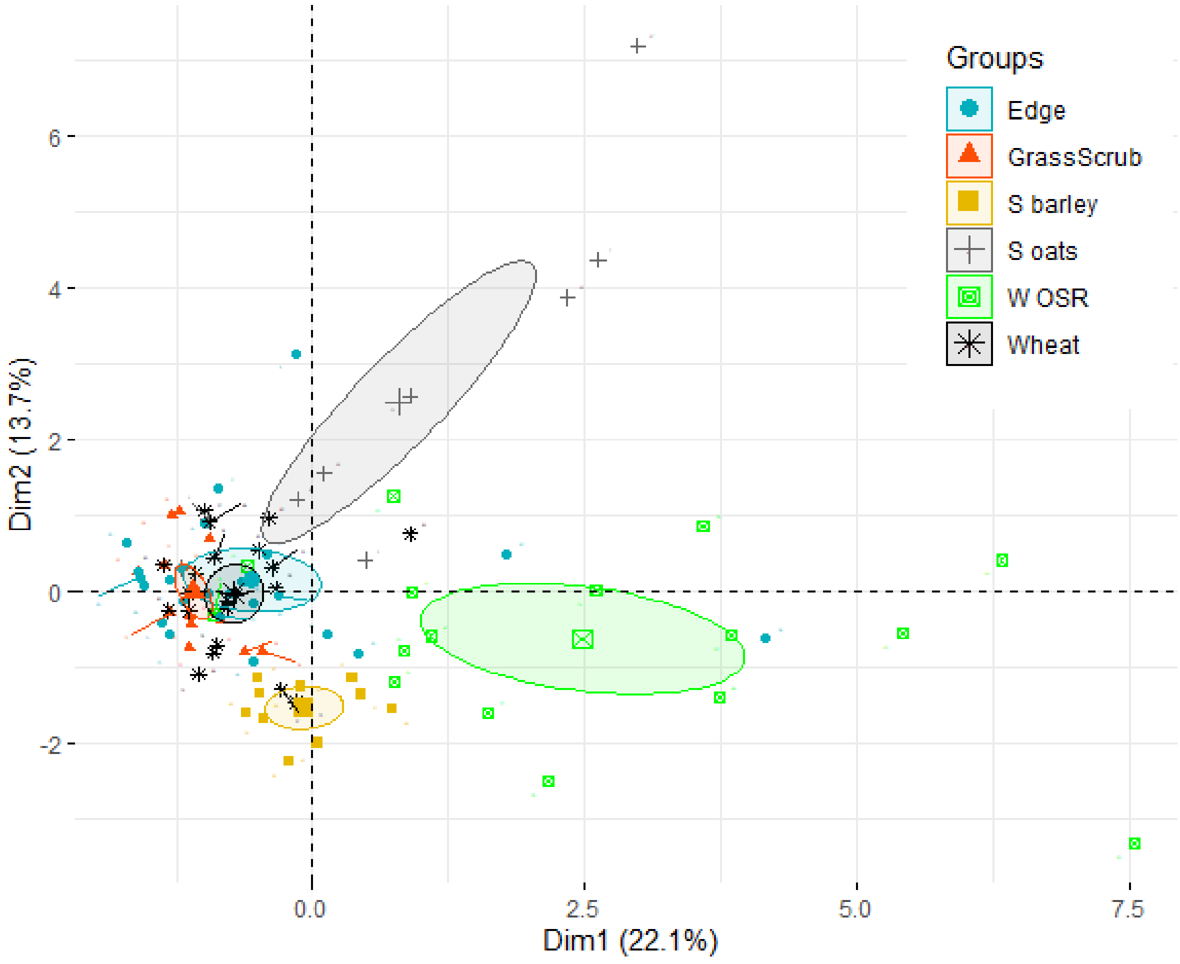


Figure 11- Subterranean pitfalls PCA plot of data points grouped by vegetation type. Edge= all experimental margin areas, S=spring, W= winter, OSR= oil seed rape.

We further subset the pitfall trap data to wheat crop only, as this crop had most sample point repetition. The PCA was performed on 102 observations of 9 species and pooled larvae. The first two axes accounted for a small proportion of variance (17.5% and 15.2%). There was a small amount of distinction visible when grouped by experimental treatment (Fig. 12). There was a much more distinctly visible cluster when grouped by adjacent habitat (Fig. 13).

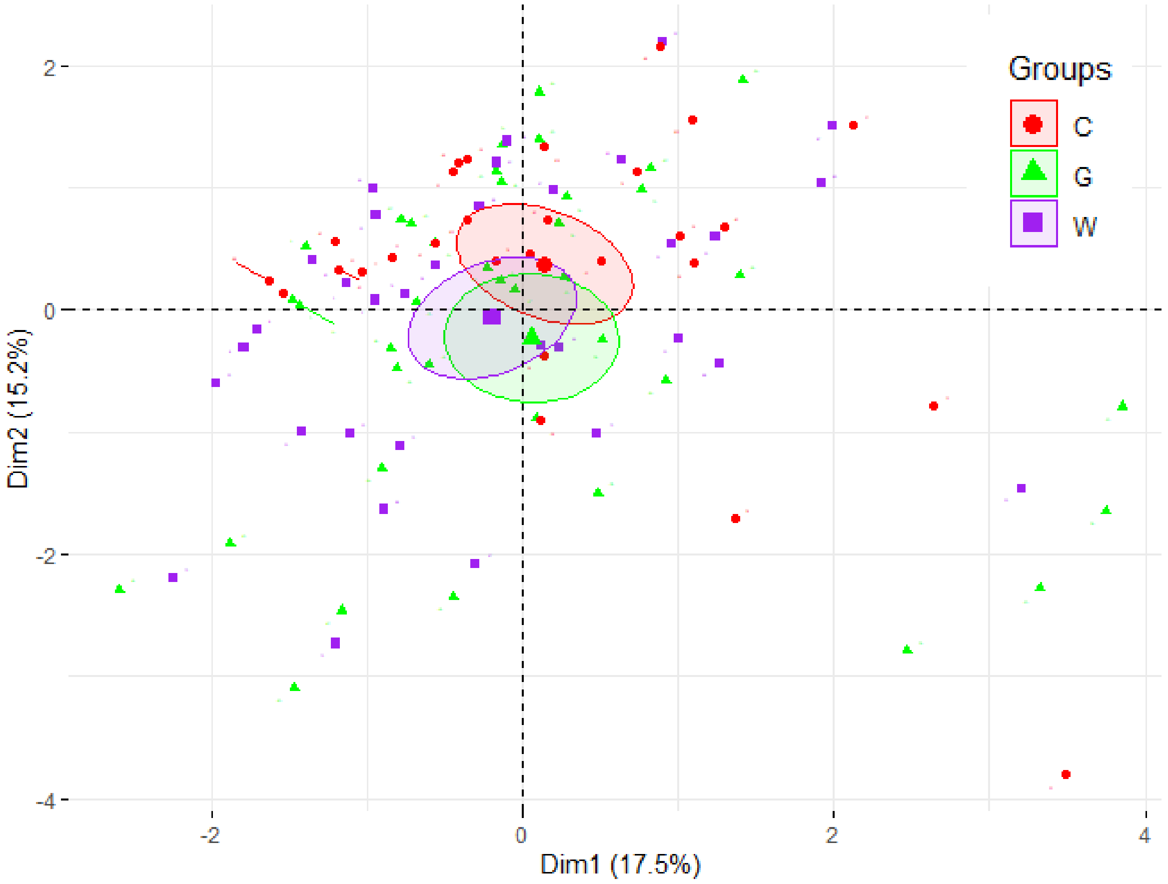


Figure 12- Wheat crop PCA plot of data points grouped by margin type. C= control, G= grass, W= wildflower.

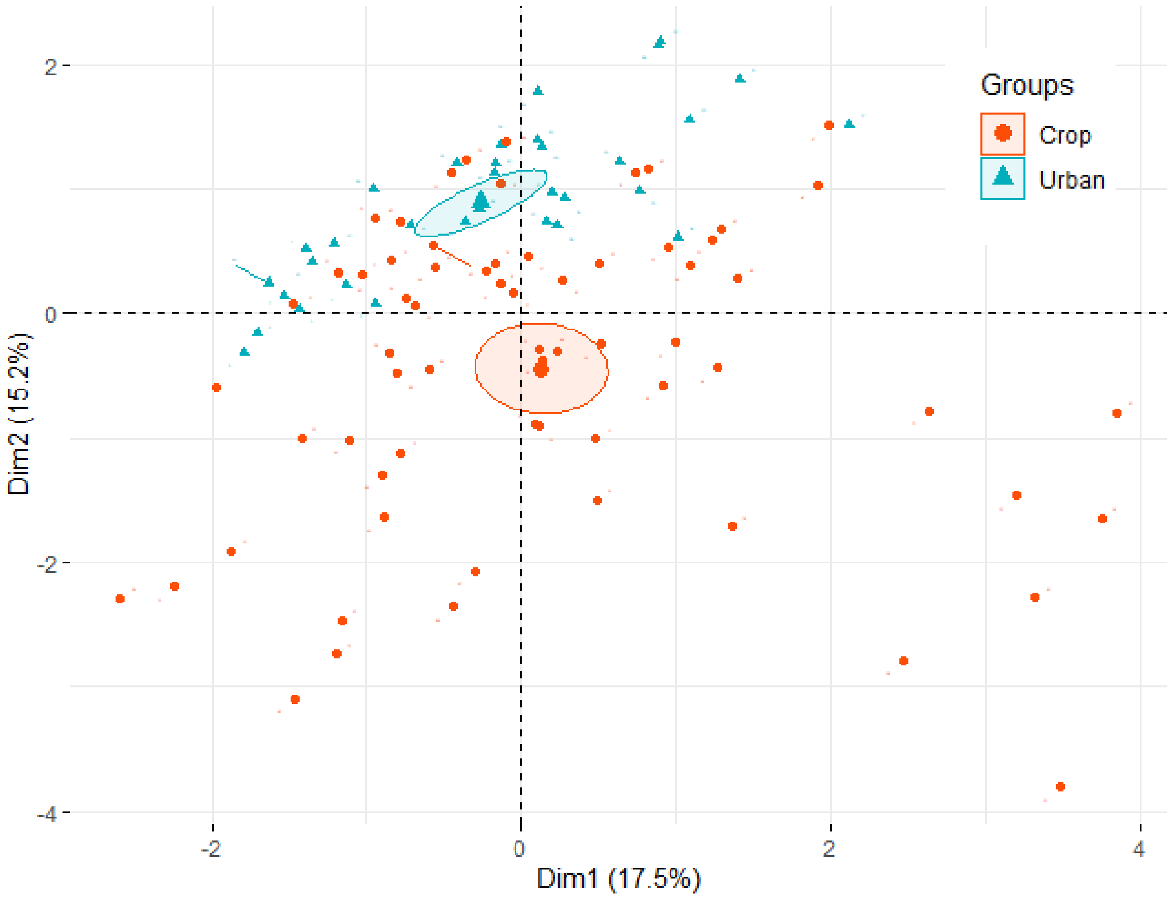


Figure 13- Wheat crop PCA plot of datapoints grouped by adjacent habitat

To investigate the species preferences driving the community differences, the top five most abundant species were modelled with LMMs: *Pterostichus melanarius, Harpalus rufipes, Pterostichus madidus, Amara eurynota*, and *Poecilius cupreus*. For *P. melanarius*, vegetation ($F_{7,21.8}$=152.59,p=<0.001), and transect position ($F_{1,20.75}$=20.75,p=<0.001) were shown to be significant. There were significant interactions between the two ($F_{6,4.95}$=29.71,p=<0.001), and between vegetation and margin type ($F_{13,2.90}$=37.66,p=<0.001), and a significant interaction between transect position and margin type ($F_{2,4.04}$=8.08,p=0.018). *Pterostichus melanarius* was more abundant at the centre than the edge, in all crops apart from spring oats. It was most abundant in winter barley, in conjunction with a grass, then wildflower margin (Fig. 14; Table 3). In the control treatment with no margin, this species was most abundant in spring barley. In the majority of crops, the difference between abundances at the edge and centre of the field are more pronounced in the presence of grass margins, particularly in winter sown crops (barley oats and wheat). Of the margin pitfall measurements, the control treatment showed the highest abundance.

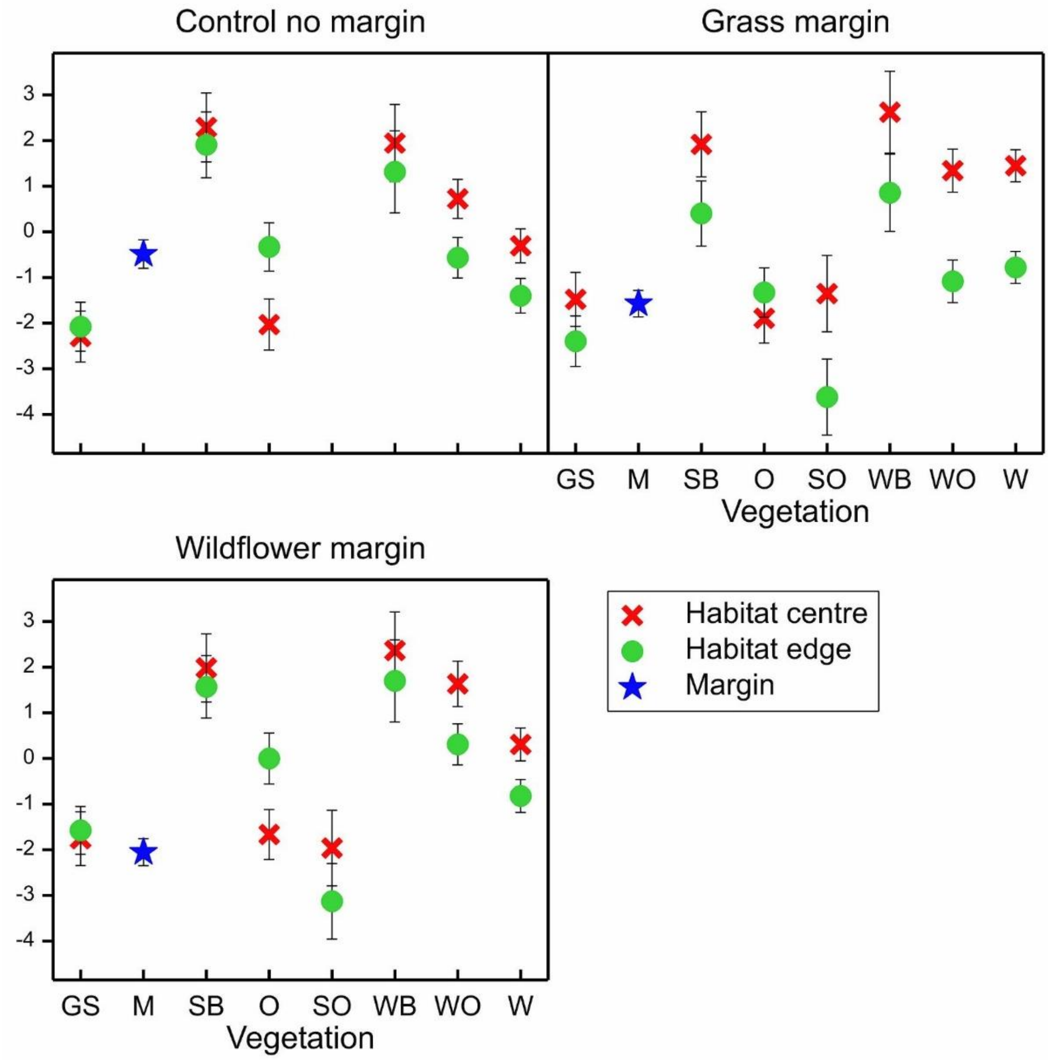


Figure 14- Fitted linear mixed model predictions for *Pterostichus melanarius* abundance by margin type, predicted means with effective standard error bars. GS= grass/scrub, M= margin, SB= spring barley, O=oats, SO= spring oilseedrape, WO= winter oilseedrape, W=wheat.

For *H. rufipes*, the LMM retained vegetation as a highly significant term ($F_{7,6.20}$=43.40, p=<0.001), and margin type as a significant term ($F_{2,\ 3.94}$=7.88, p=0.03). The model also retained a significant interaction between vegetation and transect position ($F_{6,2.48}$=14.89, p=0.023). Generally, *H. rufipes* was equally abundant in the centre and edge of habitats, apart from in spring oats, where it was more abundant at the edge. This species was most abundant in winter barley, followed by spring barley. It was least abundant in grass/scrub habitats. Overall abundances were lower in conjunction with a wildflower margin, and within the margin transect points wildflower margins showed the least abundance (Fig. 15; Table 3).

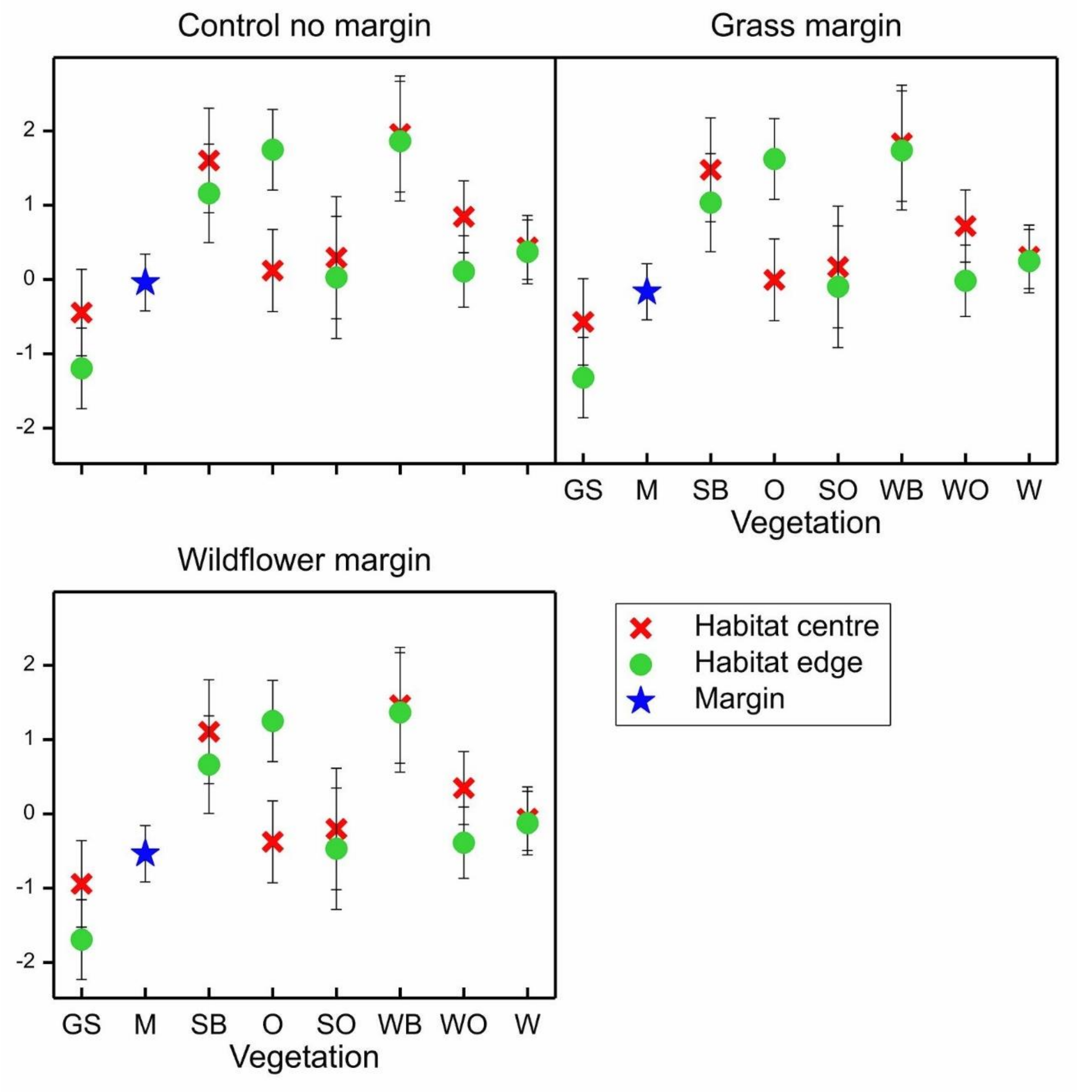


Figure 15- Fitted linear mixed model predictions for *Harpalus rufipes* abundance by margin type, predicted means with effective standard error bars. GS= grass/scrub, M= margin, SB= spring barley, O=oats, SO= spring oilseed rape, WO= winter oilseed rape, W=wheat.

For *P. madidus*, the LMM retained highly significant terms for vegetation ($F_{7,9.22}$=64.55,p=<0.001), and trap type ($F_{1,11.37}$=11.37,p=<0.001), and significant terms for margin type ($F_{2,3.16}$=6.31,p=<0.043) There were highly significant interactions between margin type and transect position ($F_{4,6.61}$=26.45,p=<0.001), and between vegetation and transect position ($F_{6,3.40}$=20.38,p=0.002). For all positions, *P. madidus* were more abundant in pitfall traps than subterranean traps (light coloured points, Fig. 16; Table 3). For spring oilseed rape, winter barley, and wheat, abundances were higher in the centre of crops. In the control treatment, and in the presence of wildflower margins, this species was most abundant in spring barley; whilst in the presence of a grass margin it was most abundant in winter barley. It was least abundant in winter oilseed rape, and spring oilseed rape. Abundances were markedly lower in spring oilseed rape and winter barley when in conjunction with a wildflower margin. *P. madidus* had higher abundances in margin transect points when this constituted a grass margin, and least in wildflower margins.

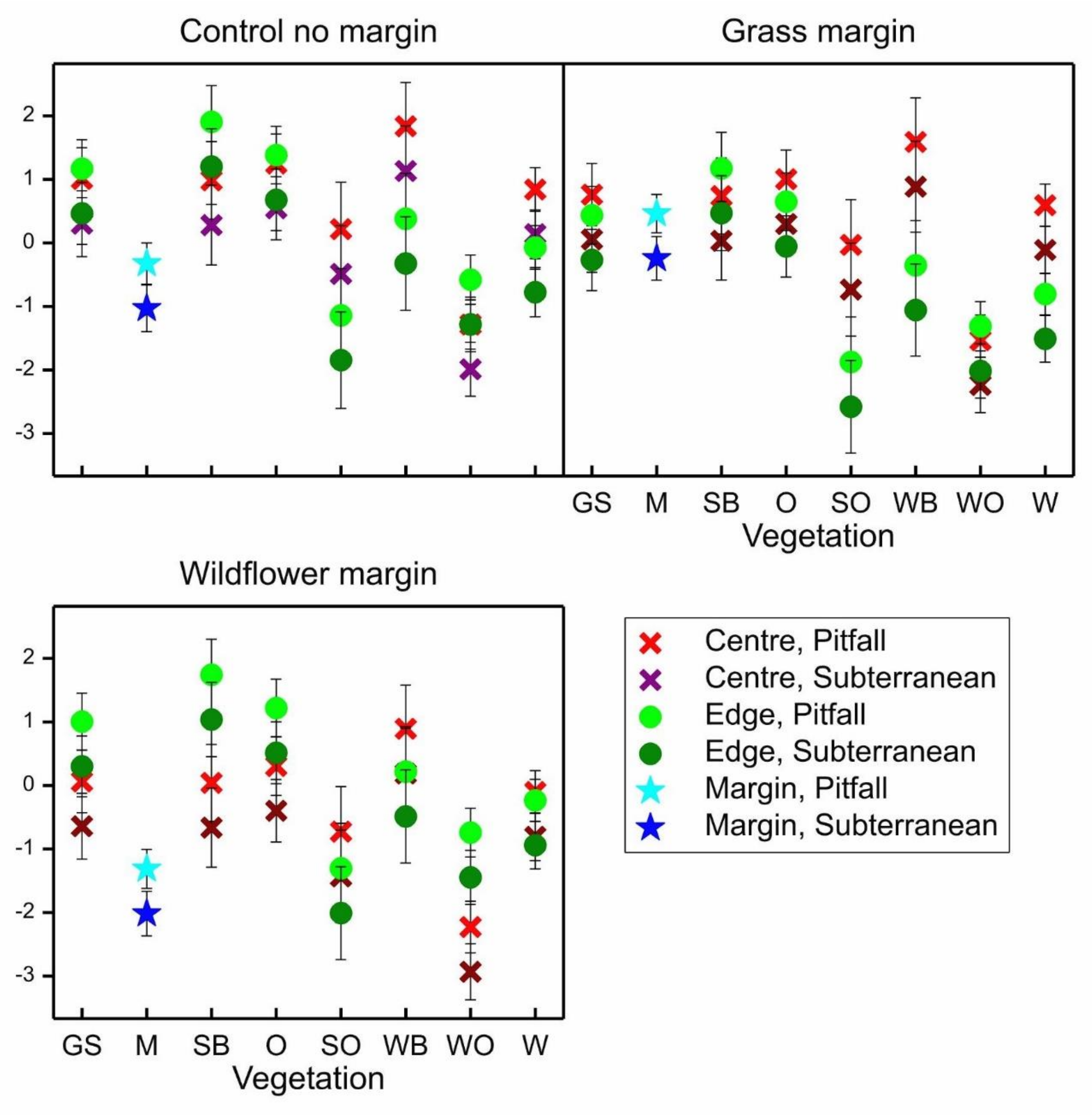


Figure 16- Fitted linear mixed model predictions for *Pterostichus madidus* abundance by margin type, predicted means with effective standard error bars. Centre= habitat centre, Edge= Habitat edge, GS= grass/scrub, M= margin, SB= spring barley, O=oats, SO= spring oilseed rape, WO= winter oilseed rape, W=wheat.

For *A. eurynota*, the LMM retained vegetation as a highly significant term ($F_{7,32.8}$=229.25, p=<0.001), and a highly significant interaction with trap type ($F_{5,4.24}$=21.22, p=<0.001). *Amara eurynota* was much more abundant in winter oilseed rape, and in this crop, distinctly more abundant in subterranean traps (Figure 17; Table 3).

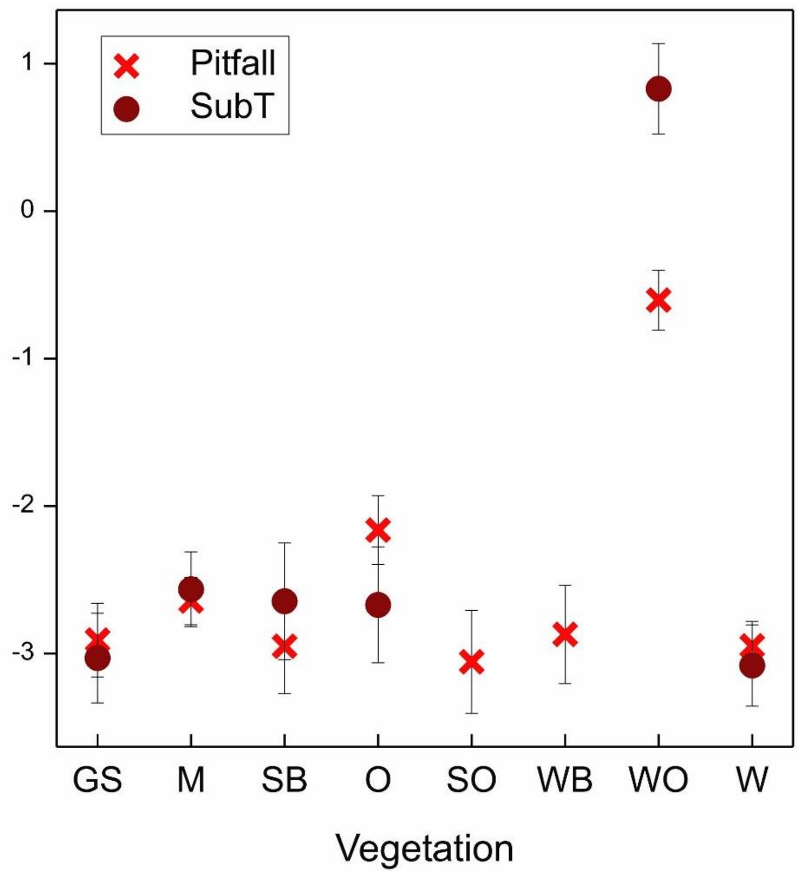


Figure 17- Fitted linear mixed model predictions for *Amara eurynota* abundance, predicted means with effective standard error bars. SubT= subterranean, GS= grass/scrub, M= margin, SB= spring barley, O=oats, SO= spring oilseed rape, WO= winter oilseed rape, W=wheat.

For *P. cupreus*, the LMM retained highly significant terms for vegetation ($F_{7,7.08}$=49.68, p=<0.001), and trap type ($F_{1,12.56}$=12.56, p=<0.001). There were highly significant interactions between vegetation and transect position ($F_{6,4.56}$=27.34,p=<0.001), and between vegetation and trap type ($F_{5,4.44}$=22.21, p=<0.001), and a significant interaction between vegetation and margin type ($F_{13,2.13}$=27.84, p=<0.014). *Poecilius cupreus* is generally equally abundant in both trap types and both centre and edge positions, apart from in spring oats, where it is more abundant in the centre, and spring barley where it is more abundant in pitfall traps (Fig. 18; Table 3). overall, it is most abundant in winter barley, when this is in conjunction with a wildflower margin, followed by spring barley in both wildflower and control treatments. In conjunction with a grass margin, abundances in winter barley are much lower, and winter oilseed rape are higher. In the margin transect points, abundances are similar between treatments.

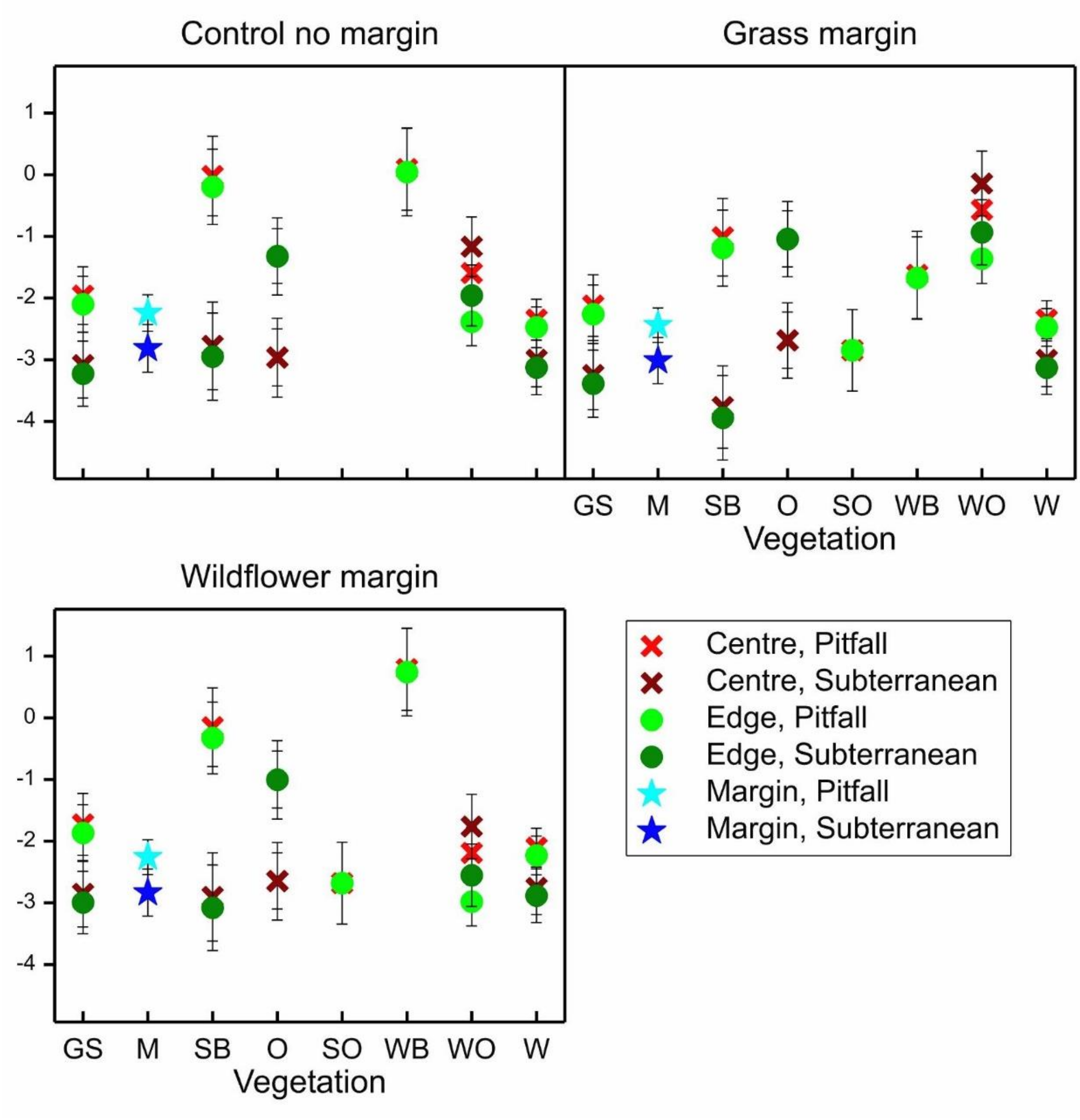


Figure 18- Fitted linear mixed model predictions for *Poecilius cupreus* abundance by margin type, predicted means with effective standard error bars. Centre= habitat centre, Edge= habitat edge, GS= grass/scrub, M= margin, SB= spring barley, O=oats, SO= spring oilseed rape, WO= winter oilseed rape, W=wheat.

For pooled carabid larvae, the LMM retained trap type ($F_{1,43.62}$=34.62, p=<0.001) vegetation ($F_{7,3.35}$=23.50, p=0.002), and margin type ($F_{2,6.69}$=13.39, p=0.003), as highly significant terms with no interaction. Larvae were clearly more abundant in subterranean traps, and more abundant in control treatments with no margin. They were most abundant in spring oats, and least abundant in spring barley (Fig. 19; Table 3).

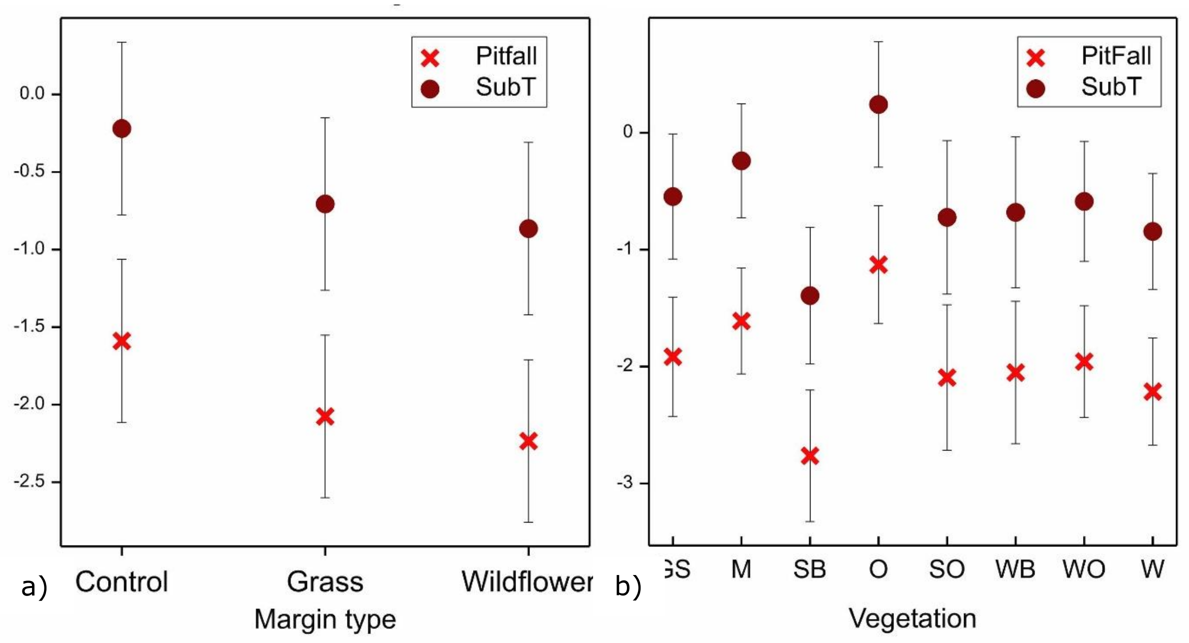


Figure 19- Fitted linear mixed model predictions for pooled carabid larvae abundance by a) margin type, and b) vegetation, predicted means with effective standard error bars. SubT= subterranean, GS= grass/scrub, M= margin, SB= spring barley, O=oats, SO= spring oilseed rape, WO= winter oilseed rape, W=wheat.

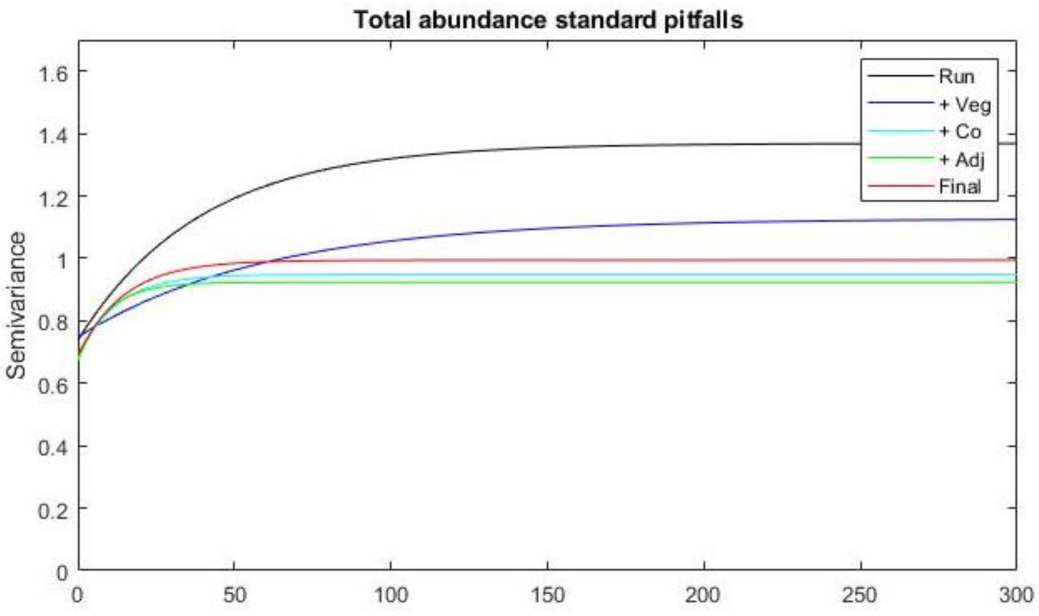
Table 3- Summary of species model predictions. Greatest predicted abundance for each species x margin or species x crop is shaded in orange, and the smallest is shaded in blue. Standard error in italics. M= margin, C=control, G=grass, W=wildflower, PF=pitfall, ST=subterranean trap. *=inestimable prediction.

		M	Grass/scrub		Spring Barley		Oats		Spring OSR		Winter Barley		Winter OSR		Wheat	
			Centre	Edge	Centre	Edge	Centre	Edge	Centre	Edge	Centre	Edge	Centre	Edge	Centre	Edge
P. melanarius	C	-0.49 *0.31*	-2.29 *0.56*	-2.08 *0.54*	2.28 *0.76*	1.91 *0.72*	-2.03 *0.56*	-0.33 *0.53*	*	*	1.94 *0.84*	1.31 *0.90*	0.72 *0.43*	-0.57 *0.44*	-0.31 *0.37*	-1.40 *0.38*
	G	-1.57 *0.30*	-1.50 *0.59*	-2.40 *0.55*	1.92 *0.71*	0.40 *0.71*	-1.89 *0.54*	-1.33 *0.54*	-1.35 0.84	-3.62 *0.83*	2.62 *0.90*	0.86 *0.85*	1.34 *0.47*	-1.08 *0.47*	1.44 *0.35*	-0.78 *0.35*
	W	-2.05 *0.30*	-1.76 *0.59*	-1.58 *0.55*	1.98 *0.74*	1.57 *0.68*	-1.67 *0.55*	-0.01 *0.56*	-1.96 *0.83*	-3.12 *0.83*	2.36 *0.84*	1.70 *0.90*	1.63 *0.50*	0.31 *0.45*	0.31 *0.36*	-0.82 *0.36*
H. rufipes	C	-0.04 *0.38*	-0.44 *0.58*	-1.19 *0.54*	1.60 *0.70*	1.16 *0.66*	0.12 *0.55*	1.75 *0.54*	0.29 *0.82*	0.03 *0.82*	1.95 *0.78*	1.86 *0.80*	0.84 *0.48*	0.11 *0.48*	0.43 *0.43*	0.37 *0.43*
	G	-0.16 *0.37*	-0.57 *0.58*	-1.32 *0.54*	1.48 *0.70*	1.03 *0.66*	-0.01 *0.55*	1.62 *0.54*	0.17 *0.82*	-0.10 *0.82*	1.83 *0.78*	1.73 *0.80*	0.71 *0.49*	-0.02 *0.48*	0.31 *0.43*	0.25 0.43
	W	-0.53 *0.38*	-0.94 *0.58*	-1.69 *0.54*	1.11 *0.70*	0.66 *0.66*	-0.38 *0.55*	1.25 *0.55*	-0.20 *0.82*	-0.47 *0.82*	1.46 *0.78*	1.37 *0.80*	0.34 *0.49*	-0.38 *0.48*	-0.07 *0.43*	-0.12 *0.43*
P. madidus	C PF	-0.33 *0.33*	1.01 *0.49*	1.17 *0.46*	0.98 *0.61*	1.91 *0.57*	1.25 *0.46*	1.38 *0.45*	0.21 *0.74*	-1.14 *0.74*	1.83 *0.69*	0.38 *0.71*	-1.28 *0.39*	-0.57 *0.39*	0.84 *0.34*	-0.07 *0.34*
	C ST	-1.03 *0.38*	0.30 *0.52*	0.46 *0.49*	0.28 *0.63*	1.20 *0.59*	0.54 *0.50*	0.68 *0.48*	-0.49 *0.76*	-1.84 *0.75*	1.13 *0.71*	-0.32 *0.74*	-1.99 *0.42*	-1.28 *0.43*	0.14 *0.38*	-0.77 *0.39*
	G PF	0.46 *0.30*	0.75 *0.49*	0.44 *0.45*	0.74 *0.60*	1.17 *0.57*	1.00 *0.46*	0.65 *0.45*	-0.03 *0.71*	-1.87 *0.70*	1.59 *0.69*	-0.35 *0.70*	-1.53 *0.40*	-1.31 *0.39*	0.59 *0.33*	-0.80 *0.33*
	G ST	-0.24 *0.34*	0.06 *0.52*	-0.26 *0.48*	0.03 *0.61*	0.47 *0.59*	0.29 *0.49*	-0.06 *0.48*	-0.73 *0.73*	-2.57 *0.73*	0.89 *0.72*	-1.05 *0.72*	-2.24 *0.44*	-2.02 *0.43*	-0.11 *0.37*	-1.51 *0.37*
	W PF	-1.31 *0.31*	0.06 *0.49*	1.01 *0.45*	0.04 *0.61*	1.74 *0.56*	0.30 *0.46*	1.21 *0.54*	-0.72 *0.71*	-1.30 *0.70*	0.89 *0.69*	0.22 *0.71*	-2.23 *0.40*	-0.74 *0.38*	-0.10 *0.34*	-0.24 *0.33*
	W ST	-2.01 *0.35*	-0.64 *0.52*	0.30 *0.48*	-0.66 *0.62*	1.03 *0.58*	-0.40 *0.49*	0.51 *0.49*	-1.43 *0.73*	-2.01 *0.73*	0.18 *0.71*	-0.48 *0.73*	-2.93 *0.44*	-1.44 *0.42*	-0.81 *0.38*	-0.94 *0.37*
A. Eurynota	PF	-2.64 *0.16*	-2.90 *0.24*		-2.95 *0.32*		-2.16 *0.23*		-3.05 *0.35*		-2.87 *0.33*		-0.60 *0.20*		-2.94 *0.17*	
	ST	-2.56 *0.25*	-3.03 *0.30*		-2.64 *0.40*		-2.67 *0.39*		*		*		0.83 *0.30*		-3.08 *0.28*	

		M	Grass/ scrub		Spring Barley		Oats		Spring OSR		Winter Barley		Winter OSR		Wheat	
			Centre	Edge	Centre	Edge	Centre	Edge	Centre	Edge	Centre	Edge	Centre	Edge	Centre	Edge
P. cupreus	C PF	-2.24 *0.30*	-1.96 *0.46*	-2.10 *0.45*	-0.02 *0.64*	-0.19 *0.61*	-2.96 *0.46*	-1.32 *0.44*	*	*	0.09 *0.67*	0.04 *0.70*	-1.59 *0.38*	-2.39 *0.39*	-2.35 *0.33*	-2.74 *0.33*
	C ST	-2.81 *0.38*	-3.08 *0.53*	-3.23 *0.52*	-2.78 0.71	-2.95 0.71	-2.97 0.64	-1.32 *0.63*	*	*	*	*	-1.17 *0.48*	-1.96 *0.49*	-3.00 *0.44*	-3.13 *0.44*
	G PF	-2.44 *0.28*	-2.12 *0.50*	-2.26 *0.48*	-1.01 0.63	-1.19 0.61	-2.68 *0.45*	-1.04 *0.46*	-2.85 *0.66*	*	-1.63 *0.71*	-1.67 *0.67*	0.57 *0.40*	-1.36 *0.40*	-2.35 *0.31*	-2.48 *0.31*
	G ST	-3.01 *0.38*	-3.24 *0.56*	-3.39 *0.54*	-3.77 *0.67*	-3.94 *0.68*	-2.67 *0.61*	-1.05 *0.61*	-2.68 *0.66*	*	*	*	-0.14 *0.52*	-0.93 *0.53*	-3.00 *0.43*	-3.13 *0.43*
	W PF	-2.26 *0.28*	-1.72 *0.50*	-1.87 *0.46*	-0.15 *0.64*	-0.33 *0.58*	-2.64 *0.45*	-1.00 *0.46*	-2.84 *0.66*	*	0.79 *0.66*	0.74 *0.71*	-2.19 *0.42*	-2.98 *0.39*	-2.11 *0.31*	-2.23 *0.31*
	W ST	-2.83 *0.38*	-2.85 *0.54*	-2.99 *0.51*	-2.90 *0.71*	-3.08 *0.69*	-2.64 *0.63*	-1.01 *0.63*	-2.68 *0.66*	*	*	*	-1.76 *0.52*	-2.55 *0.51*	-2.76 *0.43*	-2.88 *0.44*
Larvae	C PF	-1.23 *0.45*	-1.54 *0.51*		-2.38 *0.56*		-0.75 *0.50*		-1.72 *0.62*		-1.67 *0.61*		-1.58 *0.48*		-1.84 *0.46*	
	C ST	0.14 *0.49*	-0.17 *0.53*		-1.01 *0.59*		0.61 0.53		-0.34 *0.66*		-0.30 *0.64*		-0.21 *0.51*		-0.47 *0.50*	
	G PF	-1.72 *0.45*	-2.02 *0.51*		-2.87 *0.56*		-1.24 *0.50*		-2.20 *0.62*		-2.16 *0.61*		-2.06 *0.48*		-2.32 *0.46*	
	G ST	-0.35 *0.49*	-0.66 *0.53*		-1.50 *0.58*		0.13 *0.53*		-0.83 *0.53*		-0.79 *0.64*		-0.70 *0.51*		-0.95 *0.50*	
	W PF	-1.87 *0.45*	-2.18 *0.50*		-3.03 *0.56*		-1.40 *0.50*		-2.36 *0.65*		-3.31 *0.61*		-2.23 *0.48*		-2.48 *0.46*	
	W ST	-0.51 *0.49*	-0.81 *0.53*		-1.66 *0.58*		-0.02 *0.53*		-0.99 *0.65*		-0.95 *0.64*		-0.85 *0.51*		-1.11 *0.50*	

4.3.4 Aim 3- spatial patterns at a farm scale

For the total carabid abundance in pitfall traps, the sequential fitting of the models with spatially correlated random effects resulted in the retention of the factors: *vegetation*, *co-ordinates trend* (eastings and northings, and eastings*northings) and *adjacent*. The variogram models from the sequential fitting, relative to the null model where only Run is a factor, are shown in Fig. 20a, with model parameters for the final model given in Table 3. The variance in the carabid abundance not accounted for by the fixed effects is given by the sill of the variogram. A large proportion of this in the final model (67%) is the nugget variance which is attributable to sources of variation spatially correlated over distances smaller than the shortest lag distance. The spatially correlated variance has an effective range of 43.8 m, which is substantially greater than that observed for the subterrain traps where an effective range of only 5.2 m was estimated (Fig. 20b). In this case sequential fitting of models resulted in only the retention of *co-ordinates trend* (eastings and northings, and eastings*northings) and *adjacent* factors (see Table S2 and Fig. 20b). The short effective range for the subterranean model fit suggests little spatial relationship between the catches in terms of abundance, however we note that there were only 101 observations for this model fit which is too few to draw any sound conclusion.



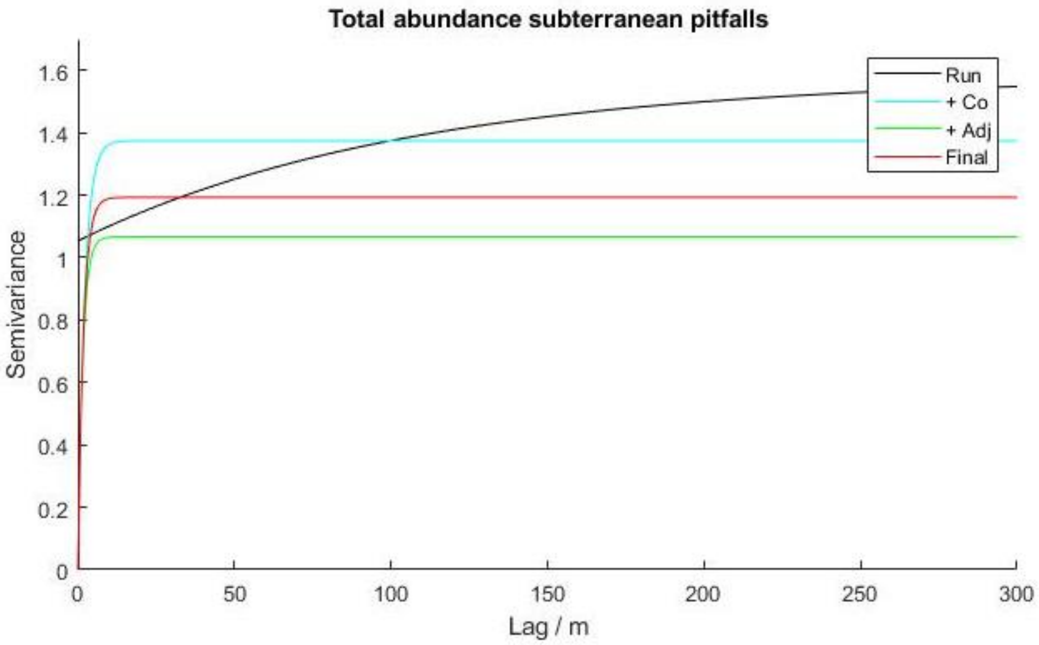


Figure 20- Variogram models (a) pitfall traps and (b) subterranean traps for the null model where only Run was fitted as a fixed effect (black), and for successive models with factors added as predictors. For dark blue vegetation was added, light blue coordinates, green adjacent, and red is the final model fitted by REML (all other models fitted by maximum likelihood).

For *P. melanarius* abundance in pitfall traps, the sequential fitting of models resulted in the retention of the factors vegetation, co-ordinates trend (eastings and northings, and eastings*northings), and adjacent. The sequential variogram models in Fig. 21 reveal that vegetation accounted for a large portion of the variation accounted for from the null model to the final REML fitted model, and coordinates trend and adjacent accounted for a much smaller proportion (Fig. 21, Table S3). The spatially correlated variance has an effective range of 110.8 metres. For *H. rufipes* abundance in pitfall traps, the sequential fitting of models resulted in the retention of vegetation, and co-ordinates trend. The variogram models reveal that similarly to *P. Melanarius*, vegetation accounted for a large portion of the variation seen from the null model, (Fig 21, Table S3). Visual inspection of the variogram for *H. rufipes* suggests it is largely nugget suggesting little to no spatial correlation. Sequential fitting of models for *P. madidus* abundance resulted in the retention of vegetation, and co-ordinates trend. The variogram functions reveal that vegetation accounted for a smaller portion of the variation seen from the null model, and coordinates trend accounted for a larger proportion, compared to *P. Melanarius* and *H. rufipes* (Fig 21, table S3). Spatially correlated variance has an effective range of 110.2, a similar range to *P. melanarius*. For *A. eurynota* the sequential fitting of models resulted in the retention of vegetation, and adjacent. Vegetation accounted for a larger portion of the variation than adjacent, though the overall variance was small. The fitted model shows the variation to be nugget suggesting little to no spatial correlation (Fig 21, table S3). Similarly, there was little evidence of spatial correlation for *P. cupreus* or pooled carabid larvae abundance. For *P. cupreus* the sequential fitting of models resulted in the retention of vegetation, and co-ordinates trend, with vegetation accounting for more of the variation than trend. For pooled carabid larvae abundance in pitfall traps, the sequential fitting of models resulted in the retention of vegetation only.

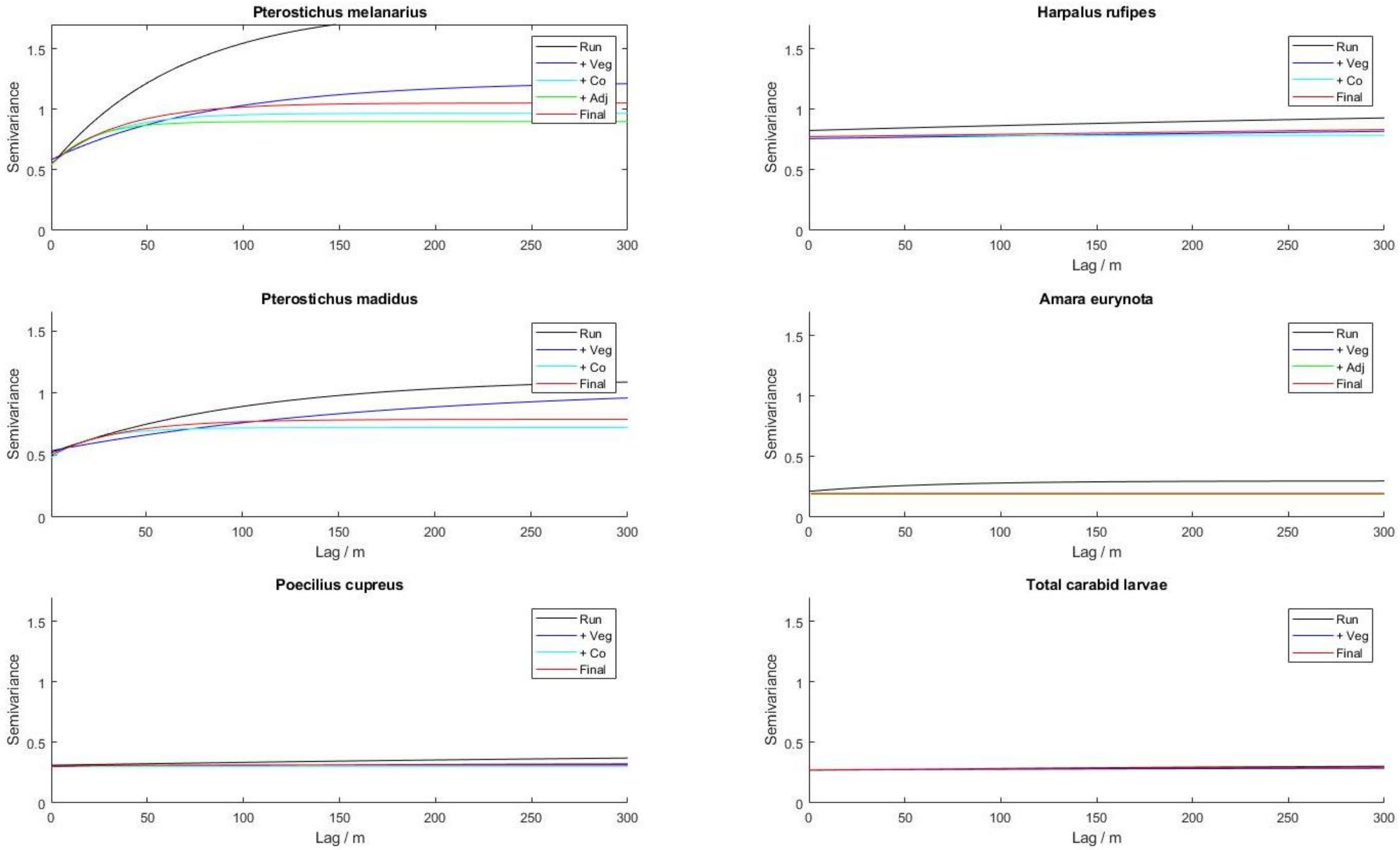


Figure 21- Variogram models for individual species, and total carabid larvae, for the null model where only Run was fitted as a fixed effect (black), and for successive models with factors added as predictors. For dark blue vegetation was added, light blue coordinates, green adjacent, and red is the final model fitted by REML (all other models fitted by maximum likelihood)..

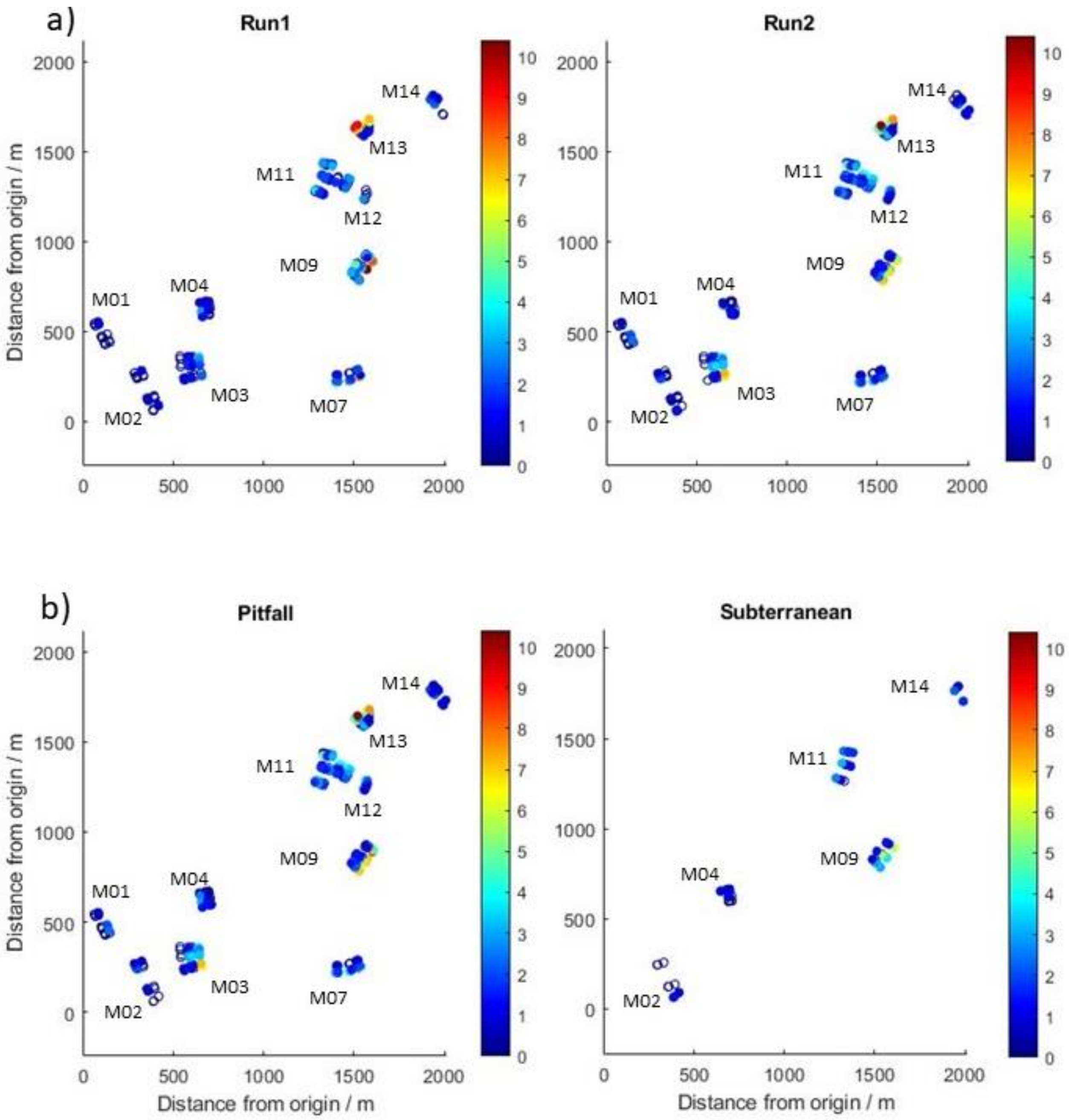


Figure 22- Spatial abundance plots for *Pterostichus melanarius*, divided by a) run; and b) trap type. Hollow circles denote zeros at sample point.

When plotted, *Pterostichus melanarius* was visibly more abundant in fields M13, M09, and M03. The areas of peak abundance are similar between runs, and trap type for the peak in field M09 (Fig. 22). *Harpalus rufipes* was visibly more abundant in fields M14, M09, and M07. Some differences were evident between runs, in M14 particularly, but also M13, M07 and M03. Between traps it is apparent that the abundances in M11 were higher in subterranean traps, however in M09 abundances peaked in standard pitfall traps (Fig. 23).

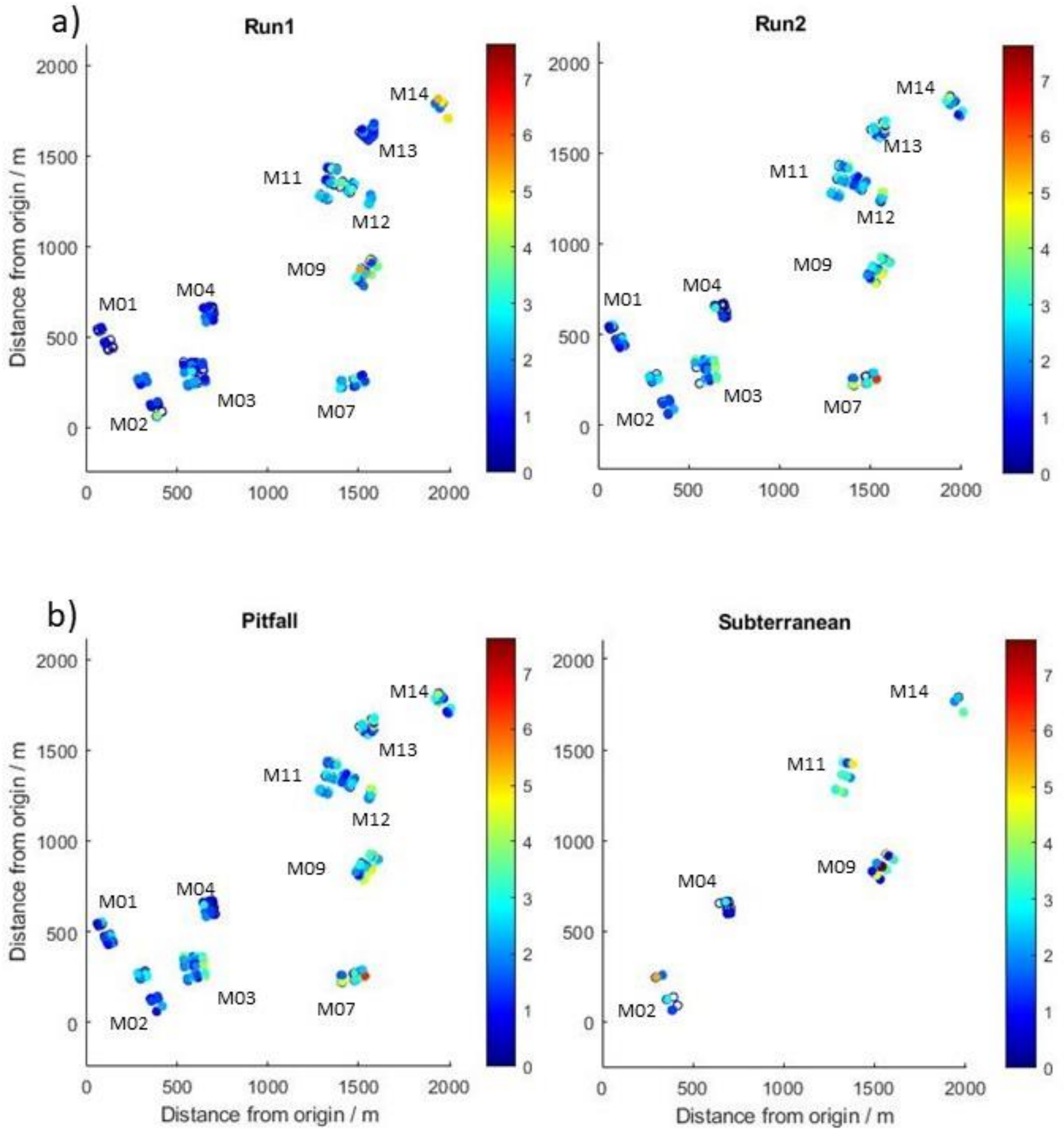


Figure 23- Spatial abundance plots for *Harpalus rufipes*, divided by a) run; and b) trap type. Hollow circles denote zeros at sample point.

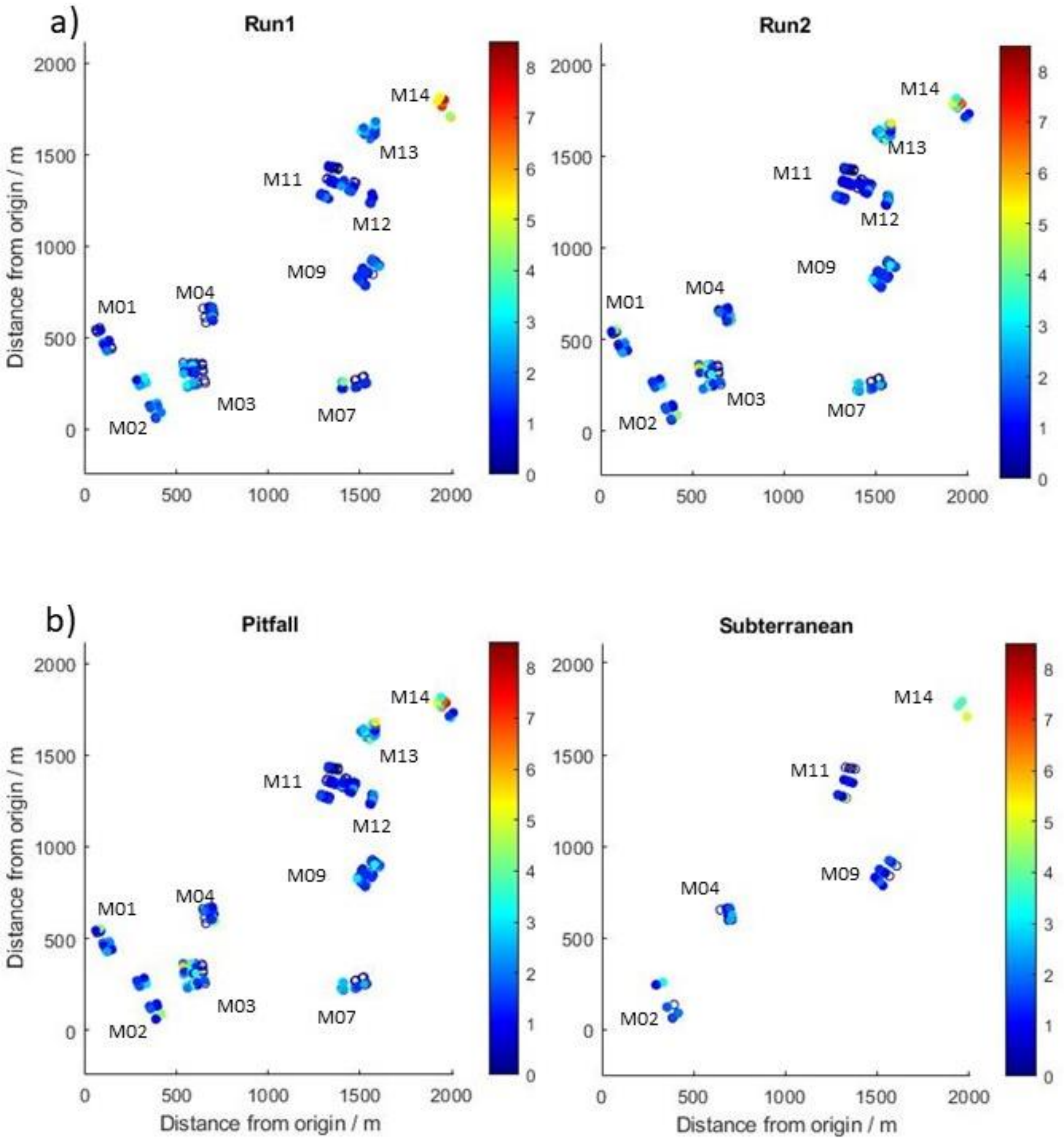


Figure 24- Spatial abundance plots for *Pterostichus madidus*, divided by a) run; and b) trap type. Hollow circles denote zeros at sample point.

Pterostichus madidus was most abundant in fields M14 and M13. Abundances appear largely similar between runs and trap types (Fig. 24). *Amara eurynota* showed highly localised peaks in fields M11 and M03. The largest of these was in M11 in a subterranean trap (Fig. 25). *Poecilius cupreus* was most abundant in fields M09 and M07. These peaks were seen in run 1, for pitfall traps (Fig. 26). Pooled carabid larvae were most abundant in fields M11, M03 and M02. Abundances were higher in run 1, and in subterranean traps (Fig. 27).

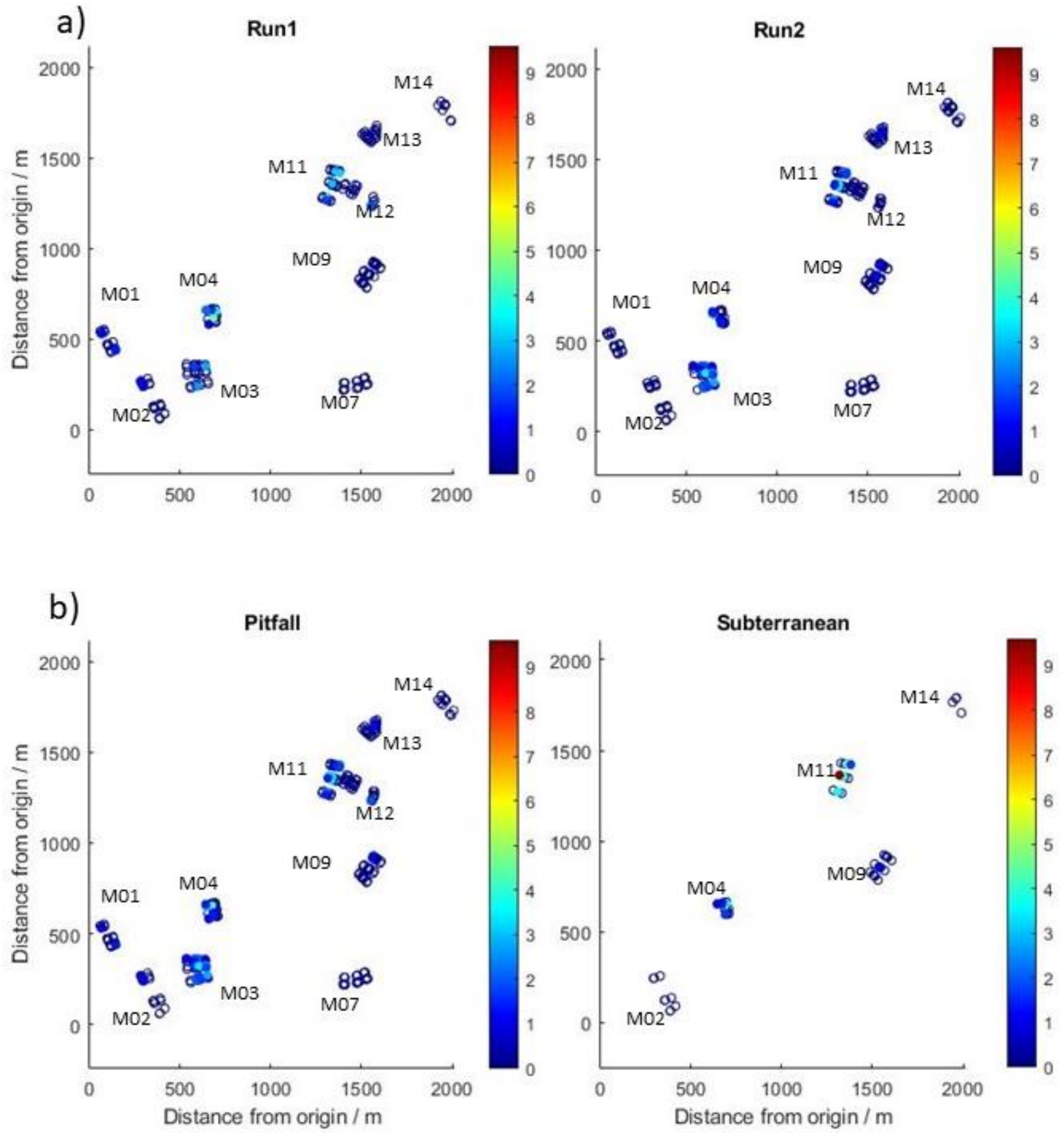


Figure 25- Spatial abundance plots for *Amara eurynota*, divided by a) run; and b) trap type. Hollow circles denote zeros at sample point.

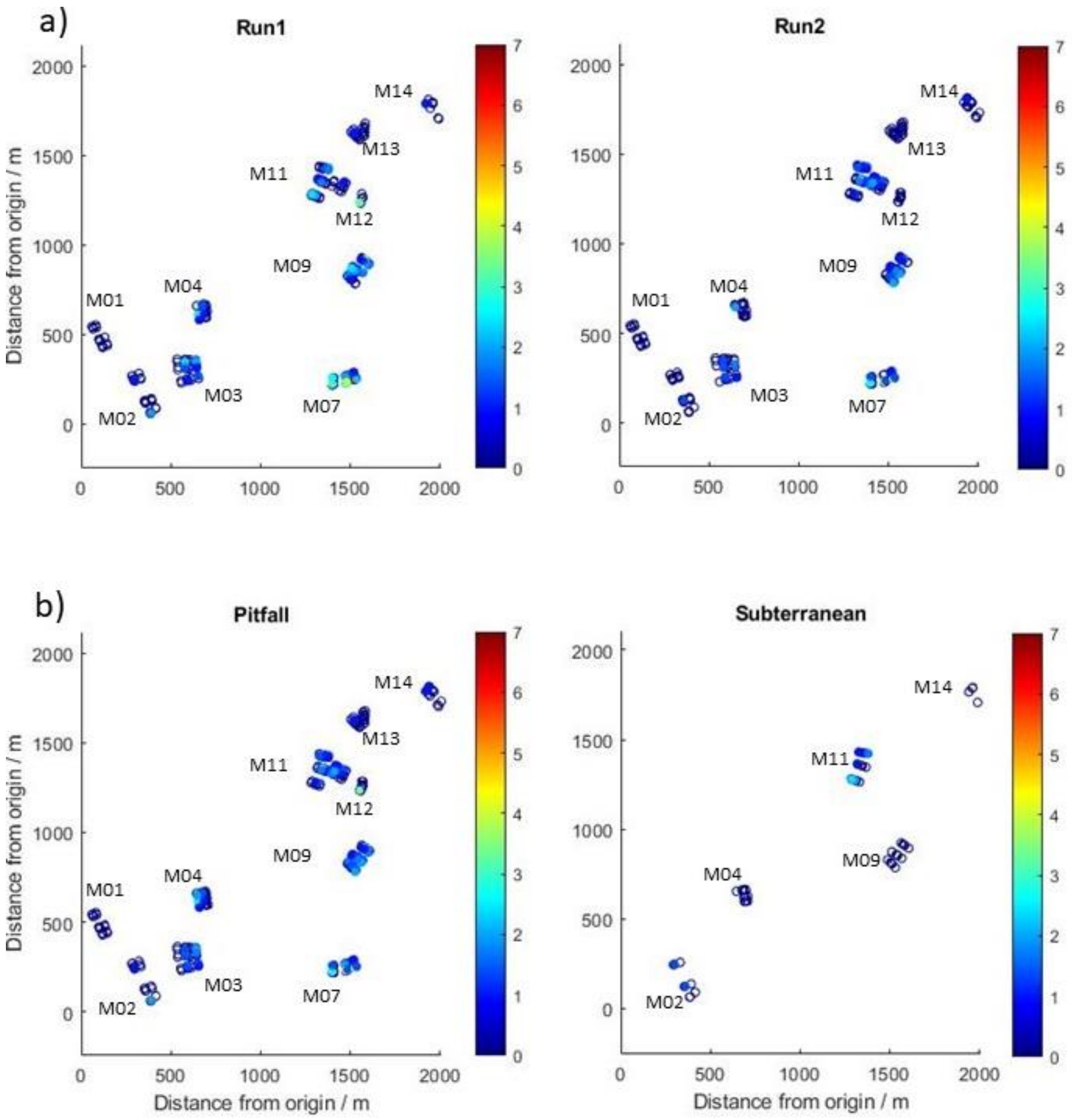


Figure 26-Spatial abundance plots for *Poecilius cupreus*, divided by a) run; and b) trap type. Hollow circles denote zeros at sample point.

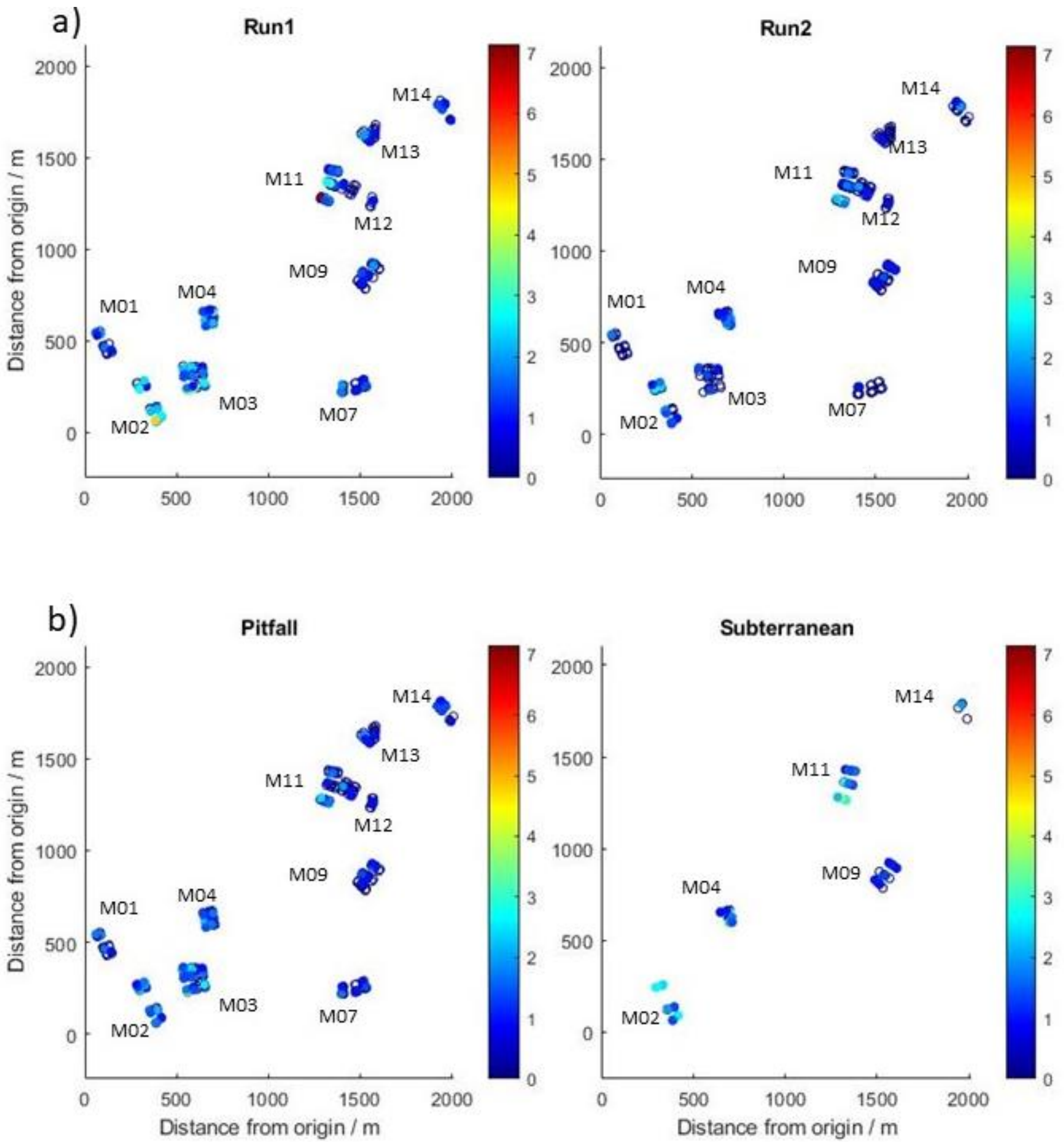


Figure 27- Spatial abundance plots for pooled carabid larvae, divided by a) run; and b) trap type. Hollow circles denote zeros at sample point.

4.4 Discussion

4.4.1 Carabids in crop areas

Our first aim was to determine the key influences on abundance, species richness, and diversity in crop areas, as these will relate directly to the natural enemy pest control acting on the crop (Holland and Luff, 2000; Kromp, 1999). They key influence, over all models, was the infield crop itself. This concurs with the literature, as the crop will govern both the microclimate, and resources available to carabids (Brooks et al., 2008; Holland and Luff, 2000; Thomas, Holland and Brown, 2003).

The influence of transect position varied in combination with other factors, denoting the movements of carabids in the crop areas. Overall, the abundance, species richness, and diversity of carabids at crop centres were relatively stable across adjacent habitats, varying mostly by crop. The crop edge positions showed most variation dependant on adjacent habitat. This may indicate the different processes acting on carabids at a field scale. Communities at crop centre positions are influenced primarily by the nature of the habitat at that point, and so subject to the structure and resources of the crop and disturbance cycles of associated management. This is in contrast to crop edge habitats, where the habitats are subject to multiple influences, as a combination of the respective habitats that comprise the edge zone (Koivula, Hyyryläinen, and Soininen, 2004; Smida and Wilson, 1985).

Where crops intersect at boundaries with other crops, this would comprise a relatively uniform gradient, especially between similar crops (Aviron et al., 2018). In contrast, where crops back onto urban environments, the edge effects will be more marked, as urban areas can be considered unsuitable habitat for agricultural carabids (Niemelä and Kotze, 2009). Abundance and species richness were generally greater in crop centre compared to the edge positions when those were next to urban, yet higher at the crop edge when this was adjacent to crops. This would explain the lack of carabids in crop areas juxtaposed with this habitat, as there will be limited immigration from urban areas into edge zones. Our previous work (Jowett et al., 2019) found similar lack of spill-over from urban areas when examining a large-scale dataset of carabids in various crops across the UK.

Where crops intersect with grass/scrub habitats, a different dynamic may be seen, with movements from a disturbed environment to a relatively stable zone of differing resources and structure. We did not see any evidence of spill-over from the grass/scrub habitats, however this may be attributed to the timing of the experiment in late summer, when migration to or from stable habitats will be limited. Labruyere, Petit, and Ricci (2018) analysed the spatiotemporal dynamics of three granivorous carabid species, finding that only one species displayed a significant movement towards margins post-harvest, and this was a smaller effect than anticipated. The authors concluded that these species may be among those that are able to overwinter in cereal fields. This accords with literature on the hibernation strategies of agricultural carabids and may indicate margins and grassy areas may not be as vital for hibernation as assumed. Moreover, the presence of hibernation habitats outside of field has not proven to translate to increased carabid presence and pest control in crop areas, and in some cases these habitats have been demonstrated to comprise sinks, rather than sources (Holland, Birkett, and Southway, 2009).

That the diversity was distinctly greater in the centre positions of wheat (which was the crop with most replicates) compared to the crop edge, was surprising given the literature on distance decay from edge habitats to field centres (Boetzl et al., 2018). This is likely to be an attribute of resource availability driving activity density of a number of species. Fornier and Loreau (2001) found that the crop centre was the most favourable habitat for starved individuals of *P. melanarius* to find food rapidly. The authors related this to prey density and biomass, prey density was higher in edge habitats, yet prey biomass was higher in crop centres, and the structure of the habitat allows for more effective foraging. In contrast, edge positions had higher diversity than crop centres in oats, and both winter and spring oilseed rape. Oilseed rape is a dense crop, with tall vegetation; the pitfall traps in the crop centre positions were therefore more like a niche habitat, comprising difficult foraging grounds (Williams et al., 2010).

Our models did not show that diversity was related to adjacent habitat, which is surprising given the literature (Duflot et al., 2017; Fusser et al., 2016; Galle et al., 2018). In a meta-analysis of landscape level effects on natural enemy communities, Aguilera et al. (2020) found that crop diversity within a 1km radius of fields was related to carabid diversity, however the abundance of carabids was negatively associated with increasing proportions of semi-natural habitats in the landscape. The main influence of crop therefore may be driving the landscape effects on agricultural carabids, in that more edge habitats in some circumstances denote smaller fields and a higher diversity of crops. For example, Galle et al. (2018) found that smaller fields and longer edges promoted carabid functional diversity.

The influence of margins

Features at the boundary of crops have the potential to alter the edge effects, as they introduce different resources and disturbance cycles. In the case of field margins, the effect has been theorised as provision of stable resources over time, to act as shelter for carabids, and therefore is extended in literature as comprising a source environment for pest control agents to recolonise crop areas (Dennis et al., 1994; Hof and Bright, 2010; Rand, Tylianakis, and Tscharntke, 2006).

When we included the margin transect points in the LMMs, interactions with *margin type* were retained in models. Thus we can conclude that margin type does not explain the variance in carabid abundance, species richness, and diversity at crop edges compared to the crop centre, but margin type does explain the difference between carabids at margin points and crop edge points. This difference is driven by different abundance, species richness, and diversity in the margins.

However, the model predictions were surprising, as total abundance and species richness was generally lower in margins than crop areas, particularly for wildflower margins; and this pattern was most distinct with species richness. Moreover, when there was a grass margin, the total abundance and species richness were generally higher in the centre of the field, which is contrary to the gradual decrease from the margin to the centre (distance decay) that would indicate a spill-over effect. This effect is particularly strong in wheat crops, where abundances were lower in the edge of the field than margin points and greatest in the centre, when next to grass margins. Since this crop type benefitted from the most replicate transects within the experiment this is unlikely to be an artefact of particular field attributes. Therefore, experimental margins did not exhibit a spill-over effect, and may even indicate a barrier effect in the case of grass margins. Frampton et al. (1995) found grassy margins to slow the movements of *H. rufipes*, *P. melanarius* and *Pterostichus niger*, in a mark-recapture experiment. Thus, when resources of grassy habitats do not exceed crop habitats, they may be avoided due to the lesser permeability of the habitat.

Werling and Gratton (2008) have likewise reported a departure from the expectation in general literature that abundances in the margins translate to spill-over to crop centres. The authors found that despite high abundance and diversity of carabids in field margins, this did not affect carabid communities structure in the crop. Moreover, they found that while increases in natural habitats within the landscape had a positive impact on carabids in crop areas, this effect was not evident in margin habitats. Margins then could be acting as an interface from adjacent habitats, rather than a source of carabid migration in to crops, and as such has a limited effect compared to an abundance of favourable habitat; but thus may have an impact on buffering unfavourable habitat.

The patterns for diversity in LMMs with the margin points included, are more aligned with carabid literature. Diversity was generally similar in crop and margin transect points, and lower in crop centre points. This is likely due to the edge effect, whereby habitats near field boundaries contain more variety of resources in juxtaposition, supporting a range of species - notably species of both juxtaposed habitats where they overlap (Gayer et al., 2019; Rand, Tylianakis, and Tscharntke, 2006 ; Smida and Wilson, 1985).

When margin points were included in the model of diversity, *adjacent* was retained as an effect. Diversity was generally greater in all transect positions when adjacent to crops, than when adjacent to urban. Contrary to the above findings relating to spill-over in abundance and species richness from the margins, this would suggest that there is a spill-over effect in the balance of species present from the larger areas of adjacent habitat. Urban areas may not support the immigration of new species able to thrive in crop areas, opposed to adjacent crop areas that support agricultural carabid species. This is important to consider in terms of NPC, as agricultural carabids are the species' predating crop pests.

The results of this study suggest the assumption of spill-over from margins may be an overly simplistic extension of carabid ecology, ignoring the various processes acting on carabids over a field to farm scale. The effects of margins were minimal compared to the effect of adjacent habitat, which is likely an attribute of the size of habitats as islands when considered in terms of a habitat matrix. The margins in this study were quite narrow at 3m, yet within typical margin size of 2-6m width (Defra, 2020). This may be too small to act as a source habitat patch promoting spill-over, as much of the area comprises exposed 'edge' (Davies and Margules, 1998; Lövei et al., 2006). However, Telfer et al. (2000) found no effect of margin size on carabid assemblages with margins of 3m and 6m.

The establishment period may be also be a factor in the limited effects of margins in this study, we assumed in this study the presence of margins for 3 years constituted sufficient stability to account for species incursion, however Alignier and Aviron (2017) noted patterns of carabid species richness corresponding to management with a 4-5 year lag time.

The habitat quality is an important consideration, the experimental margins were assumed to provide resources of shelter and alternative food. However, despite the relative stability of the margins compared to field habitats, these resources are not exploited by carabids unilaterally over time.

Shelter resources of tussocky grasses will be exploited in hibernation or aestivation periods, and weed seed, pollen, and alternative prey resources of wildflower margins will be exploited when food resources in crops are comparatively scarce (Desender, 1982; Thomas Holland and Brown 2002). In a similar study of field margin plots sampled in summer, Thomas and Marshall (1999) found no significant effect of plot type (field crop, rye grass, and wildflower mix) on carabid activity density, yet saw differences between fields of different crops. The authors also sampled overwintering arthropods, finding a greater diversity in sown plots. In the late summer period of our study, both of the margin treatments may have comprised less suitable habitat for agricultural carabids. Lagerloff and Wallin (1993) sampled different margin types in the autumn, finding no significant differences between pitfall trap samples, however, soil sampling revealed differences in overwintering adults and larvae. This then, may be attributed to the distinction between activity-density and actual abundance that pitfall trapping is prone to overstate. Subterranean trapping may reveal differential resource use in margins.

Margin and semi-natural habitat strips in fields have been demonstrated as effective in boosting carabid presence in crops, Collins et al. (2002) measured increased cereal aphid predation as significant up to 58m from a beetle bank. Our previous work showed that particular species preferences drive distributions, with abundances in crop centre and edge positions in particular crops varying by species (Jowett at al., 2019).The variability of results regarding habitat creation in farmland may be due to the considerable variation in habitat preferences, mobility, and phenology of different carabid species (Saska et al., 2007). Therefore, the interaction of habitat quality and position in the landscape with species preferences may be a key factor to consider in design of effective interventions.

4.4.2 Community composition in crops, margins, and adjacent habitats

The overarching importance of the crop was again demonstrated by the PCA results. Different carabid communities are apparent in groupings of different vegetation. This was particularly distinct for *spring barley*, *spring oats*, and *winter oilseed rape*. *Spring barley*, and *winter oilseed rape* in this experiment were well established and dense, whilst the spring oats field in the experiment had a poorly established crop edge to field edge area, that was gappy with weed incursion. Seidl et al. (2020) documented distinctions in species inhabiting crop defect areas in oilseed rape, where crop failure leads to more open habitats. This may explain the outlier status of spring oats, as driving the first axis in the standard pitfall PCA, compared to the subterranean data. This difference is likely driven by the distinction in activity density between trap types. Carabids have been shown to exhibit higher activity density in open habitats due to increased surface activity in foraging (Fornier and Loreau, 2001). However, subterranean traps capture differential activity in burrowing behaviour which may indicate below-ground resource predation, such as on crop pest larvae (Jowett et al., 2019).

Field edge habitats (here relating to the margin and control treatments) showed more overlap in the PCA plots, which would be expected from edge habitat literature (Smida and Wilson, 1985). However, grass/scrub would be more anticipated to have a distinct community from crop areas than was observed in our data (Kinnunen and Tiainen, 1999). This could be due to the position of the habitat patch within the arable landscape, as dominated by a species pool of agriculturally adapted carabid species. This emphasises the need to consider farm scale processes when interpreting plot scale differences.

There were some species level preferences exhibited in the LMMs. *Harpalus rufipes* was least abundant, and *P. melanarius* was less abundant, in the grass/scrub habitat. No species was most abundant in this habitat, however it was one of the more preferred habitats of *P. madidus*. This would indicate that *P. madidus* was the only species preferentially utilising the resources of grass/scrub habitats in the farm landscape; which is interesting given the similarity of morphology and predatory niche with *P. melanarius*. Our previous work on a large-scale dataset of carabids in farmland showed distinction in the distribution of these two species (Jowett et al., 2019) both described in the literature as eurytopic in farmed land. Gallis, Turka and Ausmane (2017) similarly found that morphologically similar species had differential responses to soil treatments and crop rotations. Our finding may then be attributed to niche differentiation in the agro-ecosystem, particularly in the late summer timing of resource appropriation. Grass habitats may well be, as described in the literature, essential to a range of species outside of this timeframe as aestivation and hibernation areas. Purtauf et al. (2005) found that both species richness and activity density of carabids increased with increasing complexity of landscape surrounding wheat fields. However, while Massaloux et al. (2020a) found that per site species number and activity density were higher in study regions with grassland cover, a follow up study (2020b) revealed that in cereal crops, the landscape parameters showed no significant effects on carabid species richness. The common species richness between grasslands and crops was explained by higher density of boundaries between them (and as such an edge effect). Furthermore, Anderson (1997) in a study of grass and cereal field over winter found that while most species were significantly more abundant in the boundaries, those species with higher populations in the grass field centres and boundaries were not considered important predators of crop pests. Aviron et al. (2018) found that spatial continuities between spring and winter crops enhanced carabid species of farmland, but crop and woody habitat patterns had an antagonistic effect on both farmland and forest carabid species. The authors stated that semi-natural habitats cannot simultaneously support both farmland and forest species. This would concur with our results, and indicates that interventions targeting in-field conditions may be of more utility to promoting winter survivorship of beneficial species.

Saska et al. (2007) distinguished distinct ecological groups of carabids occupying boundaries, field centres, and field edges. Notably, in thus study, no one species was more abundant ubiquitously in either the crop centre or crop edge; all species varied in the most abundant transect position by crop. This would suggest that abundances were connected to resource patches which varied in different crops. This was exhibited in our data in the case of *spring oats* where *P. melanarius*, cited as a predator of open habitats; and *H. rufipes*, cited as a weed seed specialist (Luff, 1993), were more abundant in the more open and weedy crop edge area detailed above (Seidl et al., 2020).

Removing the dominant effect of vegetation type, by restricting the PCAs to *wheat* crop, revealed the subtler field-scale influence of adjacent habitat on communities. Communities adjacent to urban areas were similar in composition, in comparison to communities adjacent to other crops. This is particularly strong when we consider that the two urban areas adjacent to the wheat fields were at opposite ends of the farm map (M02 and M14, Fig.1).

There was a slight visible distinction when PCA points for the *wheat* crop were grouped by margin types, in that control transects displayed a slightly different community composition than experimental grass and wildflower margins. This may indicate a subtle effect of experimental margins in an interface sense of altering the resources available at field edges, as the field edges constitute a much more open area where the crop peters out to the boundary, and margins introduce vegetative structure. However, there is much overlap, and there may be a stronger edge effect on control treatments, as these transects tended to be located at the end of the experimental margin line, which were often by necessity closer to the field edges.

Modelling the most abundant carabid species enabled us to discern the species preferences driving particular trends of community composition. Overall, no one species was driving the greatest abundance seen in *spring barley*. This would suggest that the species are largely interchangeable in terms of realised niche. This would be supported by the findings of relative abundances of the ostensibly similar *P. melanarius* and *P. madidus*. However, some species did show different crop preferences, particularly *Amara eurynota*, which was much more abundant in winter oilseed rape. Many *Amara* species show a preference for the oilseed rape crop, though *A. eurynota* is listed among these in the literature, it is not among the most typical of those cited as abundant in this crop (Williams et al., 2010; Schlein and Büchs, 2006).

The influence of margins

Pterostichus melanarius appeared to be influenced by the presence of grass margins with lower abundances in crop edge habitats where these coincided with grass margins, which is supported by this species' low abundance in the *grass/scrub* adjacent vegetation. Eyre, Luff and Leifert (2013) found *P. melanarius* to be more abundant in short vegetation at field edges, compared to denser vegetated boundaries. *P melanarius* is a noted hunter of more open crop habitats (Luff, 1994), which may explain the greater abundances in the control treatment margin transect points. This species may be less reliant on grass areas since oviposition is recorded as occurring in crop areas (Purvis and Fadl, 1996; Trefas and van Lenteren, 2008; Wallin, 1988). However, this species is also well documented as following prey distributions (Bohan et al., 2000; Winder et al., 2001) which in the case of invertebrate pests may be the driver of crop centre aggregations.

Harpalus rufipes, surprisingly was affected negatively by the wildflower margins. Overall abundances were lower in conjunction with a wildflower margin, and within the margin transect points wildflower margins showed the least abundance. This would be contrary to expectations given the granivorous habit of this species, however, at the time of both runs of this study the wildflowers within the margin had not gone to seed, yet the crop areas did exhibit weedy species that were setting seed at this point. Generally, *H. rufipes* was equally abundant in the centre and edge of habitats, apart from in spring oats, where it was more abundant at the edge. This would correspond to the characteristics of the field encompassing M02 and M03 as above, with weed seed resources in the patchy crop areas.

In contrast to *P. melanarius* again, *P. madidus* had higher abundances in margin transect points when this constituted a grass margin, and least in wildflower margins. The extent to which this is habitat choice or niche differentiation is debateable, but this species is noted to be more associated with hedgerows and sheltered habitats (Luff, 1994, Jowett et al., 2018) and so may be attracted to the structural resources afforded by the shelter of the margins, yet still differentiates between the resources available in grass and wildflower margins. Contrarily, *P. cupreus* was most abundant in winter barley, in conjunction with a wildflower margin, with similar abundances between treatments in margin transect points. Labruyere, Petit, and Ricci (2018) found the distribution of *P. cupreus* to be not significantly associated with grassy field margins, and that the post-harvest movements out of the fields were directed towards cereal fields rather than grassy areas. The authors concluded this was an attribute of the species' ability to overwinter in crop habitats. *Poecilius cupreus* is an omnivore, more predacious on weed seed resources than *P. madidus*, yet the distribution of *H. rufipes* would suggest seed resources were scant in the wildflower margins, indicating *P. cupreus* may be responding to other resources, perhaps such as pollen. Larvae were more abundant in control treatments with no margin, this may be due to the distribution of adults in during breeding times, which may follow the most numerous species of *P. melanarius*. Lagerloff and Wallin (1993) discovered twice as many carabid larvae in couch grass margins, compared to wildflower, clover, and ploughed margins. The authors related this to relative sub-soil conditions. We may similarly surmise that soil conditions were a combination of most appropriate for adults during oviposition, and providing resources for larval development, in the field edge areas.

The LMMs revealed specifics of species activity density, in terms of abundances in different trap types. *Pterostichus madidus* displayed more surface activity with abundance in pitfall traps in all positions. The aggregations of *A. eurynota* were primarily in subterranean traps, which may explain the lack of literature indicating this species as a primary predator of oilseed rape. *Poecilius cupreus* was generally equally abundant in both trap types, yet more abundant in pitfall traps in spring barley, which may point to the adaptability of this species as an omnivore. As anticipated, larvae were clearly more abundant in subterranean traps, which further underlines the need for multiple survey techniques to accurately gauge distributions of carabids (Kotze et al., 2011).

The particular assemblage at a field level therefore, is primarily driven by the vegetation in terms of canopy architecture and the availability of food resources. Similarly, Roubalah et al. (2015) in a study of field margins and crop areas, found differential species responses to plant functional diversity, plant heterogeneity, and proportion of bare ground. Likewise, Eyre, Luff and Leifert (2013) found differential species preferences by crop and margin type, in a study over nine crop types and four field boundary types. Therefore, assemblages are primarily affected by vegetation qualities. Yet this is also based on the local species pool, which may be altered significantly by adjacent habitat, and to a lesser extent, interface habitats such as field margins.

4.4.3 Do these processes vary at a farm scale irrespective of field level differences?

There was a general spatial effect, independent of habitat factors, in the total pitfall abundance. This was apparent at 45m, which corresponds to the generalised figure given in literature for carabid movements of the 50m/day distribution (Kotze et al., 2011). Corbett and Plant (1993) modelled carabid dispersal from a vegetated strip, assuming a pure diffusion effect based on species dispersal capabilities. The authors predicted carabid numbers to be enhanced up to 50m from the strip. Therefore, habitats at 45m can be expected to be similar in community composition, and communities may vary at the larger farm scale due to the dispersal capabilities and behaviour of adult carabids (Holland et al., 2005). The spatial effect for subterranean traps was much lower, at 7m, which would only correspond to the distance between traps in margins to those in the crop edge or adjacent habitat edge. This may indicate the nature of subterranean movement as localised and relatively slow, or the tendency for soil organisms to aggregate in resource patches (Ettema and Wardle, 2002; Rantalainen et al., 2004).

The sequential fits of spatial models indicated again the dominant influence of vegetation. Dependant on the landscape composition this will act differentially on communities, between crops and semi-natural habitats. Kinnunen and Tiainen (1999) found that the closer fields were to one another, the more likely the communities were to be similar, however they observed that this effect was stronger in barley crops compared to green set asides, concluding that dissimilarity of vegetation in set asides overrode the effect to an extent. Whilst Massaloux et al. (2020a) observed that strong distinctions in grassland and cropland carabid species were evident, but assemblages within 4km of each other showed higher similarity. Our study uncovers the species preferences driving spatial autocorrelation, in differential spatial influences.

Pterostichus melanarius, *P. madidus*, and *P. cupreus* were all found to have spatial autocorrelation at around 100m. These species all display similar running morphologies and a disinclination to flight (Evans and Forsythe, 1984; Luff, 1996). As such these species can be assumed to display similar dispersal capabilities. Since *Pterostichus* spp. Are known to follow prey distributions in crops (Bohan et al., 2000; Haschek et al., 2012; Winder et al., 2001), this suggests the three species have a foraging range of ~100m, whereby individual coalesce on resource patches. We found no spatial effects on the abundance of *H. rufipes*, this species is flight dispersive and may be displaying selective criteria for habitat selection due to its granivorous diet (Vanbergen et al., 2010). *Amara eurynota* likewise displayed no spatial trends. Kinnunen, Tiainen, and Tukia (2001) found *A. eurynota* present in aggregations, with 76% of individuals trapped in one field. In this study, an aggregative pattern is clearly visible in the plots in both winter oilseed rape field, primarily in subterranean traps. Holland et al. (2005) likewise found species specific spatial patterns in a farm-scale study across three years. The authors tied this to differential foraging and overwintering behaviours.

We also found no spatial effects on the abundance of carabid larvae. This could be due to their small-scale subterranean movements. However, larvae cannot be said to be distributed by their own preference at a farm scale; their presence is governed by the oviposition of the preceding generation, which in this case inhabited the previous crop (Holland, Birkett and Southway, 2009). The abundances as visible in the spatial plots correspond to the presence of the previous year crops of spring barley and winter barley (table 1). Interestingly, Trefas and van Lenteren (2008) caught more *P. melanarius* larvae in sprouts intercropped with barley, and related this under laboratory conditions to a structured environment and favourable microclimate provided by cereal stems. Since the total carabid abundance in our study was greatest in the barley crop in the experiment, this suggests that adult crop preference drives next generation larval abundance. Carabid larvae have a very high mortality rate, and as such their abundance can be tied to survivorship, and so is reliant on sufficient resources; more so than the adults, as being restricted in dispersal, the larvae display strong density dependence (Betz, 1992; Holland, 2002; Thiele 1977). Farm management such as tillage in have been shown to have a large impact on survivorship (Blubaugh, and Kaplan, 2015; Purvis and Fadl, 1996), however the areas of peak abundance were in crops with contrasting management timings. This could indicate effects to be equalised across species, particularly of spring and autumn breeding distinctions. It would be of value to examine the relative presence of different carabid larvae at a species level, and by developmental growth stage (instar), in future studies; to further elucidate the processes acting on the larval abundance.

A lesser spatial influence was evident at the farm scale, in the coordinates trend. This trend could be due to site gradients, such as soil characteristics. Haschek et al (2012) were able to correlate distributions of carabids in oilseed rape crops to soil properties. The soils at the farm site range in a gradient from sandy silt loam in the south west, to clay loam north east. *Pterostichus madidus* was the species with the strongest coordinates trend, which was somewhat more abundant in the north east, which may correlate with soil gradient, but there was also some abundance visible at the opposite end, so is likely an association with the urban boundaries and competitive exclusion from *P. melanarius*. Gailis, Turka, and Ausmane, (2017) found that different carabid species were affected by preceding crops in a rotation to winter wheat, however there were no such associations visible in our data (for previous crops see table 1), this may be due to the dominant effect of different current crops.

The spatial plots as split by trap type again display the benefits of multiple trapping methodologies in gaining a true picture of carabid distribution. For example, *H. rufipes* was visibly more abundant in standard pitfall traps in M09 (*Spring barley*), yet more abundant in subterranean traps in M11 (*winter oilseed rape*). This suggests different foraging behaviours, likely predicated by differential weed seed resources in the respective crops.

This builds a complex picture of the scales acting on carabid distributions. Holland, Birkett and Southway (2009) found complete penetration in fields up to 12ha, with the maximum distance to a boundary being 180m. Given the dispersal distances cited in literature of typically 50m, we can assume dispersal to be active searching rather than passive diffusion, and additive. Divergent foraging behaviour and dispersal capabilities mean that processes are experienced differently at a species level, which is likely to influence community composition. This means that we may make management recommendations based on species and predatory potential.

For *P. melanarius* and *P. madidus*, smaller field sizes, on a scale of <200 metres diameter may boost movement between crops in a rotation, enhancing crop centre predation of arthropod pests. To encourage weed seed predation from species such as *H. rufipes*, the approach of field penetration measures such as beetle banks may be valid in very large fields, as flight dispersal to resource patches is indicated.

Further work is needed to discern effective operative sizes, configuration and vegetative composition (particularly in alternative weed seed resources) of habitat patches provided in farmland. Under constraints of a real farm landscape we were unable to fully examine the effects of adjacent grass/scrub as repetitions were limited. It was also not possible to explore relative composition of adjacent urban carabid communities. However, this work highlights the more vital importance of crop areas to predatory carabids, and the potential to improve natural enemy pest control by considering the attributes of these habitats and their coordination at a farm scale.

4.5 Conclusions

When making recommendations for habitat management to boost carabid natural-enemy pest control, literature has tended to focus on the plot scale, or landscape scale. Our findings demonstrate that the intersection of these scales is the most vital perspective. When looking at a single field, increasing habitats such as field margins may have a significant effect. Likewise, at a landscape scale increasing semi-natural habitats such as boundary features may impact carabid abundance and diversity. However, at a farm scale we see these interventions are not ubiquitously beneficial, and this may explain the divergence in proven efficacy of farm management interventions across studies.

Our results show that field margins may not be as useful as theorised based on carabid ecology, when it comes to promoting carabid abundance in crops. These areas may be too small to act as a habitat patch, and source environment for carabids to spill over in to crops. Moreover, we saw some evidence of margins acting as a barrier to carabids in crop areas. Providing a single large margin on one side of a field may be more useful than all boundaries. Particularly the location of margins may be targeted, our spatial analyses confirmed that carabids disperse at distances equitable to large fields in many key species, and showed signs of independence in others, indicating wider flight dispersal. Therefore, placing larger margins as an interface to areas such as urban habitats may ameliorate sparse distributions, and are likely to be more effective as carabids are able to reach these more suitable habitat patches.

We also saw the specific seed mix had an impact on carabids, wildflower seed mixes may be less useful than native wildflowers or natural regeneration. Consideration of seed and pollen resources over time, in relation to crops, may be key to effective weed seed predation.

Another key finding is the utility of subterranean traps to reveal nuances in occurrence not shown by the measure of pitfall trapping and surface activity density. Particularly in this study we revealed new insight into the distribution of *Amara eurynota* in oilseed rape, and carabid larvae.

Overall, diverse cropping is the most vital factor in carabid abundance and diversity for effective natural enemy pest control, particularly at the centre of crops. The responses of different species were demonstrated to vary by crop, and as such the impacts of semi-natural habitat provision will be variable in its effect on carabid community composition. We saw that at a farm scale, crops adjacent to crops delivered more abundance, and diversity of carabids in crop edges. Also, the assumption of tussocky grasses providing overwintering habitat and spill-over into crops proves false in many predacious species. More useful interventions may comprise crop area management such as reduced tillage regimes, companion cropping, and stubble retention, in order to boost survivorship of adults and larvae emerging. Aligning the timing of management and crop rotations may be particularly useful to promote carabid larval abundance, for instance following barley (which had greatest larval abundance) with a crop susceptible to damage from below ground pests.

4.6 References

Aguilera, G., Roslin, T., Miller, K., Tamburini, G., Birkhofer, K., Caballero-Lopez, B., Lindström, S.A.M., Öckinger, E., Rundlöf, M., Rusch, A. and Smith, H.G., 2020. Crop diversity benefits carabid and pollinator communities in landscapes with semi-natural habitats. *Journal of Applied Ecology*, 57(11), pp.2170-2179.

Alignier, A. and Aviron, S., 2017. Time-lagged response of carabid species richness and composition to past management practices and landscape context of semi-natural field margins. *Journal of environmental management*, 204, pp.282-290.

Andersen, A., 1997. Densities of overwintering carabids and staphylinids (Col., Carabidae and Staphylinidae) in cereal and grass fields and their boundaries. *Journal of Applied Entomology*, 121(1-5), pp.77-80.

Aviron, S., Lalechère, E., Duflot, R., Parisey, N. and Poggi, S., 2018. Connectivity of cropped vs. semi-natural habitats mediates biodiversity: a case study of carabid beetles communities. *Agriculture, Ecosystems & Environment*, 268, pp.34-43.

Begg, G.S., Cook, S.M., Dye, R., Ferrante, M., Franck, P., Lavigne, C., Lövei, G.L., Mansion-Vaquie, A., Pell, J.K., Petit, S. and Quesada, N., 2017. A functional overview of conservation biological control. *Crop Protection*, 97, pp.145-158.

Berendse, F., Chamberlain, D., Kleijn, D. and Schekkerman, H., 2004. Declining biodiversity in agricultural landscapes and the effectiveness of agri-environment schemes. *Ambio: A journal of the Human environment*, 33(8), pp.499-502.

Betz, J.O., 1992. Studies on winter-active larvae of the ground beetle Carabus problematicus(Coleoptera, Carabidae). *Pedobiologia*, 36(3), pp.159-167.

Blubaugh, C.K. and Kaplan, I., 2015. Tillage compromises weed seed predator activity across developmental stages. *Biological Control*, 81, pp.76-82.

Blumgart, D., 2020. Investigating the Mechanisms Behind Moth Declines: Plants, Land-use and Climate. *PhD thesis*. Lancaster University, UK

Boetzl, F.A., Krimmer, E., Krauss, J. and Steffan-Dewenter, I., 2018. Agri-environmental schemes promote ground-dwelling predators in adjacent oilseed rape fields: Diversity, species traits and distance-decay functions. *Journal of Applied Ecology*.

Bohan, D.A., Bohan, A.C., Glen, D.M., Symondson, W.O., Wiltshire, C.W. and Hughes, L., 2000. Spatial dynamics of predation by carabid beetles on slugs. *Journal of Animal Ecology*, 69(3), pp.367-379.

Brooks, D.R., Perry, J.N., Clark, S.J., Heard, M.S., Firbank, L.G., Holdgate, R., Shortall, C.R., Skellern, M.P. & Woiwod, I.P., 2008. National-scale metacommunity dynamics of carabid beetles in UK farmland. *Journal of Animal Ecology*,77,265–274.

Collins, K.L., Boatman, N.D., Wilcox, A., Holland, J.M. and Chaney, K., 2002. Influence of beetle banks on cereal aphid predation in winter wheat. *Agriculture, Ecosystems & Environment*, 93(1-3), pp.337-350.Corbett, A., and Plant, R.E., 1993. Role of Movement in the Response of Natural Enemies to Agroecosystem Diversification: A Theoretical Evaluation. *Environmental Entomology*, Volume 22, Issue 3, 1 June 1993, Pages 519–531, https://doi.org/10.1093/ee/22.3.519

Davies, K.F. and Margules, C.R., 1998. Effects of habitat fragmentation on carabid beetles: experimental evidence. *Journal of Animal Ecology*, 67(3), pp.460-471.

Defra, 2020. *Countryside Stewardship Mid Tier and Wildlife Offers Manual* [online] Available at www.gov.uk/rpa/cs

Dennis, P., Thomas, M.B. and Sotherton, N.W., 1994. Structural features of field boundaries which influence the overwintering densities of beneficial arthropod predators. *Journal of Applied Ecology* 31, 361–370.

Desender, K., 1982. Ecological and faunal studies on Coleoptera in agricultural land. II. Hibernation of Carabidae in agro-ecosystems. *Pedobiologia* 23, 295–303.

Den Boer, P.J., Thiele, H.U. and Weber, F., 1979. On the evolution of behaviour in Carabid beetles. In *Proceedings of the 3rd European Carabidologists' Meeting*. Miscellaneous papers, Agricultural University Wageningen (Vol. 18, p. 222).

Diggle, P.J., and Ribeiro JR., 2001. *geoR: A package for geostatistical analysis*. R-NEWS Vol 1, No 2. ISSN 1609-3631.

Duflot, R., Ernoult, A., Aviron, S., Fahrig, L. and Burel, F., 2017. Relative effects of landscape composition and configuration on multi-habitat gamma diversity in agricultural landscapes. *Agriculture, Ecosystems & Environment*, 241, pp.62-69.

Ettema, C.H. and Wardle, D.A., 2002. Spatial soil ecology. *Trends in ecology & evolution*, 17(4), pp.177-183.

Evans, M.E.G. and Forsythe, T.G., 1984. A comparison of adaptations to running, pushing and burrowing in some adult Coleoptera: especially Carabidae. *Journal of zoology*, 202(4), pp.513-534.

Fournier, E. and Loreau, M., 2001. Activity and satiation state in Pterostichus melanarius: an experiment in different agricultural habitats. Ecological Entomology, 26(3), pp.235-244.

Frampton, G.K., Çilgi, T., Fry, G.L. and Wratten, S.D., 1995. Effects of grassy banks on the dispersal of some carabid beetles (Coleoptera: Carabidae) on farmland. *Biological conservation*, 71(3), pp.347-355.

Fusser, M.S., Pfister, S.C., Entling, M.H. and Schirmel, J., 2016. Effects of landscape composition on carabids and slugs in herbaceous and woody field margins. *Agriculture, Ecosystems & Environment*, 226, pp.79-87.

Gailis, J., Turka, I. and Ausmane, M., 2017. The most frequent ground beetles (Coleoptera, Carabidae) are differently affected by main soil treatment and crop rotation in winter wheat fields. *Acta Biologica Universitatis Daugavpiliensis*, 17(1), pp.29-52.

Gallé, R., Császár, P., Makra, T., Gallé-Szpisjak, N., Ladányi, Z., Torma, A., Ingle, K. and Szilassi, P., 2018. Small-scale agricultural landscapes promote spider and ground beetle densities by offering suitable overwintering sites. *Landscape Ecology*, 33(8), pp.1435-1446.

Gayer, C., Lövei, G.L., Magura, T., Dieterich, M. and Batáry, P., 2019. Carabid functional diversity is enhanced by conventional flowering fields, organic winter cereals and edge habitats. *Agriculture, Ecosystems & Environment*, 284, p.106579.

Haschek, C., Drapela, T., Schuller, N., Fiedler, K. and Frank, T., 2012. Carabid beetle condition, reproduction and density in winter oilseed rape affected by field and landscape parameters. *Journal of Applied Entomology*, 136(9), pp.665-674.

Hof, A.R. and Bright, P.W., 2010. The impact of grassy field margins on macro-invertebrate abundance in adjacent arable fields. *Agriculture, ecosystems & environment*, 139(1-2), pp.280-283.

Holland, J.M., 2002. *The agroecology of carabid beetles*. Intercept Limited.

Holland, J.M., Birkett, T. & Southway, S., 2009. Contrasting the farm-scale spatio-temporal dynamics of boundary and field overwintering predatory beetles in arable crops. *BioControl*, 54, 19– 33.

Holland, J.M. and Luff, M.L., 2000. The effects of agricultural practices on Carabidae in temperate agroecosystems. *Integrated pest management reviews*, 5(2), pp.109-129.

Holland, J., Thomas, C.F.G., Birkett, T., Southway, S. and Oaten, H., 2005. Farm-scale spatiotemporal dynamics of predatory beetles in arable crops. *Journal of Applied Ecology*, 42(6), pp.1140-1152.

Hyvarinen, E., Kouki, J., and Martikainen, P., 2006. A comparison of three trapping methods used to survey forest-dwelling Coleoptera. *European Journal of Entomology*. 103: p 397–407.

Jowett, K., Milne, A.E., Garrett, D., Potts, S.G., Senapathi, D. and Storkey, J., 2021. Above-and below-ground assessment of carabid community responses to crop type and tillage. *Agricultural and Forest Entomology*, 23(1), pp.1-12.

Jowett, K., Milne, A.E., Metcalfe, H., Hassall, K.L., Potts, S.G., Senapathi, D. and Storkey, J., 2019. Species matter when considering landscape effects on carabid distributions. *Agriculture, Ecosystems & Environment*, 285, p.106631.

Kinnunen, H., Tiainen, J. and Tukia, H., 2001. Farmland carabid beetle communities at multiple levels of spatial scale. *Ecography*, 24(2), pp.189-197.

Kinnunen, H. and Tiainen, J., 1999.. Carabid distribution in a farmland mosaic: the effect of patch type and location. In *Annales Zoologici Fennici* (pp. 149-158). Finnish Zoological and Botanical Publishing Board.

Kleijn, D., Baquero, R.A., Clough, Y., Díaz, M., De Esteban, J., Fernández, F., Gabriel, D., Herzog, F., Holzschuh, A., Jöhl, R. and Knop, E., 2006. Mixed biodiversity benefits of agri-environment schemes in five European countries. *Ecology letters*, 9(3), pp.243-254.

Kleijn, D. and Sutherland, W.J., 2003. How effective are European agri-environment schemes in conserving and promoting biodiversity?. *Journal of applied ecology*, 40(6), pp.947-969.

Koivula, M., Hyyryläinen, V. and Soininen, E., 2004. Carabid beetles (Coleoptera: Carabidae) at forest-farmland edges in southern Finland. *Journal of Insect Conservation*, 8(4), pp.297-309.

Kotze, D.J., Brandmayr, P., Casale, A., Dauffy-Richard, E., Dekoninck, W., Koivula, M.J., Lövei, G.L., Mossakowski, D., Noordijk, J., Paarmann, W. and Pizzolotto, R., 2011. Forty years of carabid beetle research in Europe–from taxonomy, biology, ecology and population studies to bioindication, habitat assessment and conservation. *ZooKeys*, (100), p.55.

Kromp, B., 1999. Carabid beetles in sustainable agriculture: a review on pest control efficacy, cultivation impacts and enhancement. *Agriculture, Ecosystems & Environment*. Volume 74, Issues 1–3, June 1999, Pp 187–228#

Labruyere, S., Petit, S. and Ricci, B., 2018. Annual variation of oilseed rape habitat quality and role of grassy field margins for seed eating carabids in arable mosaics. *Agricultural and Forest Entomology*, 20(2), pp.234-245.

Lagerlöf, J. and Wallin, H., 1993. The abundance of arthropods along two field margins with different types of vegetation composition: an experimental study. *Agriculture, Ecosystems & Environment* 43, 141–154.

Loreau, M., 1990. Competition in a carabid beetle community: a field experiment. *Oikos*, pp.25-38.

Lövei, G.L. and Sunderland, K.D., 1996. Ecology and behavior of ground beetles (Coleoptera: Carabidae). *Annual review of entomology*, 41(1), pp.231-256.

Lövei, G.L., Magura, T., Tóthmérész, B. and Ködöböcz, V., 2006. The influence of matrix and edges on species richness patterns of ground beetles (Coleoptera: Carabidae) in habitat islands. *Global Ecology and Biogeography*, 15(3), pp.283-289.

Luff, M.L., 2007. *The Carabidae (ground beetles) of Britain and Ireland*. Royal Entomological Society. RES Handbooks for the Identification of British Insects Volume 4 Part 2 (2nd Edition).

Luff, M.L., 1998. *Provisional atlas of the ground beetles (Coleoptera, Carabidae) of Britain*. Biological Records Centre Institute of Terrestrial Ecology.

Luff, M.L., 2002. Carabid assemblage organization and species composition. In: Holland, J.M., 2002. *The agroecology of carabid beetles*. Intercept Limited.

Massaloux, D., Sarrazin, B., Roume, A., Tolon, V. and Wezel, A., 2020a. Complementarity of grasslands and cereal fields ensures carabid regional diversity in French farmlands. *Biodiversity and Conservation*, 29, pp.2861-2882.

Massaloux, D., Sarrazin, B., Roume, A., Tolon, V. and Wezel, A., 2020b. Landscape diversity and field border density enhance carabid diversity in adjacent grasslands and cereal fields. *Landscape Ecology*, 35(8), pp.1857-1873.

McGavin, G., 1997. *Expedition Field Techniques. Insects: and other terrestrial arthropods*. London: Royal Geographical Society.

New, T. R., 1998. *Invertebrate surveys for conservation*. Oxford: Oxford University Press

Niemelä, J. and Kotze, D.J., 2009. Carabid beetle assemblages along urban to rural gradients: A review. *Landscape and Urban Planning*, 92(2), pp.65-71.

Niemelä, J., 1993. Interspecific competition in ground-beetle assemblages (Carabidae): what have we learned?. *Oikos*, pp.325-335.

Noordhuis, R., Thomas, S.R. and Goulson, D., 2001. Overwintering populations of beetle larvae (Coleoptera) in cereal fields and their contribution to adult populations in the spring. *Pedobiologia,* 45(1), pp.84-95.

Owen, J.A., 1995. A pitfall trap for repetitive sampling of hypogean arthropod faunas. *Entomologist's record and journal of variation,* 107, p 225-228.

Paill, W., 2000. Slugs as prey for larvae and imagines of Carabus violaceus (Coleoptera: Carabidae). In: Brandmayr, P. ed., 2000. *Natural History and Applied Ecology of Carabid Beetles: Proceedings of the IXth European Carabidologists' Meeting* (26-31 July 1998, Camigliatello, Cosenza, Italy) (No. 19). Pensoft Publishers. Pp 221-227

Purtauf, T., Roschewitz, I., Dauber, J., Thies, C., Tscharntke, T. and Wolters, V., 2005. Landscape context of organic and conventional farms: influences on carabid beetle diversity. *Agriculture, Ecosystems & Environment*, 108(2), pp.165-174.

Purvis, G. and Fadl, A., 1996, January. Emergence of Carabidae (Coleoptera) from pupation: A technique for studying the'productivity'of carabid habitats. In *Annales Zoologici Fennici* (pp. 215-223). Finnish Zoological and Botanical Publishing Board.

Rand, T. A., Tylianakis, J. M., & Tscharntke, T., 2006. Spillover edge effects: The dispersal of agriculturally subsidized insect natural enemies into adjacent natural habitats. *Ecology Letters*, 9, 603–614.

Rantalainen, M.L., Kontiola, L., Haimi, J., Fritze, H. and Setälä, H., 2004. Influence of resource quality on the composition of soil decomposer community in fragmented and continuous habitat. *Soil Biology and Biochemistry*, 36(12), pp.1983-1996.
Ricci, B., Lavigne, C., Alignier, A., Aviron, S., Biju-Duval, L., Bouvier, J.C., Choisis, J.P., Franck, P., Joannon, A., Ladet, S. and Mezerette, F., 2019. Local pesticide use intensity conditions landscape effects on biological pest control. *Proceedings of the Royal Society B*, 286(1904), p.20182898.

Rouabah, A., Villerd, J., Amiaud, B., Plantureux, S. and Lasserre-Joulin, F., 2015. Response of carabid beetles diversity and size distribution to the vegetation structure within differently managed field margins. *Agriculture, Ecosystems & Environment*, 200, pp.21-32.

Saska, P., Vodde, M., Heijerman, T., Westerman, P. and van der Werf, W., 2007. The significance of a grassy field boundary for the spatial distribution of carabids within two cereal fields. *Agriculture, ecosystems & environment*, 122(4), pp.427-434.

Schlein, O. and Büchs, W., 2006. The ground beetle Amara similata as a predator of pest larvae in oil seed rape fields; ignored but influential in biological control. In International Symposium on *Integrated Pest Management in Oilseed Rape*, 3 rd–5 th April 2006.

Segre, H., Segoli, M., Carmel, Y. and Shwartz, A., 2020. Experimental evidence of multiple ecosystem services and disservices provided by ecological intensification in Mediterranean agro-ecosystems. *Journal of Applied Ecology*, 57(10), pp.2041-2053.

Seidl, M., González, E., Kadlec, T., Saska, P. and Knapp, M., 2020. Temporary non-crop habitats within arable fields: The effects of field defects on carabid beetle assemblages. *Agriculture, Ecosystems & Environment*, 293, p.106856.

Sims, I., and Cole, J., 2016. Hypogean Pitfall Trapping: A Novel Technique for Assessing Soil Biodiversity in Agroecosystems. *British Journal 0f Entomology and Natural History*, 29: 2016

Sims, I., and Cole, J., 2017. Baeus seminulum (hymenoptera:scelionidae) new to Berkshire and a review of records from the British Isles. *British Journal 0f Entomology and Natural History.*, 30: 2017

Shmida, A. V. I., and Wilson, M. V., 1985. Biological determinants of species diversity. *Journal of Biogeography,* 12, 1–20. https ://doi.org/10.2307/2845026

Sotherton, N.W., 1984. The distribution and abundance of predatory arthropods overwintering on farmland. *Annals of applied Biology*, 105(3), pp.423-429.

Sotherton, N.W., 1985. The distribution and abundance of predatory Coleoptera overwintering in field boundaries. *Annals of applied biology*, 106(1), pp.17-21.

Telfer, M., 2017. *Subterranean pitfall traps for beetles* [online blog] Available at: http://www.markgtelfer.co.uk/beetles/techniques-for-studying-beetles/subterranean-pitfall-traps-for-beetles/ [accessed 20/11/2017]

Telfer, M.G., Meek, W.R., Lambdon, P., Pywell, R.F., Sparks, T.H. and Nowakowski, M., 2000. The carabids of conventional and widened field margins. *Aspects of Applied Biology*, 58, pp.411-416.

Thomas, C.G., Holland, J.M. and Brown, N.J., 2002. The spatial distribution of carabid beetles in agricultural landscapes.*In*: Holland, 2003. *The agroecology of carabid beetles*. Andover: Intercept, pp.305-344.

Thomas, C.F.G. and Marshall, E.J.P., 1999. Arthropod abundance and diversity in differently vegetated margins of arable fields. *Agriculture, Ecosystems & Environment*, 72(2), pp.131-144.

Traugott M., 1998. Larval and adult species composition, phenology and life cycles of carabid beetles (Coleoptera: Carabidae) in an organic potato field. *European Journal of Soil Biology* 34, 189-197. Abstract

Trefas, H. and van Lenteren, J.C., 2008. Egg-laying-site preferences of Pterostichus melanarius in mono-and intercrops. *Bulletin of Insectology*, 61(2), pp.225-231.

Vanbergen, A.J., Woodcock, B.A., Koivula, M., Niemelä, J., Kotze, D.J., Bolger, T., Golden, V., Dubs, F., Boulanger, G., Serrano, J. and Lencina, J.L., 2010. Trophic level modulates carabid beetle responses to habitat and landscape structure: a pan-European study. *Ecological Entomology*, 35(2), pp.226-235.

Van Dijk, T.S., 1994. On the relationship between food, reproduction and survival of two carabid beetles: Calathus melanocephalus and Pterostichus versicolor. *Ecological Entomology*, 19(3), pp.263-270.

Wallin, H., 1988. The effects of spatial distribution on the development and reproduction of Pterostichus cupreus L., P. melanarius Ill., P. niger Schall. and Harpalus rufipes DeGeer (Col., Carabidae) on arable land. *Journal of Applied Entomology*, 106(1-5), pp.483-487.

Webster, R. and Oliver, M.A., 2007. *Geostatistics for environmental scientists*. John Wiley & Sons.

Werling, B.P. and Gratton, C., 2008. Influence of field margins and landscape context on ground beetle diversity in Wisconsin (USA) potato fields. *Agriculture, Ecosystems & Environment*, 128(1-2), pp.104-108.

Williams, I.H., Ferguson, A.W., Kruus, M., Veromann, E. and Warner, D.J., 2010. Ground beetles as predators of oilseed rape pests: incidence, spatio-temporal distributions and feeding. In *Biocontrol-based integrated management of oilseed rape pests* (pp. 115-149). Springer, Dordrecht.

Winder, L., Alexander, C.J., Holland, J.M., Woolley, C. and Perry, J.N., 2001. Modelling the dynamic spatio-temporal response of predators to transient prey patches in the field. *Ecology Letters*, 4(6), pp.568-576.

Chapter 5

Engagement for the future of agriculture

This chapter lays the foundation of the experimental design towards objective 3, engagement and knowledge exchange with farmers. The work within this chapter was initiated to deliver educational content, in an engaging way, whilst gathering data on public preferences in relation to the future of agriculture. The engagement by experiment approach builds trust and the interaction that is necessary to design future solutions, both at the high level of public visions of the future, and at the more practical level of implementing management by farmers covered in the subsequent chapters.

Communicating farming futures to the public: engagement by experiment

Kelly Jowett[1], Helen Metcalfe[1], Alice Milne[1], Michael Mielewczik[1], Kevin Coleman[1], Erangu Purath Mohankumar Sajeev[1], Adelia de Paula[2], Gordon Dailey, Andrew P Whitmore [1]

[1]Rothamsted Research, West Common, Harpenden, Hertfordshire, AL5 2JQ, UK

[2]University of Herts

Abstract

Under conflicting pressures, our food system has become highly complex. Re-design must take a balanced view of the requirements of multiple stakeholders. In two separate engagement events we elicited the views of members of the public on the future of agriculture.

Employing a tied voting system on future scenarios, within an interactive and experimental approach , we were able to communicate the issues behind agricultural trade-offs as well as discover synergies in the preferences of members of the public stratified by age.

We recommend interactive exhibits and engagement by experiment for two-way knowledge exchange, and detail extension for demographic targeting.

This chapter was submitted and peer reviewed for Science Communication, with one resubmission before rejection, and subsequently submitted to People and Nature Journal where it was also rejected. Both journals commended the work but expressed the need for more detailed analysis from the social science perspective. It is the intention of the authors to submit elsewhere when time allows amendments.

5.1 Introduction

Food systems are under increasing and conflicting pressures including (i) population growth and associated needs to raise production, (ii) environmental degradation, (iii) shifting consumer demands, (iv) geopolitical and trade processes, and (v) competition for resources and space. Planning the future of farming, therefore, needs to balance environmental, economic and social aspects (World Bank, 2006).

Public perception is critical in influencing consumer acceptance, behaviour and preferences. It also leads to a shift in consumer demand and affects the design of agricultural policies. The public makes food choices everyday based on food prices, their knowledge of nutritional requirements, and subjective values and norms they place on agricultural production, the support of rural communities and the natural environment. These consumer decisions influence upstream production decisions such as which crops are grown, regulations on farm practice, and incentive schemes for environmental and social benefits (De Schutter, 2011; Herring, R J, 2014; Mayer, 2005; Woolthuis, Lankhuizen, and Gilsing, 2005.)

Public perception of food and farming is shaped by relatively few sources, however. People rarely learn about farming from direct observation, and do so more often either through information on food packaging at point of sale, or via media coverage (Brook Lyndhurst 2006; Perloff 2003; Verbeke 2005). However, these limited sources of information do not entirely capture the realities of farming and at times communicates the wrong message to the public. Other studies echo this disconnect and highlight the lack of connection of public with agriculture (Garforth and Usher 1997; Moser 2014; Rucker and Petty 2006). There is a definite need for the provision of unbiased information to the public.

At the opposite end of the scale, this disconnect between the public and food production results in a bias of input influencing the system from the top. Political processes cater to the opinions of the engaged few, with over-representation of some groups driven by lobbying. Market forces are biased by a small number of middle of the chain actors (such as supermarkets) driving the actualisation of a biased portion of latent demands (Tischner et al 2010; Verbeke 2005).

When considering the future of agriculture, there are many possible trajectories. For example, some might advocate a move towards community-supported agriculture and localised diverse production and linked social outcomes. However, the land and resources may not exist for our society to achieve optimal environmental and social aspects whilst maintaining sufficient and affordable food. Trade-offs and a balancing of objectives is necessary. To design farming systems that meet the needs of society, it is important that the public have a better understanding of the conflicting pressures on agricultural systems to put them in a position to properly engage with, debate and support future agricultural policies.

Our objective was to design and use an interactive exhibit to communicate potential scenarios for UK agriculture to the public. We wanted to encourage them to think about the implications in terms of (i) food production, (ii) environmental protection, (iii) affordability of food, (iv) support of rural communities, (v) profitable farming and (vi) quality of food and good nutrition. In particular, we wanted to not only encourage members of the public contemplate potential trade-offs and synergies in terms of these specified outcomes but also gauge their opinions through a voting experiment.

Engagement using exhibits is an increasingly popular approach particularly in museums and science centres, where it has been used with great success covering a wide range of disciplines (Hamm 2015; Honigs et al. 2018). Engagement through exhibits has a long-standing history in agriculture. Displays in museums ranged from farm management, equipment, and the history of agriculture. However, scientific exhibits focusing on the future of agriculture and farming have only emerged in a modern sense relatively recently (Dewar et al. 2018). On a smaller scale, many scientific institutes and companies organise open days to to exhibit their technical equipment and advances. Notable examples include botanical gardens using agricultural displays to provide easy to understand information on the trade-offs between agricultural processes and possible implications on human health and the environment (Krishnan & Novy 2018; Miller et al. 2015). However, incorporating an experimental approach is difficult to design and apply - and as such little has been reported in application with only a few notable examples — Lackner et al (2018) found their interactive exhibits effective in engaging the public with climate change issues and actions, and Corner (2015) notes several case studies for youth engagement, incorporating opinion gathering, music, video, and games. To our knowledge, the study presented here is the first reported that aims to engage and measure public opinion on the future of British agriculture.

We used the opportunities afforded by an open weekend event at Rothamsted Research, Harpenden, UK and a school science and technology event hosted at a farm south of Luton, UK, to engage with the public and involve them in a scientific experiment around directions of farming futures. Central to the design of our method was the importance of communicating concepts visually and intuitively, and incorporating an aesthetically engaging voting system. Here we describe the design of our exhibit and its deployment and report on this approach as a vehicle to (1) promote awareness of the trade-offs associated with agricultural production; (2) gather data on participants’ choices and values in relation to the future of farming.

5.2 Methods

We designed an exhibit to communicate key trade-offs that need to be made for agriculture to become or continue to be sustainable, and to raise public awareness of some of the kinds of farming that might result in the future. We designed the exhibit around six future farming scenarios and encouraged participants to consider the key trade-offs associated with each direction for the future of farming. Our aim was to not only engage the public in thinking about potential directions for farming but also to gather information on their opinions as part of an experiment.

The Events

We showcased the exhibit at two local science communication events. The first was at Rothamsted Research (Hertfordshire, UK), which is the oldest agricultural research institutes in the world. In 2018 Rothamsted celebrated 175 years of agricultural research and to mark this event the institute organised a science festival, opening the doors of the institute to the public and industry stakeholders. This event, the "Festival of Ideas", took place in June 2018 and saw over 8000 visitors over two days. The event featured exhibits showcasing the research done at Rothamsted Research. Our exhibit was located in a central area of the exhibition close to the event reception and so received good footfall.

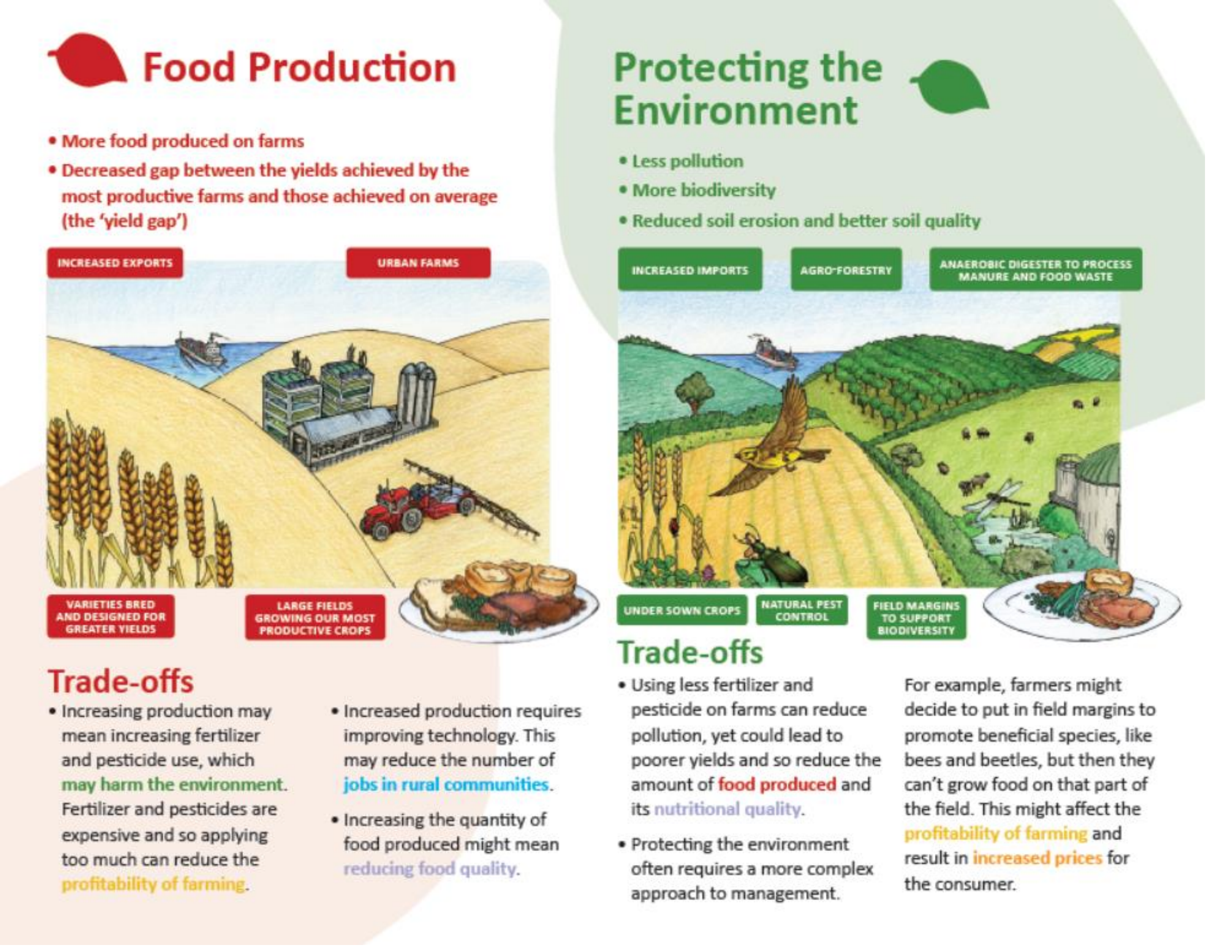
The second event was run by LEAFed, which is a charity working to educate young people about farming, food and the countryside and is part of Linking Environment And Farming (Squire et al. 2013). In September 2018, LEAFed held a teenager engagement day at The Farmschool (Hertfordshire, UK), where school children aged 15–16 and local dignitaries visited a working farm and took part in supervised learning activities and workshops on sustainable agriculture.

The Exhibit

Our exhibit was built around on a small but life-size cut out tree approximately 3m in height. The tree was designed to be eye-catching enough to attract curious passers-by (Figure 1). Surrounding the tree were six large posters each outlining one potential future farming scenario (Figures 2–4) that emphasised a particular vision of how farming may develop in Britain. They were focused on (i) food production, (ii) protecting the environment, (iii) affordable food, (iv) supporting, (v) profitable farming and (vi) Quality of food rural communities. Each poster had a description of the key aspects of the scenario it depicted, but also some examples of potential synergies or trade-offs with the other scenarios. The number of synergies and conflicts stated were the same on all posters to reduce bias.

Figure 1-The Tree of trade-offs exhibit at the Festival of Ideas. a) with visiting dignitaries, and b) a visitor hanging leaves aided by team member

In addition to the text on the poster, we designed a visual representation of a British arable landscape and for each poster illustrated how that landscape could differ given the focus of that future farming scenario. Each illustrated landscape included implications of imports, exports, production qualities and quantities and trade-offs in different values. A typical plate of food resulting from that farming scenario was also illustrated (Figure 2–4). We tried hard to ensure that the illustrations did not guide perceptions of any future, good or bad, to gain as an unbiased a measurement of opinions and choices as possible.



Food Production

- More food produced on farms
- Decreased gap between the yields achieved by the most productive farms and those achieved on average (the 'yield gap')

Trade-offs

- Increasing production may mean increasing fertilizer and pesticide use, which may harm the environment. Fertilizer and pesticides are expensive and so applying too much can reduce the profitability of farming.
- Increased production requires improving technology. This may reduce the number of jobs in rural communities.
- Increasing the quantity of food produced might mean reducing food quality.

Protecting the Environment

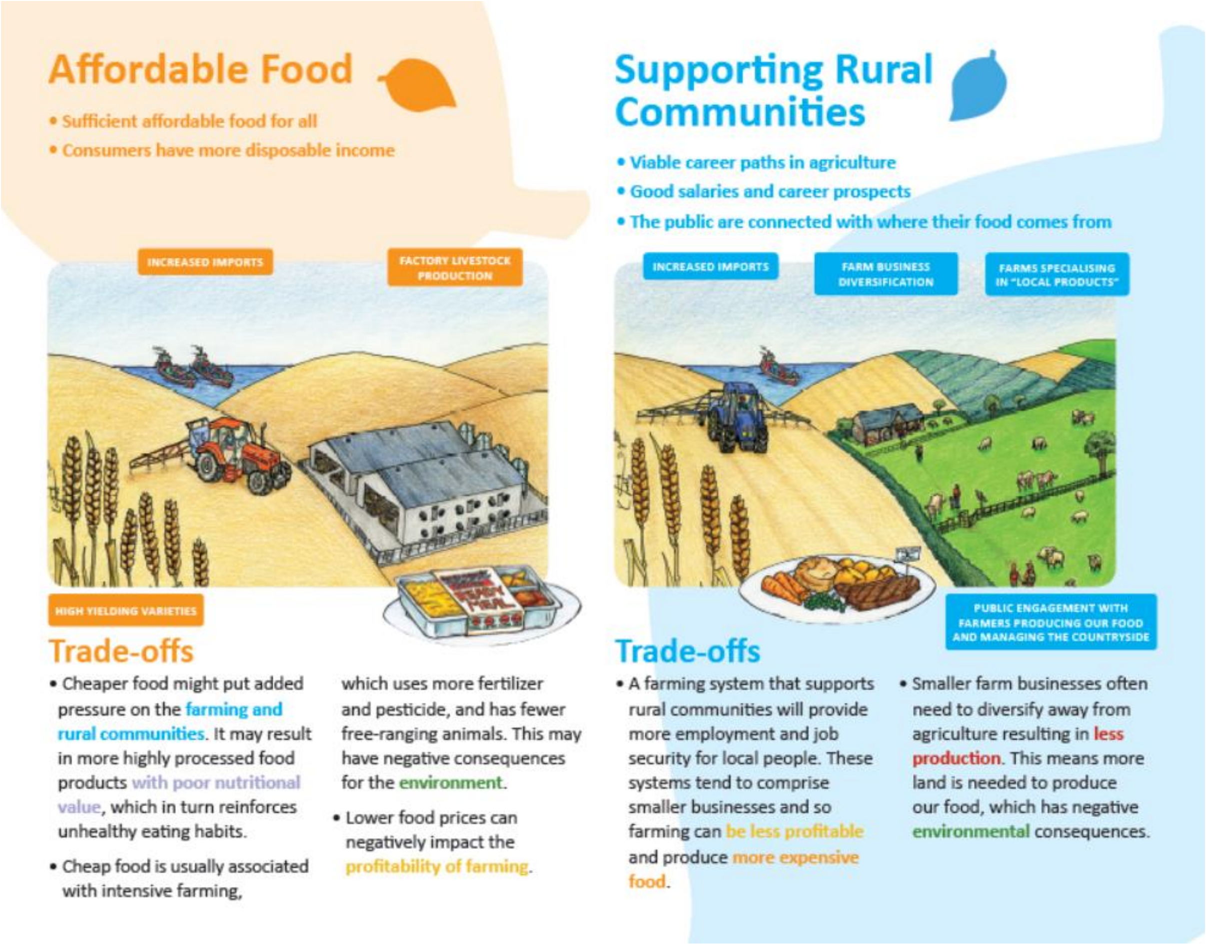
- Less pollution
- More biodiversity
- Reduced soil erosion and better soil quality

Trade-offs

- Using less fertilizer and pesticide on farms can reduce pollution, yet could lead to poorer yields and so reduce the amount of food produced and its nutritional quality.
- Protecting the environment often requires a more complex approach to management.

For example, farmers might decide to put in field margins to promote beneficial species, like bees and beetles, but then they can't grow food on that part of the field. This might affect the profitability of farming and result in increased prices for the consumer.

Figure 2- Future Farming scenario poster illustrating the possible implications of farming futures focused on (i) food production and (ii) protecting the environment. Each poster has an illustration of a typical British agricultural landscape and an associated plate of food showing the type of production we might expect from such a scenario. There are key points to provide a definition of the scenario at the top of each poster and below the image we list four potential trade-offs.



Affordable Food

- Sufficient affordable food for all
- Consumers have more disposable income

Trade-offs

- Cheaper food might put added pressure on the farming and rural communities. It may result in more highly processed food products with poor nutritional value, which in turn reinforces unhealthy eating habits.
- Cheap food is usually associated with intensive farming, which uses more fertilizer and pesticide, and has fewer free-ranging animals. This may have negative consequences for the environment.
- Lower food prices can negatively impact the profitability of farming.

Supporting Rural Communities

- Viable career paths in agriculture
- Good salaries and career prospects
- The public are connected with where their food comes from

Trade-offs

- A farming system that supports rural communities will provide more employment and job security for local people. These systems tend to comprise smaller businesses and so farming can be less profitable and produce more expensive food.
- Smaller farm businesses often need to diversify away from agriculture resulting in less production. This means more land is needed to produce our food, which has negative environmental consequences.

Figure 3- Future Farming scenario poster illustrating the possible implications of farming futures focused on (i) affordable food and (ii) supporting rural communities.

Profitable Farming

- Net profit achieved on farms
- Efficient farm businesses
- Farm businesses are resilient to changes in the environment and wider economy

Trade-offs

- For farming to be profitable the consumer may have to pay more for food.
- Profitable farms are often large scale enterprises which rely on contractors rather than providing jobs for the local community.
- For farms to be profitable, farmers may need to diversify into other businesses which may impact the quantity of food produced in the UK.
- Profitable crops are not necessarily those that provide the best nutrition.

Quality of Food: good nutrition

- Increased nutritional quality of livestock and arable production
- Important micro-nutrients are available in produce
- Products available with fewer substances that can make some people unwell (e.g. gluten) or that are rich in important nutrients (e.g. omega-3 fatty acids)

Trade-offs

- Ensuring food is free from toxins that result from fungal diseases might mean using more fungicide which can impact the environment.
- Meat provides important micronutrients and essential amino acids that single plant species do not always provide, however, livestock systems usually produce fewer calories per area of land than arable systems.
- Crop varieties with greater nutrient density can be less profitable for farmers and more expensive for the consumer.

Figure 4- Future Farming scenario poster illustrating the possible implications of farming futures focused on (i) profitable farming and (ii) quality of food.

The exhibit was staffed by three to five researchers at any time, who engaged with participants to discuss the potential benefits and disadvantages of each scenario and how the different scenarios could be synergistic or antagonistic. The researchers were instructed to give unbiased and scientifically-based information and not to express a personal opinion on what scenario they thought best.

Participants were asked to indicate which of the scenarios were most important to them. Each future farming scenario was associated with a different colour and leaves of each colour were used as voting tokens. We did not want to make the activity a simple vote with participants choosing the scenario most important to them (i.e. picking one farming future), but to give participants the option of selecting up to four choices. Therefore, we designed a linked voting systems whereby participants were asked to choose four coloured leaves from the six options presented to them (repetition in choices was allowed), with linked votes representing the participants' balance of values. A key message for the participants at the voting stage was that you can't "have it all". The four leaves were then stapled together, and participants were asked to write their age category on the back, and any comments that they had, before they hung them on the Tree (time constraints ruled out writing comments at the LEAFed event). As the event went on the tree became covered in leaves providing immediate visual impact and an indication of the views of the event participants.

Data Analysis

The data gathered at each event comprised the composite sets of four leaves representing the choice made by each participant and an age category provided voluntarily by the participating visitors. The age categories were predefined before the event as a very broad range to be as inclusive as possible. So, for each set of four leaves, the number of leaves of each colour, age of participant, the event the participant attended, and any written comments were recorded.

We analysed the data to determine whether there were significant differences in choice of future farming scenario and whether this was affected by age or event. We did this fitting the data to a generalised linear model (GLM) assuming a Poisson distribution (natural logarithm link function). This statistical model is suited to the analysis of count data. We also considered the combined choice made by each individual by recording the frequency of each combination of four leaves across both events as well as within each event and each age category. Finally, to determine if there was any relationship between the different future farming scenarios and how likely they were to be chosen in combination we did hierarchical cluster analysis using the complete linkage method on the Canberra distance (weighted version of the Manhattan distance used for ranked lists) matrix (Jurman et al. 2009). The Canberra distance (d) between leaf choices (vectors $\mathbf{p}$ and $\mathbf{q}$) in n-dimensional vector space (where n is the number of participants) were given by

$$d(\mathbf{p},\mathbf{q}).=\sum_{i=1}^{n}\frac{|p_i-q_i|}{|p_i|+|q_i|} \qquad (1)$$

Equation 1

All analyses were done using R (2018). We analysed the comments written on the leaves by grouping them into categories of interest (i.e. future scenarios), and topics raised frequently by participants.

5.3 Results

Quantitative Analysis

Across the two events, 693 people took part: 663 at the Festival of Ideas and 30 at the LEAFed teenager engagement day. At the Festival of Ideas the majority of participants were in either the "under 11" or "Age 36–65" age category, whilst the LEAFed teenager engagement day was largely attended by teenagers aged 11–15 (Figure 5). A small number of participants did not record their age category and so we excluded these from the subsequent analyses. As there were so few participants at the teenager engagement day due to the supervised nature of the event we decided to combine the data from the two events and only consider age category as the main demographic variable of interest.

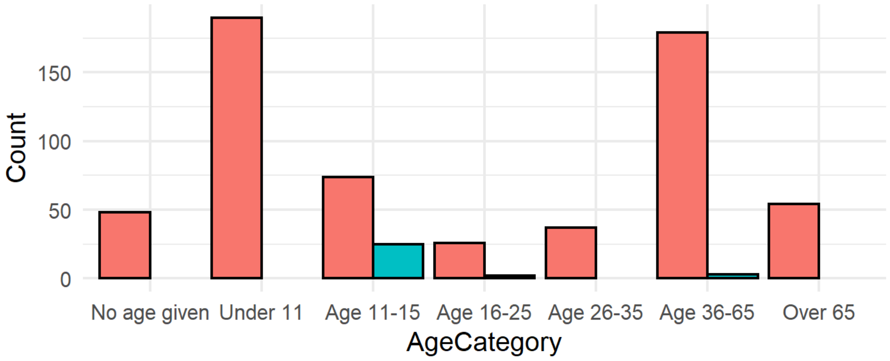


Figure 5- The count of people participating at each event presented according to age category. Participants in the Festival of Idea event are represented by red bars whilst participants in the LEAFed teenager engagement day are depicted by blue bars.

Of the total leaves recorded across all participants, the most popular scenario choice was *protecting the environment* with "*quality of food: good nutrition*" proving the second most popular. "*Food production*", "*affordable food*" and "*profitable farming*" all attracted relatively low numbers of votes, whilst "supporting rural communities" received intermediate support.

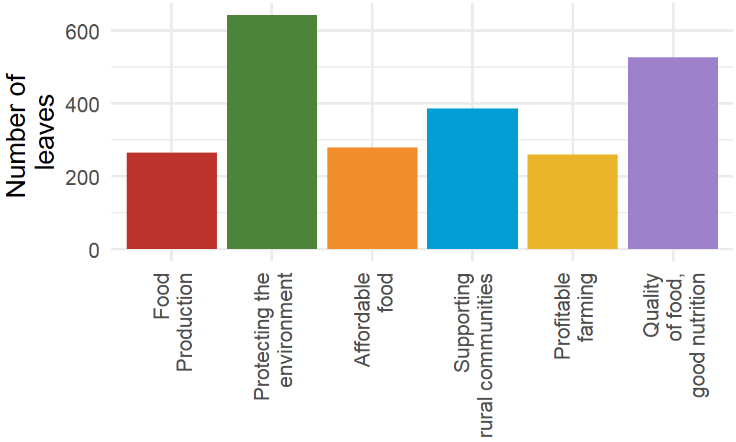


Figure 6- Total count of the number of leaves in each colour selected by participants across both events. Each colour of leaf represented a different future farming scenario.

There were significant differences between the number of leaves chosen for each secnario (P<0.001) but no significant differences between age categories (main effect or interaction, Figures 6 or 7), despite some emerging visual trends in the data indicating that the 26-35 age category have the greatest variation in their selections — this group selected the largest proportion of green leaves (protecting the environment) and the lowest proportion of yellow leaves (profitable farming) (Figure 7b).

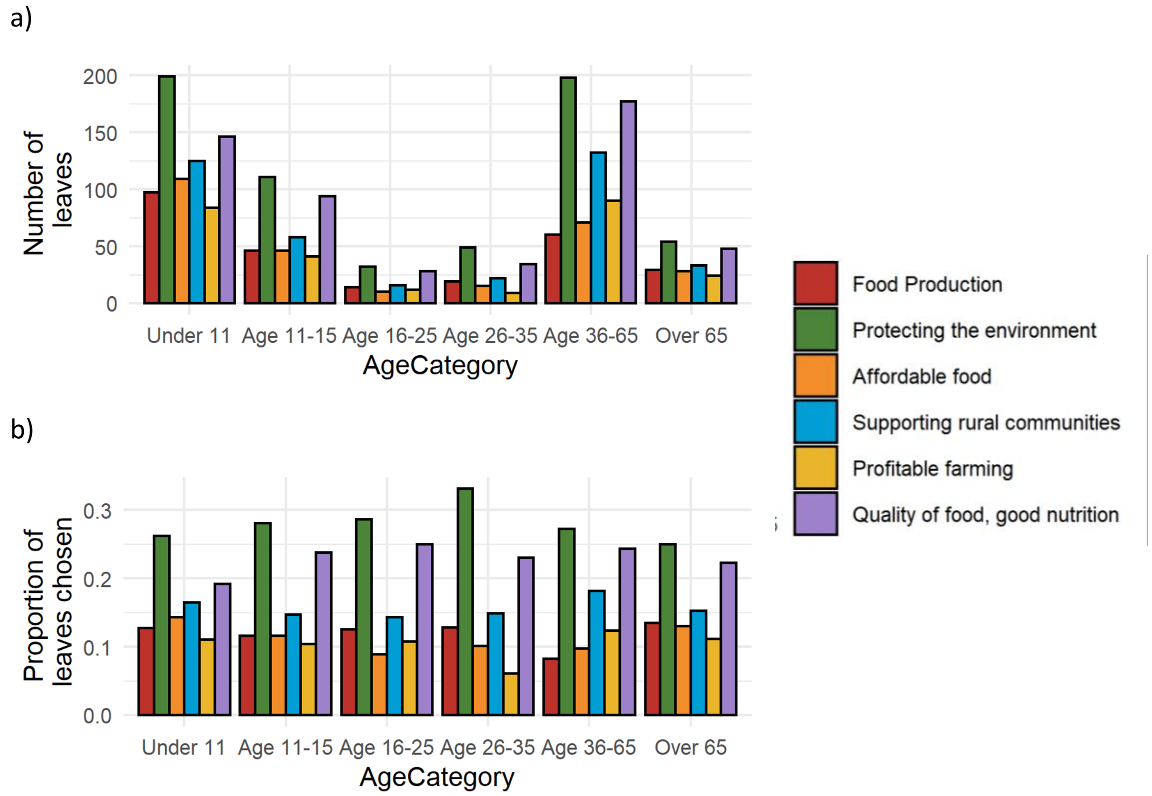


Figure 7- a) the total number of leaves chosen for each scenario according to age category, b) these counts were then scaled by the total number of participants in the age category.

Although we showed that there was no statistically significant effect of age, we omitted the under 11 age group from our subsequent quantitative analysis as it was clear to the researchers manning the exhibit that some smaller children were picking leaves according to colour and not scenario. When we considered the combined choice made by each individual some interesting trends emerged. Despite the very large possible number of combinations of four leaves (1296) that could have been chosen we only observed 45 different combinations across all participants from both events. Of these, 17 combinations were only observed once meaning that the remaining 28 combinations we observed were selected by more than one individual. In fact, some of the most popular combinations of scenario choices were made repeatedly by many different participants (see Table 1). Despite *profitable farming* being the least frequently selected scenario it appeared in the most frequently selected combination of leaves, which was *protecting the environment, supporting rural communities, profitable farming and quality of food* (chosen by 81 participants). The most popular leaf choice, “protecting the environment”, was in fact present in all ten of the leaf combinations chosen by over 10 people (Table 2)

Table 5- The most commonly chosen combinations of leaves (selected by more than 10 participants) and the number of participants choosing that combination across both events.

Combination of Leaf Choices	Number of People choosing that combination
Protecting the environment/Supporting rural communities/ Profitable farming/Quality of food	81
Protecting the environment/Affordable food/ Supporting rural communities/Quality of food	60
Food production/Protecting the environment/ Affordable food/Quality of food	40
Food production/Protecting the environment/ Supporting rural communities/Quality of food	34
Protectingtheenvironment/Protectingthe environment/Supporting rural communities/Quality of food	25
Food production/Protecting the environment/ Profitable farming/Quality of food	24
Protecting the environment/Affordable food/ Profitable farming/Quality of food	20
Food production/Protecting the environment/ Affordable food/Supporting rural communities	11
Protecting the environment/Protecting the environment/ Quality of food/Quality of Food	10

Finally, our cluster analysis (Figure 8) determined that the future scenarios most likely to be chosen in combination represented *Protecting the environment* and *Quality of food* and these were more closely linked with *Supporting rural communities* and *Profitable farming* than with *Food production* and *Affordable food*. This indicates that there was some cohesion in the way multiple participants considered the trade-offs between the future farming scenarios and there were certain scenarios that were deemed to be more compatible with one another than with the other scenarios.

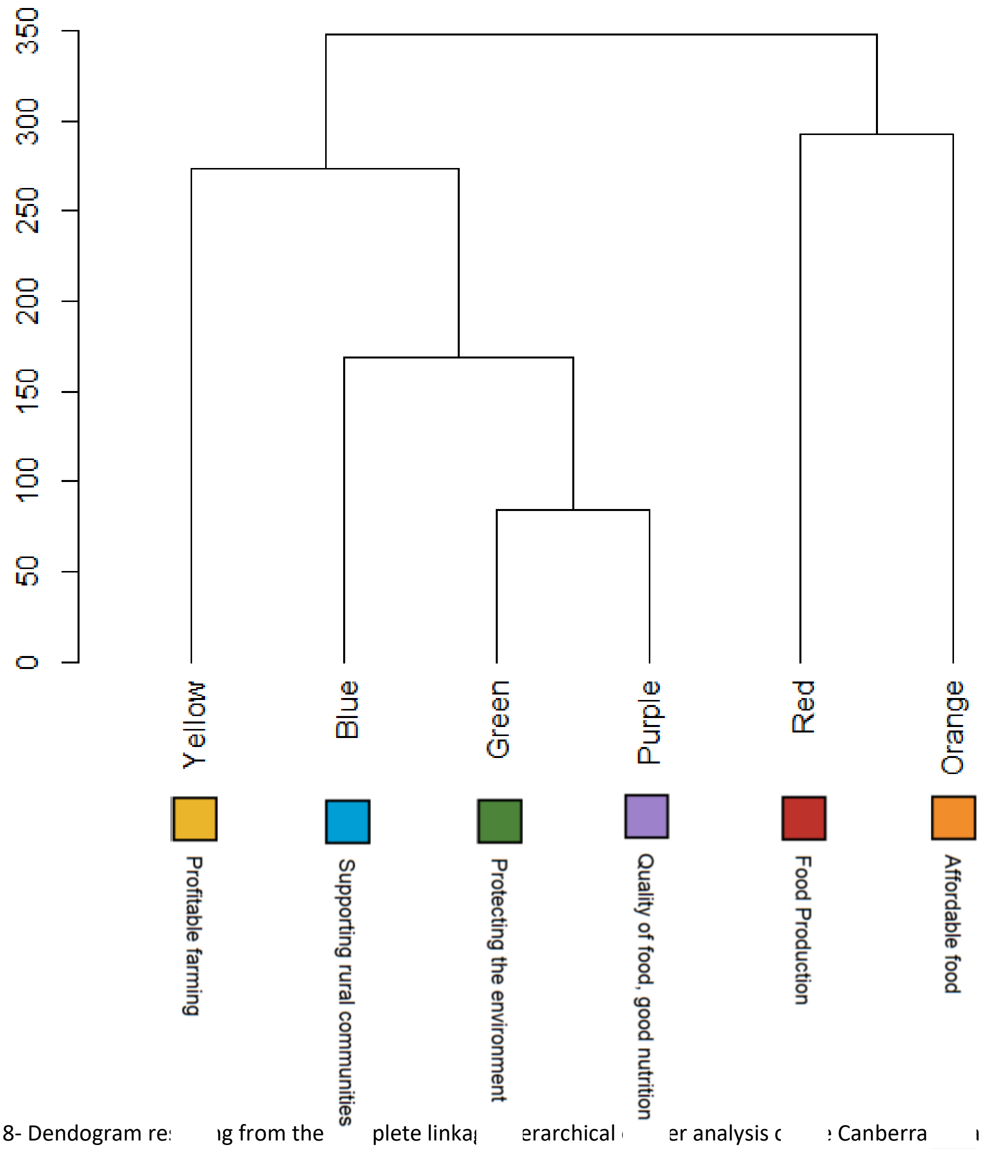


Figure 8- Dendogram re ng from the plete linka erarchical er analysis c Canberra nces between leaf choices. The axis shows the Canberra distance (d, see Equation 1) between choices. The distance between two choices is indicated by the score associated with the horitontal line which joins them,

Qualitative Analysis

Of the 633 leaf votes at the Festival of Ideas event, 49 had comments. Most of these were short sentences, but 42% were over 10 words, and 30% were over 20 words (Table 2).

Nearly half the comments detailed specifics or opinions on how to address future farming problems for example: *"Lifestyle change is crucial - if everyone cut down on the amount of meat they ate, there would be less need to increase food production to make farming profitable and food affordable as vegetables are cheaper."*, and over one quarter explained the choices of leaves for example: “*Food quality leaf: I am fortunate to be able to buy good quality. So this is important to me. Profitable farming leaf: Farmers have to make a living”.*

The most mentioned topic was the environment which appeared on 40% of the leaf-sets written on. The specific term “sustainable” was mentioned on 6 leaves. Animal welfare was commented on 7 leaves, and 3 leaves suggested vegetarian and vegan diets as a direction for future agriculture. The rising population was mentioned twice, and the need for increased production was recognised on 6 leaves. Profitability of farming was mentioned 8 times, mostly linked to rural community concerns which were mentioned 7 times. Concerns over rural communications were noted twice.

Quality of food was commented on as important 11 times, this was frequently linked to health and wellbeing (the word “health” was used in 6 comments). Themes of food security were raised in 12 comments, and 6 comments suggested that affordable food was particularly important. Divided by age, over a quarter of comments were left by under 11-year-olds, with far fewer comments left by the over 65s. (see Table 3). Generally younger people commented more explaining their choices, mentioning a broad range of topics, and using more words.

Table 6- Qualitative responses given as comments on leaves- categorised by attributes and topics, with percentage breakdown according to age group. Percentages of total of 25 and over in bold.

	Total		The percentage of participants according to age category / %						
Comment categorisation	N	%	under 11	11 to 15	16 to 25	26 to 35	36 to 65	over 65	not stated
Explaining choice	16	28	38	25	6	6	6	0	19
Specifics & opinions	24	42	8	17	21	13	17	0	25
> 10 words	17	30	24	24	29	6	0	0	18
> 20 words	10	18	10	40	30	0	0	0	20
Topic: Environment	23	40	17	22	26	9	9	4	13
Topic: Food quality	11	19	27	27	18	0	0	0	27
Topic: affordable food	6	11	50	17	17	0	0	0	17
Topic: Food security	12	21	17	33	25	0	8	0	17
Topic: Population	2	4	0	50	50	0	0	0	0
Topic: Production	6	11	17	33	33	0	0	0	17
Mentions: "health"	6	11	33	0	50	0	0	0	17
Mentions: vegan&/vegetarian	3	5	0	0	33	33	0	0	33
Mentions: "sustainability"	6	11	17	17	33	17	17	0	0
Mentions: animal welfare	7	12	43	14	0	29	0	0	14
Mentions: Rural communications	2	4	0	0	0	0	0	0	100
Mentions: Rural communities	7	12	29	29	14	0	14	0	14
Includes picture or smiley	8	14	50	0	0	13	13	0	25
Praises exhibit quality	2	4	0	0	0	50	50	0	0
Total number of comments	57		15	9	8	6	9	1	9
Percentage total comments			26%	16%	14%	11%	16%	2%	16%

The team of researchers who manned the Tree of Trade-offs reported that visitors across all age groups engaged well with the activity, with even young children taking the task seriously, although some young children did choose leaves based on colour. The researchers noted that participants found the trade-off concept stimulating with comments such as: *‘I want it all why can’t I have all of it’,* and *‘It’s really complex isn’t it’.* Some researchers found that through interactions and answering questions on the trade-offs and future scenarios, participant changed their initial choices of leaf votes. The researchers noted that generally young people wrote ‘long essays’ on the leaves, whilst older people tended to be more verbal-. Overall many visitors said that they had never really thought about the future direction of agriculture before, even though they realised it was very important.

5.4 Discussion

Aim 1: Promote awareness of the trade-offs associated with agricultural production

At each event the Tree of Trade-offs proved a successful exhibit for engaging participants across all age groups. The exercise was flexible enough to challenge each age group and stimulate input. Whilst teenagers and young adults can be motivated by environmental issues, it is usually difficult to engage young people with politics (Corner, 2015) and to encourage them to think about the impacts of policy. We found this exhibit was particularly powerful with younger people and noted that the longest and most detailed comments were written by young adults who truly engaged with the debate and complexities of the issue

The majority of comments was to be expected in the under 11 category because it was our largest group of participants (Fig. 2), however the 16-25 year olds (who formed a relatively small group) accounted for 14% of comments. These were frequently lengthy responses with specific recommendations and covered a broad range of issues. This may be because the 16-25 year olds will mostly still be in education, and so are more accustomed to explaining their answers in writing at school. The 35-65 year-old class, which was the second largest, left a similar number of comments. These comments were shorter and covered a smaller range of issues. This may be because many of the 36-65 year olds were looking after children and so were more pressed for time. We also noted that the older group was more likely to express opinions verbally.

Although the Festival of Ideas was an open public event with no entry fee, similar to many engagement activities of this kind our audience were self-selecting and so were already likely to be interested in farming, science and the environment. In addition, Harpenden is a commuter town a short distance from London, hence very affluent. Therefore, we must accept that although our data are useful they represent a biased sample of the population. The bias in the population sampled may limit the universal application of our findings. However, both verbal and written feedback from participants supported the idea that this technique was one that could be used to gather opinion from a more diverse cross section of the population.

Aim 2: Gather data on their choices and values.

The gathering of data from participants across a wide-range of ages was a key attribute of the exhibit. We were able to determine the differences in opinion between younger and older participants. Corner et al (2015) noted that younger participants in climate change studies have a more optimistic attitude to climate-change solutions than older participants. In their segmentation of farmers by beliefs and attitudes, Collier et al (2010) were able to make recommendations for targeted policy communication and direction for agricultural management. We noted that the top three leaf choices were consistent across age groups-, but the valuation of productivity, affordable food, and profitable farming varied (although not significantly). Discounting the views of the under 11s we noted that the 36-65 age group were the only group to value *Food production* lowest; and the 16-25 year olds were the only group to value affordable food least. Comments and feedback indicated that the younger participants had a broad awareness of issues, whilst older participants had narrower fields of concern. These aspects may be of value in segmenting the audience- perhaps older audiences need more awareness raising of the spectrum of issues, whilst younger audiences would benefit from specific case studies or linking to personal experiences.

Our voting system allowed us to discern the key trends in attitudes to the future direction of farming in the UK. Most notable was the high value placed on the environment, followed by the quality of food, and then supporting rural communities. Comments on the leaves elucidated opinions, the environment was seen as both valuable in its own right- for example *"if we don't protect the environment then it won't be sustainable for farming in the future*". The quality of food was frequently linked to human health and wellbeing, and rural communities with enterprise and productivity. This reflects participants values and priorities in recognition that the three pillars of environmental, social, and economic aspects are interconnected and interdependent.

The linked voting system allowed us to discern the synergies and antagonistic combinations of potential farming futures according to stakeholders' perceptions. The most frequently selected combination of leaves showed that many participants (12 %) believed *protecting the environment*, *supporting rural communities*, *profitable farming*, and *high quality food* should be key aims for future farming. The cluster analysis further confirmed that these choices were regularly linked, but showed that *profitable farming* was most closely linked to *supporting rural communities* and there is a clear conceptual synergy here. Interestingly *profitable farming* appeared in the most commonly chosen grouping but was the least voted for scenario. Notably, the cluster analysis showed that *affordable food* (which did not appear in the most common set of scenarios, Table 1) and *Food production* were least commonly associated with any other scenario.

Success and extension

Though the true representativeness of the dataset generated by the tree of trade-offs exhibit was limited by the events we exhibited at, our activity was successful in engaging a large sample of visitors at the Festival of Ideas, across all age groups. The extension at the LEAFed event to a slightly different audience was also successful, due to the flexibility of the concept and accessibility of the context visually and with advisory input.

In respect to gathering data on the opinions of different demographic groups, we discovered that younger people were more motivated to extend their answers in comments rather than verbal communication noted in older participants. In the social data-gathering literature there is a noted data bias in responses from the group of middle-aged working public, whose opinions may be vital for policy, health, and marketing purposes. This non-response error arises from the perceived effort and time in participation, also when the survey effort may occur- in work hours or downtime (Cui, 2003; Dillman 1991; MacDonald et al 2009). However, in our engagement by experiment, we managed to gather many responses from the usually non-responsive 35-65 year age group, with the leaf voting system. This may be due to the event providing a captive audience, and the activity may be perceived to be quick, fun and easy, and at the same time an educational and social activity for family members they are likely attending with. However, the exercise did not allow for gathering of more detailed opinions such as those of youth participants because the leaves were too small and the time too limited for extensive comment, that was desired by this group. We therefore recommend extending the exercise to give more space or opportunity for comments from youth participants, perhaps with follow-up questionnaires, workshops, or linked online message feedback.

Acknowledgements

Rothamsted Research receives grant aided support from the Biotechnology and Biological Sciences Research Council (BBSRC) of the United Kingdom. This research was funded by a DEFRA and EU collaborative project “Targets for Sustainable And Resilient Agriculture” (TSARA), received as part of the FACCE-JPI Surplus initiative, the Biotechnology and Biological Sciences

Research Council (BBSRC) Institute Strategic Programme (ISP) grants, “Soils to Nutrition” (S2N) grant number BBS/E/C/000I0330, and the joint Natural Environment Research Council (NERC) and Biotechnology and Biological Sciences Research Council (BBSRC) ISP grant “Achieving Sustainable Agricultural Systems” (ASSIST) grant number BBS/E/C/000I0100, using facilities funded by the BBSRC.

5.5 References

Ajzen, I., 2011. *The theory of planned behaviour: reactions and reflections*.

Ballantyne, A.G., 2016. Climate change communication: what can we learn from communication theory?. Wiley Interdisciplinary Reviews: *Climate Change*, 7(3), pp.329-344.

Brook Lyndhurst, 2006. Innovative Methods for Influencing Behaviours & Assessing Success, Triggering widespread adoption of sustainable behaviour. *Final Report for Defra* March 2006 [Online]. Available at: https://studylib.net/doc/18910649/final-report---defra-science-search

Bubela, T., Nisbet, M.C., Borchelt, R., Brunger, F., Critchley, C., Einsiedel, E., Geller, G., Gupta, A., Hampel, J., Hyde-Lay, R. and Jandciu, E.W., 2009. Science communication reconsidered. *Nature biotechnology*, *27*(6), p.514.

Cui, W.W., 2003. Reducing error in mail surveys. *Practical assessment, research & evaluation*, 8(18), pp.1-7.

Collier, A., Cotterill, A., Everett, T., Muckle, R., Pike, T. and Vanstone, A., 2010. Understanding and influencing behaviours: a review of social research, economics and policy making in Defra. *DEFRA, London*.

Corner, A., Roberts, O., Chiari, S., Völler, S., Mayrhuber, E.S., Mandl, S. and Monson, K., 2015. How do young people engage with climate change? The role of knowledge, values, message framing, and trusted communicators. Wiley Interdisciplinary Reviews: *Climate Change*, 6(5), pp.523-534.

De Schutter, O., 2011. The right of everyone to enjoy the benefits of scientific progress and the right to food: from conflict to complementarity. *Human Rights Quarterly*, 33(2), pp.304-350.

Dillman, D.A., 1991. The design and administration of mail surveys. *Annual review of sociology*, 17(1), pp.225-249.

Gaventa, J. and Barrett, G., 2010. So what difference does it make? Mapping the outcomes of citizen engagement. *IDS Working Papers*, *2010*(347), pp.01-72.

Gifford, R., 2011. The dragons of inaction: psychological barriers that limit climate change mitigation and adaptation. *American Psychologist*, 66(4), p.290.

Goodwin, J. and Dahlstrom, M.F., 2014. Communication strategies for earning trust in climate change debates. Wiley Interdisciplinary Reviews: *Climate Change*, 5(1), pp.151-160.

Hamm, A. 2015. Wissensvermittlung im Science Center – Kontextualisierte interaktive Ausstellungen als Wissensquelle für Erwachsene. PhD thesis Justus-Liebig-Universität Gießen.

Herring, R J, 2014. State science, risk and agricultural biotechnology: Bt cotton to Bt Brinjal in India. *Journal of Peasant Studies* 42, no. 1 (2015): 159-186.

Honigs, S., Stoll, S., and Finke, E., 2018. Düsseldorf: Aquazoo Löbbecke Museum Düsseldorf. Zoological Collections of Germany. In: Beck L. (eds.) Zoological Collections of Germany. *Natural History Collections.* Springer, Cham. https://doi.org/10.1007/978-3-319-44321-8_24

Jurman, G., Riccadonna, S., Visintainer, R. and Furlanello, C., 2009. Canberra distance on ranked lists. In Proceedings of advances in ranking NIPS 09 workshop (pp. 22-27). Citeseer.

Krishnan, S., & Novy, A. (2016). The role of botanic gardens in the twenty-first century. *CAB Reviews*, *11*(023), 1-10.

Lackner, B.C., Mohankumar, S.E.P., Damert, M., Petz, D., Meyer, L., Klug, R. and Reiter, B., 2018. Communicating Climate Change in a Museum Setting—A Case Study. In *Handbook of Climate Change Communication: Vol. 3* (pp. 225-240). Springer, Cham.

MacDonald, S.E., Newburn-Cook, C.V., Schopflocher, D. and Richter, S., 2009. Addressing nonresponse bias in postal surveys. *Public Health Nursing*, 26(1), pp.95-105.

Mayer, J.E., 2005. The Golden Rice controversy: useless science or unfounded criticism?. *BioScience*, 55(9), pp.726-727.

Mills, J., Gaskell, P., Ingram, J., Dwyer, J., Reed, M. and Short, C., 2017. Engaging farmers in environmental management through a better understanding of behaviour. *Agriculture and Human Values*, *34*(2), pp.283-299.

Miller, A. J., Novy, A., Glover, J., Kellogg, E. A., Maul, J. E., Raven, P., & Jackson, P. W., 2015. Expanding the role of botanical gardens in the future of food. *Nature plants*, 1(6), 15078.

Moser, S.C., 2014. Communicating adaptation to climate change: the art and science of public engagement when climate change comes home. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(3), pp.337-358.

Nerlich, B., Koteyko, N. and Brown, B., 2010. Theory and language of climate change communication. Wiley Interdisciplinary Reviews: *Climate Change,* 1(1), pp.97-110.

Nolan, J.M., Schultz, P.W., Cialdini, R.B., Goldstein, N.J. and Griskevicius, V., 2008. Normative social influence is underdetected. *Personality and social psychology bulletin*, *34*(7), pp.913-923.

Papanicolaou, T. N., Wacha, K. M., & Wilson, C. (2013). Exploring the role of multifunctional agriculture on the future of agriculture and rural development.

Petty, R.E. and Cacioppo, J.T., 2012. *Communication and persuasion: Central and peripheral routes to attitude change*. Springer Science & Business Media.

Rucker, D.D. and Petty, R.E., 2006. Increasing the effectiveness of communications to consumers: Recommendations based on elaboration likelihood and attitude certainty perspectives. *Journal of Public Policy & Marketing*, 25(1), pp.39-52.

Shome, D., Marx, S., Appelt, K., Arora, P., Balstad, R., Broad, K., Freedman, A., Handgraaf, M., Hardisty, D., Krantz, D. and Leiserowitz, A., 2009. The psychology of climate change communication: a guide for scientists, journalists, educators, political aides, and the interested public.

Squire, G.R., 2013. *LEAF Linking Environment and Farming: history, aims and Achievements*. https://www.hutton.ac.uk/sites/default/files/files/LEAF/LEAF_history_aims_achievements.pdf , last accessed 24/09/2019.

Stiff, J.B. and Mongeau, P.A., 1994. *Persuasive Communication*, NY.

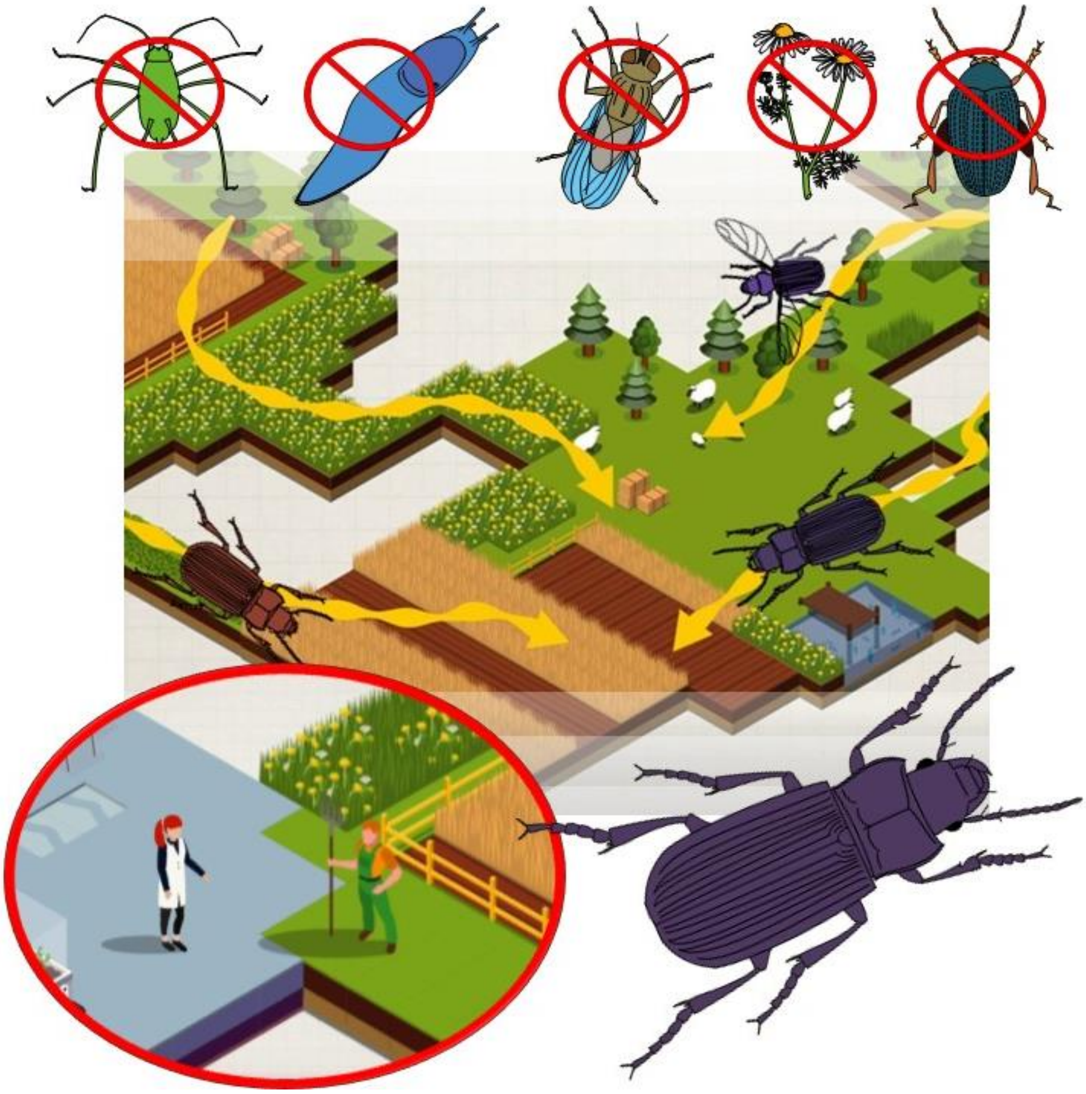
Tischner, U., Sto, E., Kjaernes, U., and Tukker, A., 2010. *System Innovation for Sustainability 3: Case studies in Sustainable Consumption and Production- Food and Agriculture*. Sheffield: Greanleaf.

Verbeke, W., 2005. Agriculture and the food industry in the information age. *European review of agricultural economics*, 32(3), pp.347-368.

World Bank, 2006. *Enhancing Agricultural Innovation: How to Go Beyond the Strengthening of Research Systems*. Washington DC: The International Bank for Reconstruction and Development/The World Bank.

Woolthuis, R.K., Lankhuizen, M. and Gilsing, V., 2005. A system failure framework for innovation policy design. *Technovation*, 25(6), pp.609-619.

Chapter 6



Two-way communication for multiple answers

This chapter comprises the first half of the engagement by experiment to complete objective 3. The work comprised engagement materials and a survey which was designed to answer multiple questions under the same umbrella; in attitudes to carabids, past and current management, management preferences, perceptions of self-monitoring of management, and barriers and opportunities for monitoring carabids. As such, the work was split in order to make a conceptually tight and succinct writeup for publications. Ideally a pre-post design would have more fully captured the treatment effects, but would have compromised the reach, completion, and therefore engagement aspect of the research. This chapter is currently under review for the journal Pest Management Science.

Communicating Carabids: Engaging farmers to encourage uptake of Integrated Pest Management.

Kelly Jowett[1,2], Alice E Milne[1], Simon G. Potts[3], Deepa Senapathi[3], Jonathan Storkey[1]

[1]Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK

[3]Centre for Agri-Environmental Research, School of Agriculture Policy and Development, University of Reading, Reading, RG6 6AR, UK

Corresponding Author: Kelly Jowett, Sustainable Agricultural Sciences, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK, Kelly.jowett@rothamsted.ac.uk

Abstract

BACKGROUND: Natural enemy pest control (NPC) is becoming more desirable as restrictions increase on pesticide use. Carabid beetles are proven agents of NPC, controlling pests and weeds in crop areas. Agro-ecological measures can be effective for boosting carabid abundance and associated NPC, however specifics of this are seldom communicated to farmers. We explore pathways to improved NPC by increasing knowledge about Farm Management Practices (FMPs) beneficial to carabids, within a framework of the Theory of Planned Behaviour. We used a questionnaire to measure awareness, beliefs, and attitudes to carabids with two treatments: a control, and engagement intervention. Engagement comprised of educational talks, animation, quiz, and factsheet.

RESULTS: We found awareness of carabid predation to be associated with beliefs of pest and weed control efficacy. Within the framework of TPB, we found that current implementation of FMPs was higher if farmers perceived them to be both important for carabids, and easy to implement. This was also true for future intention to implement, yet the perceived importance was influenced by engagement materials. Field margins/buffer strips and beetle banks were the most favoured by farmers as interventions for carabids.

CONCLUSION: The TPB is a valuable tool with which to examine the antecedents of farmer behaviour. Raising awareness of NPC associated with certain FMPs has the potential to change attitudes and increase uptake of sustainable practices. In this study self-selected participants were influenced by online engagement, yet more practical interventions may be necessary to increase general uptake of measures for NPC.

6.1 Introduction

6.1.1 Carabids as beneficial organisms in agro-ecosystems

The over-reliance on chemical crop protection products (CCPPs) has resulted in negative unintended consequences such as impacts on non-targets organisms and pollution of water courses. This has led policy makers to support more sustainable alternatives to controlling pests, weeds and diseases. The concept of Integrated Pest Management (IPM), which aims to integrate non-chemical approaches with pesticides to reduce the reliance of CCPPs, is central to the new approach. Eight principles of IPM have been identified[1] one being the prevention and suppression of pests by the protection and enhancement of beneficial organisms. This includes the management of crops and surrounding semi-natural habitats to build up populations of natural enemies of pests, elsewhere termed 'conservation biocontrol'.[1] The increased implementation of IPM by farmers is now explicitly acknowledged as a policy goal both at the European and UK level.[2] The UK government [3] recently published its 25 Year Environment Plan within which it states that: "We should put Integrated Pest Management (IPM) at the heart of an in-the-round approach, using pesticides more judiciously and supplementing them with improved crop husbandry and the use of natural predators." Barriers currently exist to meeting this goal. Some are to do with a lack of scientific understanding of the response of beneficials and pests to habitat management, and others are socio-economic, such as the lack of appropriate advisory support. Reducing the reliance of pesticides using an IPM approach means both equipping farmers with the required knowledge and convincing them of its efficacy. In particular, increasing the uptake of natural pest control (NPC) is particularly challenging as the natural control agents are often cryptic and not easily observed. In this paper, we explore the potential for overcoming barriers to take up of NPC, specifically by influencing farmers' attitudes to IPM, using the example of carabid beetles.

Carabid beetles have been comprehensively shown to be effective NPC agents, and much is known of the ecology and utility of their ecosystem services in agriculture. [4,5,6] The impact of management on carabids has also variously been described including impacts of machinery operations, fertiliser inputs, pesticide effects, and habitat provision.[7,8,9] Decades of carabid research would seem to have covered all the bases to inform practice. However, practice is still substantially lagging behind theory. Despite the documented utility of carabids in relation to crop protection, and growing demand for sustainable solutions to pest management [10,11] carabid beetles are not widely considered in farm management planning. This is in contrast to more charismatic taxa such as farmland birds that may be less cryptic but have a lesser functional role in supporting crop production.

6.1.2 The disconnect of science and application

Agri-environment schemes (AES) were introduced in the UK to mitigate the negative environmental impacts of the expansion and industrialisation of agriculture.[12] These schemes provide funding to farmers and land managers to farm in a way that supports biodiversity, enhances the landscape, and improves the quality of water, air and soil. Many AES options are potentially beneficial to carabid beetles. Measures such as tussocky grass margins, beetle banks, and hedges provide stable resources for carabids between the disturbed habitats that crop areas constitute.[9] Studies have confirmed that these areas encourage abundance and diversity of carabid beetles, that can 'spill over' into crop areas.[13,14,15] However, there is no mention in the current AES programme design, or documents given to farmers [12,16] of their value as agents of pest and weed seed regulation.

Studies have shown that mentioning specific taxa (farmland birds and pollinators) and options targeted at their ecological requirements in AES can often be effective for their conservation .[17,18,19] Carabids, as a suite of pest and weed seed predators are vital to the productivity of most farming systems.[10,11] Yet the only mention of beetles, and the justification for inclusion of beetle banks in AES is as food resources for farmland birds, [12] and there is potential to enhance the value of this and other AES options by also considering their role in NCP. Explicitly linking the conservation of biodiversity with its functionality in supporting crop production is also a necessary step to deliver to the stated UK policy goal of increasing the uptake of IPM.[3,4,20]

6.1.3 The problems of extension

It has been shown that when practitioners understand the premise and appreciate the benefits of a course of action, they are more likely to implement it effectively.[21,22,23] Some commentators have argued that is one of the reasons for the inconsistency of results from AES.[24] Extension comprising advice on the application of measures has typically been top-down knowledge transfer. Information from scientists is available to farmers, but often from third parties in a limited and inaccessible format that does not engender trust in practical application and efficacy.[25,26,27] In addition to this, educational content within AES communication focusses on the practical aspects of how to integrate measures into farming systems, crucially missing the contextual element of why and how the measures work to increase biodiversity and benefit ecosystem functioning and sustainability of farming.[16,24] Extension by bodies that are trusted by farmers can do more to capture hearts and minds, particularly in the case of farmland birds.[18, 19,28]

The main focus of AES extension has tended to address external factors, such as financial needs and technical abilities.[18,19] Influencing attitudes, therefore, may be one of the missing ingredients of extension when seeking to increase the uptake of IPM. In this regard, Ajjzen's [29] Theory of Planned behaviour (TPB) has proven to be a viable predictor of farmer behaviours.[30,31] The TPB posits *attitudes* as resulting from *beliefs*, multiplied by the *evaluation* of those beliefs.[29] Both knowledge about the theoretical basis of management interventions, and belief in its importance and efficacy are necessary to build the behavioural intent to implement measures in the face of uncertainty (Fig. 1). Knowledge *transfer* alone may therefore not have a strong effect on attitudes, as it has a weak effect on belief evaluation. A growing body of literature supports knowledge *exchange* as a way forward in building attitudes conducive to uptake of Agri-environmental measures, acting on perceptions of efficacy, [32,33,34] in the agricultural sphere this may comprise schemes for farmer education and farmer groups operating at a local scale and trialling AES design.[16,35,36,37] Efficacy is also largely interpreted in terms of biodiversity conservation *per se* as opposed to the potential contribution the enhancement of beneficial invertebrates to crop production in the context of IPM.[38] As yet, practical application of this is also piecemeal.[39]

6.1.4 Communicating carabids

Our aim was to identify the key factors that determine the likelihood of farmers implementing management strategies for improved NPC by carabids, and to assess their willingness to monitor the impact of management interventions. To that end, we framed our methodology around testing for evidence that if an intervention was *perceived* to be straightforward to implement, and *perceived* to have benefit in terms of crop protection, it was more likely to be adopted (Fig. 1). In support of this, we designed a questionnaire ('The Beneficial Beetles Survey') to measure current awareness of the role carabids play in NPC and the farm management practices (FMPs) that may increase their numbers. To investigate how likely farmers were to uptake FMPs we asked more general questions about the interventions they had previously adopted in support of sustainable production, whether these were done through AES or voluntarily and how difficult farmers perceived each was to implement.

We hypothesised that knowledge exchange would have significant positive impact on farmers attitudes to (i) the role carabids play in natural crop protection, (ii) their understanding of the importance of certain FMPs for enhancing NPC and (iii) their perceptions of how difficult implementing certain FMPs might be. To test this, we applied our questionnaire to two groups. A control group, who completed the questionnaire with no known prior interaction with the research team, and an intervention group who, prior to completing the questionnaire undertook an 'engagement intervention'. For this we designed several resources including a short educational video, to give an overview of how to conserve carabids in farmland and why it is important; a carabid ID quiz to build self-efficacy and familiarity with carabid species; and a factsheet to build self-efficacy in monitoring carabids (see appendix).

Our expectation was that the knowledge transfer and knowledge exchange interventions in the treatment group will act strongly on beliefs and evaluations, leading to a higher willingness to implement measures to support carabids.[29]

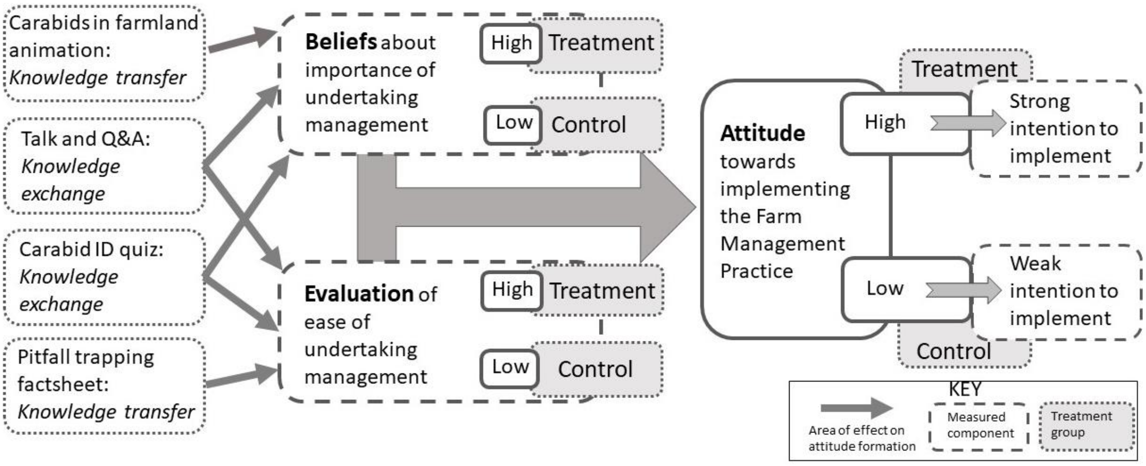


Figure 1-Hypothesised treatment effects, incorporating attitude formation as posited by the Theory of Planned Behaviour. The four engagement interventions (left hand boxes) impact beliefs about Farm Management Practices, and result in higher positive attitudes

6.2 Methods

An online questionnaire was disseminated in two rounds. For the first round, participants were not subjected to the knowledge exchange treatment, and we view this as our control group in the second round we also deployed a knowledge exchange treatment (see below). In the first round (April 2020 to June 2020), participants were enlisted through requests included in articles, podcasts, newsletters, and social media communications of researcher, institute, and agricultural organisations (supplementary). We were dependent on voluntary responses to an open request and were constrained by the numbers of respondents; although providing sufficient power for the control / treatment comparison, an a-priori selection based on controlling factors such as gender, educational background and experience was not possible. However, these factors were captured in the questionnaire and potential effects on the results included in the statistical analysis.

The questionnaire started with an opening statement explaining that carabid beetles are known to play a role in natural pest control predating on weeds and insect pests. This statement was given as context, with no indication of the significance of the predation. No additional educational information was given to this group, who we refer to as the Control Group. A review of the existing extension material available to farmers on habitat creation for NPC highlighted the paucity of information on habitat requirements of carabids and their potential contribution to pest control at the level delivered by our new material. We were, therefore, confident that the control group was not biased by previous access to equivalent educational material.

For the second-round (June 2020 to September 2020) participants were enlisted through four online events, as well as promotion on social media and relevant agricultural media and newsletters. At each event, there was a talk about carabids in farmland and question-answer session, and farmers were given details to take part in the study. Participants in the second round, who we refer to as the Treatment Group, were asked to view engagement material (see Section 2.2 for details) before completing the questionnaire. The Treatment Group questionnaire was kept separate by closing the control questionnaire, all questions remained the same, with the exception of a verification question ensuring participants had viewed all educational materials prior to the questionnaire.

6.2.1 Online questionnaire

The questionnaire was designed to measure knowledge and beliefs about carabid beetles, their role in NCP and farm management practices (FMPs) to conserve them. Following a context statement about carabids and pest control, the first section measured awareness of carabids and their importance for NPC. In this section we also measured their belief in their ability to identify carabids, and in the importance of carabids for pest control (see S1 for details).

Table 1: A summary of the questions asked in the questionnaire. The questions that were expected to be influenced by the intervention in the treatment group are indicated by *. See appendix for full content.

Question Description	**Response type**
Section 1 Carabids	

Q1 Before today were you aware that the beetles inhabiting your agricultural fields included carabid beetles?	Tickbox response, one could be selected of *Yes* or *No*
Q2 Do you believe you could identify a carabid beetle?	Tickbox response, one could be selected of *(i) Yes - many species; (ii) Yes- a few species and families (iii) Yes- as distinct from other types of beetle; (iv) Not sure; (v) Probably not; (vi) Definitely not*
Q3a Before today were you aware that carabid beetles eat crop pests such as aphids, slugs, caterpillars, grubs and mites?	Tickbox response, one could be selected of *Yes* or *No*
Q3b Before today were you aware that carabid beetles eat crop weed seeds such as dandelion, shepherds purse and chickweed?	Tickbox response, one could be selected of *Yes* or *No*
Q4a* Do you believe that carabid beetles can make a significant contribution to Crop insect pest control?	Tickbox response, one could be selected of *Yes, No*, or *Not sure*
Q4b* Do you believe that carabid beetles can make a significant contribution to Crop weed control?	Tickbox response, one could be selected of *Yes, No*, or *Not sure*
Question Description	**Response type**
Section 2 The farm environment and conservation	
Q5 Have you implemented the following farm management? (AES= agri-environment schemes)	The response was in the form of a table with rows associated with the FMPs listed in Table 2 and the columns associated with the responses *(i) In the past, through AES, (ii) In the past, voluntarily (iii) Currently, through AES, (iv) Currently, voluntarily (v) No/Not applicable.* Multiple columns could be selected for each FMP.
Q6 Do you carry out any of the above [FMPs] particularly with the aim of increasing the abundance of carabid beetles and their associated natural-enemy pest control? If so could you indicate which and provide some details please.	*Yes* or *No* with Qualitative response facilitated by a text entry box.
Q7* Which, if any, of the above options would you consider carrying out, or increasing the amount you do, in order to boost the abundance of carabid beetles and their associated natural-enemy pest control?	Qualitative response facilitated by a text entry box
Q8* Is there any reason you would be apprehensive about implementing any of the above options?	Qualitative response facilitated by a text entry box
Q9a* How important in your opinion is the following FMP to improving the control of crop pests by natural-enemies such as carabids?	The response was in the form of a table with rows associated with the FMPs listed in Table 2 and the columns associated with the responses *(i) Extremely important; (ii) Very important (iii) Moderately important- Slightly important (iv) Not at all important (v) Not sure*

Q9b How difficult would you rate the following farm management, in terms of implementing it on your farm (in terms of cost, labour, knowledge, equipment, and time)?	The response was in the form of a table with rows associated with the FMPs listed in Table 2 and the columns associated with the responses *(i) Extremely difficult; (ii) Moderately difficult; (iii) Slightly difficult (iv) Not at all difficult; (v) Not sure (vi) Impossible due to soil or landscape constraints (vii) Impossible due to legal or tenancy constraints.*
Section 3 Farmer attributes	
Q10 What is your farm type? Please tick the box that most accurately describes your farming enterprise.	Tickbox response, one could be selected of 10 options, from Defra categories (Defra 2020a): *(i) Dairy; (ii) LFA/upland Grazing Livestock; (iii) Lowland Grazing Livestock; (iv) Cereals; (v) General cropping; (vi) Pigs; (vii) Poultry; (viii) Mixed; (ix) Horticulture; (x) Not applicable* Classified for analysis as: Cereals; Livestock; General cropping; and Mixed
Question Description	**Response type**
Q11 What is the size of your farm?	Tickbox response, one could be selected of *(i) Under 20 hectares; (ii) 21 to 50 hectares; (iii) 51- 100 hectares; (iv) 101 - 500 hectares; (v) Over 500 hectares; (vi) Not applicable* Classified for analysis as: Under 50 ha; 50-100ha; 100-500ha; and Over 500ha
Q12 What are the sources of your farming experience and knowledge? Please tick all that apply (multiple boxes can be checked)	Tickbox response, one could be selected of *(i) Farming background;* *Farm work from childhood/ leaving school; (ii) College course/further education (agricultural); (iii) University level education (agricultural); (iv)* *Agricultural industry qualification- e.g. BASIS* Classified for analysis as: Non-formal education; Formal education; and Industry qualification
Q13 Do you receive advice on farm management from any of the following? Please tick all that apply (multiple boxes can be checked)	Tickbox response, one could be selected of *(i) Agricultural groups/bodies; (ii) Conservation organisations; (iii) Governmental organisations; (iv)Agronomists /professional advisors; (v) Industry representatives; (vi) Farm events/ training; (vii) Farmer networks/farming colleagues* Classified for analysis as: top-down advice *(i)-(v)*, and participatory advice *(vi)* and *(vii)*

The second section focused on options for enhancing NPC by carabids on farmland. We based our questions around 16 FMPs identified in the literature to have effects on carabids (Table 1). The practices can be divided into the provision of suitable non-cropped habitat (for which farmers can receive an AES subsidy) and changes in crop management that could also be part of an IPM strategy. In order to measure experience and implementation, we gathered data on current and past FMPs. To examine motivations, we also asked whether these were undertaken voluntarily or under subsidised AES, and if they carried out any of the practices specifically for carabids. We measured behavioural intent by asking whether they would consider carrying out or increasing the amount that they do of the FMPs in order to benefit carabids. We also asked about the barriers to implementing any of the FMPs. Respondents were asked how important they considered each FMP to be, to sustainable pest control mediated by carabids, and they were asked how difficult they perceived undertaking the measures to be (both on a 7-point likert scale).

Table 2- Farm management practices included in the questionnaire

Farm management practice (FMP)	**Literature citing significance to carabid abundance or distribution**
Habitat provision on un-cropped land	
Hedgerow maintenance	5, 6, 9, 14, 40, 41
Hedgerow establishment	4, 5, 6, 9, 14, 40
Beetle banks	9, 14, 40, 42
Field margins/ buffer strips	5, 6, 9, 41, 43, 44, 45
Ditch maintenance	6, 9, 14, 40, 41
Ponds/ wet areas/ waterbody creation	5, 6, 9, 41
Fallow land	9, 14
Natural area retention (e.g. woods, grassland)	4, 6, 9, 13, 46, 47
Crop management	
Cover cropping	14, 40, 48
Under sowing /companion crop	14, 49, 50, 51
Extensive (low) grazing	5, 52, 53
Low fertiliser input	5, 6, 14, 43, 40
Reduced tillage	7, 14, 43, 48, 54, 55, 56
Diverse cropping/rotations	14, 40, 57, 58
Low herbicide use	40, 59
Low pesticide/ antihelminth use	5, 6, 40, 60

To set the results of the questionnaire in context, and to control for mediating variables, the third section related to questions on basic farmer demographic data. This comprised information on profession, farm typology, farm size, education and sources of advice.

The questionnaire was piloted in interviews with four farmers from diverse backgrounds. Content was altered according to feedback. The questionnaire took between 20 – 45 minutes to complete.

6.2.2 Engagement materials

The engagement material made available to the treatment group comprised an interactive talk, an animation, a factsheet, and an educational quiz (appendix 4). The talk was 30-minutes long, split into three sections, i) carabid ecology ii) farm measures for carabid abundance and diversity, and iii) how and why to monitor carabids. After each section farmers were given the opportunity to ask questions and make comments. The three-minute ‘Carabid beetles in farm environments’ animation was designed to communicate key concepts of carabid ecology, including how and why they move in farm landscapes landscape, and highlight their role in pest and weed-seed control. The factsheet was designed to build self-efficacy and engage farmers in carabid monitoring. The short ID quiz was designed to engage farmers with carabid ID and teach basic ID skills. Questions were multiple choice with pictures of carabid beetles, followed by explanatory text on ID techniques. Participants for the Treatment Group were recruited from three 1-hour events where the talk was given (Table S1). Participants were emailed materials and an ethics statement.

6.2.3 Statistical analysis

Due to the impacts of the Covid19 outbreak in 2020, engagement events took place online rather than in person as planned. In all we received 190 responses to the questionnaire, 160 in the control, and 30 in the treatment group. The treatment group was smaller than we anticipated but large enough for valid statistical comparison. We chose to exclude responses where the first two questions were not completed, leaving 138 responses. For analysis of Section 2 of the questionnaire, (farm environment and conservation measures), we further excluded responses where less than 80% of this section was answered.

For the questions in Section 1, to account for mediating variables, we first tested to see if there were significant differences in responses according to demographic data (farm type, farm size). To do this we constructed contingency tables where the columns of the table related to the demographic class (e.g. in the case of farm type, the columns were the farm classification) and the rows the responses to the question ask (e.g. for Question 1, the rows related to “yes” and “no”). The categories for farmer demographic (farm type, size, background and source of advice) were relatively detailed. To avoid categories with too few responses we aggregated to coarser scale categories (coarse scale categories are shown in Table 1).

Under the null hypothesis responses are independent of demographic type, and so the same distribution of responses is expected. That is to say, the expected number of responses in a cell is the product of the respective marginal (row and column) totals divided by the total number of responses in the table. If the expected number of responses in the i th cell (out of N) is e_i and the observed number is o_i we then compute a statistic to measure the evidence against the null hypothesis. In principle under the null hypothesis, and with n_r rows and n_c columns in the table

$$X^2 = \sum_{i=1}^{N} (o_i - e_i)^2 / e_i$$

is distributed by χ^2 with $(n_c - 1)(n_r - 1)$ degrees of freedom, but the fact that o_i is an integer introduces an approximation when the o_i over many cells is small. For this reason, we obtain a *p*-value for the X^2 under the null hypothesis by the permutation method (Payne, 2011). In the event, we found no significant differences according to farmer demographics and so we did not test for these differences in relation to the responses for questions in Sections 2 and 3 (which were more complex in structure).

To test our hypothesis that engagement with farmers would have a positive impact on awareness, beliefs and perceptions of FMPs to enhance natural-enemy IPM, we used the χ^2 permutation test to determine whether there were significant differences in responses between control and treatment groups for questions indicated by * in Table 1. To analyse Q5, we also used the χ^2 permutation test to determine whether there were significant differences in the types of FSM undertaken voluntarily compared with AES both now and in the past (Q5 from Section 2). We also pooled responses over AES and voluntary for the two time periods and used a χ^2 permutation test to test for significant differences in the FMPs adopted by farmers between the two time periods. Qualitative comments (Q6 – 8) were categorised according to whether they mentioned particular practices or not. We were particularly interested in the types of FMP that farmers implemented with the aim of increasing the abundance of carabid beetles and their associated natural-enemy pest control (Q6) and which they might consider implementing for this reason in the future (Q7). For Q9 we also used the χ^2 permutation test to determine whether there were significant differences according to management type.

Under the TPB, attitudes are a product of beliefs multiplied by evaluations.[29] To visualise Q9a and Q9b under this framework, we calculated the average 'belief' in first the importance (Q9a) and secondly the difficulty of implementation (Q9b) for each FMP by applying numerical scoring to the categories and plotted them together. We scored 'Extremely important' as 4, through lowering importance, down to 0 for 'Not at all important'; and 'Not at all difficult' as 4, down to 1 for 'Extremely difficult'. We excluded categories of 'Impossible' as outside of theoretical decision making, and scored 'Not sure' as median.[61,62]

To determine to what extent the probability of an implementation of a FMP for natural pest control accorded was determined by these beliefs, responses to Q6 and Q7 (FMP that farmers are currently doing or would consider doing in the future) were modelled using data on belief in the importance of a FMP (Q9a) and difficulty of application (Q9b) as explanatory variables. We took the categorised responses to Q6 and Q7 and assigned 1 for mentioning, or 0 for not mentioning each FMP. Responses indicating that the participant did not practice any FMPs for carabids (Q6) or intend to do so (Q7) were excluded. We fitted General Linear Models (GLMs) using the Genstat statistical software package [63] to determine the effect of perceived importance of FMP (Q9a), perceived difficulty of FMP (Q9b), on the response variables quantified from Q6 and Q7. This included Treatment and Control groups as a factor to test our main hypothesis. We modelled only participants answering Q9. We excluded those answering "impossible" to Q9 as these can't be said to be making a decision, and "not sure" for both questions as these cannot fit into an ordinal scale of perception. We assumed a binomial distribution, and considered the importance, difficulty, and treatment level factors as fixed effects with three-way interactions. We selected terms using backwards elimination according to the largest p-value given by the Kenward-Roger approximate F -tests. The final predictive model was chosen when all remaining terms gave significant values ($P \leq 0.05$) when dropped from the model.

6.3 Results

6.3.1 Summary of data

For the control questionnaire 116 responses contained enough data for analysis. The subset of full responses to Section 2 of the questionnaire comprised 66 responses. Qualitative answers were collected from 67 responses. For the treatment questionnaire 22 responses contained enough data for analysis. The subset of responses to Section 2 of the questionnaire responses comprised 19 responses, all of which included qualitative responses.

There were no significant differences in farmer demographics between treatments. The majority of participants were arable farmers (cereal crops 34%, general cropping 18%). A large proportion had mixed farms (35%), with a much lower proportion farmed livestock alone (9%). The smallest proportion comprised horticulture (4%). The majority of participants reported farm size of 101-500 hectares (60%), followed by larger farms of >500 ha (20%). The smallest proportion of respondents (2%) had farms less than 20 ha in size. The demographics of our participants varied from national averages (Defra 2020a) in a larger median farm size and a greater proportion of cereal farmers.

Participants could select multiple sources of knowledge and experience. A ‘farming background’ and farming ‘from childhood’ were most frequently selected with 81.0% and 48.8% of participants selecting these options. Formal education was most frequently selected as college (47.6%), followed by industry qualifications (38.1%), then university (29.8%). Similarly, multiple sources of advice could be selected. Most frequent were events and training (77.1%), farmer networks (74.7%), agronomists (72.3%), agricultural groups (66.3%) and conservation groups (63.9%). Less frequently selected was governmental advice (39.8%), and industry representatives (34.9%).

6.3.2 Section 1: Awareness of carabids and beliefs around natural-enemy pest control (NPC)

For the four awareness questions (Q1 – 4), there were no significant effects of treatment group, or the demographic groups (farm type, size) on the responses. Therefore, we pooled the data across typologies and treatments. Of the 138 respondents, 87.0% were aware of carabid beetles before participation (Q1). One third indicated that they could identify a carabid beetle as distinct from other beetles, whilst 30.4% were unsure (Q2). Responses of confidence in identifying many species, and responses that they could not identify carabids at all shared the lowest frequency, both at 4.3%. Although 80.4% of respondents were aware before participation in the questionnaire that carabid beetles ate crop pests, only 25.9% were aware that carabid beetles eat weed seeds (Q3). Similarly, 77.5% of respondents believed that carabids could make a significant contribution to crop pest control, and only 2.9% did not believe as such, with a further 19.6%

unsure, whilst only 29.6% believed that carabids could make a significant contribution to weed control, 16.2% did not believe as such, with the largest proportion at 54.0% unsure (Q4). There was no significant difference in the responses to Q4a and b according to treatment.

6.3.3 Section 2: Farm environment and conservation

Answers to Q5 showed that most respondents had adopted one of the FMPs listed. The most frequently selected was Margins/buffer strips, followed by Hedgerow maintenance, Natural area retention, Diverse rotations, and Reduced tillage. The least selected were Beetle banks, Fallow land and Undersow/companion crop (Fig. 2).

There was a significant difference between past and current implementation (p<0.001, X^2 62.40, 15d.f), overall there has been an increase in implementation of the FMPs (Fig. 2). There were also significant differences in the types of FMPs adopted. Hedgerow establishment and Beetle banks were more frequently adopted in the past, and Reduced tillage more frequently adopted currently, than would be expected under the null hypothesis. Of the past implementation, there was a highly significant difference in FMPs adopted voluntarily or through AES (p<0.001, X^2 61.26, 30d.f.). Reduced tillage and Diverse crop rotation were adopted more voluntarily, whilst Beetle banks and Field margins/buffers were adopted more under AES than would be expected under the null hypothesis.

Of the current implementation, there was a significant difference between voluntary and AES implementation (p<0.001, X^2 153.10, 30d.f.). Reduced tillage, Diverse rotation, and Low pesticide use were adopted voluntarily more than expected under the null hypothesis. Whereas the adoption of Margins/buffer strips, both Hedgerow establishment, and maintenance, and Beetle banks was less than expected. The difference between the FMPs adopted voluntarily in the past was significantly different from that adopted currently (p=0.006, X^2 52.76, 30 d.f.) and the difference between past and current implementation by AES was not significant (p=0.953, X^2 18.31, 30d.f).

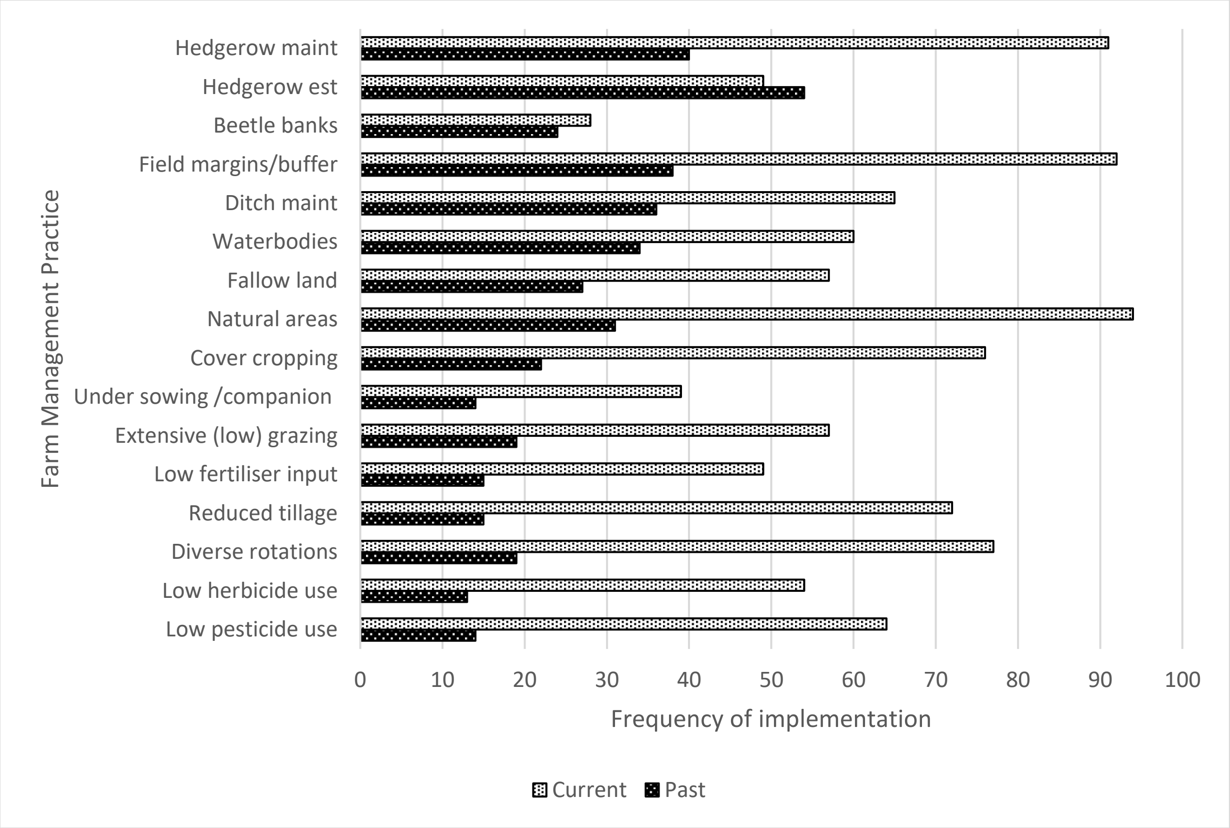


Figure 2- Question 5 responses: Farm Management Practices implemented by participants in the past, and currently

There were 72 qualitative responses to Q6. Given that this question relates to past activities we pooled the responses for analysis. Overall, 66% of responses indicated that they currently carry out FMPs for carabids. The FMP most frequently mentioned for carabids was reduced insecticide use (30.0%), followed by Beetle banks (15.0%) and Reduced tillage (12.0%). In further comments, the general value of invertebrates or ecosystem function was mentioned in 18% of responses, with pollinators specifically in 4%, for example "*Main aim is to increase abundance of ALL insects, carabids, pollinators and other predatory species alike*". A further 8% specifically mentioned soil health for example "*We are actively cover cropping and moving to zero tillage to promote all aspects of soil health including being a positive contributor to the insect world*".

For Q7, there were 73 qualitative responses. This question relates to the future intent of participants and so we expected to see a difference between the groups. For the Control group 89%, and Treatment group 100%, indicated that they would consider carrying out or increasing FMPs for carabids. For both groups, the FMP most frequently mentioned with intention to implement or increase implementation was Margins/buffer strips (16.9%), followed by Beetle banks (13.3%), then Cover crops (12.0), and Reduced tillage (10.8%). Notably, 12.5% of the Control

Group indicated they would consider reducing insecticides, whilst no one from the Treatment Group specifically mentioned this. The most frequent comment (control 26.3% treatment 18.7%) was that they would consider all of the FMPs, for example "*Any of them if I understand what they do and the benefits".* In further comments 3.1% of Control and 10.5% of Treatment group indicated the need for further advice for example "*I would like an advisor to visit to see what would be best for the farm as my knowledge is limited*.". In 7.8% of Control and 5.3% of Treatment responses, participants stated that they already do all or nearly all they can, for example "*as it is an organic farm much of this is done anyway"*. For the control 10.9 % indicated a need for AES support, with 4.5% specifically mentioning financial constraints, a further 1.6% mentioned potential loss of productivity for example "*depending on finances and schemes available*".

There were 79 qualitative responses for Q8 which asked about apprehension around implementation. For both groups, nearly 60%, indicated that there was a reason they would be apprehensive. For both groups, financial constraints were the most cited, followed by loss of productive land, and the potential for weed incursion into crops, for example "*…have a large influence on yield and therefore financial return"*. Time effectiveness, risk of crop loss, and crop quality concerns were less mentioned, along with physical constraints such as drainage

For Q9a, on the importance of FMPs for crop pest control by natural-enemies such as carabids, the most frequently ranked as '*Extremely important*' was Low pesticide use, followed by Reduced tillage, Margins/buffer strips, and Natural area retention. The most frequently ranked as '*Not at all important*' was Fallow land, followed by Low fertiliser use (Fig. 3). There were no significant differences between treatment groups.

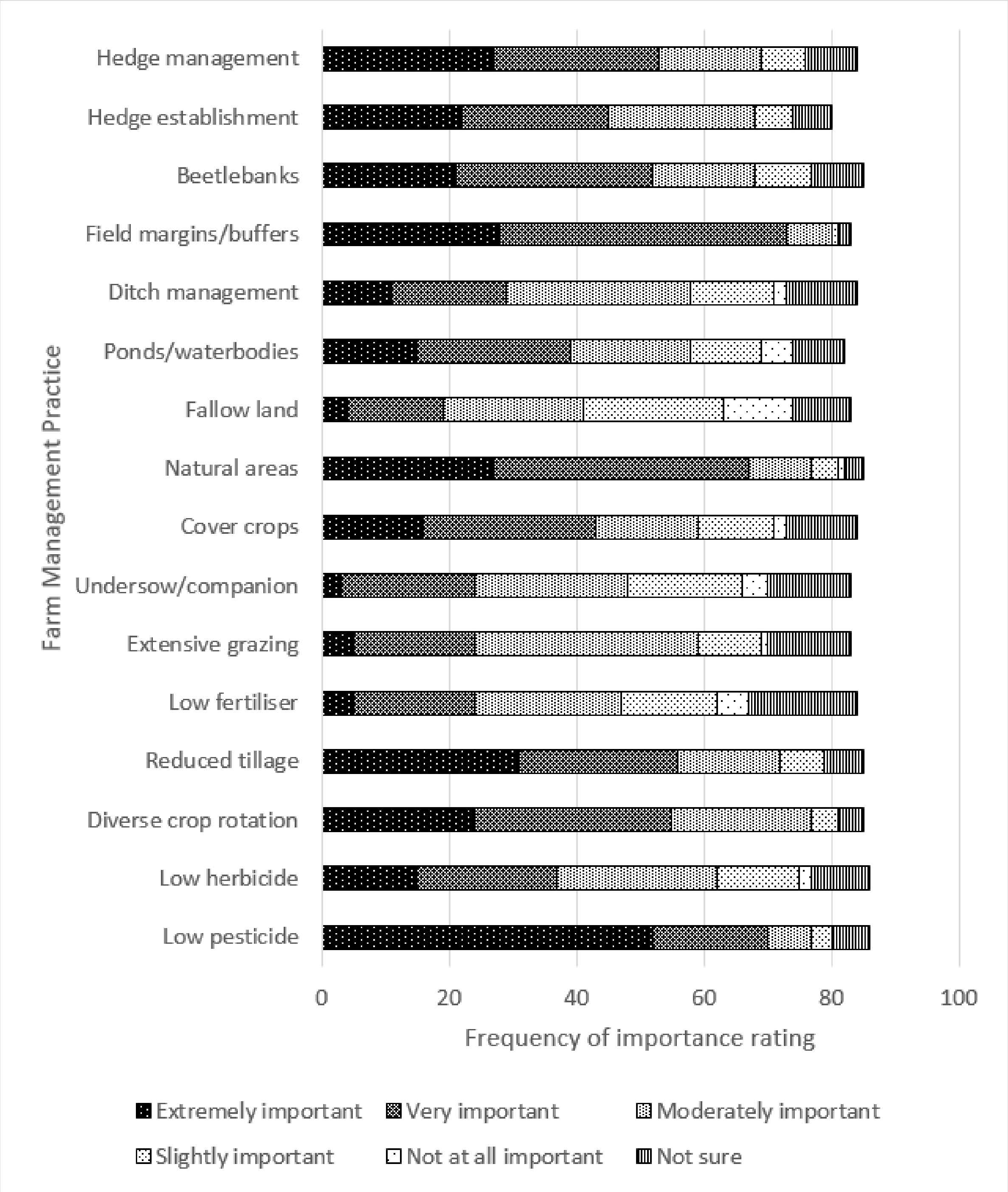


Figure 3- Farm management practices and perceptions of importance for carabids, as rated in responses to Q9a.

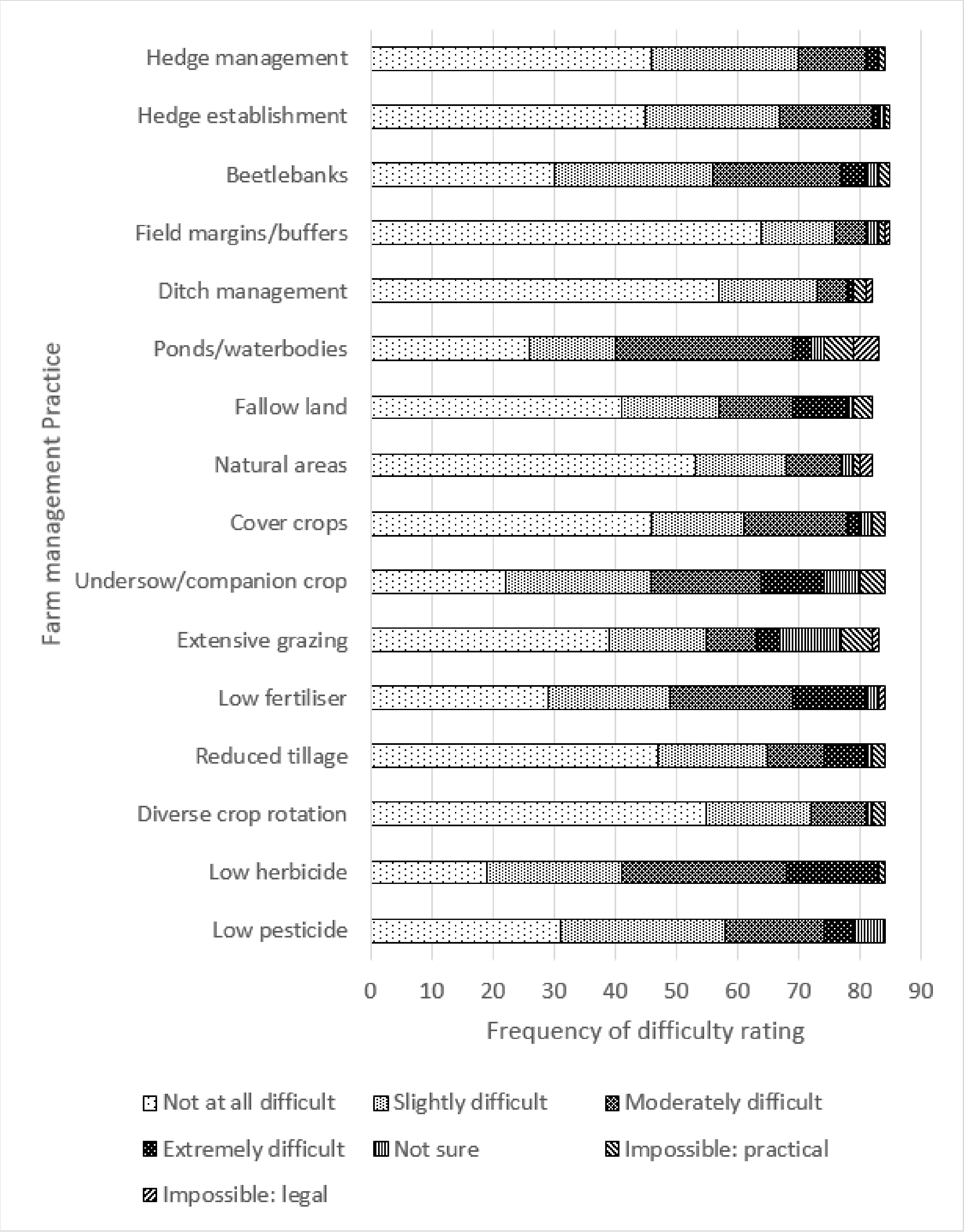


Figure 4-Farm management practices and perceptions of difficulty to implement, as rated in responses to Q9b

For Q9b, on the perceived difficulty of implementation, the most frequently ranked as '*Not at all difficult'* was Margins/buffer strips, followed by Ditch maintenance, Diverse rotation, and Natural area retention. Low herbicide use, and Low fertiliser use were most frequently ranked as '*Extremely difficult'*. Ponds/waterbodies and Low herbicide use were most frequently ranked as '*Moderately difficult'*, and Low Pesticide use and Beetle banks were most frequently ranked as '*Slightly difficult'* (Fig.4). There was no significant differences between treatment groups.

To visualise Q9a and Q9b under the TPB framework, scored responses were plotted together (Figure 5). Margins/buffer strips scored highest for both importance and ease, followed by Diverse rotation and Natural area retention. Ditch maintenance scored highly for ease, yet low for importance, and conversely Low pesticide use scored high for importance, and lower for ease. Undersow/companion crop and Low fertiliser use scored low for both importance and ease.

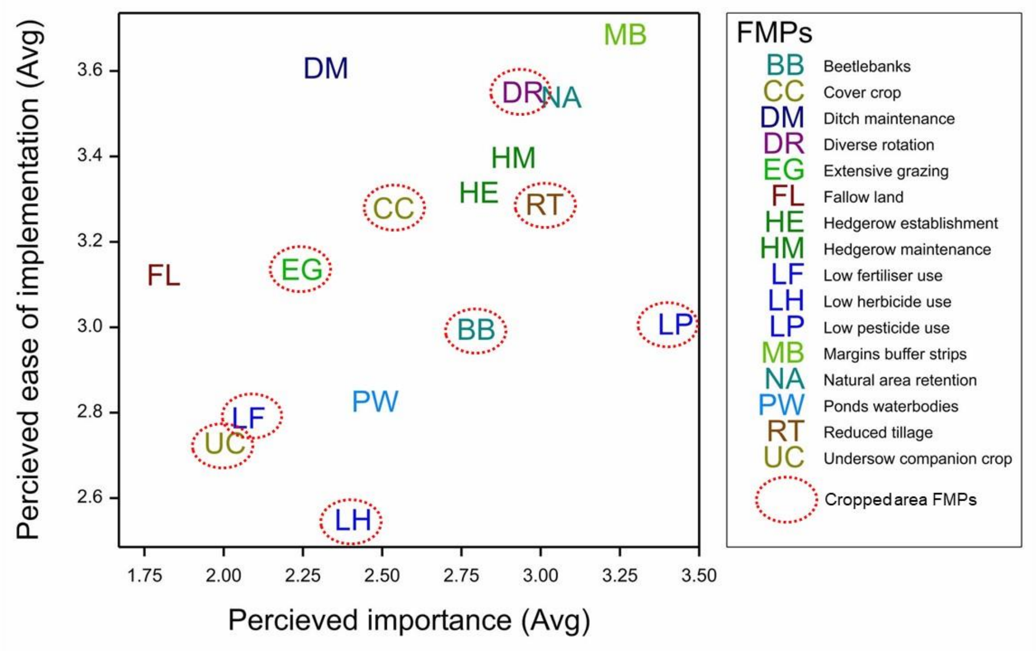


Figure 5- Average scores for Q9a Perceived importance of Farm Management Practice (FMP) for carabids, and Q9b Perceived difficulty of implementing the FMP

The fitted GLMM model for current implementation of FMPs for carabids retained both difficulty and importance (d.f. 7, F=13.82, p<0.001). Treatment was not retained in the model, and there were no interaction effects (Figure 6).

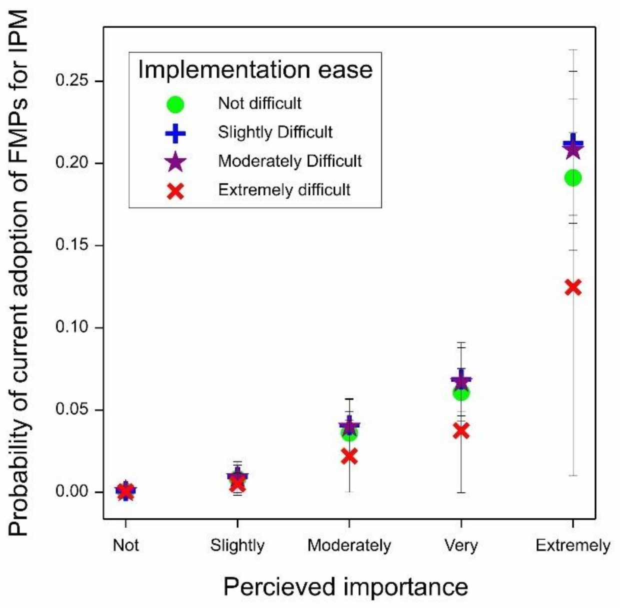


Figure 6- Model predictions for TPB framework. Q6 Current implementation of Farm Management Practices (FMPs) for Integrated Pest Control (IPC) by carabids, with Importance of FMP and percieved Ease of FMP.

The fitted model for intention to implement FMPs for carabids retained all terms, of treatment, difficulty, and importance (Figure 7a), with an interaction of importance and treatment (Figure 7b) (d.f. 12, F=3.51, p=0.007).

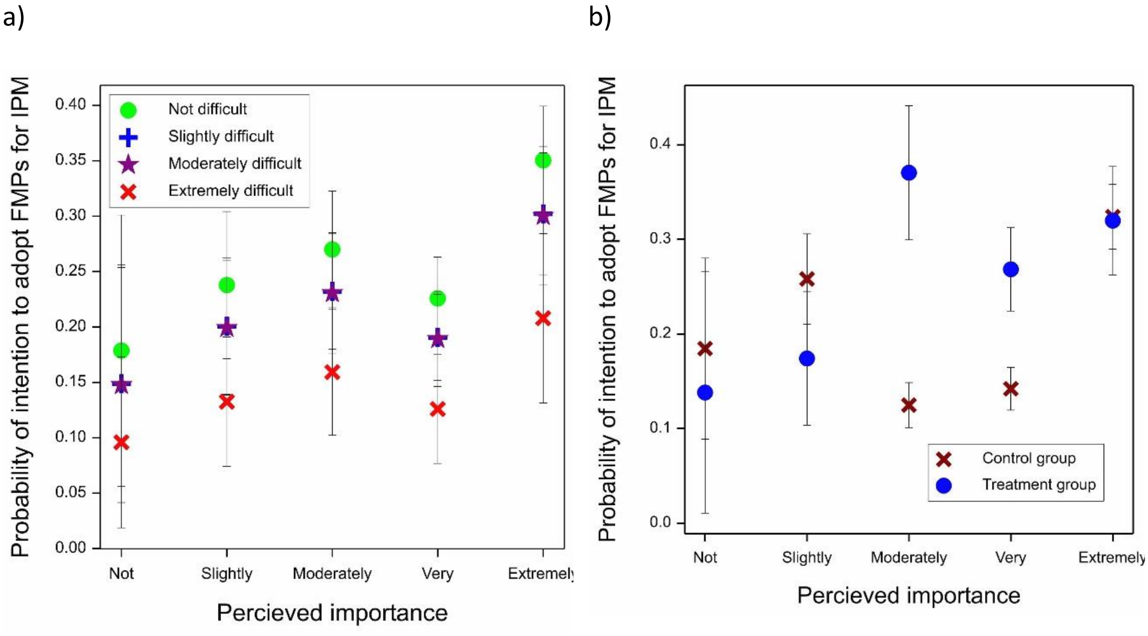


Figure 7- Model predictions for TPB framework. Q7 Future intent to implement of Farm Management Practices (FMPs) for Integrated Pest Control (IPC) by carabids, with a) Percieved Importance of FMP and perceived Ease of FMP and b) Control group and Treatment group

6.4 Discussion

6.4.1 The Theory of Planned Behaviour and UK farmer decision making

In this study we aimed to elucidate the key factors influencing the implementation of Farm Management Practices (FMPs) for Integrated Pest Management (IPM) by carabids, using a theoretical framework based on Ajzen's [29] Theory of planned Behaviour (TPB). The results show that the TPB is a useful framework when considering the factors surrounding implementation. Firstly, we see that those FMPs generally perceived to be both highly important for carabids, and easy to implement, were the ones that had already had the highest uptake. The responses to Q5 (past and current implementation) revealed that the most frequently adopted FMPs were Margins/buffer strips, Hedgerow maintenance, Natural area retention, Diverse rotations, and Reduced tillage, and the plot of average scores (Fig. 5) shows these particular FMPs clustered around the top right corner; where we would expect to see practices that are likely to be adopted under the TPB.

Some interesting nuances are apparent. Low pesticide use is ranked as very important for carabids yet somewhat difficult to implement, and this was in the median of FMPs adopted. Other in-field options, including reduced herbicide use, fertiliser use, and companion cropping were also perceived as being difficult to implement but of less importance for carabids. However, we note that Q5 asked only what FMPs had been adopted, not those adopted specifically for carabids; although Q6 (implementation for carabids) further reveals that the FMP most commonly adopted for natural-enemy pest control (NPC) was low pesticide use. Ditch maintenance was ranked as very easy, yet not ranked as very important for carabids (Fig. 5). Similarly, the discrepancy of the least adopted FMP according to Q5 being Beetle banks, despite its central position on the plot of perceived importance x perceived ease of implementation, may be attributed to the fact that it was carried out specifically for the benefit of natural enemies including carabids as seen in frequent comments for Q6.

The model explaining uptake of FMP further confirmed the TPB framework, with significant terms of both perceived importance and difficulty of implementation explaining which FMPs were adopted specifically for natural-enemy pest-control. Treatment proved not to be a significant factor in the model, and this is to be expected as it could not have affected the decisions already made (i.e. current management). Regarding future intention to implement management for carabids as evidenced by Q7 (future intention to implement for carabids), the model-based analysis revealed that importance and difficulty were again significant (Fig. 5), but this time

Treatment was also retained in the model (Fig. 7). This supports our hypothesis in that the Treatment had an effect on the strength of future intent to implement FMPs for carabids. This result also demonstrated the potential to encourage uptake of specific FMPs by influencing farmer perceptions about the efficacy of NPC. It also provides evidence for the importance of evaluation; shared experience of the successful implementation and efficacy of a current FMP is likely to encourage increased uptake in the future.

Figure 5 shows the Treatment had the largest effect in relation to participants responding with rankings of 'moderately' and 'very important', shifting the probability of adoption higher in the Treatment group compared to the Control. This may be attributed to the top portion being already persuaded, as the TPB hypothesises that strong beliefs of importance alone can lead to adoption, despite difficulty (Azjen 1991). This is supported in Qualitative responses to Q7 where some participants felt they already did all they could. The Elaboration Likelihood Model (Petty Haugtvedt and Smith, 1995) suggests that beliefs of importance creates stronger attitude change through higher engagement with persuasive materials. A high motivation causes receivers of a message to cognitively appraise the message content, whilst low motivation in receivers results in less scrutiny of the message (Stiff and Mongeau 2003). This may explain the responses of 'not important' and 'slightly important' being less influenced by the Treatment content, for example by cognitive dismissal of FMPs mentioned in the talks that were perceived as unimportant. These results could be used to target knowledge exchange activities at FMPs for which there is most potential to influence farmer behaviour.

6.4.2 Targeting of FMPs for outcomes

The most favoured FMP in respect to future intent was Margin/buffer strips, which accords with Fig. 5 and the TPB. Field margins and buffer strips have been comprehensively shown to be beneficial habitats for carabids, providing hibernation, aestivation, and stable resources in proximity to crop areas prone to disturbance. [6, 9, 43] However, margins are not necessary for all carabid species of significance to IPM, and moreover spill-over into crop habitats for pest and weed control is not guaranteed.[41] Other FMPs may be more desirable to boost abundance of beneficial species for IPM.

Butler, Vickery and Norris [64] examined the uptake of FMPs for cropped and non-cropped areas and found that despite there being more AES options for cropped areas, the main focus of current agreements was on hedgerow and margin management. This accords with our findings (Fig. 5) which largely confirm that interventions in non-cropped areas are more favoured. However, diverse rotations and reduced tillage are more popular than expected considering Butler et al's work, and this is likely to be because interest in regenerative farming practices has grown since the publication of the Butler study. These options were not widely supported in the past by AES,[65] yet farmers increasingly deem them of sufficient importance and lack of difficulty to implement, which may also reflect importance for other farmer priorities such as soil conservation.

Beetle banks are designed to support beetles, whilst not exclusively aimed at carabids, they provide a range of microclimates and alternative food resources, and are connected to edge habitats, theoretically nudging carabid abundances to field centres for IPM. [9, 14, 40, 42] Despite the potential benefits for crop pest control we found Beetle banks to be the least adopted overall (Q5).

Beetle banks were however, the second most mentioned as currently implemented for carabid beetles in Q6, and second most mentioned with future intent in Q7. This may be due to the balance of values in decision making. Farmers are subject to a range of influences on their decision making. IPM by natural enemies is only one facet of a healthy farm environment, and other FMPs may have perceived benefits outweighing the consideration of FMPs for carabids.

6.4.3 Lessons for communicating carabids to increase the uptake of IPM.

The questionnaire responses showed that prior to the survey most participants were aware of carabids in agricultural fields and their role as predators of crop invertebrate pests This was reflected in their beliefs about the efficacy of carabids for IPM of invertebrate pests. However, there was much lower awareness of their weed seed predation, likewise reflected in their lower level of belief in efficacy for weed seed regulation; contrary to the evidence in the literature.[5, 66]

We hypothesised that engagement materials would have the effect of more positive beliefs in efficacy, and more willingness to apply FMPs for carabids. The lack of difference for questions of attitude and belief between treatments may have been due to the sample attributes. Participants were self-selected, and as such were likely motivated individuals.[67] Farmer participants had a higher than average education level, and tended to participate in training and networking to acquire information , rather than relying on advisors alone.[68,69,70] The overwhelming majority also responded positively to Q7 on intent to apply FMPs for IPM in the future, demonstrating high motivation. The lack of significant differences between demographic variables may likewise be attributed to the homogenous sample.

Figure 1 is a simplified diagram showing only the conceptualised treatment effects upon attitudes, as a determinate of behavioural intent. In actualised scenarios, decision makers are subject to a range of factors and constraints governing the uptake of FMPs. Financial concerns were raised in qualitative responses, notably as unprompted responses from the control group to Q7- future intent. Since we see that the most popular measures for IPM by carabids have been adopted more by AES (Q5) this is important to consider. In light of this, and the higher biodiversity gain [64] in cropped area FMPs, leads us to propose that more effective financial support, or a demonstration of long-term financial benefits, for FMPs such as Diverse rotations, Reduced tillage, and Low pesticide use may have a higher impact. In Figure 5 we show that attitudes are positive towards these FMPs, so targeting practical constraints may bridge the gap between attitudes and adoption.

Given past disconnection from science to application, the high level of general engagement with the survey demonstrates the interest of farmers in beneficial insects for IPM. Attendance of talk events on carabids, and qualitative comments demonstrates the desire for information which further feeds into an argument for better provision of advice to support natural-enemy IPM.

6.5 Conclusions

The Theory of Planned Behaviour (TPB) is widely used in research around farmer behaviours, yet few studies document agro-ecological applications of this theory. Our findings confirm the utility of the TPB in examining where interventions may impact farmer decision making on Farm Management Practices (FMPs) for natural-enemy pest control (NPC). Online engagement materials were useful in targeting perceptions of the importance of FMPs for NPC and increasing the probability of future adoption of FMPs to benefit carabids for IPM. Perceptions of difficulty of application may be better targeted by practical engagement.

Farmer perceptions about the importance of FMPs in relation to NPC and how difficult these practices were to implement varied. This corresponded to past and current patterns of FMP adoption. Farmers had the highest positive attitudes to Margins/buffer strips, Hedgerow management, and Natural area retention. These may be easy wins in terms of take up, but more impactful intervention would target cropped areas for example Diverse crop rotations and Reduced tillage. These results highlighted the need for natural scientists to engage with and address socio-economic barriers to uptake when designing management interventions for IPM.

Farmers participating in this study were engaged by information about carabid beetles, and the implementation of IPM principles for sustainable pest control. We saw a level of trust in direct science communication which is encouraging. We recommend targeted engagement for enhanced uptake of IPM principles. Online materials were effective on farmers with neither very positive or very negative beliefs, more practical interventions may change attitudes and combat negative views on importance. The approach taken here could readily be applied to other components of functional biodiversity linked to farm production (e.g. earthworms) to help inform and motivate farmers to adopt sustainable practices for IPM.

Authors' Contributions

KJ, AEM, and JS conceived and designed the study. The research and analysis were performed by KJ and AEM with input from JS. All authors contributed to interpretation of results and writing the manuscript.

Acknowledgements

We thank Gary Frewin for animation design, and the Rothamsted communications dept for promotion. We thank William MacAlpine for agricultural organisation outreach, and the organisations LEAF, Agricology, BASE, CFE, FWAG, Agri-Tech- east, ADHB, RSPB and NFU for promotion activities.

KJ is grateful for funding from the Rothamsted-Reading Alliance. JS and AEM are supported by research programmes NE/N018125/1 LTS-M ASSIST – Achieving Sustainable Agricultural Systems, funded by NERC and BBSRC (BBS/E/C/000I0140), and the Smart Crop Protection (SCP) strategic programme (BBS/OS/CP/000001) and the Soil to Nutrition (S2N) strategic programme (BBS/E/C/000I0330) both funded by the BBSRC.

6.6 References

1 Barzman, M., Barberi, P., Birch, A.N.E., Boonekamp, P., Dachbrodt-Saaydeh, S., Graf, B., Hommel, B., Jensen, J.E., Kiss, J., Kudsk, P., Lamichhane, J.R., Messean, A., Moonen, A.C., Ratnadass, A., Ricci, P., Sarah, J.L., Sattin, M. Eight principles of integrated pest management. *Agronomy for Sustainable Development* **35**, 1199-1215. (2015).

2 EU. *Directive 2009/128/EC of the European parliament and of the council of 21 October 2009 establishing a framework for community action to achieve the sustainable use of pesticides*. Off J Eur Union 52:71–86, Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:2009:309:TOC [Accessed 13/01/21] (2009).

3 UKGOV. *A green future: our 25 year environment plan to improve the environment*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf [Accessed 13/01/21] (2018).

4 Bianchi, F.J., Booij, C.J.H. and Tscharntke, T. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proceedings of the Royal Society of London B: Biological Sciences*, **273(1595)**, pp.1715-1727. (2006).

5 Kotze DJ, Brandmayr P, Casale A, Dauffy-Richard E, Dekoninck W, Koivula MJ, Lövei GL, Mossakowski D, Noordijk J, Paarmann W, Pizzolotto R. Forty years of carabid beetle research in Europe–from taxonomy, biology, ecology and population studies to bioindication, habitat assessment and conservation*. ZooKeys.* (**100**):55. (2011).

6 Thielle, H.U. *Carabid beetles in their environments: a study on habitat selection by adaptations in physiology and behaviour* (**Vol. 10**). Springer Science & Business Media. (1977).

7 Baguette, M. and Hance, T.H. Carabid beetles and agricultural practices: influence of soil ploughing. *Biological Agriculture & Horticulture*, **15(1-4)**, pp.185-190. (1997).

8 Scopel, E., Triomphe, B., Affholder, F., Da Silva, F.A.M., Corbeels, M., Xavier, J.H.V., Lahmar, R., Recous, S., Bernoux, M., Blanchart, E. and de Carvalho Mendes, I. Conservation agriculture cropping systems in temperate and tropical conditions, performances and impacts. A review. *Agronomy for Sustainable Development*, **33(1)**, pp.113-130. (2013).

9 Thomas, C.G., Holland, J.M. and Brown, N.J. The spatial distribution of carabid beetles in agricultural landscapes. *The agroecology of carabid beetles*. Andover: Intercept, pp.305-344. (2002).

10 Sunderland, K. Invertebrate pest control by carabids. In: Holland, J.M. *The Agroecology of Carabid Beetles*. Andover: Intercept (2002).

11 Wezel, A., Casagrande, M., Celette, F., Vian, J.F., Ferrer, A. and Peigné, J. Agroecological practices for sustainable agriculture. A review. *Agronomy for sustainable development*, **34(1)**, pp.1-20. (2014).

12 HMGOV. *Countryside Stewardship Mid Tier and Wildlife Offers Manual*. Version 1.0. Available online at [www.gov.uk/rca/cs; accessed 09.03.20] (2020).

13 Boetzl, F.A., Krimmer, E., Krauss, J. and Steffan-Dewenter, I. Agri-environmental schemes promote ground-dwelling predators in adjacent oilseed rape fields: Diversity, species traits and distance-decay functions. *Journal of Applied Ecology*. (2018).

14 Kromp, B. Carabid beetles in sustainable agriculture: a review on pest control efficacy, cultivation impacts and enhancement. *Agriculture, Ecosystems & Environment*. **74, 1–3**, June 1999, Pp 187–228 (1999).

15 Tscharntke, T., Tylianakis, J.M., Wade, M.R., Wratter, S.D., Bengtsson, J. and Kleijn, D. Insect Conservation in Agricultural Landscapes. . In- Stewart A.J.A, New, T.R. and Lewis, O.T., 2007. Insect Conservation Biology. *Proceedings of the Royal Entomological Societies 23rd symposium*. Oxford: CABI. Pp 383-404. (2007).

16 Defra. *Environmental Land Management Policy discussion document February 2020*. Available online at [https://consult.defra.gov.uk/elm/elmpolicyconsultation/supporting_documents/elmdiscussion document20200225a%20002.pdf] accessed 09.03.20 (2020).

17 Baker, D.J., Freeman, S.N., Grice, P.V. & Siriwardena, G.M. Landscape-scale responses of birds to agri-environment management: a test of the English Environmental Stewardship scheme. *Journal of Applied Ecology,* **49**, 871– 882. (2012)

18 Perkins, A.J., Maggs, H.E., Watson, A. and Wilson, J.D. Adaptive management and targeting of agri-environment schemes does benefit biodiversity: a case study of the corn bunting Emberiza calandra. *Journal of Applied Ecology*, **48(3)**, pp.514-522. (2011).

19 Pywell, R.F., Heard, M.S., Bradbury, R.B., Hinsley, S., Nowakowski, M., Walker, K.J. & Bullock, J.M. Wildlife-friendly farming benefits rare birds, bees and plants. *Biology Letters*, **8,** 772– 775. (2012).

20 Bommarco, R., Vico, G. and Hallin, S. Exploiting ecosystem services in agriculture for increased food security. *Global Food Security*, **17**, pp.57-63. (2018).

21 Mills, J., Gaskell, P., Ingram, J. and Chaplin, S. Understanding farmers' motivations for providing unsubsidised environmental benefits. *Land use policy*, **76,** pp.697-707. (2018).

22 McCracken, M.E., Woodcock, B.A., Lobley, M., Pywell, R.F., Saratsi, E., Swetnam, R.D., Mortimer, S.R., Harris, S.J., Winter, M., Hinsley, S. and Bullock, J.M. Social and ecological drivers of success in agri-environment schemes: the roles of farmers and environmental context. *Journal of Applied Ecology*, **52(3)**, pp.696-705. (2015).

23 Riley, M. How does longer term participation in agri-environment schemes [re] shape farmers' environmental dispositions and identities? *Land Use Policy*, **52**, pp.62-75. (2016).

24 De Snoo, G.R., Herzon, I., Staats, H., Burton, R.J., Schindler, S., van Dijk, J., Lokhorst, A.M., Bullock, J.M., Lobley, M., Wrbka, T. and Schwarz, G., 2013. Toward effective nature conservation on farmland: making farmers matter. *Conservation Letters*, **6(1)**, pp.66-72.

25 Burton, R.J.F., Kuczera, C. & Schwarz, G. Exploring farmers' cultural resistance to voluntary agri-environmental schemes. Sociologia Ruralis, 48, 16– 37. (2008).

26 Mills, J., Gaskell, P., Ingram, J., Dwyer, J., Reed, M. and Short, C. Engaging farmers in environmental management through a better understanding of behaviour. *Agriculture and Human Values*, **34(2)**, pp.283-299. (2017).

27 Sutherland, L.A., Mills, J., Ingram, J., Burton, R.J., Dwyer, J. and Blackstock, K. Considering the source: Commercialisation and trust in agri-environmental information and advisory services in England. *Journal of environmental management*, **118**, pp.96-105. (2013).

28 Smallshire, D., Robertson, P. and Thompson, P. Policy into practice: the development and delivery of agri-environment schemes and supporting advice in England. *Ibis,* **146**, pp.250-258. (2004).

29 Ajzen, I. The theory of planned behavior. *Organizational behavior and human decision processes*, **50(2)**, pp.179-211. (1991).

30 Sok, J., Borges, J.R., Schmidt, P. and Ajzen, I. Farmer behaviour as reasoned action: a critical review of research with the theory of planned behaviour. *Journal of Agricultural Economics*. (2020).

31 Milne AE, Teiken C, Deledalle F, van den Bosch F, Gottwald T, McRoberts N. Growers' risk perception and trust in control options for huanglongbing citrus-disease in Florida and California. *Crop Protection*. **Dec** 1;114:177-86. (2018)

32 Burton, R.J. and Paragahawewa, U.H. Creating culturally sustainable agri-environmental schemes. *Journal of Rural Studies*, **27**(1), pp.95-104. (2011).

33 Ingram, J. Agronomist–farmer knowledge encounters: an analysis of knowledge exchange in the context of best management practices in England. *Agriculture and Human Values*, **25(3)**, pp.405-418. (2008).

34 Morris, C. Negotiating the boundary between state-led and farmer approaches to knowing nature: an analysis of UK agri-environment schemes. *Geoforum*, **37(1)**, pp.113-127. (2006).

35 Franks, J.R. and Emery, S.B. Incentivising collaborative conservation: Lessons from existing environmental Stewardship Scheme options. *Land Use Policy*, **30(1)**, pp.847-862. (2013).

36 Reed, M.S., Moxey, A., Prager, K., Hanley, N., Skates, J., Bonn, A., Evans, C.D., Glenk, K. and Thomson, K. Improving the link between payments and the provision of ecosystem services in agri-environment schemes. *Ecosystem Services*, **9**, pp.44-53. (2014).

37 Schomers, S., Matzdorf, B., Meyer, C. and Sattler, C. How local intermediaries improve the effectiveness of public payment for ecosystem services programs: the role of networks and agri-Environmental assistance. *Sustainability***, 7(10)**, pp.13856-13886. (2015).

38 Kleijn. D., and Sutherland, W.J. How effective are European agri-environment schemes in conserving and promoting biodiversity? *Journal of Applied Ecology*. **2003 40**. Pp 947–969 (2003).

39 Klerkx, L. and Proctor, A. Beyond fragmentation and disconnect: networks for knowledge exchange in the English land management advisory system. *Land Use Policy*, **30(1)**, pp.13-24. (2013).

40 Holland, J.M. and Luff, M.L. The effects of agricultural practices on Carabidae in temperate agroecosystems. *Integrated pest management reviews*, **5(2)**, pp.109-129. (2000).

41 Jowett, K., Milne, A.E., Metcalfe, H., Hassall, K.L., Potts, S.G., Senapathi, D. and Storkey, J. Species matter when considering landscape effects on carabid distributions. *Agriculture, Ecosystems & Environment*, **285**, p.106631. (2019).

42 Thomas, M.B., Mitchell, H.J. and Wratten, S.D. Abiotic and biotic factors influencing the winter distribution of predatory insects. *Oecologia*, **89(1)**, pp.78-84. (1992).

43, Eyre, M.D., Luff, M.L. and Leifert, C. Crop, field boundary, productivity and disturbance influences on ground beetles (Coleoptera, Carabidae) in the agroecosystem. *Agriculture, ecosystems & environment*, **165**, pp.60-67. (2013).

44 Holland, J.M., Birkett, T. and Southway, S. Contrasting the farm-scale spatio-temporal dynamics of boundary and field overwintering predatory beetles in arable crops. *Biocontrol*, **54(1)**, pp.19-33. https://doi.org/10.1007/s10526-008-9152-2 (2009).

45 Saska, P., Vodde, M., Heijerman, T., Westerman, P. & van der Werf, W.. The significance of a grassy field boundary for the spatial distribution of carabids within two cereal fields. *Agriculture, Ecosystems and Environment*, **122,** 427–434. (2007).

46 French, B.W. and Elliott, N.C. Temporal and spatial distribution of ground beetle (Coleoptera: Carabidae) assemblages in grasslands and adjacent wheat fields. *Pedobiologia*, **43(1)**, pp.73-84. (1999).

47 Labruyere, S., Bohan, D.A., Biju-Duval, L., Ricci, B. and Petit, S. Local, neighbor and landscape effects on the abundance of weed seed-eating carabids in arable fields: A nationwide analysis. *Basic and applied ecology*, **17(3)**, pp.230-239. https://doi.org/10.1016/j.baae.2015.10.008 (2016).

48, Gareau, T.P., Voortman, C. and Barbercheck, M. Carabid beetles (Coleoptera: Carabidae) differentially respond to soil management practices in feed and forage systems in transition to organic management. *Renewable Agriculture and Food Systems*, pp.1-18. (2019).

49, Armstrong, G. and McKinlay, R.G. The effect of undersowing cabbages with clover on the activity of carabid beetles. *Biological agriculture & horticulture*, **15(1-4)**, pp.269-277. (1997).

50 Theunissen, J. Intercropping in field vegetable crops: pest management by agrosystem diversification—an overview. *Pesticide Science*, **42(1)**, pp.65-68. (1994).

51 Theunissen, J. and Schelling, G. Undersowing carrots with clover: suppression of carrot rust fly (Psila rosae) and cavity spot (Pythium spp.) infestation. *Biological agriculture & horticulture*, **18(1)**, pp.67-76. (2000).

52 McFerran, D.M., Meharg, M.J., Montgomery, W.I. and McAdam, J.H. The impact of grazing on communities of ground-dwelling beetles (Coleoptera: Carabidae) in upland vegetation in north-east Ireland. In *Carabid beetles: ecology and evolution* (pp. 325-330). Springer, Dordrecht. (1994).

53 Woodcock, B.A., Potts, S.G., Westbury, D.B., Ramsay, A.J., Lambert, M., Harris, S.J. and Brown, V.K. The importance of sward architectural complexity in structuring predatory and phytophagous invertebrate assemblages. *Ecological Entomology*, **32(3)**, pp.302-311. (2007).

54 Blubaugh, C.K. and Kaplan, I. Tillage compromises weed seed predator activity across developmental stages. *Biological Control*, **81**, pp.76-82. (2015).

55 Hatten, T.D., Bosque-Pérez, N.A., Labonte, J.R., Guy, S.O. and Eigenbrode, S.D. Effects of tillage on the activity density and biological diversity of carabid beetles in spring and winter crops. *Environmental entomology*, **36(2)**, pp.356-368. (2007).

56 Lami, F., Boscutti, F., Masin, R., Sigura, M. and Marini, L. Seed predation intensity and stability in agro-ecosystems: Role of predator diversity and soil disturbance. *Agriculture, Ecosystems & Environment*, **288**, p.106720. (2020).

57, Kinnunen, H. and Tiainen, J. Carabid distribution in a farmland mosaic: the effect of patch type and location. In *Annales Zoologici Fennici* (pp. 149-158). Finnish Zoological and Botanical Publishing Board. (1999).

58 Redlich, S., Martin, E.A. and Steffan-Dewenter, I. Landscape-level crop diversity benefits biological pest control. *Journal of Applied Ecology*. (2018).

59 Brust, G.E. Direct and indirect effects of four herbicides on the activity of carabid beetles (Coleoptera: Carabidae). *Pesticide Science*, **30(3)**, pp.309-320. (1990).

60 Chiverton, P.A. Pitfall-trap catches of the carabid beetle Pterostichus melanarius, in relation to gut contents and prey densities, in insecticide treated and untreated spring barley. *Entomologia experimentalis et applicata*, **36(1)**, pp.23-30. (1984).

61 Denman, D.C., Baldwin, A.S., Betts, A.C., McQueen, A. and Tiro, J.A. Reducing “I don’t know” responses and missing survey data: Implications for measurement. *Medical Decision Making*, **38(6)**, pp.673-682. (2018).

61 Shoemaker, P.J., Eichholz, M. and Skewes, E.A. Item nonresponse: Distinguishing between don't know and refuse. *International Journal of Public Opinion Research*, **14(2)**, pp.193-201. (2002).

63 Payne, R.W. ed. *Genstat 5 release 3 reference manual*. Oxford University Press. (1993).

64 Butler, S.J., Vickery, J.A. & Norris, K. A risk assessment framework for evaluating progress towards sustainability targets. *Aspects of Applied Biology*, **81**, 317–323. (2007).

65 Defra. *Countryside Stewardship: Mid Tier Manual*. Published 14 March 2016. London: HMGOV (2016).

66 Petit, S., Bohan, D.A. and Dijon, A. The use of insects in integrated weed management. In *Integrated weed management for sustainable agriculture* (pp. 453-468). Burleigh dodds Science publishing. DOI: 10.19103/AS.2017.0025.23 (2018).

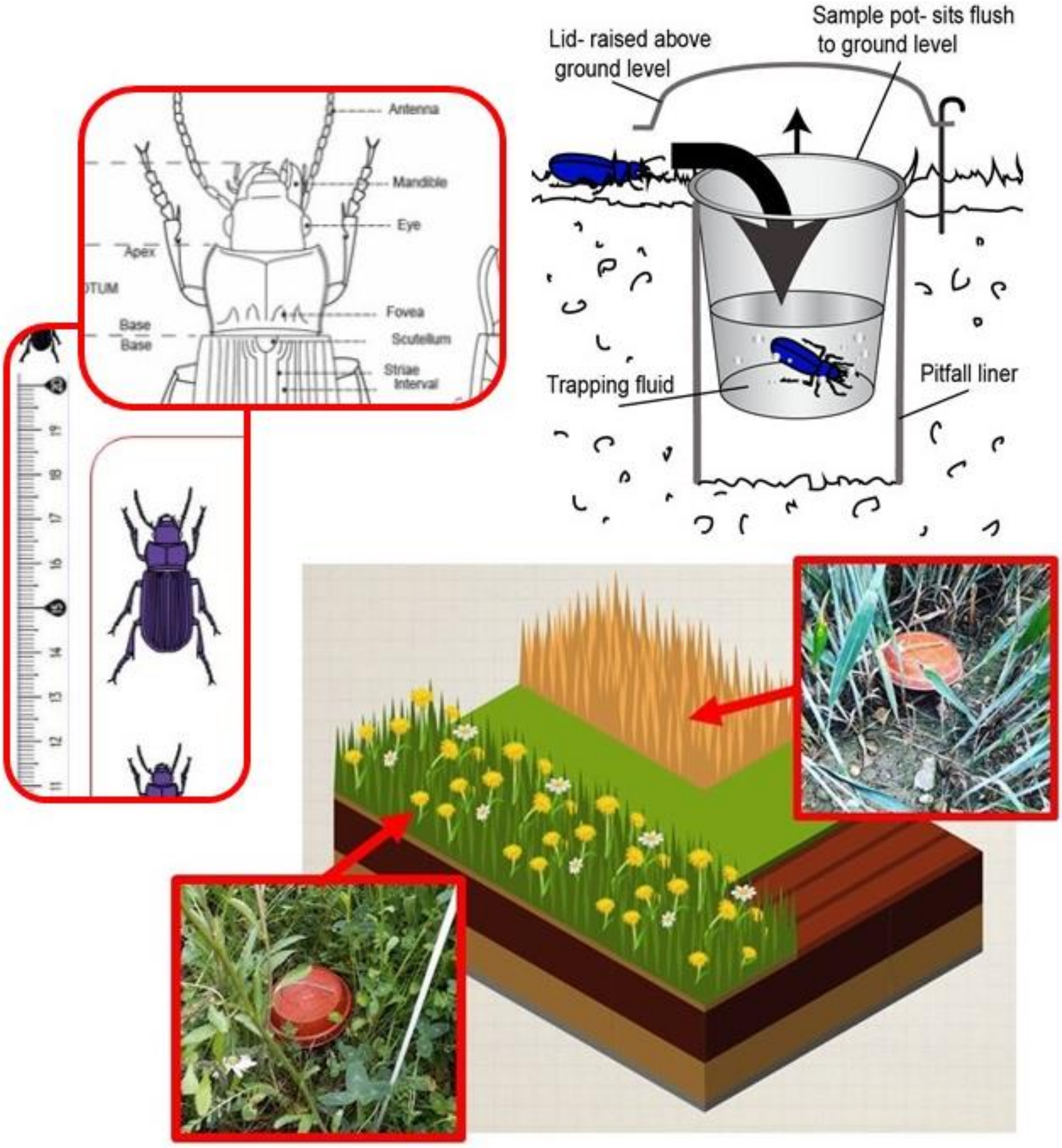
67 Petty, R., Haugtvedt, C. and Smith, S. Elaboration as a determinant of attitude strength: Creating attitudes that are persistent, resistant, and predictive of behavior. In *Attitude strength: Antecedents and consequences*, Edited by: Petty, R. and Krosnick, J. 93–103. Hillsdale, MI: Erlbaum (1995).

68 Defra. Farm labour profiles from the England and UK farm structure survey [Online]. Available at: https://www.gov.uk/government/statistics/farm-labour-profiles-from-the-england-and-uk-farm-structure-survey [Accessed 18/01/21] (2020).

69 Cole, A. Agri-Environment Monitoring and Evaluation Programme Annual Report 2017/18: A summary of findings from recently published projects. *Natural England Research Reports n079*. (2019).

70 Gasson, R. Educational qualifications of UK farmers: A review. *Journal of Rural Studies*, **14(4)**, pp.487-498. (1998).

Chapter 7



Ongoing engagement by experiment

This chapter comprises the second half of the engagement by experiment to complete objective 3. Some of the questions and content in this chapter resulted from the original thesis plan to run experimental workshops with farmers, with treatment groups of different ID materials. This part of the engagement was very popular, attracting interest in the materials further to the survey participation. Farmers expressed interest in monitoring experiments following the engagement, and materials have subsequently been used for engagement activities at agricultural events. There is considerable scope to build on the prospect of farmer self-monitoring to build adaptive management and provide large scale datasets.

Communicating Carabids: Engaging farmers with monitoring

Kelly Jowett[1,2], Alice E Milne[1], Simon G. Potts[3], Deepa Senapathi[3], Jonathan Storkey[1]

[1]Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK

[3]Centre for Agri-Environmental Research, School of Agriculture Policy and Development, University of Reading, Reading, RG6 6AR, UK

Corresponding Author: Kelly Jowett, Sustainable Agricultural Sciences, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK, Kelly.jowett@rothamsted.ac.uk

7.1 Introduction

7.1.1 Carabids as beneficials in farmland

Carabid beetles are effective agents of Natural-enemy Pest Control (NPC), predating on crop pests and weed seeds (Sunderland, 2002). Yet despite the documented utility of carabids in relation to crop protection, and growing demand for sustainable solutions to pest management (Wezel et al., 2014) carabid beetles are not widely considered in farm management planning. Furthermore, there is evidence that their numbers are in general decline across agricultural landscapes in the UK (Brooks et al., 2012).

Studies have shown that targeted Agri-environment Schemes (AES) for bird or pollinator groups have been effective for their conservation (Pywell et al., 2012). Since carabid declines are affecting the functioning of agro-ecosystems, AES in the UK are missing a key opportunity: conserving carabids in farmland can support a suite of mutually beneficial crop and weed control agents. Increasing restrictions on chemical pesticides and herbicides mean that NPC is becoming more important. Moreover, NPC by carabids is resource efficient and sustainable, supporting healthy environments (Sunderland et al., 2002; Wezel et al., 2014).

7.1.2 Farmer perceptions and agri-environment scheme uptake for carabids

Though no agri-environment scheme (AES) options are currently aimed specifically at carabids, many AES options (such as grass margins, beetle banks, and hedges), may encourage abundance and diversity of carabid beetles, that 'spill over' into crop areas (Bianchi, Booij, and Tscharntke, 2006; Dennis and Fry, 1992; Jowett et al., 2019). AES interventions in the UK are a primarily financial incentive, supporting agro-ecological principles by replacing income forgone in application of designed Farm Management Practices (FMPs) that target desired environmental outcomes. However, it has been shown that when agents understand the premise and benefits of a course of action, they are more likely to implement it effectively (Ajzen 1991). Commentators have argued that this is a major reason for the inconsistency of results from AES (De Snoo et al., 2013). Top-down advice within AES communication is missing the contextual elements of why and how the measures work to increase biodiversity and benefit ecosystem functioning, especially at a local level where it is important for farmers to understand impacts on productivity (Winter et al 1996). Specifically, for carabids there is no mention in the AES programme design, or documents given to farmers (Defra, 2020; HMGOV, 2020) of their value as agents of pest and weed seed regulation. This is in contrast to other 'ecosystem services', such as pollination (Nowalski, Edwards and Pywell 2020).

The Theory of planned Behaviour (TPB) has been used extensively in farmer behaviour, describing uptake of agricultural innovations including agro-ecology (Daxini, 2019, Sok et al., 2020). This theory leads us to posit that uptake of AES will be improved if farmers believe they are able to implement necessary actions, and that those actions will achieve desired results (Ajzen 1991; McCracken et al.,2015; Mills et al.,2017). A growing body of literature supports *knowledge exchange*, as a way forward in building attitudes conducive to uptake of agri-environmental measures, acting strongly on perceptions of efficacy (Ingram, 2008). However, practical application of this is as yet piecemeal, with even top-down knowledge transfer lacking in AES communication. Knowledge exchange with farmers has the potential to increase understanding of the benefits of agro-ecological approaches, whilst drawing in expertise to refine the application of these principles.

7.1.3 Monitoring as a tool or incentive for carabid conservation

A more direct component to farmer perceptions of importance and efficacy of management interventions is evidence that their undertaking is having an effect. Biodiversity monitoring is undertaken as a measure of efficacy of agri-environmental measures, yet past appraisal of ecological impacts has mainly been undertaken as site-based proof of concept (Boatman et al., 2019; Heard et al., 2012; Oatway, 2018). Individual indicators of success at a farm level are predominantly based on quality standards with little correlation to the ecological improvement afforded by interventions, and undertaken by external agents (MacDonald et al., 2019; Waylen et al., 2019). Voluntary monitoring schemes such as the BTO farmland bird survey have been successful in farmland, returning valuable data and engaging farmers in conservation (Gillings et al., 2005; Gregory, Noble, and Custance 2004). More recent studies have focused on monitoring species that have a more direct impact on crop yield, such as pollinators (Cole, 2019; Breeze et al., 2020; Gaba and Bretagnolle, 2020). Farmer self- monitoring that is more outcome-focussed and yield applicable have been recently trialled (Billaud, Vermeersch, and Porcher, 2020; Matzdorf, and Lorenz, 2010; Schroeder et al., 2013; Stroud, 2019), that show the benefits of engaging farmers with conservation outcomes. However, these have not focussed on pest control services for the farmer. Moving forward it is likely that monitoring will become a requirement for results-based payments in the new ELMS (Defra, 2020). Therefore, monitoring is important both in terms of reinforcing that actions have positive affect and to make quantitative measures for EMS.

Carabids are sensitive environmental indicators used in many scientific studies, but notably as indicators of environmental change in farmland, and as a proxy measure of predatory invertebrates (Sunderland, 2002). They are easy to capture with pitfall traps and are relatively easy to identify compared to other beneficial invertebrate genera. Therefore, monitoring of carabid beetles in farmland has great potential as part of a self-reinforcing cycle to improve attitudes and the application of measures, by demonstrating to farmers the efficacy of different interventions.

In order to promote uptake by farmers, it is important to understand the barriers to undertaking monitoring. As with AES measures, many of these may be practical or financial, for example, the materials needed for pitfall trapping, and the investment of time by the farmer. Therefore, the motivations of farmers may be a key aspect to examine when considering potential for uptake of monitoring. Past governance has assumed that as a financial enterprise, farmers are primarily motivated by financial considerations, and as such scheme design has centred on provision of reimbursement for income forgone in AES provisions (Lobley et al., 2013; Mills et al., 2017; Pike, 2008). However, much recent work is recognising the role of intrinsic motivations (internal beliefs) in farmer decision making, which may be as significant as extrinsic (external factors such as financial incentives) motivations (Bopp et al., 2019; Pederson et al., 2012; Russi et al., 2016; Valeeva, Lam and Hogeveen, 2017). This is supported by the literature on behavioural intent—whereby behavioural intent is formed on the basis of beliefs (Ajzen, 1991), and thus psychological barriers such as belief in efficacy or perceived abilities may act more strongly on decision making when considering a novel activity (Rodgers 2010).

7.1.4 Communicating carabids

Of central interest in this study was the willingness of farmers to monitor carabids and how this related to their perceptions of how straightforward monitoring was and why it might be important. The framework of the Theory of Planned Behaviour (TPB) (Azjen, 1991) is widely used in the agricultural sector to explore farmer decision making (Garforth and Rehman 2006; Mills et al 2017; Pike, 2008; Sok et al., 2010). The TPB has proven to be a useful tool in examining behavioural intent towards environmental management on farms (Daxini et al., 2019; Emery and Franks 2012; Mills et al, 2018; Schroeder, Chaplin, and Isselstein, 2015; Sutherland 2010), and particularly, farmer attitudes to Farm Management Practices (FMPs) beneficial to carabids (appendix 4 table 1) (Bagheri et al., 2019; Despotović, Rodić, and Caracciolo, 2019; Jowett et al., 2022). Therefore, we examine the willingness to monitor under three hypotheses:

H^1: We hypothesise that willingness to monitor, and motivations to monitor, will be affected by beliefs about perceived barriers to monitoring and beliefs about carabid beetles; and that this may vary by demographic group.

H^2: Under the TPB, attitudes may be considered as a multiplication of beliefs and evaluations. We also hypothesise that FMPs that farmers choose to prioritise for monitoring will be those they perceive to be important for carabids, and those that are easy to implement in their current farm system.

H^3: Further, we hypothesise that engagement would have significant positive impact on farmers (i) understanding of the importance of monitoring and (ii) their perceptions of how difficult this might be.

7.2 Methods

Our aim was to determine the willingness of farmers to monitor the impact of management interventions, and the key factors influencing this. In support of this, we designed a questionnaire (“The Beneficial Beetles Survey”) to measure current awareness of the role carabids play in natural crop protection and the management practices that may increase their numbers. The findings around the uptake of AES measures has previously been reported in Jowett et al., (2021). The willingness of farmers to monitor carabids is a separate issue, yet related to the content of the survey. Therefore, we also asked a set of questions around willingness to monitor, and the motivations and constraints surrounding this.

To test our hypotheses, we implemented our questionnaire with two groups. A control group, who completed the survey with no known prior interaction with the research team, and an intervention group who, prior to completing the survey undertook an “engagement intervention”. For this we designed several resources including a short educational video, to give an overview of how to conserve carabids in farmland and why it is important; a carabid ID quiz to build self-efficacy and familiarity with carabid species; and a pitfall trap factsheet to build self-efficacy in monitoring carabids. Our expectation was that the knowledge transfer and knowledge exchange interventions in the treatment group will act strongly on self-efficacy values, building a higher willingness to monitor carabids themselves (Rodgers, 2010) (Figure 1).

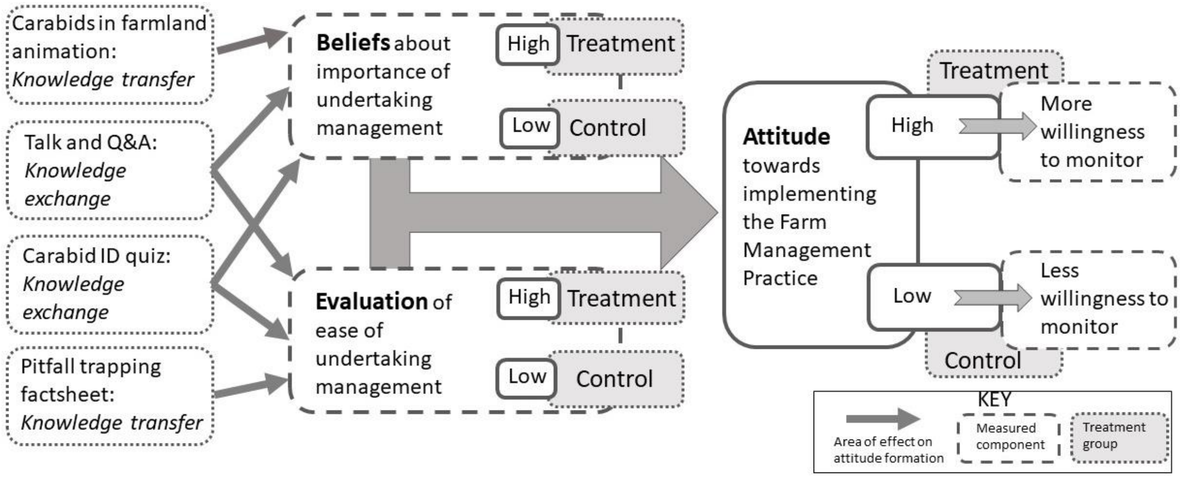


Figure 1- Hypothesised treatment effects, incorporating attitude formation as posited by the Theory of Planned Behaviour. The four engagement interventions (left hand boxes) impact beliefs about Farm Management Practices, and result in higher positive attitudes compared to a control group not receiving interventions; resulting in greater willingness to monitor.

Farmer attitudes and attributes were collected by an online questionnaire. The questionnaire (described below) was disseminated in two rounds. In the first round, participants were enlisted through a social media campaign. The questionnaire started with an opening statement explaining that carabid beetles are known to play a role in natural pest control predating on weeds and insect pests. No additional educational information was given to this group, who we refer to as the Control Group. For the second-round participants were enlisted through four online events, as well as promotion on social media and relevant agricultural media and newsletters. At each event, there was a talk about carabids in farmland and question-answer session, and farmers given further details to take part in the study. Participants in the second round were asked to view three educational materials before responding to the questionnaire: i) Carabids in farmland animation, ii) Carabid identification quiz, and iii) Pitfall trapping factsheet. This group receiving educational materials we refer to as the Treatment Group.

7.2.1 Online questionnaire

The questionnaire was designed to measure knowledge and beliefs about carabid beetles, farm management to conserve them, therefore the questionnaire was split into three sections. Following a context statement about carabids and pest control, the first section measured awareness, with questions about their awareness pre-questionnaire, of carabids, and carabid pest and weed control capabilities. In this section we also measured their beliefs, in self-efficacy to identify carabids, and in the significance of carabid pest control. In the second section the questions focused on farm environment conservation measures (see table 2, appendix 4 for details).

The third section focused on the farmers' willingness and motivation to monitor carabids. After a brief statement explaining tools for monitoring— their preferences for using ID books, field guides and phone apps was measured, along with their experience of using these tools. They were then asked about what FMPs they would prioritise for monitoring, and their current indicators of successful management.

Table 1: A summary of the questions analysed from the questionnaire. For full questionnaire see appendix 4.

Question Description	**Response type**
Section 1 Carabids	
BQ1 Do you believe you could identify a carabid beetle?	(i) Yes - many species; (ii) Yes- a few species and families (iii) Yes- as distinct from other types of beetle; (iv) Not sure; (v) Probably not; (vi) Definitely not
BQ2 Do you believe that carabid beetles can make a significant contribution to Crop insect pest control?	Yes, no, or not sure
BQ3 Do you believe that carabid beetles can make a significant contribution to Crop weed control?	Yes, no, or not sure
Section 2 The farm environment and conservation	
AQ1a * How important in your opinion is the following FMP to improving the control of crop pests by natural-enemies such as carabids?	The response was in the form of a table with rows associated with the FMPs listed in Table 2 and the columns associated with the responses (i) Extremely important; (ii) Very important (iii) Moderately important-(iv) Slightly important (v) Not at all important (vi) Not sure
AQ1b * How difficult would you rate the following farm management, in terms of implementing it on **your** farm (in terms of cost, labour, knowledge, equipment, and time)?	The response was in the form of a table with rows associated with the FMPs listed in Table 2 and the columns associated with the responses (i) Extremely difficult; (ii) Moderately difficult; (iii) Slightly difficult (iv) Not at all difficult; (v) Not sure (vi) Impossible due to soil or landscape constraints (vii) Impossible due to legal or tenancy constraints.
Section 3- Monitoring	
MQ1 Would you be willing to monitor the populations of carabid beetles relative to measures on your farm?	(i) Yes I already do this; (ii) Yes, if agronomist or advisor could do this; (iii) Yes, I would be willing to try myself if I had advice (iv) Yes, I feel I could do this myself without other advice (v) No, I would not be willing to do this (vi) I'm not sure
MQ2 Which of the following motivates you, or would motivate you, to monitor carabids on your farm? Please tick all that apply (multiple responses can be selected).	(i) Knowing they contribute to pest control; (ii) If I would receive support in farm payments; (iii) Knowing they contribute to weed control; (iv) If it supported evidence for farm payments; (v) I am interested in wildlife generally; (vi) If it was advised (e.g. by agronomist) as part of an IPM plan.
MQ3 How likely would you be to use the following, if they were available to you, for monitoring invertebrates on your farm?	The response was in the form of a table with rows associated with ID options (a) ID books with dichotomous (choice) keys; (b) Field guides/sheets; (c) Phone app and the columns associated with the responses (i) Extremely likely; (ii) Moderately likely (iii) Slightly likely (iv) Neither likely nor unlikely (v) Slightly unlikely (vi) Moderately unlikely (vii) Extremely unlikely.
MQ4 Do you currently use any of the above for monitoring or personal enjoyment of farmland wildlife such as insects, birds, or wildflowers, on your farm? Please give detail.	Qualitative response facilitated by a text entry box

Question Description	**Response type**
MQ5 What do you think are barriers to monitoring carabids yourself? Please tick all that apply	6 tick boxes, multiple could be ticked. Lack of time, lack of training/knowledge, Lack of equipment/resources, Do not believe it is an informative measure of effectiveness of management, Do not believe it is important to monitor carabids, There are no barriers to me doing this.
MQ6 If you were going to monitor farm habitats or management on your farm, which would you prioritise? i.e. to measure the effectiveness of maintaining or managing that aspect of your farm practices.	The responses related to the FMPs (listed in Table 3, appendix 4). Multiple boxes can be ticked
MQ7 How do you currently judge the success of agri-environment measures you have put in on your farm?	Qualitative response facilitated by a text entry box
Section 4 Farmer attributes	
FQ1 What is your farm type? Please tick the box that most accurately describes your farming enterprise.	10 options, from DEFRA categories (ref): (i) Dairy; (ii) LFA/upland Grazing Livestock; (iii) Lowland Grazing Livestock; (iv) Cereals; (v) General cropping; (vi) Pigs; (vii) Poultry; (viii) Mixed; (ix) Horticulture; (x) Not applicable
FQ2 What is the size of your farm?	(i) Under 20 hectares; (ii) 21 to 50 hectares; (iii) 51- 100 hectares; (iv) 101 - 500 hectares; (v) Over 500 hectares; (vi) Not applicable
FQ3 What are the sources of your farming experience and knowledge? Please tick all that apply? (multiple boxes can be checked)	(i) Farming background; Farm work from childhood/ leaving school; (ii) College course/further education (agricultural); (iii) University level education (agricultural); (iv) Agricultural industry qualification- e.g. BASIS
FQ4 Do you receive advice on farm management from any of the following? Please tick all that apply? (multiple boxes can be checked)	(i) Agricultural groups/bodies; (ii) Conservation organisations; (iii) Governmental organisations; (iv) Agronomists/professional advisors; (v) Industry representatives; (vi) Farm events/training; (vii) Farmer networks/ farming colleagues

To set the results of the questionnaire in context, the fourth section related to questions on basic farmer demographic data. This comprised information on profession, farm typology, farm size, education and sources of advice. Ethical clearance was granted by the University of Reading, and participants were made aware of the usage and storage of personal and anonymised data.

The questionnaire was piloted in interviews with four farmers from diverse backgrounds. Content was altered according to feedback. The questionnaire took between 20 – 45 minutes to complete. Participants were enlisted by requests included in newsletters and social media communications of agricultural organisations, and in print in an agricultural magazine [Practical Farm Ideas - 12,000 farmer readers]. It was also promoted in two agricultural podcasts, and researcher and institutional social media. The control treatment questionnaire was open online from 20th April

2020 to 8th June 2020. The Treatment questionnaire was kept separate, all questions remained the same, with the addition of a verification question ensuring participants had viewed all educational materials prior to the questionnaire. The treatment questionnaire and materials were open online from the 9th June 2020 until 9th September 2020.

7.2.2 Engagement materials

The engagement material made available to the treatment group comprised an interactive talk, an animation, a factsheet, and an educational quiz. The materials were designed to engage participants with a variety of knowledge transfer and interactive knowledge exchange— in order to maximise learning, and therefore engagement.

The talk was 30 minutes long, split into three sections, i) carabid ecology ii) farm measures for carabid abundance and diversity, and iii) how and why to monitor carabids. Each section was followed by a 10-minute section, where farmers could ask questions and make comments on the content.

The three-minute "Carabid beetles in farm environments" animation was designed to communicate key concepts of carabid ecology and associated pest control and weed seed control, how and why they move in farm landscapes landscape, different species variations, and why and how to monitor.

The factsheet was designed to communicate knowledge of pitfall trapping, methodology, methods, and sample processing. This included diagrams and non-specialist language. This was sent out with questionnaire requests as a pdf, and also available online (appendix 4).

The short ID quiz was designed to engage farmers with carabid ID and teach basic ID skills. Questions were multiple choice with pictures of carabid beetles, followed by explanatory text on ID techniques, communicating concepts of carabid versus non-carabid, genus level, and species level ID.

The materials were presented at the online 'Cereals' agricultural show 9-11 June 2020, and a magazine article (Farm Wildlife UK, 2020). Participants for the Treatment Group were recruited from three 1-hour events (Table 1, appendix 3). Attendees of each event were emailed materials and ethics statement for participation in the study (appendix 4).

7.2.3 Analysing farmer responses

In total we received 190 responses to the questionnaire, 160 in the control, and 30 in the treatment group. We chose to exclude responses where the first two questions were not completed, leaving 138 responses. Due to the impacts of the Covid19 outbreak on engagement events the treatment group was smaller than intended, yet statistical comparisons were still valid. The questions in Sections 1 and 2 were previously analysed in Jowett et al. (2021). Truncated results are reported here as they relate to analyses on Section 3.

Under the TPB attitudes are a product of beliefs multiplied by evaluations (Ajzen 1991, Rodgers 2010). To determine to what extent the prioritisation of FMPs for monitoring accorded with this theory (H^1), responses to MQ6 (monitoring question on prioritisation) were modelled with the attitudes questions AQ1 as explanatory variables: importance of practice as a proxy for belief (AQ1a), and difficulty of application as a proxy for evaluation (AQ1b). We took the responses to MQ6 and assigned 1 for mentioning, or 0 for not mentioning each FMP. We fitted General Linear Models (GLMs) using the Genstat statistical software package (Payne, 1993) to determine the effect of perceived importance of FMP(AQ1a), perceived difficulty of FMP(AQ1b), and the response variables. We modelled only participants answering AQ1. We excluded those answering "impossible" to AQ1b as these can't be said to be making a decision, and "not sure" for both questions as these cannot fit into an ordinal scale of perception. We assumed a binomial distribution, and considered the importance, and difficulty level factors as fixed effects with two-way interactions. We did not test for treatment effects, as the treatments did not include content on which FMPs might be important to monitor. We selected terms using backwards elimination according to the largest non-significant P-value given by the Kenward-Roger approximate F -tests. The final predictive model was chosen when all remaining terms gave significant values ($P \leq 0.05$) when dropped from the model.

To test our hypothesis of beliefs and demographics effects (H^2) we first tested to see if there were significant differences in responses according to demographic data (farm type FQ1, farm size FQ2, background FQ3, and source of advice FQ4). We then tested to see if there were differences according to beliefs (Belief in ID skills BQ1, belief in pest control efficacy BQ2, and belief in weed control efficacy BQ3). To do this we constructed contingency tables where the columns of the table related to the demographic class or belief response (e.g. in the case of farm type, the columns were the farm classification) and the rows the responses to the question asked (Willingness MQ1, motivations MQ2, and barriers MQ5). The categories for farmer demographic (farm type, size, background and source of advice) were relatively detailed. To avoid categories with too many responses we aggregated to coarser scale categories. For farm type we aggregated to cereal, livestock, mixed, and other cropping. For farm size we aggregated to small (under 100 ha) medium (101 to 500ha) and large (over 500ha). For advice we aggregated to top-down, and participatory advice, for education we aggregated to formal and informal. Likewise, we grouped ID capabilities into no/not sure, and yes.

Under the null hypothesis responses are independent of demographic or belief groupings, and so the same distribution of responses is expected. Under the null hypothesis the expected number of responses in a cell is the product of the respective marginal (row and column) totals divided by the total number of responses in the table. If the expected number of responses in the i th cell (out of N) is e_i and the observed number is o_i we then compute a statistic to measure the evidence against the null hypothesis. In principle under the null hypothesis, and with n_r rows and n_c columns in the table

$$X^2 = \sum_{i=1}^{N} (o_i - e_i)^2 / e_i$$

is distributed by χ^2 with $(n_c - 1)(n_r - 1)$ degrees of freedom, but the fact that o_i is an integer introduces an approximation when the o_i over many cells is small. For this reason, we obtain a *p*-value for the X^2 under the null hypothesis by the permutation method (Payne, 2011).

Similarly, we used the χ^2 permutation test to test our hypothesis (H3) that engagement with farmers would have a positive impact on willingness to monitor, and affect the perception of motivations and barriers surrounding this, we tested questions QM1, QM2 and QM3 (see Table 1) to determine whether there were significant differences in responses between control and treatment groups. To do this we constructed contingency tables where the columns of the table related to the Treatment group (Control and Treatment) and the rows the responses to the question asked (e.g. for question QM1, the rows related to “yes[…]” and “no”).

Qualitative comments were categorised according to whether they mentioned each of the given ID resources for QM4 and grouped by topic for both QM4 and QM7. These were used to further examine the psychological influences surrounding monitoring.

7.3 Results

7.3.1 Summary of data

The control treatment questionnaire was open online from 20th April 2020 to 08th June 2020. In total 160 responses were received, of which 116 contained enough data for analysis. The subset of full responses to Section 2 of the questionnaire comprised 66 responses. Qualitative answers were collected from 67 responses. The Knowledge exchange treatment questionnaire and materials were open online from the 9th June 2020 until 9th September 2020. In total 30 responses were received, 22 of which contained enough data for analysis. The subset of responses to Section 2 of the questionnaire responses comprised 19 responses, all of which included qualitative responses.

There were no significant differences in farmer demographics between treatments. The majority of participants were arable farmers (cereal crops 34%, general cropping 18%). A large proportion had mixed farms (35%), with a much lower proportion farmed livestock alone (9%). The smallest proportion comprised horticulture (4%). The majority of participants reported farm size of 101-500 hectares (60%), followed by larger farms of >500 ha (20%). The smallest proportion of respondents (2%) had farms less than 20 ha in size.

Participants could select multiple sources of knowledge and experience. A 'farming background' and farming 'from childhood' were most frequently selected with 68 and 41 participants selecting this option. Formal education was most frequently selected as college (40 participants), followed by industry qualifications (32 participants), then university (25 participants). Similarly, multiple sources of advice could be selected. Most frequent were events and training (selected by 64 participants), farmer networks (62 participants), agronomists (55 participants), and conservation groups (53 participants). Less frequently selected was governmental advice (33 participants), and industry representatives (29 participants).

7.3.2 Section 1: Beliefs around identification and natural-enemy pest control (NPC)

For the belief questions (BQ1 and BQ2), there were no significant effects of treatment group, or the demographic groups (farm type, size, background education, current source of information) on the responses. Therefore, we pooled the data across typologies and treatments. One third indicated that they could identify a carabid beetle as distinct from other beetles, whilst 30.4%

were unsure (BQ1). Responses of confidence in identifying many species, and responses that they could not identify carabids at all shared the lowest frequency, both at 4.3%. For BQ2, 77.5% of respondents believed that carabids could make a significant contribution to crop pest control, and only 2.9% did not believe as such, with a further 19.6% unsure. Conversely 29.6% believed that carabids could make a significant contribution to weed control (BQ3), 16.2% did not believe as such, with the largest proportion at 54% unsure. There was no significant difference in the responses to BQ1 and BQ2 according to treatment.

7.3.3 Section 2- The farm environment and conservation

For Q9a, on the importance of FMPs for crop pest control by natural-enemies such as carabids, the most frequently ranked as 'Extremely important' was Low pesticide use (52 participants), followed by Reduced tillage, Margins/buffer strips, and Natural area retention (31, 28 and 27 participants). The most frequently ranked as 'Not at all important' was Fallow land followed by low fertiliser use and ponds/waterbodies (11, 5 and 5 participants). Responses of 'Not sure' were most frequent for low fertiliser use, followed by extensive grazing, under sown /companion crop, cover crop, and ditch maintenance (17, 13,13,11 and 11 participants) (Figure 2).

For Q9b, on the perceived difficulty of implementation, the most frequently ranked as 'Not at all difficult' was *margins/buffer strips*, followed by *ditch maintenance*, *diverse rotation*, and *natural area retention* (64, 57, 55, and 53 Participants). Whilst no FMP was very frequently ranked as 'Extremely difficult', *low herbicide use*, and *low fertiliser* use were most frequent (15, and 12 participants). *Ponds/waterbodies* and *low herbicide use* were most frequently ranked as 'Moderately difficult' (29 and 27 participants), and *low Pesticide use* and *beetlebanks* were most frequently ranked as 'Slightly difficult' (27 and 26 participants). The amount of 'Not sure' responses was much lower than in Q9a, with most participants unsure about *extensive* grazing and Under sow/companion cropping (10 and 6 participants). *Ponds/waterbodies* and *extensive grazing* were the only frequently selected as 'Impossible' due to practical soil or landscape constraints (5 participants both), and *ponds* likewise for 'Impossible' due to legal or tenancy constraints (4 participants) (Figure 3).

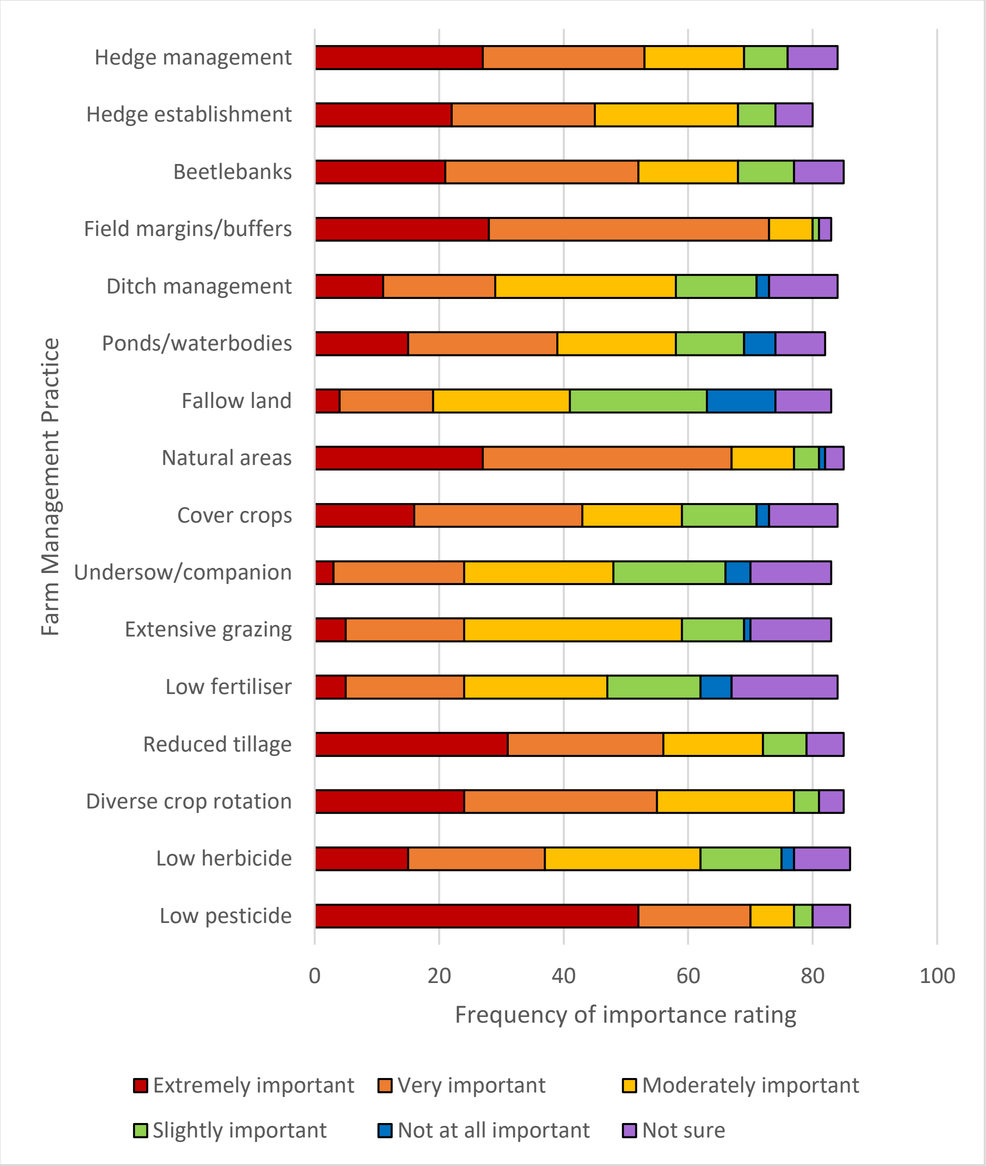


Figure 2- Farm management practices and perceptions of importance as ranked in responses to AQ1a.

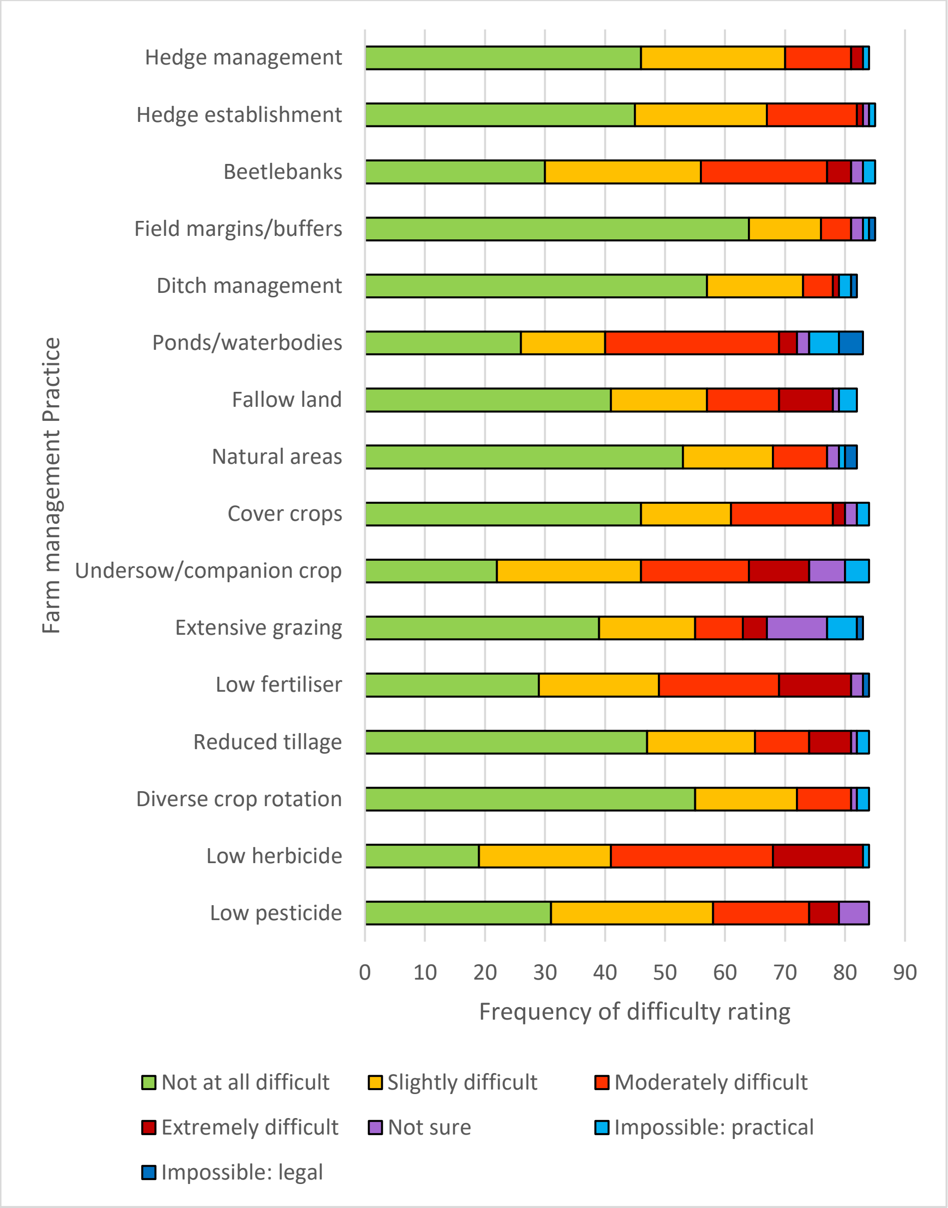


Figure 3-Farm management practices and perceptions of difficulty as ranked in responses to AQ1b

7.3.4 Section 3: Carabid monitoring

For the quantitative monitoring questions (MQ1, MQ2, MQ3, MQ5) there were no significant effects of treatment group on the responses. Therefore, we pooled the data across treatments for statistical analysis.

In response to MQ1, the majority of participants (65.4%) indicated that they would be willing to try to monitor carabids if they had advice. This was followed by willingness if an advisor could carry it out (13.6%), and willingness to do without advice (12.3%). Nearly 5% already carried out monitoring of carabids, and only 2.5% indicated they would be unwilling to monitor carabids (Fig. 4).

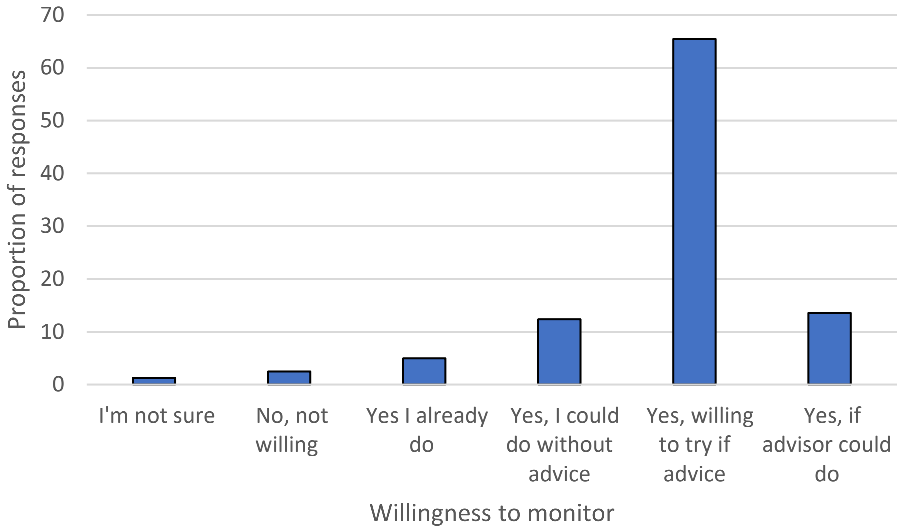


Figure 4- Willingness to monitor carabids as a proportion of responses for question MQ1. See table 1 for detail.

There was a significant difference in the willingness of participants to undertake monitoring between groups of participants with different beliefs in the significance of pest control by carabids (p<0.001, X^2 47.73, 10d.f). Where participants had no belief in the significance of carabid pest control, the observed values for uncertainty whether they would monitor, were higher than the expected. Where participants indicated uncertainty whether carabids were significant in pest control, there was a greater than expected value for willingness to try with advice. For participants with a positive belief in the significance of carabid pest control, there was a greater than expected value of willingness if an advisor could carry out the monitoring.

There was a significant difference in willingness by farm type (p<0.039, X^2 25.95, 15d.f). For cereal farmers, there was a higher than expected value of already carrying out monitoring. In other cropping farms (including horticulture) there was a higher than expected level of uncertainty about monitoring, and higher than expected value for willingness if an advisor could carry it out. For livestock farmers, there was a higher than expected value for unwillingness to monitor.

Multiple responses could be selected for MQ2, on the motivations to monitor, so here we report pooled frequencies from a total of 81 responses. The most frequently selected motivation was a general interest in wildlife (66 participants). This was closely followed by the contribution of carabids to pest control, then weed control (64, and 55 participants). Providing evidence for farm payments, receipt of financial support to do so, and if it were advised by a farm advisor were less frequently selected (31,28, and 25 participants) (Fig. 5). There were no significant effects of beliefs or farmer demographics texted with X^2 contingency tables on the motivations of farmers to monitor carabids.

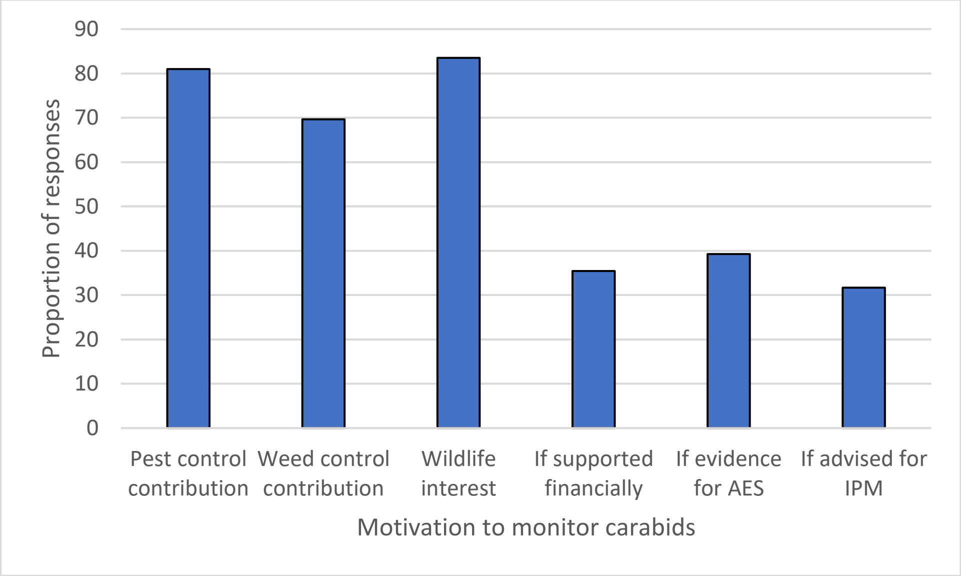


Figure 5- Motivations to monitor carabids as a proportion of number of participants answering question MQ2 (multiple motivations could be selected). AES= Agri-Environment Schemes, IPM= Integrated Pest Management. See table 1 for detail.

Considering the perceived likelihood of using ID tools (MQ3), the majority of participants selected Phone app as extremely likely (49.4%), followed by Field guides (40.7%), then ID books with keys (32.1%). Tools were not frequently ranked as unlikely to use, with only 16 participants (of a total 81) selecting one or more tools as unlikely to use. In the category of extremely unlikely, this was split between Phone apps and ID books, both 3 participants (3.7%) with only one response for field guides (1.2%) (Fig.6).

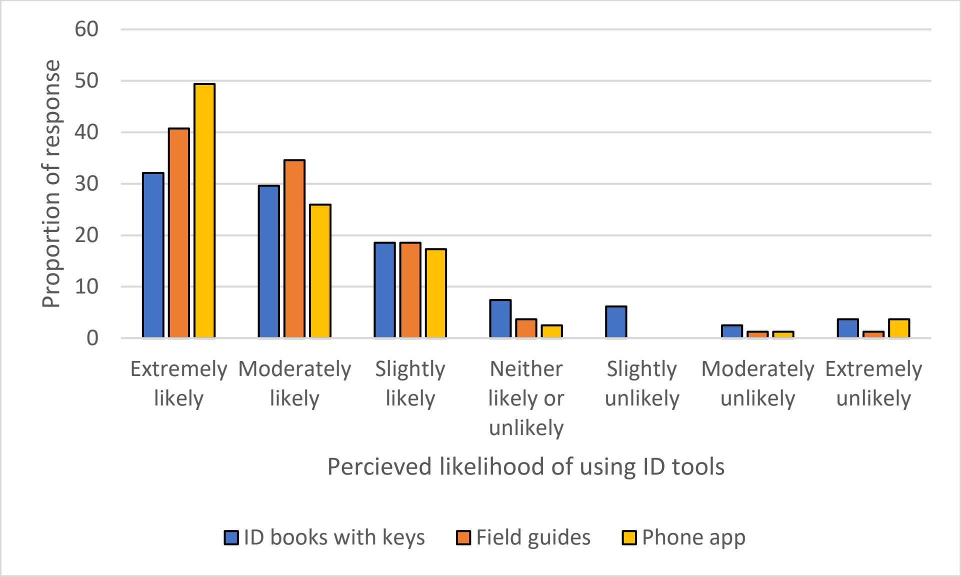


Figure 6- Perceived likelihood of using identification tools for carabid monitoring, as proportion of total responses. For detail see table 1.

There were 70 qualitative responses to MQ4, which asked if participants used ID books, field guides, or phone apps for monitoring or personal enjoyment of wildlife on their farms. The majority indicated that they do (84%), and the most frequently mentioned was books (27 participants), though there was likely some confusion between ID books with keys and field guide style pictorial books, as only 2 responses mentioned keys. This was followed by phone apps, then field guides (20, and 17 participants). Internet search as an ID tool was mentioned 6 times. The majority of participants currently used these tools for ID of farmland birds, followed by wildflowers, and invertebrates (20, 18, and 12 participants). Only 2 responses mentioned that others undertake the ID. The access to ID tools was raised in two responses "*have looked at apps but the free ones seem poor*" "*[phone] app, which can be very unreliable. Many of the good books are out of print or extremely expensive*", whilst one participant noted ongoing improvements "*Yes and finding apps are get[ting] a lot easier to use*".

Multiple responses could be selected for QM5, on the barriers that farmers perceived might prevent them monitoring carabids themselves. Out of a total 77 responses (multiple barriers could be selected per response), training (49 participants) and time (49 participants) were selected most frequently. This was followed by a lack of equipment (19 participants), then an indication that there were no barriers (14 participants). Frequencies were much lower in responses selecting that monitoring may not be informative, or may not be important (2, and 2 participants) (Fig.7). There were no significant effects of beliefs about ID skills or carabid predatory efficacy, or farmer demographics texted with X^2 contingency tables on the perceived barriers to farmers monitoring carabids.

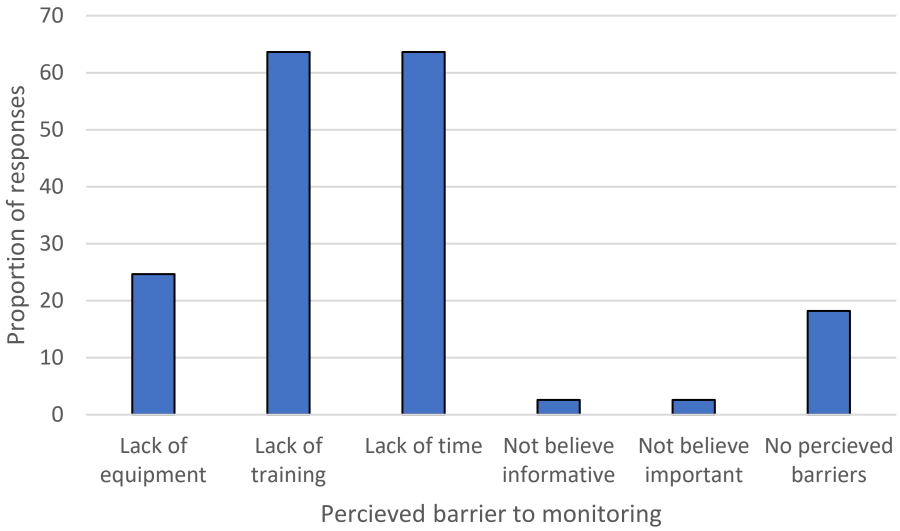


Figure 7- Perceived barriers to monitoring carabids, as a proportion of number of participants answering question M5 (multiple motivations could be selected). See table 1 for detail.

For MQ6, participants were asked if they were to monitor farm habitats or management on their farm, which would they prioritise. Participants could select multiple FMPs, comprising one response. From a total of 77 responses, the most frequently selected FMP was *margins/buffer strips* (58 participants), followed by *cover crops*, *reduced tillage*, and *hedgerow maintenance* (50, 44, and 42 participants). The least frequently selected for monitoring were *extensive grazing* and *fallow land* (9, and 10 responses).

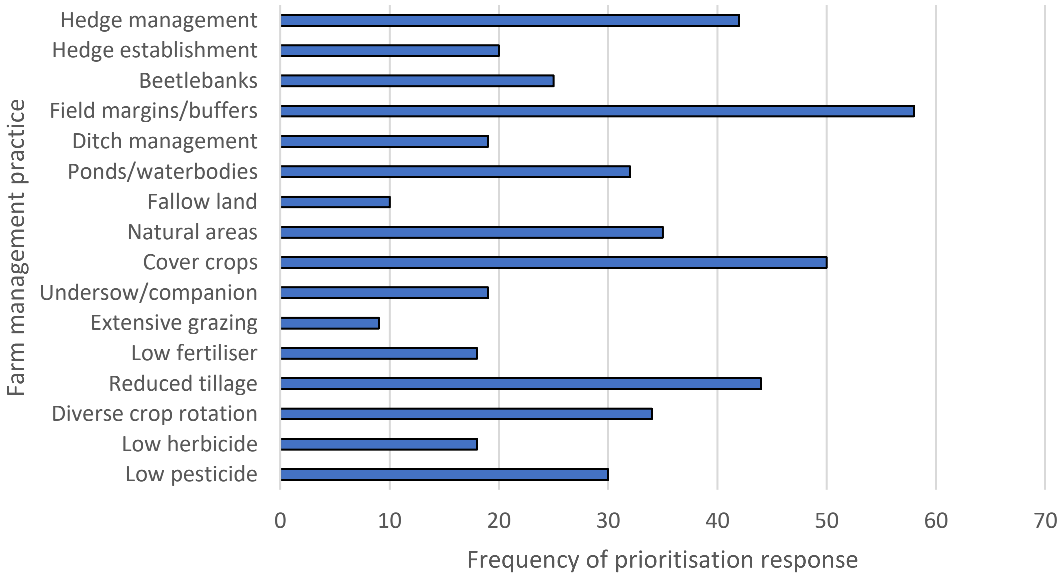


Figure 8- Frequency of responses to QM6 on which Farm Management Practices (FMPs) they would prioritise for monitoring. Multiple FMPs could be selected per participant.

The fitted GLMM model for prioritisation of monitoring FMPs for carabids exploring the TPB framework retained both difficulty and importance (d.f. 7, F=5.57, p<0.001). There were no interaction effects (Figure 10).

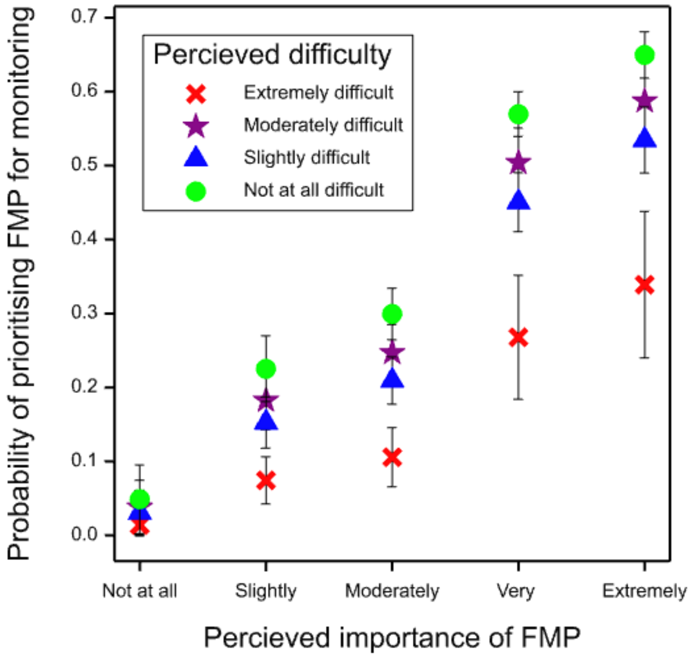


Figure 9- Model predictions for Theory of Planned Behaviour. Prioritisation of Farm Management Practices (FMPs) for monitoring, with perceived importance of FMPs, and perceived difficulty of implementing FMPs.

For QM7, asking how participants currently judge the success of agri-environmental measures on their farms, there were 65 qualitative responses. The majority of responses mentioned informal visual appraisals (26 participants), and general increases in farm wildlife (24 participants), with fewer mentioning a general impression or 'gut feeling' (5 participants). More formal and specific monitoring strategies mentioned were farmland birds, pollinators, and financial aspects (18, 9, and 7 participants). Fewer responses mentioned ease of application, soil quality, and crop/animal health (3,3, and 3 participants). Many participants used this response to express enjoyment of farm wildlife, for example: *"I like to see my animals and crops are healthy as a result of a healthy farm. I would like to see a decrease in chemical inputs with plants forming resistance to diseases through a healthy soil system. The healthy soil system is result of holistic management approaches which includes beetles. If the cows are happy, the stream flows clear, the wheat is golden, the birds are singing, bees are buzzing, and I have made a profit then I'll be happy*".

7.4 Discussion

This study aimed to elucidate the willingness of farmers to monitor carabids, and the beliefs that influence their attitudes to monitoring. We found that support for carabid monitoring was high, and therefore monitoring may be practicable to raise the efficacy of IPM interventions on farms. However, practical interventions may be necessary to raise willingness and capacity to self-monitor.

7.4.1 Effects of beliefs

The beliefs of participants on significance of carabids as pest control agents (BQ2) affected the willingness to monitor (MQ1), supporting our first hypothesis. However, the significant effects were more subtle than anticipated. We may expect that farmers with a strong belief in the efficacy of carabids in pest control would result in a higher willingness to monitor, but this was not strongly apparent. The concurrent was somewhat seen in that a low belief in carabid pest control efficacy was more associated with uncertainty on monitoring. The lack of significance observed in the unwillingness to monitor category may be attributed to low response for this option. Responses indicating uncertainty around carabid pest control efficacy were more associated with willingness if they had advice, and positive beliefs in efficacy were associated with a higher than expected value for willingness if an advisor could carry it out. Since there is such a high proportion of willingness in general, these results could indicate the effects on barriers. If a farmer believes monitoring to be important, this may override practical constraints and perceived self-efficacy, to the effect of paying for an advisor to undertake this task.

Mills et al (2017) found that personal beliefs farmers held about wildlife were a key influence on environmental behaviour, stressing that such deep-held beliefs were a trigger for management actions. Riley (2016) examined the beliefs of long-term AES participants, finding that environmentally sensitive practices may become tied with self-identity, and the perception of a 'good farmer'. Therefore, our findings that motivations to monitor were not affected by either beliefs around carabid pest control or ID skills, may indicate that motivations, particularly an interest in wildlife, are related to core self-image beliefs and as such not influenced by subsidiary attitudes.

Similarly, there were no effects of beliefs about ID skills (BQ1) or pest control (BQ2) on barriers to monitoring (MQ5). The barriers identified by the majority of participants are not related to beliefs, as they are practical barriers. Lack of time, training, and equipment may fall under aspects of 'Perceived Behavioural Control' (PBC) in the Ajzens' (1991) Theory of Planned Behaviour (TPB). This describes practical attributes of behavioural intent that the actor feels are out of their control, for example a farmer cannot undertake a task if they feel they have no spare time to do it in. We may have expected an influence of the treatment in descriptions of how to carry out monitoring, but as discussed below, this may have been a very minor influence compared to feeling very busy, and the need for training and equipment.

In the validation of the TPB theoretical framework by the modelling of Farm Management Practices (FMPs) for prioritisation (MQ6), our second hypothesis was supported. The influence of both beliefs about the importance of each FMP for carabids (AQ1a), and the evaluation of that belief in the perceived difficulty of implementation of each FMP(AQ1b), were significant predictors of which FMPs farmers prioritised for monitoring. Since the attitude constructed from this multiplication of beliefs and evaluations relates directly to the implementation of FMPs for carabids (Ajzen 1991), we conclude that a positive attitude to the implementation is connected to a desire to monitor the outcomes of implementation. In deconstructing the attributes of importance and difficulty, we see that the most frequently selected for prioritisation accord largely with those rated as both important and easy to implement, notably the top rated for each is Margins/buffer strips. Cover crops was an interesting departure, as one of the most selected for prioritisation, it is among the middle range of frequency for importance, but does rank more highly in ease. This is interesting, as some FMPs ranked as very important seem to be drawn downwards for prioritisation by difficulty, for example Pesticide use. There may also be an attribute of the aims of monitoring: in-field or field boundary FMPs seem to be more popular for prioritisation than non-crop FMPs. This may be due to the fact that monitoring in the field will be more immediately informative on predation in crops, and is more typical of IPM monitoring strategies as seen with pest species (ADHB, 2016).

7.4.2 Farmer typology

The type of farm enterprise (FQ1) had a significant effect on the willingness to monitor (MQ1), which further supports our first hypothesis. There was a higher than expected value for already carrying out monitoring, in cereal farms. This may be due to the higher communicated utility of carabids as pest controlling agents in cereal systems, and the advice available on interventions such as margins and beetle banks (ADHB 2020; Holland et al., 2005; Saska et al., 2007; Sotherton 1985). The converse was true for livestock systems, these had a higher than expected value for unwillingness. This concurs with the FMP Extensive grazing as least prioritised for monitoring. Little research exists to prove the beneficial impacts of carabids on livestock pests (Fincher, 1990; Oyazun, Quiroz, and Birkett, 2008), and this may not be as significant as contributions to crop pest control. We note that the belief question was worded as ‘a significant contribution to crop insect pest control’, so livestock farmers still may be influenced by their beliefs in that it is not relevant to them. This may be important, grassland is proven to benefits carabid beetle populations (Boetzl et al., 2018; French and Elliot, 1999), it may be desirable to investigate and communicate carabid pest control in livestock. The association with unwillingness was not seen in mixed farms, where perhaps farmers focussed on the beneficial aspects to crops.

There were no significant effects of farmer demographic groups (FQ1-4) on motivations (MQ2) or barriers (MQ5) to monitoring. This may suggest that the motivations and barriers acting upon the self-selected sample of participants are quite homogenous. However, the category groupings necessitated by the low responses in categories may have resulted in a loss of variation for individual categories. Since demographic variation is noted in farmer behavioural literature (Garforth and Rehman 2006; Mills et al 2017; Pike, 2008; Sok et al., 2010), future work with larger sample sizes would be desirable to discern these influences.

7.4.3 Engagement treatments

Our third hypothesis was not supported in that there was no significant effect of the engagement treatments on willingness to monitor (MQ1), the motivations to monitor (MQ2), or the perceived barriers to monitoring (MQ5). The knowledge transfer and knowledge exchange treatments delivered in an online format may have been too weak of an intervention to act on a cognitively heavy and time-consuming activity. The qualitative responses (MQ4, MQ7) indicated that the majority of participants may not be familiar with formal survey techniques, preferring to assess the success of agri-environmental management by visual and casual observation of wildlife on the farm. Furthermore, the response to MQ5 reveals the perception that monitoring may be complicated and time consuming. When considering an activity that will have such an investment of time and energy, actors are more likely to appraise the costs and benefits through cognitive consideration as opposed to heuristic cues such as source credibility (Petty and Cappacio 2012; Rodgers, 2010). Added to this, the sample of participants were self-selected, and likely to have well-formed beliefs about agro-ecological solutions before the event (Ajzen, 1991).

7.4.4 Practical attributes

Whilst likely use of a phone app was most frequently selected, there was not a large difference between the groups, though ID books with keys was more frequently selected in unlikely scores. Qualitative responses highlighted potential confusion in books, as opposed to books with keys. Dichotomous choice keys were briefly explained on the survey, but may still be misunderstood, as unfamiliar to farmers: these books are expensive and sold in specialist shops. The majority of participants indicated that they use similar tools for ID of other species on their farms. The qualitative responses indicated that they sought out tools themselves, encountering poor quality and expense as barriers. This is likely an attribute of the pro-active self-selected sample, but nevertheless indicates that the availability of ID tools may be a target for intervention, with good potential for uptake.

Other practical barriers to take up of monitoring include perceived barriers of time, equipment, and training. Designing a monitoring system that fits well with farm schedules, and making suitable equipment available to farmers is therefore likely to increase uptake of monitoring (Rodgers, 2010). The need for training and support is further evidenced by two thirds of responses indicating that they would be willing to try monitoring themselves, if they had advice. Billaud, Vermeersch and Porter (2020) report the findings of the farmland biodiversity observatory project, whereby farmers conducted surveys across France on farmland invertebrates. The farmers selected which taxa to monitor and had access to advice. Often fieldworkers undertook the monitoring, rather than the farmers themselves. The project was successful over 7 years, returning valuable data on biodiversity trends, and despite high turnover in participants uptake was maintained. This can be attributed to efficient standardised protocols with limited equipment needs that address the barriers cited in our results. In Stroud's (2019) #60minworms survey of earthworms for farmland soil health assessments, the author notes the necessity to balance trade-off between data quality and practicability, particularly recommending quick assessments to maximise participation. Since it has been estimated that farmer self-monitoring could lower the cost of biodiversity monitoring by 46%, and of 77% with volunteer involvement (Targetti et al., 2014), and that invertebrate monitoring 'pays for itself' when balanced with the cost of ecosystem service decline (Breeze et al., 2020), the provision of support and development of equipment and optimised protocols for carabid monitoring may be cost effective.

7.4.5 Hearts and minds

The overwhelming majority of participants were willing to monitor carabids. Some sample bias can be attributed to the fact that respondents were self-selecting and so are likely to have had an interest in carabids and natural-enemy pest control, that may not be seen so strongly in farmers generally. However, according to innovation theories, the uptake of such innovate behaviours as monitoring would trickle down from innovators (such as our engaged sample), to general farmers when it is observed to be practicable and effective (Rodgers, 2010; Stroud, 2019).

That the most frequent motivation for monitoring (MQ2) was a general interest in wildlife is surprising given the predominance of financial interventions for agri-environmental outcomes, and the literature consensus that this is the primary concern of farmers (Kleijn et al., 2018; Lobley et al., 2013; Mills et al., 2018). However, Pannell and Zilberman (2020) argue that research into farmer adoption behaviour needs to go beyond the 'profit maximising paradigm' to examine institutional, informational, and cognitive aspects. Our finding reinforce the multiple influences acting on farmers, particularly the emotional and cognitive connection with wildlife.

Pest and weed control were also frequently selected motivations for monitoring. This may be related to pre-existing beliefs, yet there was no evidence for the belief in significance of pest control (BQ2) or weed control (BQ3) resulting in different motivations. Also, the indication that knowing carabids contribute to weed control would motivate them to monitor, given the low frequency of beliefs that weed control by carabids is significant (BQ3), is surprising. This may indicate that more communication of evidence of carabid weed control would increase uptake of measures.

In qualitative responses (MQ4, MQ7), the mention of monitoring farmland birds suggests that the promotion of conservation organisations, is successful in engaging farmers in the identification of farmland birds, feeding into the conservation of them in farm practices. Farmland bird surveys originated as awareness raising tools, the success of which has led to increased uptake of farm management for bird conservation (Gregory, Noble, and Custance, 2004; Gillings et al., 2005). Our study hoped to explore a similar engagement trajectory for beneficial invertebrates.

However, the mention of wildflowers and invertebrates in qualitative responses, indicates a self-motivated interest in wildlife, which as demonstrated by the frequent motivation for monitoring (MQ2), includes carabid beetles. As a less charismatic genera than the frequently targeted birds and pollinators (Hart, 2020), this is encouraging for their conservation. It would appear that farmers understand the value of carabids above and beyond their utility to production. The unsolicited expression of enjoyment in farm wildlife seen in qualitative responses (MQ7), demonstrates the influence of emotional connection on farmer decision making. This is currently undervalued in governmental communication, and may be used to increase uptake of monitoring, for example by provision of contextual information on ecology and their place in the ecosystem.

7.5 Conclusion

Though this study centres on a self-selected sample of farmers interested in beetles and IPM—the positive response to the survey, in of itself, indicates that carabid monitoring may be a valuable intervention to raise the efficacy of IPM interventions on farms.

We show that beliefs of efficacy may be targeted to increase willingness to monitor. We also recommend the development and provision of efficient protocols, ID tools, and advisory support to reduce the barriers farmers perceive to uptake. Whilst online engagement was successful in attracting participants to the study, an online knowledge transfer and knowledge exchange format was not effective in influencing willingness to monitor. We recommend multiple and practical interventions to act strongly on behavioural intent.

Our findings highlight the importance of capturing hearts and minds to encourage uptake of agro-ecological practices, and the potential for even non-charismatic species such as carabids to be promoted with an emotional connection. A focus on raising awareness of ecological linkages, and providing evidence to support beliefs in efficacy may substantially improve the uptake of measures beneficial to carabids.

Authors' Contributions

KJ, AEM, and JS conceived and designed the study. The research and analysis were performed by KJ and AEM with input from JS. All authors contributed to interpretation of results and writing the manuscript.

Acknowledgements

We thank Gary Frewin for animation design, and the Rothamsted communications dept for promotion. We thank William MacAlpine for agricultural organisation outreach, and the organisations LEAF, Agricology, BASE, CFE, FWAG, Agri-Tech- east, ADHB, RSPB and NFU for promotion activities.

KJ is grateful for funding from the Rothamsted-Reading Alliance. JS and AEM are supported by research programmes NE/N018125/1 LTS-M ASSIST – Achieving Sustainable Agricultural Systems, funded by NERC and BBSRC (BBS/E/C/000I0140), and the Smart Crop Protection (SCP) strategic programme (BBS/OS/CP/000001) and the Soil to Nutrition (S2N) strategic programme (BBS/E/C/000I0330) both funded by the BBSRC.

7.6 References

ADHB, 2016. *Encyclopaedia of pests and natural enemies in field crops*. Agriculture and Horticulture Development Board.

Ajzen, I., 1991. The theory of planned behavior. *Organizational behavior and human decision processes*, 50(2), pp.179-211.

Bagheri, A., Bondori, A., Allahyari, M.S. and Damalas, C.A., 2019. Modeling farmers' intention to use pesticides: An expanded version of the theory of planned behavior. *Journal of Environmental Management*, 248, p.109291.

Bianchi, F.J., Booij, C.J.H. and Tscharntke, T., 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. Proceedings of the *Royal Society of London B: Biological Sciences*, 273(1595), pp.1715-1727.

Billaud, O., Vermeersch, R.L. and Porcher, E., 2020. Citizen science involving farmers as a means to document temporal trends in farmland biodiversity and relate them to agricultural practices. *Journal of Applied Ecology.*

Boatman, N.D., Jones, N.E., Gaskell, P. and Dwyer, J.C., 2010. Monitoring of agri-environment schemes in the UK. *Aspects of Applied Biology*, (100), pp.9-18.

Boetzl, F.A., Krimmer, E., Krauss, J. and Steffan-Dewenter, I., 2018. Agri-environmental schemes promote ground-dwelling predators in adjacent oilseed rape fields: Diversity, species traits and distance-decay functions. *Journal of Applied Ecology*.

Bopp, C., Engler, A., Poortvliet, P.M. and Jara-Rojas, R., 2019. The role of farmers' intrinsic motivation in the effectiveness of policy incentives to promote sustainable agricultural practices. *Journal of environmental management*, 244, pp.320-327.

Breeze, T.D., Bailey, A.P., Balcombe, K.G., Brereton, T., Comont, R., Edwards, M., Garratt, M.P., Harvey, M., Hawes, C., Isaac, N. and Jitlal, M., 2020. Pollinator monitoring more than pays for itself. *Journal of Applied Ecology*.

Brooks, D.R., Perry, J.N., Clark, S.J., Heard, M.S., Firbank, L.G., Holdgate, R., Shortall, C.R., Skellern, M.P. & Woiwod, I.P., 2008. National-scale metacommunity dynamics of carabid beetles in UK farmland. *Journal of Animal Ecology*,77,265–274.

Cole, A., 2019. Agri-Environment Monitoring and Evaluation Programme Annual Report 2017/18: A
summary of findings from recently published projects. *Natural England Research Reports, Number*
079.

Daxini, A., Ryan, M., O'Donoghue, C. and Barnes, A.P., 2019. Understanding farmers' intentions to follow a nutrient management plan using the theory of planned behaviour. *Land Use Policy*, 85, pp.428-437.

Defra, 2020. *Environmental Land Management Policy discussion document* February 2020. Available online at [https://consult.defra.gov.uk/elm/elmpolicyconsultation/supporting documents/elmdiscussiondocument20200225a%20002.pdf] [accessed 09.03.20]

Dennis, P. and Fry, G.L., 1992. Field margins: can they enhance natural enemy population densities and general arthropod diversity on farmland?. *Agriculture, Ecosystems & Environment*, 40(1-4), pp.95-115.

Despotović, J., Rodić, V. and Caracciolo, F., 2019. Factors affecting farmers' adoption of integrated pest management in Serbia: an application of the theory of planned behavior. *Journal of Cleaner Production,* 228, pp.1196-1205.

De Snoo, G.R., Herzon, I., Staats, H., Burton, R.J., Schindler, S., van Dijk, J., Lokhorst, A.M., Bullock, J.M., Lobley, M., Wrbka, T. and Schwarz, G., 2013. Toward effective nature conservation on farmland: making farmers matter. *Conservation Letters*, 6(1), pp.66-72.

Emery, S.B. and Franks, J.R., 2012. The potential for collaborative agri-environment schemes in England: Can a well-designed collaborative approach address farmers' concerns with current schemes?. *Journal of Rural Studies*, 28(3), pp.218-231.

Farm wildlife UK 2019. *Case study- Carabid beetles for natural enemy pest control.* [online blog] Available at: https://farmwildlife.info/2020/07/12/case-study-carabid-beetles-for-natural-enemy-pest-control/… [Accessed 10/09/21]

Fincher, G.T., 1990. Biological control of dung-breeding flies: pests of pastured cattle in the United States. In- Rutz, D.A.;Patterson, R.S. eds, 1990. *Biocontrol of arthropods affecting livestock and poultry*. pp. 137-151

French, B.W. and Elliott, N.C., 1999. Temporal and spatial distribution of ground beetle (Coleoptera: Carabidae) assemblages in grasslands and adjacent wheat fields. *Pedobiologia*, 43(1), pp.73-84.

Gaba, S., and Bretagnolle, V., 2020 Designing multifunctional and resilient agricultural landscapes: lessons from long-term monitoring of biodiversity and land use. In: The Changing Status of Arable Habitats in Europe (Eds. Hurford C, Wilson, P. & Storkey J.). *Springer Nature Publishing*. In press

Garforth, C. and Rehman, T., 2006. *Research to understand and model the behaviour and motivations of farmers in responding to policy changes* (England). Department for Environment, Food and Rural Affairs Research project EPES 0405/17

Gregory, R.D., Noble, D. and Custance, J., 2004. The state of play of farmland birds: population trends and conservation status of lowland farmland birds in the United Kingdom. *Ibis,* 146, pp.1-13.

Gillings, S., Newson, S.E., Noble, D.G. and Vickery, J.A., 2005. Winter availability of cereal stubbles attracts declining farmland birds and positively influences breeding population trends. *Proceedings of the Royal Society B: Biological Sciences*, 272(1564), pp.733-739.

Hart, A.G., 2020. Marketing Insects: Can Exploiting a Commercial Framework Help Promote Undervalued Insect Species?. *Insect Diversity and Conservation*.

Heard, M.S., Botham, M., Broughton, R., Carvell, C., Hinsley, S., Woodcock, B. and Pywell, R.F., 2012. *Quantifying the effects of entry level stewardship (ELS) on biodiversity at the farm scale: the Hillesden experiment*. NERC.

HMGOV, 2020. *Countryside Stewardship Mid Tier and Wildlife Offers Manual*. Version 1.0. Available online at [www.gov.uk/rca/cs; accessed 09.03.20]

Holland, J., Thomas, C.F.G., Birkett, T., Southway, S. and Oaten, H., 2005. Farm-scale spatiotemporal dynamics of predatory beetles in arable crops. *Journal of Applied Ecology*, 42(6), pp.1140-1152.

Ingram, J., 2008. Agronomist–farmer knowledge encounters: an analysis of knowledge exchange in the context of best management practices in England. *Agriculture and Human Values*, *25*(3), pp.405-418.

Jowett, K., Milne, A.E., Potts, S.G., Senapathi, D. and Storkey, J., 2022. Communicating Carabids: Engaging farmers to encourage uptake of Integrated Pest Management. *Pest Management Science*. In press.

Jowett, K., Milne, A.E., Metcalfe, H., Hassall, K.L., Potts, S.G., Senapathi, D. and Storkey, J., 2019. Species matter when considering landscape effects on carabid distributions. *Agriculture, Ecosystems & Environment*, 285, p.106631.

Kleijn, D., Bommarco, R., Fijen, T.P., Garibaldi, L.A., Potts, S.G. and van der Putten, W.H., 2018. Ecological Intensification: Bridging the Gap between Science and Practice. *Trends in ecology & evolution.*

Kotze, D.J., et al.,2011 Forty years of carabid beetle research in Europe–from taxonomy, biology, ecology and population studies to bioindication, habitat assessment and conservation. *ZooKeys*, (100), p.55.

Lobley, M., Saratsi, E., Winter, M. & Bullock, J.M., 2013. Training farmers in agri-environmental management: the case of Environmental Stewardship in lowland England. *International Journal of Agricultural Management*, 3, 12– 20.

MacDonald, M.A., Angell, R., Dines, T.D., Dodd, S., Haysom, K.A., Hobson, R., Johnstone, I.G., Matthews, V., Morris, A.J., Parry, R. and Shellswell, C.H., 2019. Have Welsh agri-environment schemes delivered for focal species? Results from a comprehensive monitoring programme. *Journal of Applied Ecology*, 56(4), pp.812-823.

Matzdorf, B. and Lorenz, J., 2010. How cost-effective are result-oriented agri-environmental measures?—An empirical analysis in Germany. *Land use policy,* 27(2), pp.535-544.

McCracken, M.E., Woodcock, B.A., Lobley, M., Pywell, R.F., Saratsi, E., Swetnam, R.D., Mortimer, S.R., Harris, S.J., Winter, M., Hinsley, S. and Bullock, J.M., 2015. Social and ecological drivers of success in agri-environment schemes: the roles of farmers and environmental context. *Journal of Applied Ecology*, 52(3), pp.696-705.

Mills, J., Gaskell, P., Ingram, J. and Chaplin, S., 2018. Understanding farmers' motivations for providing unsubsidised environmental benefits. *Land use policy*, 76, pp.697-707.

Mills, J., Gaskell, P., Ingram, J., Dwyer, J., Reed, M. and Short, C., 2017. Engaging farmers in environmental management through a better understanding of behaviour. *Agriculture and Human Values*, 34(2), pp.283-299.

Nowakowski, M., Edwards, M., and Pywell, R.F. (2020) Habitat Creation and Management for Pollinators, UK Centre for Ecology & Hydrology, Wallingford, UK.

Oatway, R., 2018. *Agri-Environment Monitoring and Evaluation Programme Annual Report 2016/17*- A summary of findings from recently published projects. Natural England Research Reports, Number NERR074.

Oyazun, M.P., Quiroz, A. and Birkett, M.A., 2008. Insecticide resistance in the horn fly: alternative control strategies. *Medical and Veterinary Entomology*, 22: pp 188–202.

Payne, R.W. ed., 1993. *Genstat 5 release 3 reference manual*. Oxford University Press.

Pedersen, A.B., Nielsen, H.Ø., Christensen, T. and Hasler, B., 2012. Optimising the effect of policy instruments: a study of farmers' decision rationales and how they match the incentives in Danish pesticide policy*. Journal of Environmental Planning and Management*, 55(8), pp.1094-1110.

Petty, R.E. and Cacioppo, J.T., 2012. *Communication and persuasion: Central and peripheral routes to attitude change.* Springer Science & Business Media.

Pike, T., 2008. Understanding Behaviours in a Farming Context: Bringing theoretical and applied evidence together from across Defra and highlighting policy relevance and implications for future research. *Defra Agricultural Change and Environment Observatory Discussion Paper*. HMGOV

Pywell, R.F., Heard, M.S., Bradbury, R.B., Hinsley, S., Nowakowski, M., Walker, K.J. & Bullock, J.M., 2012. Wildlife-friendly farming benefits rare birds, bees and plants. *Biology Letters*, 8, 772–775.

Rogers, E.M., 2010. *Diffusion of innovations* (5th edition). Simon and Schuster.

Russi, D., Margue, H., Oppermann, R. and Keenleyside, C., 2016. Result-based agri-environment measures: Market-based instruments, incentives or rewards? The case of Baden-Württemberg. *Land Use Policy*, 54, pp.69-77.

Saska, P., Vodde, M., Heijerman, T., Westerman, P. & van der Werf, W., 2007. The significance of a grassy field boundary for the spatial distribution of carabids within two cereal fields. *Agriculture, Ecosystems and Environment,* 122, 427–434.

Schroeder, L.A., Chaplin, S. and Isselstein, J., 2015. What influences farmers' acceptance of agri-environment schemes? An ex-post application of the 'Theory of Planned Behaviour'. *Appl Agric Forestry Res,* 1(65), pp.15-28.

Schroeder, L.A., Isselstein, J., Chaplin, S. and Peel, S., 2013. Agri-environment schemes: Farmers' acceptance and perception of potential 'Payment by Results' in grassland—A case study in England. *Land Use Policy*, 32, pp.134-144.

Sok, J., Borges, J.R., Schmidt, P. and Ajzen, I., 2020. Farmer behaviour as reasoned action: a critical review of research with the theory of planned behaviour. *Journal of Agricultural Economics*.

Stroud, J.L., 2019. Soil health pilot study in England: Outcomes from an on-farm earthworm survey. *PloS one*, 14(2), p.e0203909.

Sotherton, N.W., 1985. The distribution and abundance of predatory Coleoptera overwintering in field boundaries. *Annals of applied biology*, 106(1), pp.17-21..

Sutherland L.A., 2010. Environmental grants and regulations in strategic farm business decision-making: a case study of attitudinal behaviour in Scotland. *Land Use Policy* 27:415–423.

Sunderland, K., 2002. Invertebrate pest control by carabids. *In:* Holland, J.M. *The Agroecology of Carabid Beetles.* Andover: Intercept .

Targetti, S., Herzog, F., Geijzendorffer, I.R., Wolfrum, S., Arndorfer, M., Balázs, K., Choisis, J.P., Dennis, P., Eiter, S., Fjellstad, W. and Friedel, J.K., 2014. Estimating the cost of different strategies for measuring farmland biodiversity: Evidence from a Europe-wide field evaluation. *Ecological Indicators*, 45, pp.434-443.

Thiele, H.U., 1977. *Carabid beetles in their environments: a study on habitat selection by adaptations in physiology and behaviour* (Vol. 10). Springer Science & Business Media.

Thomas, C.G., Holland, J.M. and Brown, N.J., 2002. The spatial distribution of carabid beetles in agricultural landscapes. *The agroecology of carabid beetles*. Andover: Intercept, pp.305-344.

Valeeva, N.I., Lam, T.J.G.M. and Hogeveen, H., 2007. Motivation of dairy farmers to improve mastitis management. *Journal of Dairy Science*, 90(9), pp.4466-4477.

Wezel, A., Casagrande, M., Celette, F., Vian, J.F., Ferrer, A. and Peigné, J., 2014. Agroecological practices for sustainable agriculture. A review. *Agronomy for sustainable development*, 34(1), pp.1-20.

Chapter 8

General discussion

8.1 Discussion

'Carabidologists do it all'

-Niemelä 1996

In his preface to the 3rd international symposium of carabidology, Niemela (1996a) describes the difficulties of working with carabid beetles; an "inordinate" number of species, with an astonishing variety of morphology and behaviours. Carabids have been variously used to study ecological theory and applied research, from systematics to conservation— this thesis adds human behavioural intent to that extensive list. With this work I have attempted to contribute to filling the knowledge gaps that remain, and take carabidology research forwards, towards effective natural enemy pest control (NPC). The key questions drawn from the literature review are:

a) Does the response of carabids to landscape and farm management significantly vary by species?

b) How does larvae service provision differ to adult carabids?

c) Which farm management interventions are most beneficial?

d) Can increasing farmers' positive beliefs about carabids increase uptake of measures for natural-enemy pest control?

e) What are the factors influencing beneficial assemblages at the farm scale?

I will answer each question in turn, drawing on the findings of multiple chapters. Since NPC, and indeed agricultural carabids themselves, sit at the juncture of human interests and the functioning of natural systems (delivering 'ecosystem services'), it is crucial to integrate social, psychological, biological and economic considerations into the application of research. Here, I tie together the ecological and anthropogenic findings of my studies, and present a consilient picture of the factors governing carabid mediated NPC, and the opportunities for more effective management.

a) Does the response of carabids to landscape and farm management significantly vary by species?

The variety of carabid morphology and behaviours produces a variety of responses to environmental variables. Studies on carabids tend to use metrics of abundance and diversity, which fails to capture the detail of species level responses to management, and therefore, species specific differences in ecosystem service delivery related to predation.

In this thesis, I have comprehensively answered the first key question arising from the literature review. In chapter 2, I analysed the carabid species data from the Farm Scale Evaluations (FSE) experiment, and I found distinct differences in species responses to landscape factors and management. In the ten species modelled, soil type, crop type, distance into crop, adjacent habitat and presence of landscape features hedge, margin, waterbody, track, or ditch were all found to have significant effects on one or more species. The impact of these factors varied with species, for example *Bembidion lampros* and *Nebria brevicollis* were both most abundant at the edge of crops, however when a margin was present *B. lampros* had significantly greater abundances, whilst the converse was true for *N. brevicollis*. The FSE dataset comprises observations from multiple time points from across the UK, and as such the intraspecific variation of species responses is likely to be representative (Firbank et al., 2003; McGill et al., 2006). With this work I demonstrated that pooled carabid abundances can be misleading, and may not be detailed enough to guide management to boost carabid abundance and diversity for NPC. For example, *Harpalus rufipes*— a notable weed seed specialist (Birthisel, Gallandt, and Jabbour, 2014), and

Pterostichus melanarius— a generalist predator of crop arthropods (McKemey et al., 2001), showed contrasting responses to management, landscape factors and distance from crop edge.

In chapter 3, I gathered data on species counts from the Large Scale Rotation Experiment (LSRE) experiment at Brooms Barn, and again I found that species level responses were more informative than pooled abundance and diversity measures. For instance, there was no significant effect of tillage on pooled abundance measures, which may be attributed to the short establishment period, low frequency of tillage, or the small plot sizes. However, at a species level I observed significant responses to tillage for three of the six species modelled (*Bembidion lampros*, *Calathus melanocephalus*, and *Carabus violaceus*). In chapter 4, I gathered data on species counts from across the Rothamsted farm. Here species level modelling informed on farm level distinctions in carabid communities. Again, I found that, as well as field scale habitat management affecting carabid community assembly, responses to landscape and management also varied between species. Spatial autocorrelation was evident for some key crop pest arthropod predators at a range of 100 metres, while some showed site-scale spatial trends, and others showed no spatial dependence. This was related to differences in dispersal ability and predatory behaviour between species.

Differences in species responses to management were further explored through the use of different trap types. In chapter 3, *Trechus quadristriatus* and *Amara eurynota* were associated more with subterranean traps, and *B. lampros* varied in associations between subterranean traps in the first run, to standard pitfalls in the second. In chapter 4, *Pterostichus madidus*, *A. eurynota*, and *Poecilius cupreus* varied in trap association by crop type. This reflects their differential hypogean activity, which may be a stable behavioural preference for species such as *T. quadristriatus*, noted in the literature as a predator of hypogean pests (Williams et al., 2010); or a behavioural response to differing environmental conditions such as crop type or weather (e.g. the drought conditions in Run 1 of chapter 3). Particularly notable was the prevalence of *A. eurynota* in both chapters. This species is little mentioned in the literature as a predator on oilseed rape (in contrast to other *Amara* sp.)(Williams et al., 2010), yet its hypogean preference may indicate predation of key pests such as cabbage stem flea beetles. It would be of benefit to expand this work in the future to elucidate hypogean predation.

Throughout chapters 2, 3 and 4, I have found strong evidence that species level differences are important to understanding the responses of carabids to landscape and farm management factors. However, this species level analysis is uncommon in the literature when considering plot or site assemblages. This is an attribute of the scientific approach to replicability— not all sites will host the same species and so may be incomparable. Moreover, the limited time available and low technical ability of land managers to discern site species assemblages means that recommendations based at a species level may be difficult to implement.

There have been many approaches in carabid literature to reducing the variation inherent in pooled carabid abundances, by grouping by trait attributes. Trait based approaches attempt to retain some of the discriminatory power of autecological approaches, without the need to study every species in depth. These traits approaches work on the premise that, all environmental variables being equal, a given species pool in a given habitat will always give rise to a similar assemblage of species, as governed by ecological processes — chiefly competition between species for realised niche space. Furthermore, the traits approach generally assumes that species with similar traits are interchangeable and will be filtered by environmental variables in the same manner – so-called ‘response traits’ (Shipley, Vile, and Garnier, 2006). Therefore, these approaches have the advantage that they may be comparable for similar habitats or management, in different sites that begin with a different species pool, as the assemblage of traits will follow the same filtering process. Traits that are linked to ecosystem service delivery are termed ‘effect traits’ (Nock, Vogt, and Beisner, 2016), these are attributes of the species that determine its influence on ecosystem properties— in the case of carabids this is usually predatory capability. Following this approach, there is often an assumption that filtering by response traits will produce the same effects traits (Diaz et al., 2007).

Most trait-based approaches in carabid ecology use morphology as a grouping factor. At a very simple level, grouping by size allows a rapid assessment. Carabids of a larger body size are likely to consume a greater biomass of crop pests, their movements tend to be limited, and they tend to inhabit stable habitats; whilst smaller carabids are likely to consume less, and be flight dispersive, and more likely to move across disturbed habitats (Barbaro and Van Halder, 2009; Cole et al., 2002; Gayer et al., 2019; Pedley and Dolman, 2020; Zhang et al., 2020). Whilst this is generally true, there is still a considerable amount of variation in the species across the spectrum of size, particularly in the median classes where for example *P. melanarius* and *H. rufipes* would be classed together; yet they differ in diet and dispersal tremendously (Ribera et al., 1999).

Functional traits are described as those strongly influencing the performance of an organism (Brooks et al., 2012; McGill et al., 2006). In carabid literature, morphology has been used to infer these functional traits, such as dispersal ability from wing length (Gayer et al., 2019; Gobbi et al., 2010; Ribera et al., 1999; Woodcock et al., 2014). Unfortunately, the plasticity of carabids means that simplistic inference from singular traits will not translate to accurate analysis. Ingerson-Mahar

(2002 p131), in his review of traits in agricultural carabids, notes “there seems to be no one trait that can be applied across the Carabidae that will indicate specific feeding habits”. However, the author reviews a number of morphological traits that may be useful in combination: body form (wedge shaping, forebody character, flexibility of movement); leg form (runner, pusher, combination); flight ability (fully winged and flight able, winged not fight able, and non-functionally winged) which may vary by season or population process; mandible and maxillary characteristics (fluid feeders, fragment feeders, mixed feeders, and elative food handling strength).

The complication in this approach with agricultural carabids appears to be that they are generalists, noted in literature to have wide tolerances and occur in a range of environments. This is likely to be an attribute of an adaptive response to the rapid expansion (relative to evolutionary timescales) of agricultural land: areas of shifting resources, constant disturbance and ecologically speaking, ubiquitous edge effects. But much work has shown that the distribution of these generalist species varies in space and time and so there must be effects of competition and predation, resulting in more refined actualised niches (Holland, 2002; Kotze et al., 2011).

Den Boer, Thielle and Weber (1979) state that “the variation in carabid behaviour surmounts that of their external properties” (p1) and consider habitat choice to be governed by behaviour, which in itself is the precursor of evolutionary divergence apparent across the 40,000 species of carabids globally. The authors list the complexes of behaviour in the annidation (i.e. adaptation of the various genotypes to different ecological niches) of species such as: brood care, food choice, mobility, diurnal rhythm of activity, and annual periodicity of development, added to the broad preference denoted by these within species specific preference for microclimatic conditions. Thielle (1977) notes that “complicated and only recently recognised forms of behaviour play a part in habitat affinity” (p273). Yet work on the particulars of this has only been done in terms of broad categories such as the distinctions in forest and grassland species - and the drivers and effects of this on distributions.

In chapter 2, I elucidated the habitat preferences of ten “eurytopic” farmland species, showing them to have marked and differential actualised niches. This work showed the morphologically similar *Pterostichus melanarius* and *Pterostichus madidus* to have differing occurrence, associated with field centres and tracks, and woodland and urban areas, respectively. These two species have the same body size, body form, leg form, flight capability and mandible and maxillary characteristics, and so would be expected to be interchangeable in a traits approach. Thielle (1977) likewise notes the morphological similarity of *Abax ater*, *paralelus*, and *ovalis* and the respective species’ differential distributions based around their brood care behaviours (p.272).

Traits-based approaches have been shown to be extensively useful in predicting plant communities (Gaudet and Keddy, 1988; McGill et al., 2006), however the translation to invertebrates and mammals has arguably ignored the problem that motile organisms have an element of choice in habitat selection (Moretti et al., 2017). In the case of carabid beetles particularly, morphological traits alone cannot accurately predict the niche organisation, and inform on the communities arising from particular environmental filters—i.e. management. Therefore, behavioural traits need to be integrated into future trait analysis. Since these behavioural traits are hard to infer from laboratory observations (due to difficulty in replicating real world environments and stimuli), inference from observed distributions is likely to be necessary in a modelling approach, such as my work in chapter 2. Whilst this is plausible, it brings us back to our starting argument in the feasibility of a species level approach. Accurate identification of multiple functional traits, incorporating behavioural traits, is likely to result in species level analysis. Moreover, a species level approach negates the influence of subjective classifications such as ranked dispersal capabilities (McGill et al, 2006; Moretti et al., 2017). Diaz et al. (2007) detail the steps that may be taken to reduce uncertainty in functional traits approaches. The authors state that idiosyncratic effects of particular species, where functional traits are not obvious from first principles or literature, may be responsible for failures of the approach to accurately explain the effects on ecosystem properties — this would appear to apply to agricultural carabids. The species level approach therefore accounts for species level differences in effects traits, and allows for more accurate estimation of ecosystem service delivery.

I have argued that the variation of response at a species level may be responsible for the disparity of results in measurements of efficacy of management on carabid populations, as represented by pooled data. I have also observed that land managers may be willing and able to identify key carabid species (chapter 7). In the case of elucidating the predation potential of agricultural carabids, my approach of selecting the most abundant species, and developing management recommendations based on their responses to environmental variables may be key to delivering effective management for carabid abundance and associated NPC. However, a direct comparison between community traits and species level modelling with a robust dataset would be desirable, to guide future analyses.

b) How does larvae service provision differ to adult carabids?

Carabid larvae are both a key life stage in determining adult abundance, and a predatory organism in their own right. Larvae are active in different areas and at different times to adults, and therefore the contribution of larvae to ecosystem services may be considerable. However, this life-stage has been poorly studied due to the difficulty in capture and identification.

The novel subterranean trapping method described in chapters 3 and 4 proved effective and informed on carabid larvae in a ground-breaking way. Previous work on carabid larvae has relied on standard pitfall trapping, and soil cores, as discussed in chapter 3 (Luff, 2004). In chapter 3, I found subterranean traps to be more effective in sampling larvae than pitfall traps, however overall numbers were low in both trap types, which we attributed to the drought conditions. In chapter 4, sampling of carabid larvae was much more successful, returning a catch of larvae comprising 14% of the total carabids; compared to 3.5% with standard pitfalls (Table 1). This is comparable to Traugott's (1998) work on carabid adults and larvae, for which the author used a combination of pitfalls and soil cores. However, the subterranean pitfall technique benefits from much less labour and time (Luff, 2004). Barney and Pass (2017) trapped a higher proportion of larvae with standard pitfalls in alfalfa crops, yet without a direct comparison it is difficult to draw conclusions — I have demonstrated adequately in chapters 2 and 3 that differential trapping in the same location captured both different species and different activity density.

Table 7- Comparison of chapter 3 and 4 sampling techniques for carabid adults and larvae, with catches detailed in the literature

	Adults	Larvae	Total n
Brooms barn standard pitfalls	500 98.8 %	6 1.2%	506
Brooms barn subterranean pitfalls	1158 96.7%	39 3.2%	1197
Rothamsted standard pitfalls	7990 96.5%	293 3.5%	8283
Rothamsted subterranean pitfalls	2097 85.8%	348 14.2%	2445
Traugott (1998) standard pitfalls and soil cores	5870 89.2%	710 10.8%	6580
Barney and Pass (2017) standard pitfalls	1200 80.0%	300 20.0%	1500

Standard pitfall traps measure activity density of surface-active arthropods, and as such can underestimate the abundance of cryptic species, or those active below the soil surface (Kotze et al., 2011). Subterranean traps sample the differential activity density of hypogean movements that is more stable, especially under climatic variation (Jowett et al., 2019). Measuring activity-density at the surface will only capture surface activity of larvae, which, as soil dwelling organisms for the most part, is limited. Also, surface activity is limited to certain predation, such as granivorous species surface foraging (Traugott, 1998), and may also be a measure of dispersal in areas of low resource availability (Betz, 1992). I found in chapter 3, that granivorous larvae were weakly associated with subterranean traps, yet still more associated with subterranean rather than standard pitfalls. Predatory larvae were strongly associated with subterranean traps. This extends to other key predation knowledge gaps — for instance cabbage stem flea beetles inhabit the soil as larvae and pupae, and as such are vulnerable to predation (Williams et al., 2020). Standard pitfall trapping may underestimate the capacity of carabids, particularly the larvae, to control soil dwelling pests, or those with vulnerable life-stages belowground. Future work on subterranean predation should focus on carabid larvae as key potential predators of crop pests.

In chapter 3, I reported that barley under-sown with grass promoted the abundance of predatory carabid larvae. This finding was only evident in subterranean traps. Pitfall trapping showed an opposite picture, whereby larvae were least abundant in that crop type. This particularly highlights the limitation of relying on standard pitfall trapping and the measure of activity density to inform on how management impacts the potential for carabid beetle predation.

In chapter 4, the Rothamsted farm experiment enabled me to explore the effect management interventions and landscape factors governing carabid larvae abundance. This work indicated that previous crop may also be associated with larval abundances. This finding is potentially important to guide management, however, the experimental design did not include enough repetitions of this factor to for statistical analysis. Future work to discern the significance of this effect would be valuable. Based on the findings from chapter 4, it could be assumed that margin treatments may afford more below ground resources, and therefore promote larval abundances. Yet the control treatment had distinctly higher abundances than either margin type. I argued within the chapter that the weedy edge area of the control areas was a likely area for oviposition, and the small-scale movements (as seen in spatial models) supported their residence near where they were deposited as eggs. The abundance of larvae in the adjacent grass/scrub habitats implies that this dense vegetation does not preclude oviposition (as was assumed in the margins), however these may be different species of carabid. It is important to understand the spatio-temporal habitat requirements of carabids in different life stages, not only to understand the contribution to NPC, but also to apply management to increase abundance and survivorship at each developmental stage.

External limitations meant that I was not able to complete species level identification of larvae, which could have identified the species-specific responses to management and landscape factors. Some work has been done on relative abundances by species, showing that larvae can be active in different places and at different times to adults, which has implications for predatory potential — however, the spatial relationship has not been explored (Barney and Pass, 2017; Luff, 2004; Sims, 2017; Traugott, 1998). Completing the identification and analysis of larvae trapped in chapter 4 would feed into a large knowledge gap elucidating the factors influencing the abundance and predatory capacity of larval communities. Work on carabid larvae is limited by the difficulty of identification, I found it to be particularly time consuming. Molecular identification, using metabarcoding approaches would be beneficial to explore for future methods, for faster and more conclusive identification to a species level (Kajtoch, 2014; Toju and Baba, 2018). Additionally, a metabarcoding approach could elucidate pest consumption of carabid larvae at both an individual and population level using gut content analysis (Kamenova et al., 2018; Staudacher et al., 2011). Larvae from the experiments have been stored appropriately to allow this analysis in future work.

c) Which farm management interventions are most beneficial?

To answer my third key question, I employed a dual approach, since farm management comprises aspects of both ecological and anthropogenic influence. In chapter 2, using the FSE dataset I uncovered the key factors influencing carabid abundance and diversity, in terms of management these were crop type, hedges, ditches, and margins. In chapter 4, crop type, or vegetation generally, was comprehensively shown to be the most vital factor influencing carabid communities and key predatory species.

In the Beneficial Beetles Survey (chapter 6), diverse crop rotations were much more widely implemented by farmers currently than in the past — which may be attributed to greening requirements of the basic payment and agri-environment schemes (AES) (HMGOV, 2021). This farm management principle was most frequently viewed by participating farmers as very important to the carabid beetles on their farms, and among the top three rated as not at all difficult to implement. In this chapter, I linked the perceived importance and ease of implementation to behavioural intent using the theory of planned behaviour (TPB) (Ajzen, 1991). Since farmer participants would have a high intention to implement diverse crop rotations in the future, this constitutes a win-win strategy to boost carabid abundance and diversity on farms.

Chapter 3 reiterated the importance of crop, with the nuance of under-sowing as beneficial to both adults and larvae. In the survey (chapter 6) undersowing/companion cropping was among the least practised, both in the past and currently. This management was among the lowest ranked as important, and most frequently ranked as slightly difficult. Therefore, this type of management is unlikely to be implemented currently despite the potential to boost carabid abundance in field areas. Future work would be needed to quantify the potential of undersowing and companion cropping to boost carabid abundance and associated NPC, and informing farmers of the wider benefits to this approach. As I showed in chapter 7, enlisting farmers in data gathering whilst monitoring their own farm habitats is practicable, and has the benefit of producing a large quantity of field data for analysis, whilst engaging farmers with conservation biocontrol, and feeding directly into adaptive management.

In chapter 3, I explored the effect of tillage on pooled carabid abundances and community assemblages. Despite the relative short-term of experimental establishment, the small plot scale, and the single tillage event (literature suggests an incremental effect of multiple tillage operations) (Hatten et al., 2007), I was able to identify species level responses. This suggests that the assemblage is more affected by this management than the pooled abundance. Since key predators may be affected negatively, this impacts potential predation. For example, *Carabus violaceus*, a large carabid species which is a key predator of slugs and snails, showed a negative response to tillage. I discovered from the farmer survey (chapter 6) that tillage was an increasingly popular management option. Farmer participants viewed tillage most frequently as extremely important to carabid beetles, and among the least difficult of the 16 farm practices to implement. However, this was one of the practices that some farmers responded was impossible on their farms due to landscape or drainage concerns. Further work with farmers to discern which tillage regimes impact less on key carabid species would be desirable, particularly to elucidate interventions to ameliorate effects where zero-till is impractical, or undesirable with regard to other farm management objectives.

A surprising finding in chapter 4 was that margins may not be as useful to carabid mediated NPC (compared to infield measures) as previously assumed from the literature. Therefore, the overwhelming preference by farmers for margins revealed in chapter 6 is problematic to recommendations based on this finding. Margins have been shown to be beneficial to biodiversity in farmland, particularly farmland birds and pollinators, and this has been extensively communicated to farmers (Carreck, Williams and Oakley, 1999; Vickery, Feber, and Fuller, 2009). Blumgart’s (2020) work on the experimental margins at Rothamsted showed contrasting results, in that the wildflower margins greatly enhanced the diversity of moth species, and enhanced the abundance of moths compared to the two other margin treatments. Whilst margins may not be as vital to carabid presence in crop areas (and therefore NPC), as formerly assumed, they may still be a key measure to support other agents of NPC such as Syrphinae (hoverflies), Coccinellidae (ladybirds), and Chrysopidae (lacewings) (Dennis and Fry, 1992; Holland et al., 2008; Ramsden et al., 2015).

However, a focus on providing the ecological requirements of birds and pollinators, as highly mobile organisms, may not translate to a suitability for other organisms, such as I found with carabids. Margins therefore should not be discouraged outright, rather the size and positioning within the farm landscape should be further investigated. In chapter 4, I discussed that margins may be of more utility if not sited between adjacent crops, and perhaps larger margins should be used, and more sparingly, as interface zones and buffers to unsuitable habitat such as urban areas. More work is necessary to test this alternative approach.

In chapter 6, I discussed the relative importance of in-crop interventions, according to the work of Butler Vickery and Norris (2007). In chapter 4, I raised the issue of residency of key carabid species in the crop centre. This supports the argument for prioritisation of interventions such as diverse crop rotation, reduced tillage, and low pesticide use — as opposed to semi-natural areas and margin interventions. This would seem to fit more with a ‘sharing’ rather than a ‘sparing’ argument, whereby farmers would benefit from agro-ecological measures within the productive system, rather than setting aside productive land as natural areas.

Farm management objectives at a broader scale are often driven by societal values, as filtered by governmental regulation and incentive schemes, and also public demand for food products (Verbeke, 2005; Woolthuis, Lankhuizen and Gilsing, 2005). In chapter 5, I detailed the public preference for farming futures that included protecting the environment, with much lower support for profitable farming, food production, and affordable food; even when the current pressures and trade-offs were communicated. Public demand and policy support for sustainable agriculture is rising, and with increased transparency of food production there is a push for demonstrable and visible nature friendly farming (Arnot, Vizzier-Thaxton, and Scanes, 2016). Farm management therefore has to balance a number of objectives, of which NPC is only one. For example, flowering field margins are a popular intervention (Bullock, 2012; Junge, 2015) so, given my findings of the limited value of one commercial flowering mix to carabids (chapter 4), it would be valuable to investigate if other seed mixes would be more amenable to predatory carabids. This could include reverse engineering plant species that provide for the ecological requirements of carabids, such as seed production when weed seed resources in crop areas are low (particularly spring).

A particular all-round win demonstrated by my work in chapter 6, is reducing pesticide use. Public opprobrium to pesticides continues to rise (Petersen, 2000; Schaub, Huber, and Finger, 2020), and the impacts on natural enemies, such as carabids are well documented (Douglas, Rohr and Tooker, 2015; Huusela-Viestola, 1996; Navntoft, Esbjerg, and Riedel, 2006). Use of pesticides and fertilisers in the farming futures posters for affordable food and food production were cited as a trade-off with protecting the environment — which may have been a factor in the unpopularity of these scenarios (chapter 5). In chapter 6, I discovered that whilst the practice of low pesticide use had increased, and farmers perceived it to be very important for carabids, it was rated frequently as slightly difficult and moderately difficult, and as such was less likely to be implemented under the TPB construct (Ajzen 1991). Recent work has shown that in the presence of natural enemies, pesticides do not significantly reduce arthropod pest densities in the long-term, due to pest resurgence with natural enemy suppression (Janssen and van Rijn, 2021). Managing carabid communities effectively at a farm scale has the potential to regulate pest populations and reduce the need for pesticide sprays. Further work in this vein is needed to quantify agro-ecological theory, and in particular it should be communicated to farmers in the context of integrated pest management (IPM), to support the use of pesticides only when absolutely necessary (in threshold-based approaches) and when it will not damage the capacity of carabids to provide NPC (Douglas, Rohr and Tooker, 2015).

d) Can increasing farmers' positive beliefs about carabids increase uptake of measures for natural-enemy pest control?

In chapter 5, I demonstrated the effectiveness of engagement by experiment, whereby I communicated key farm system trade-offs and gathered data on preferred future farming scenarios. Within the results, particularly qualitative responses, I saw that peoples' beliefs were intrinsically linked to their consumer behaviour, in the food they chose, and therefore the farming they decided to support — for example in comments around vegetarian diets, and sustainable use of resources. This was similarly strong in the Beneficial Beetles Survey (chapter 6). It bears mentioning in the first instance that the strength of response was encouraging, given that carabids are not among the most charismatic of beneficial invertebrates (Oberhauser and Guiney, 2009). Though I took efforts to promote the survey widely to engage a range of farmers, those attending the talks particularly had some belief in conservation biocontrol. Furthermore, the level of awareness of carabid beetles as agents of NPC measured in the survey was high. However, many farmers were unaware of their role in weed seed predation, and this was reflected in their uncertainty over the significance of weed seed control, compared to a high level of belief in the efficacy of arthropod pest control.

In chapter 6, I found that knowledge exchange treatments impacted intentions — raising intent to implement in farmers who did not hold strong beliefs either for or against the implementation of measures. In chapter 7, beliefs again influenced behavioural intent, in the choice of which farm management practices to monitor, and the beliefs around significance of carabid pest control affected the willingness to monitor carabids. Therefore, I can conclusively say that increasing farmers positive beliefs can increase the uptake of measures for NPC. This means that communicating the benefits of such measures as undersowing could raise the uptake of this type of management. Uncertainty remains in the literature around the efficacy of different management interventions in encouraging carabids, particularly at a species level — for example tillage. Establishing an iterative loop of increasing knowledge exchange of carabid ecology and impacts of management would reduce this uncertainty, both in scientific terms and towards positive farmer attitudes.

It will likewise be important to communicate the theory behind placement of margins, as these are a popular management type with farmer and the public, and strong beliefs will have been formed, which may result in cognitive dissonance and rejection of the new idea by farmers (Stiff and Mongeau, 2016). A possible avenue to ameliorate both the need for further research, and the need to persuade farmers to use margins effectively, is monitoring. Farmer participants in the survey (chapter 7) indicated that the farm management practice they would prioritise for monitoring would be field margins and/or buffer strips. Therefore, under a sampling protocol over time, farmers can monitor the effectiveness of margins on their own farms, feeding into adaptive management, and also supplying field data to refine our understanding of margin attributes and placement and their effects on carabid communities in crop areas and their potential for NPC. Farmers also frequently indicated that their measures of success were subjective visual evaluations of farm wildlife, and ‘gut feelings’. Seeing carabids and other beneficials in the process of monitoring thus will feed strongly into their beliefs and attitudes, and guide future behaviour (Pike, 2013).

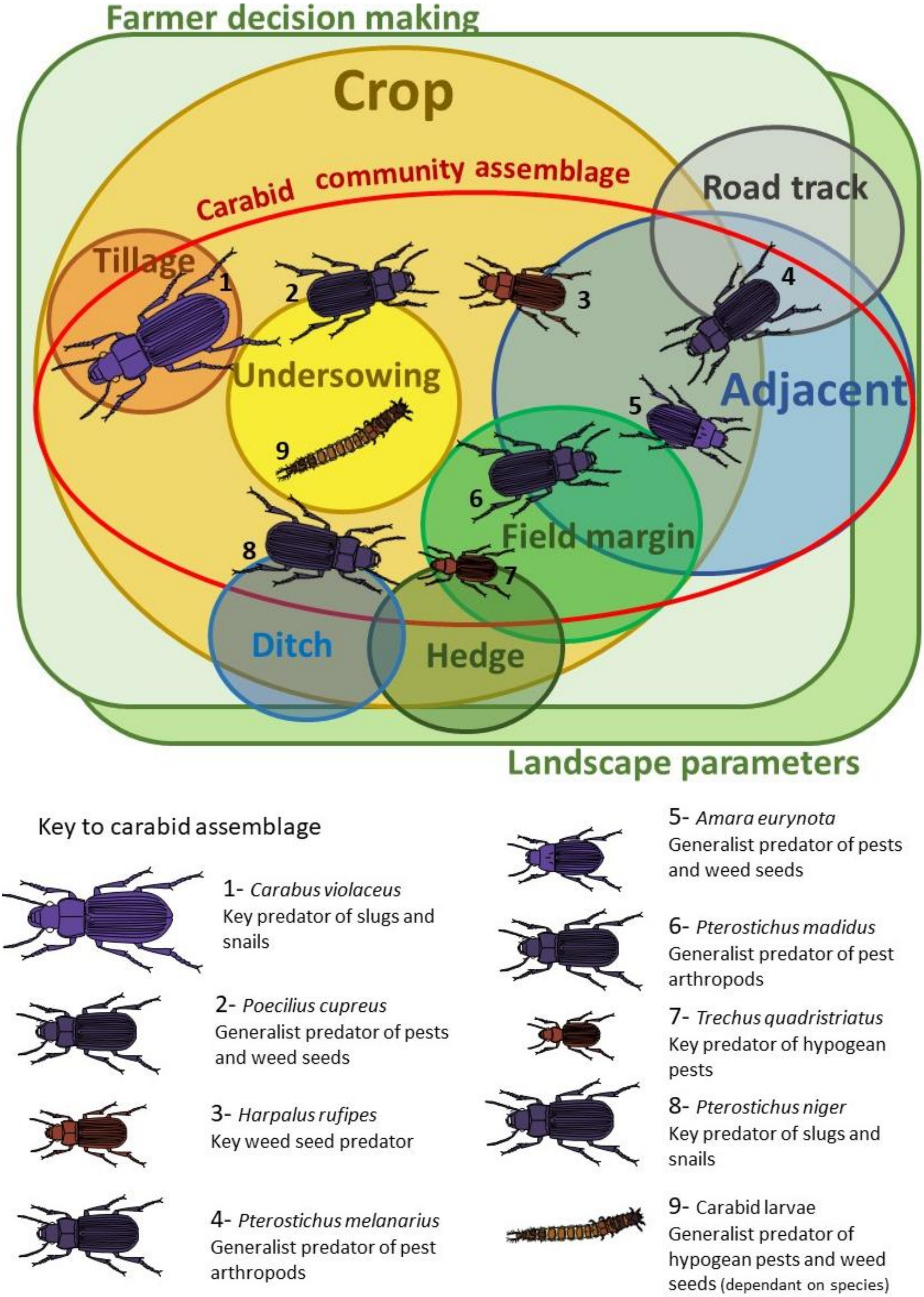


Figure 8- Summary of key influences as elucidated in this work. The size of circles denotes their relative level of influence, and overlap denotes synergies and overlaps in influence. Placement of species indicates the differential species responses to various factors, and therefore the specifics of habitat filtering that produces the carabid community assemblage.

e) What are the factors influencing beneficial assemblages at the farm scale? Integration of knowledge.

In chapter 1, I identified factors from the literature likely to have an impact on carabid predation in crop areas. In chapter 2, I took this understanding and applied it to a large-scale UK dataset, examining the distribution of carabid beetles in crops by factors I identified in the data. However, some key gaps were missing, in measurements informing on margin and adjacent area communities, and the scarcity of larvae captured in samples. Yet the most notable gap, identified in chapter 1, is the paucity of data informing on relative influences of management on carabids at a farm scale. As this is the scale at which farmers make decisions and balance management objectives this information is both of scientific and practical value.

In my own fieldwork therefore, I filled these gaps by gathering data from two established field experiments to explore identified factors of interest, with subterranean trapping along standard pitfalls (chapter 3 and 4), and measurements in experimental margins, and adjacent grass/scrub areas (chapter 4). I designed the sampling strategy in chapter 4 to test the key influences at a farm scale, and deliver meaningful recommendations for management.

As detailed above, the main factor influencing agricultural carabid species is vegetation, as this determines the micro-climate and food and shelter resources (Fig. 1). For key predatory species, this vegetation comprises the crop — as these species overwinter and breed primarily in crop areas. Therefore, abundances may be boosted by improving the food and shelter the crop area provides, with undersowing and companion cropping, and low tillage systems (chapter 3). Species richness at a farm scale, and the populations of beneficial species may be enhanced by diverse cropping. Consideration of crop rotations may help with NPC of arthropod pests with belowground life-stages, as I demonstrated in chapter 4 with larval abundances; however, this warrants further investigation before solid recommendations can be made.

Landscape features can have a significant impact of beneficial assemblages (Fig. 1). The key effect I discovered was the impact of adjacent habitat, and the impact of urban areas on crop abundances and diversity. I was unable to pick apart the full influence of grass/scrub areas as the repetitions were not evident over different crop types for comparison. This is an element of the practicalities of farm scale studies and the inherent compromises in statistical power. Future work over a number of sites would be desirable. I was however, able to discern the influence of grass/scrub habitats on the top five species and larvae. It appears that this habitat is not as vital as assumed from the literature, at least where the farm scale communities of beneficial species are concerned.

In chapter 2, the FSE dataset allowed me to verify the effect of landscape factors as cited in the literature. In chapter 4, I investigated the effect of margins, however I was unable to examine the effects of hedges and tracks, as there were not enough repetitions of these landscape conditions to examine in LMMs. Therefore, I balanced the effects of hedges and tracks over the sampling design. However, given the argument of hedges as potential barriers between crops as experienced by agricultural carabids, and some dissention in the literature as to their status as barrier or corridor (Mauremooto et al., 1995) future work on species specifics of these landscape features is warranted. In chapter 2, I also discovered that roads and tracks were associated with the abundance of *P. melanarius*, a key predatory species — as such, these features should be considered in future experimental design.

The boundary management feature of margins, was not as influential as assumed from ecological theory and literature, as expounded above, particularly in some situations, margins may act as a barrier to key predatory species moving between crops. Moreover, I showed in chapter 4 that key species are able to distribute over longer distances around crop areas, as seen in the spatial models of autocorrelation. This led me to the recommendation for farmers to focus on establishing fewer, but larger margins, preferably at interface areas to unfavourable habitat such as urban areas. However, in practice farmers must balance other management considerations, such as the practicalities of margin management and the other ecosystem services provided.

To be practically applicable, it is important to realise that recommendations do not operate in a vacuum, but evaluated against other advice, experience, and objectives (Rodgers, 2010). In my social research I discovered that while farmers' beliefs, and therefore behavioural intent, can be influenced, this is moderated by the perceived and actual ability to carry out actions; the so called KAP (knowledge-action-practice) gap (Stiff and Mongeau, 2016). In the Beneficial Beetles Survey, I found that participants engaged with range of advisory services, and were subject to various financial constraints (chapters 6 and 7). There was a perception that specific advice was necessary to feel confident in the uptake of new management principles to boost carabid abundances. In the case of margins, farmers are advised by agro-ecological NGOs to site wildflower resources for pollinators them in sunny and sheltered areas, for general biodiversity to connect margins together to create corridors, and to site when possible next to ditches and hedges as a buffer (Agricology, 2021). Margins are also a common management intervention prescribed in agri-environmental schemes, where farmers choose from options dictating area allocations and minimum widths of margins and buffer areas, for specific objectives (Natural England, 2012). Therefore, the consilience of guidance, and appropriate financial incentives to support farmers in their own preferred objectives is also a key factor influencing farmer decision making, and thus, beneficial assemblages at the farm scale (Fig. 1). Additionally, farmers may be constrained by landscape factors outside of their decision making, such as drainage, soils, and adjacent habitat — all of which influence carabid communities (Fig. 1). The new environmental land management schemes support monitoring as a measure of intervention efficacy (Defra, 2020). As covered above, this could be an effective strategy to both improve our understanding of measures for multiple ecosystem service outcomes, and to support farmers in adaptive management.

As expounded in answering key question A, the response of carabids to each factor will vary by species. Figure 1 shows some of the species-specific responses of species to factors tested throughout the thesis. Since each species performs different predatory services, this illustrates the potential of management and landscape factors to govern the NPC potential of the resultant assemblage. Considering the impacts of influences and interventions at a farm scale will allow for adaptive management towards more effective pest control.

8.2 Conclusion and applications

By answering my five key questions, this project has met its overarching aim. I have informed on the ecology of carabids, and the pertinent anthropogenic factors, and therefore contributed to the improvement of the efficacy and applicability of farm management interventions that increase the abundance and diversity of carabid species that contribute to natural-enemy pest control.

In chapters 2, 3 and 4. I elucidated the key spatial relationships, habitat, and management factors acting on carabid communities. This included novel work at the fine scale of individual species responses. From the work in chapters 3 and 4, I was able to inform on the predatory potential of assemblages arising from differential responses to management interventions. Particularly, I was able to highlight the utility of a novel trapping technique to gather data on larvae, and add to the knowledge gaps on the predatory potential of larvae in agro-ecosystems.

From my work in chapter 5 I was able to design the approach of engagement by experiment used in chapters 6 and 7. With this I was able to examine the attitudes and behavioural intent of farmers with and without knowledge-exchange treatments, showing that this engagement resulted in improved behavioural intent to key management of benefit to carabid beetles.

Moreover, I was able to prove the approach of self-monitoring to be a practicable approach to both engage farmers, and refine farm management for carabid beetles and associated natural-enemy pest control.

Based on the findings from this project, I would recommend a number of principles to guide future work:

- Carabid larvae should be taken account of, both in estimation of ecosystem services, and design of measures to boost abundance and diversity of agricultural carabid species.
- Incorporating this, and addressing differential adult activity, sampling to inform fully on predatory potential of assemblages should use different measures of activity density. Subterranean trapping is advisable, as it has proven cost effective and time efficient in relation to other hypogean sampling.
- Sampling at a farm scale proved effective to inform on management as applicable, yet was highly labour intensive. A protocol of monitoring over a number of sites could be practicable by farmers themselves, with a streamlined protocol.
- Differential activity also occurs at different time points. Year-round sampling, particularly in the spring (which was not possible under project constraints), and in the winter (where larvae may be more actively predatory than adults), would be valuable to build a robust picture of communities and predation potential.

The work in this project also enabled me to make practical recommendations for management by farmers:

- Different species of carabids specialise in different predation— on various crop pests and weed seeds. Different species are also tolerant to different climatic conditions and are active at different times of the year. A diversity of different crops in rotations, and semi natural habitats (such as hedges, ditches, margins and grass or scrubby areas) around the farm will encourage many different species of carabid to thrive.
- The infield crop is the main habitat influencing predatory carabids that control pests. Making this crop area more resource rich will encourage their numbers in fields. Measures such as reduced tillage will reduce mortality, whilst measures such as undersowing and companion cropping will provide structure and alternative food.

- Margins should not be sited between crops where the two crop areas meet, rather than multiple smaller margins all around the boundary of a field, larger single margins on one edge would be more beneficial for carabids— especially if this boundaries unsuitable habitat for agricultural carabids, such as urban areas or dense woodland.

Finally, my findings also point towards some key recommendation for policy to support carabid mediated NPC:

- Infield measures should be prioritised when considering support for NPC. Particularly, minimum tillage, and undersowing should be well supported financially as agri-environmental options.
- The 'how and why' theory of agri-environmental interventions should be communicated, not only to increase the accuracy of application, but also to influence the beliefs and attitudes of farmers relating to the management in question. This could be influential in raising the uptake of practices such as undersowing where there was limited experience and a lack of awareness of the potential benefits.
- Support from farmers for carabid mediated NPC was high, communication of measures beneficial to carabids may be useful in agri-environment scheme supporting documents.
- Advisory support was frequently raised by farmers participating in the survey. Free, centralised and impartial advice would be preferable, as farmer environmental advice is not universally available across the UK. A useful format could be online delivery, but multiple interventions are likely to be more effective, and practical on-site advice more impactful.
- Farmer self-monitoring was shown to have potential, which should be investigated as it has potential to inform results-based payments, facilitate adaptive management, and feed data into scientific analysis to inform on scheme effectiveness

There is still a lot of work to be done to improve the natural-enemy pest control of carabid beetle assemblages in farmland. This thesis has contributed substantially towards identifying the key directions towards mutually beneficial solutions for sustainable agriculture. I believe that effective future change lies in multi-directional knowledge exchange and data gathering, to engage and utilise all actors in applicable and efficient actions. The public believes in agro-ecological solutions, and farmers want to do their best for wildlife on their farms, whilst still producing quality food—now research needs to bring together the threads to design solutions that work for everyone.

8.3 References

Arnot, C., Vizzier-Thaxton, Y. and Scanes, C.G., 2016. Values, trust and science–building trust in today's food system in an era of radical transparency. *Poultry science*, 95(9), pp.2219-2224.

Agricology, 2021. *Field margins* [online]. Available at: https://www.agricology.co.uk/sites/default/ files/Field%20margins%2C%20hedgerows%2C%20woodland%20and%20scrub.pdf [Accessed 31/08/21]

Ajzen, I., 1991. The theory of planned behavior. *Organizational behavior and human decision processes*, 50(2), pp.179-211.

Barbaro, L. and Van Halder, I., 2009. Linking bird, carabid beetle and butterfly life-history traits to habitat fragmentation in mosaic landscapes. *Ecography*, 32(2), pp.321-333.

Barney, R.J. and Pass, B.C., 2017. Pitfall trap collections of ground beetle larvae (Coleoptera: Carabidae) in Kentucky alfalfa fields. *The Great Lakes Entomologist*, 19(3), p.2.

Betz, J.O., 1992. Studies on winter-active larvae of the ground beetle Carabus problematicus(Coleoptera, Carabidae). *Pedobiologia*, 36(3), pp.159-167.

Birthisel, S.K., Gallandt, E.R. and Jabbour, R., 2014. Habitat effects on second-order predation of the seed predator Harpalus rufipes and implications for weed seedbank management. *Biological control*, 70, pp.65-72.

Blumgart, D., 2020. Investigating the Mechanisms Behind Moth Declines: Plants, Land-use and Climate. *PhD thesis*. Lancaster University, UK

Brooks, D.R., Storkey, J., Clark, S.J., Firbank, L.G., Petit, S. and Woiwod, I.P., 2012. Trophic links between functional groups of arable plants and beetles are stable at a national scale. *Journal of Animal Ecology*, 81(1), pp.4-13.

Bullock, J.M., McCracken, M.E., Bowes, M.J., Chapman, R.E., Graves, A.R., Hinsley, S.A., Hutchins, M.G., Nowakowski, M., Nicholls, D.J., Oakley, S. and Old, G.H., 2021. Does agri-environmental management enhance biodiversity and multiple ecosystem services?: A farm-scale experiment. *Agriculture, Ecosystems & Environment*, 320, p.107582.

Butler, S.J., Vickery, J.A. & Norris, K. (2007b) A risk assessment framework for evaluating progress towards sustainability targets. *Aspects of Applied Biology*, 81, 317–323.

Carreck, N.L., Williams, I.H. and Oakley, J.N., 1999. Enhancing farmland for insect pollinators using flower mixtures. *Aspects of Applied Biology*, 54, pp.101-108.

Cole, L.J., McCracken, D.I., Dennis, P., Downie, I.S., Griffin, A.L., Foster, G.N., Murphy, K.J. and Waterhouse, T., 2002. Relationships between agricultural management and ecological groups of ground beetles (Coleoptera: Carabidae) on Scottish farmland. *Agriculture, Ecosystems & Environment*, 93(1-3), pp.323-336.

Defra, 2020. *Environmental Land Management Policy discussion document* February 2020. Available online at [https://consult.defra.gov.uk/elm/elmpolicyconsultation/supporting_documents/elmdiscussiondocument20200225a%20002.pdf] accessed 09.03.20

Den Boer, P.J., Thiele, H.U. and Weber, F., 1979. On the evolution of behaviour in Carabid beetles. In *Proceedings of the 3rd European Carabidologists' Meeting*. Miscellaneous papers, Agricultural University Wageningen (Vol. 18, p. 222).

Dennis, P. and Fry, G.L., 1992. Field margins: can they enhance natural enemy population densities and general arthropod diversity on farmland?. *Agriculture, Ecosystems & Environment*, 40(1-4), pp.95-115.

Diaz, S., Lavorel, S., de Bello, F., Quetier, F., Grigulis, K., Robson, M., 2007. Incorporating plant functional diversity effects in ecosystem service assessments. *Proceedings of the National Academy of Sciences of the United States of America* 104, 20684-20689.

Douglas, M.R., Rohr, J.R. and Tooker, J.F., 2015. EDITOR'S CHOICE: Neonicotinoid insecticide travels through a soil food chain, disrupting biological control of non-target pests and decreasing soya bean yield*. Journal of Applied Ecology*, 52(1), pp.250-260.

Firbank, L.G., Heard, M.S., Woiwod, I.P., Hawes, C., Haughton, A.J., Champion, G.T., Scott, R.J., Hill, M.O., Dewar, A.M., Squire, G.R. and May, M.J., 2003. An introduction to the Farm-Scale Evaluations of genetically modified herbicide-tolerant crops. *Journal of Applied Ecology*, pp.2-16.

Gaudet, C.L. and Keddy, P.A., 1988. A comparative approach to predicting competitive ability from plant traits. *Nature*, 334(6179), pp.242-243.

Gayer, C., Lövei, G.L., Magura, T., Dieterich, M. and Batáry, P., 2019. Carabid functional diversity is enhanced by conventional flowering fields, organic winter cereals and edge habitats. *Agriculture, Ecosystems & Environment*, 284, p.106579.

Gobbi, M., Caccianiga, M., Cerabolini, F., De Bernardi, F., Luzzaro, A. & Pierce, S. (2010) Plant adaptive responses during primary succession are associated with functional adaptations in ground beetles on deglaciated terrain. *Community Ecology*, 11, 223– 231.

Hatten, T.D., Bosque-Pérez, N.A., Labonte, J.R., Guy, S.O. and Eigenbrode, S.D., 2007. Effects of tillage on the activity density and biological diversity of carabid beetles in spring and winter crops. *Environmental entomology*, 36(2), pp.356-368.

HMGOV 2021. Basic Payment Scheme- Rules for 2021 [online] Available at: https://assets.publishing.service.gov.uk/media/6051d391e90e07527ad4017b/Basic_Payment_Scheme_-_Rules_for_2021_v2.0.pdf [Accessed 26/08/21]

Holland, J.M., Oaten, H., Southway, S. and Moreby, S., 2008. The effectiveness of field margin enhancement for cereal aphid control by different natural enemy guilds. *Biological Control*, 47(1), pp.71-76.

Huusela-Veistola, E., 1996, January. Effects of pesticide use and cultivation techniques on ground beetles (Col., Carabidae) in cereal fields. In Annales Zoologici Fennici (pp. 197-205*). Finnish Zoological and Botanical Publishing Board*.

Ingerson-Mahar, J., 2002. Relating diet and morphology in adult carabid beetles. *The Agroecology of Carabid Beetles*, pp.111-136.

Janssen, A. and van Rijn, P.C., 2021. Pesticides do not significantly reduce arthropod pest densities in the presence of natural enemies. *Ecology Letters*.

Jowett, K., Milne, A.E., Metcalfe, H., Hassall, K.L., Potts, S.G., Senapathi, D. and Storkey, J., 2019. Species matter when considering landscape effects on carabid distributions. *Agriculture, Ecosystems & Environment*, 285, p.106631.

Junge, X., Schüpbach, B., Walter, T., Schmid, B. and Lindemann-Matthies, P., 2015. Aesthetic quality of agricultural landscape elements in different seasonal stages in Switzerland. *Landscape and Urban Planning*, 133, pp.67-77.

Kajtoch, Ł., 2014. A DNA metabarcoding study of a polyphagous beetle dietary diversity: the utility of barcodes and sequencing techniques. *Folia Biologica* (Krakow), 62(3), pp.223-234.

Kamenova S., Mayer R., Rubbmark O., Coissac E., Plantegenest M. & Traugott M., 2018. Comparing three types of dietary samples for prey DNA decay in an insect generalist predator. Molecular Ecology Resources, doi: 10.1111/1755-0998.12775

Kotze, D.J., et al.,2011. Forty years of carabid beetle research in Europe–from taxonomy, biology, ecology and population studies to bioindication, habitat assessment and conservation. *ZooKeys*, (100), p.55.

Luff, M., 2004. Densities of carabid beetle (Coleoptera: Carabidae) larvae in agricultural land in north-east England. *Baltic Journal of Coleopterology*.

Mauremooto, J.R., Wratten, S.D., Worner, S.P. and Fry, G.L.A., 1995. Permeability of hedgerows to predatory carabid beetles. *Agriculture, ecosystems & environment*, 52(2-3), pp.141-148.

McGill, B.J., Enquist, B.J., Weiher, E. and Westoby, M., 2006. Rebuilding community ecology from functional traits. *Trends in ecology & evolution*, 21(4), pp.178-185.

McKemey, A.R., Symondson, W.O.C., Glen, D.M. and Brain, P., 2001. Effects of slug size on predation by Pterostichus melanarius (Coleoptera: Carabidae). *Biocontrol Science and Technology*, 11(1), pp.81-91.

Moretti, M., Dias, A.T., De Bello, F., Altermatt, F., Chown, S.L., Azcárate, F.M., Bell, J.R., Fournier, B., Hedde, M., Hortal, J. and Ibanez, S., 2017. Handbook of protocols for standardized measurement of terrestrial invertebrate functional traits. *Functional Ecology*, 31(3), pp.558-567.

Natural England, 2012. *Entry Level Stewardship- Environmental Stewardship Handbook*. Fourth Edition – January 2013. Natural England. Defra.

Navntoft, S., Esbjerg, P. and Riedel, W., 2006. Effects of reduced pesticide dosages on carabids (Coleoptera: Carabidae) in winter wheat. *Agricultural and Forest Entomology*, 8(1), pp.57-62.

Niemelä J (1996a) From systematics to conservation – carabidologists do it all. *Annales Zoologici Fennici* 33: 1–4.

Nock, C.A., Vogt, R.J. and Beisner, B.E., 2016. Functional traits. *eLS*, pp.1-8.

Oberhauser, K. and Guiney, M., 2009. Insects as flagship conservation species. *Terrestrial Arthropod Reviews*, 1(2), pp.111-123.

Pedley, S.M. and Dolman, P.M., 2020. Arthropod traits and assemblages differ between core patches, transient stepping-stones and landscape corridors. *Landscape Ecology*, pp.1-16.

Peterson, R.K., 2000. Public perceptions of agricultural biotechnology and pesticides: Recent understandings and implications for risk communication. *American entomologist-lanham-*, 46(1), pp.8-16.

Pike, T., 2013. Farmer engagement: an essential policy tool for delivering environmental management on farmland. *Aspects of Applied Biology*, (118), pp.187-191.

Ramsden, M.W., Menéndez, R., Leather, S.R. and Wäckers, F., 2015. Optimizing field margins for biocontrol services: the relative role of aphid abundance, annual floral resources, and overwinter habitat in enhancing aphid natural enemies. *Agriculture, Ecosystems & Environment*, 199, pp.94-104.

Ribera, I., McCracken, D.I., Foster, G.N., Downie, I.S. and Abernethy, V.J., 1999. Morphological diversity of ground beetles (Coleoptera: Carabidae) in Scottish agricultural land. *Journal of Zoology*, 247(1), pp.1-18.

Rogers, E.M., 2010. *Diffusion of innovations* (5th edition). Simon and Schuster.

Schaub, S., Huber, R. and Finger, R., 2020. Tracking societal concerns on pesticides–a Google Trends analysis. *Environmental Research Letters*, 15(8), p.084049.

Shipley, B., Vile, D. and Garnier, É., 2006. From plant traits to plant communities: a statistical mechanistic approach to biodiversity. *science,* 314(5800), pp.812-814.

Sims, I., Cole, J. and Verdon, P., 2016. Hypogean pitfall trapping: a novel technique for assessing soil biodiversity in agroecosystems. *British Journal of Entomology and Natural History*, 29(4), pp.211-229.

Staudacher K., Wallinger C., Schallhart N. & Traugott M., 2011. Detecting ingested plant DNA in soil-living insect larvae. *Soil Biology & Biochemistry* 43, 346-350.

Stiff, J.B. and Mongeau, P.A., 2016. *Persuasive communication*. Guilford Publications.

Thiele, H.U., 1977. *Carabid beetles in their environments: a study on habitat selection by adaptations in physiology and behaviour* (Vol. 10). Springer Science & Business Media.

Toju, H. and Baba, Y.G., 2018. DNA metabarcoding of spiders, insects, and springtails for exploring potential linkage between above-and below-ground food webs. *Zoological letters*, 4(1), pp.1-12.

Traugott, M., 1998. Larval and adult species composition, phenology and life cycles of carabid beetles (Coleoptera: Carabidae) in an organic potato field. *European Journal of Soil Biology*, 34(4), pp.189-197.

Verbeke, W., 2005. Agriculture and the food industry in the information age. *European review of agricultural economics*, 32(3), pp.347-368.

Vickery, J.A., Feber, R.E. and Fuller, R.J., 2009. Arable field margins managed for biodiversity conservation: a review of food resource provision for farmland birds. *Agriculture, ecosystems & environment*, 133(1-2), pp.1-13.

Williams, I.H., Ferguson, A.W., Kruus, M., Veromann, E. and Warner, D.J., 2010. Ground beetles as predators of oilseed rape pests: incidence, spatio-temporal distributions and feeding. In *Biocontrol-based integrated management of oilseed rape pests* (pp. 115-149). Springer, Dordrecht.

Woolthuis, R.K., Lankhuizen, M. and Gilsing, V., 2005. A system failure framework for innovation policy design. *Technovation,* 25(6), pp.609-619.

Woodcock, B.A., Harrower, C., Redhead, J., Edwards, M., Vanbergen, A.J., Heard, M.S., Roy, D.B. and Pywell, R.F., 2014. National patterns of functional diversity and redundancy in predatory ground beetles and bees associated with key UK arable crops. *Journal of Applied Ecology*, 51(1), pp.142-151.

Zhang, X., Axmacher, J.C., Wu, P., Song, X., Yu, Z. and Liu, Y., 2020. The taxon-and functional trait-dependent effects of field margin and landscape composition on predatory arthropods in wheat fields of the North China Plain. *Insect Conservation and Diversity*, 13(4), pp.328-339.

Appendix 1 (chapter 2)

Models and effects requested by reviewer as supplemental.

Pterostichus melanarius

```
Generalized linear mixed model analysis

Method:                  c.f. Schall (1991) Biometrika
Response variate:        X2715
Distribution:            poisson
Link function:           logarithm
Random model:            SITE_CODE + SITE_CODE.TRANSECT + SITE_CODE.TRANSECT.VISIT_DATE
Fixed model:             Constant + Adjacent + RoadTrack + CROP + DISTANCE + SOIL_CATEGORY +
Adjacent.DISTANCE + RoadTrack.DISTANCE + CROP.DISTANCE + DISTANCE.SOIL_CATEGORY


Dispersion parameter estimated


Estimated variance components

Random term                                      component          s.e.
SITE_CODE                                            0.702         0.121
SITE_CODE.TRANSECT                                   0.000         bound
SITE_CODE.TRANSECT.VISIT_DATE
                                                     0.545         0.042


Residual variance model

Term                                 Model(order)       Parameter            Estimate
                                     s.e.
Dispersn                             Identity           Sigma2                  9.688
0.374


Estimated variance matrix for variance components


                    SITE_CODE   1      0.01471
           SITE_CODE.TRANSECT   2      0.00000        0.00000
SITE_CODE.TRANSECT.VISIT_DATE   3     -0.00034        0.00000        0.00174
                     Dispersn   4     -0.00050        0.00000       -0.00278
                                             1              2              3


                     Dispersn   4      0.14004
                                             4
```

```
Wald tests for fixed effects

Sequentially adding terms to fixed model

Fixed term                          Wald statistic     d.f.      Wald/d.f.    chi pr
Adjacent                                      2.39        5           0.48     0.794
RoadTrack                                     3.06        2           1.53     0.217
CROP                                         22.06        3           7.35    <0.001
DISTANCE                                    135.92        2          67.96    <0.001
SOIL_CATEGORY                                 5.40        3           1.80     0.145
Adjacent.DISTANCE                            13.39       10           1.34     0.202
RoadTrack.DISTANCE                           18.67        4           4.67    <0.001
CROP.DISTANCE                                17.98        6           3.00     0.006
DISTANCE.SOIL_CATEGORY                       24.05        6           4.01    <0.001

Dropping individual terms from full fixed model

Fixed term                          Wald statistic     d.f.      Wald/d.f.    chi pr
DISTANCE.SOIL_CATEGORY                       24.05        6           4.01    <0.001
CROP.DISTANCE                                24.96        6           4.16    <0.001
RoadTrack.DISTANCE                           11.33        4           2.83     0.023
Adjacent.DISTANCE                            19.51       10           1.95     0.034


Table of effects for Constant

 3.211   Standard error: 0.2133


Table of effects for Adjacent


  Adjacent          Crop        Grass     Ploughed     Semi-Nat       Urban
                  0.0000      -0.2344      -0.4296      -0.1476     -0.1967


  Adjacent          Wood
                 -0.2051


Standard errors of differences

Average:                    0.3449
Maximum:                    0.5771
Minimum:                    0.1308

Average variance of differences: 0.1386


Table of effects for RoadTrack


  RoadTrack        Absent        Road       Track
                   0.0000     -0.1190      0.3807
```

```
Standard errors of differences

Average:                        0.2501
Maximum:                        0.3056
Minimum:                        0.1742

Average variance of differences: 0.06563
```

Table of effects for CROP

```
CROP                 B            M            SR            WR
                0.0000      -0.6334       -0.8860       -1.8122
```

```
Standard errors of differences

Average:                        0.4196
Maximum:                        0.6040
Minimum:                        0.2310

Average variance of differences: 0.2082
```

Table of effects for DISTANCE

```
 DISTANCE                 2            8            32
                    0.00000      0.07899       0.08195
```

```
Standard errors of differences

Average:                       0.08001
Maximum:                       0.08300
Minimum:                       0.07716

Average variance of differences: 0.006407
```

Table of effects for SOIL_CATEGORY

```
 SOIL_CATEGORY          Heavy        Light       Medium        Organic
                       0.0000       0.4457       0.1188        -0.6737
```

```
Standard errors of differences

Average:                        0.3567
Maximum:                        0.4712
Minimum:                        0.2075
```

```
Average variance of differences: 0.1337
```

Table of effects for Adjacent.DISTANCE

```
       DISTANCE           2           8          32
       Adjacent
           Crop      0.0000      0.0000      0.0000
          Grass      0.0000      0.1504      0.1882
       Ploughed      0.0000      0.0402      0.2432
       Semi-Nat      0.0000      0.1075      0.3246
          Urban      0.0000      0.4298      0.4012
           Wood      0.0000      0.2432      0.1096


Standard errors of differences

Average:                           0.2322
Maximum:                           0.5173
Minimum:                          0.07445

Average variance of differences: 0.07435
```

Table of effects for RoadTrack.DISTANCE

```
       DISTANCE                2                8               32
      RoadTrack
         Absent           0.0000           0.0000           0.0000
           Road           0.0000          -0.3409          -0.1961
          Track           0.0000          -0.2120          -0.2373


Standard errors of differences

Average:                           0.1451
Maximum:                           0.2060
Minimum:                          0.08470

Average variance of differences: 0.02360
```

Table of effects for CROP.DISTANCE

```
       DISTANCE                2                8               32
           CROP
              B           0.0000           0.0000           0.0000
              M           0.0000          -0.0124           0.1526
             SR           0.0000           0.3012           0.3617
             WR           0.0000           0.2829           0.3308
```

Standard errors of differences

Average:	0.2443
Maximum:	0.4852
Minimum:	0.07805

Average variance of differences: 0.09548

Table of effects for DISTANCE.SOIL_CATEGORY

SOIL_CATEGORY	Heavy	Light	Medium	Organic
DISTANCE				
2	0.00000	0.00000	0.00000	0.00000
8	0.00000	0.06624	-0.17921	0.15035
32	0.00000	0.22205	0.08840	0.28876

Standard errors of differences

Average:	0.1151
Maximum:	0.1693
Minimum:	0.07036

Average variance of differences: 0.01439

Pterosticus madidus

Generalized linear mixed model analysis

Method: c.f. Schall (1991) Biometrika
Response variate: X2714
Distribution: poisson
Link function: logarithm
Random model: SITE_CODE + SITE_CODE.TRANSECT + SITE_CODE.TRANSECT.VISIT_DATE
Fixed model: Constant + Adjacent + RoadTrack + Verge* + CROP + DISTANCE + SOIL_CATEGORY + Adjacent.DISTANCE + RoadTrack.DISTANCE + CROP.DISTANCE + DISTANCE.SOIL_CATEGORY + Verge.DISTANCE

Dispersion parameter estimated

Estimated variance components

Random term	component	s.e.
SITE_CODE	0.857	0.187
SITE_CODE.TRANSECT	0.000	bound
SITE_CODE.TRANSECT.VISIT_DATE	0.746	0.075

Residual variance model

```
Term                              Model(order)    Parameter            Estimate
                                  s.e.
Dispersn                          Identity        Sigma2                  7.457
0.387
```

Estimated variance matrix for variance components

```
                      SITE_CODE    1      0.03496
             SITE_CODE.TRANSECT    2      0.00000      0.00000
  SITE_CODE.TRANSECT.VISIT_DATE    3     -0.00141      0.00000      0.00565
                       Dispersn    4     -0.00075      0.00000     -0.00433
                                                1            2            3


                       Dispersn    4      0.14976
                                                4
```

Wald tests for fixed effects

Sequentially adding terms to fixed model

Fixed term	Wald statistic	d.f.	Wald/d.f.	chi pr
Adjacent	3.02	5	0.60	0.697
RoadTrack	0.34	2	0.17	0.843
Verge	0.73	1	0.73	0.394
CROP	5.53	3	1.84	0.137
DISTANCE	3.23	2	1.61	0.199
SOIL_CATEGORY	3.13	3	1.04	0.372
Adjacent.DISTANCE	28.31	10	2.83	0.002
RoadTrack.DISTANCE	9.36	4	2.34	0.053
CROP.DISTANCE	14.78	6	2.46	0.022
DISTANCE.SOIL_CATEGORY	41.70	6	6.95	<0.001
Verge.DISTANCE	8.61	2	4.30	0.014

Dropping individual terms from full fixed model

Fixed term	Wald statistic	d.f.	Wald/d.f.	chi pr
Verge.DISTANCE	8.61	2	4.30	0.014
DISTANCE.SOIL_CATEGORY	34.80	6	5.80	<0.001
CROP.DISTANCE	25.12	6	4.19	<0.001
RoadTrack.DISTANCE	13.69	4	3.42	0.008
Adjacent.DISTANCE	25.86	10	2.59	0.004

Table of effects for Constant

2.412 Standard error: 0.3095

Table of effects for Adjacent

```
 Adjacent           Crop        Grass     Ploughed     Semi-Nat        Urban
                  0.0000       0.1939      -0.4394       0.2498      -0.1559

 Adjacent           Wood
                  0.2818
```

```
Standard errors of differences

Average:                        0.5099
Maximum:                        0.8346
Minimum:                        0.1999

Average variance of differences: 0.2968
```

Table of effects for RoadTrack

```
 RoadTrack         Absent         Road        Track
                  0.00000      0.12586     -0.06917
```

```
Standard errors of differences

Average:                        0.3435
Maximum:                        0.4068
Minimum:                        0.2499

Average variance of differences: 0.1226
```

Table of effects for Verge

```
 Verge          Absent         Verge
              0.000000     -0.003968
```

```
Standard error of differences: 0.2086
```

Table of effects for CROP

```
CROP                B             M            SR            WR
               0.0000       -0.4260       -0.4188       -1.5728
```

```
Standard errors of differences

Average:                     0.6782
Maximum:                      1.032
Minimum:                     0.3159

Average variance of differences: 0.5817


Table of effects for DISTANCE


  DISTANCE              2            8           32
                   0.0000      -0.1445      -0.3859


Standard errors of differences

Average:                     0.1453
Maximum:                     0.1470
Minimum:                     0.1431


Table of effects for SOIL_CATEGORY


  SOIL_CATEGORY         Heavy        Light       Medium      Organic
                       0.0000      -0.1143      -0.2439      -2.0452


Standard errors of differences

Average:                      1.003
Maximum:                      1.654
Minimum:                     0.2824

Average variance of differences: 1.411


Table of effects for Adjacent.DISTANCE


        DISTANCE            2            8           32
        Adjacent
            Crop       0.0000       0.0000       0.0000
           Grass       0.0000      -0.3098      -0.0240
        Ploughed       0.0000       0.4484       0.0780
        Semi-Nat       0.0000      -0.8642      -0.6256
           Urban       0.0000       0.0436       0.7842
            Wood       0.0000       0.0347      -0.0937


Standard errors of differences

Average:                     0.4503
```

```
Maximum:                        1.230
Minimum:                       0.1171

Average variance of differences: 0.3408


Table of effects for RoadTrack.DISTANCE


     DISTANCE            2            8           32
    RoadTrack
       Absent       0.0000       0.0000       0.0000
         Road       0.0000       0.2107      -0.3289
        Track       0.0000       0.1946       0.2648


Standard errors of differences

Average:                       0.1666
Maximum:                       0.2227
Minimum:                       0.1335

Average variance of differences: 0.02859


Table of effects for CROP.DISTANCE


     DISTANCE            2            8           32
         CROP
            B       0.0000       0.0000       0.0000
            M       0.0000      -0.1594       0.0939
           SR       0.0000       0.2684       0.5706
           WR       0.0000      -0.1558       0.1822


Standard errors of differences

Average:                       0.7730
Maximum:                        2.006
Minimum:                       0.1232

Average variance of differences: 1.216


Table of effects for DISTANCE.SOIL_CATEGORY


SOIL_CATEGORY        Heavy        Light       Medium      Organic
     DISTANCE
            2       0.0000       0.0000       0.0000       0.0000
            8       0.0000       0.4667      -0.0076       0.4449
           32       0.0000       0.6445       0.3031       0.5028
```

Standard errors of differences

Average:	0.9026
Maximum:	2.116
Minimum:	0.1023

Average variance of differences: 1.699

Table of effects for Verge.DISTANCE

DISTANCE	2	8	32
Verge			
Absent	0.00000	0.00000	0.00000
Verge	0.00000	-0.12351	-0.28807

Standard errors of differences

Average:	0.09964
Maximum:	0.1028
Minimum:	0.09830

Average variance of differences: 0.009930

Harpalus rufipes

Generalized linear mixed model analysis

Method: c.f. Schall (1991) Biometrika
Response variate: X3924
Distribution: poisson
Link function: logarithm
Random model: SITE_CODE + SITE_CODE.TRANSECT + SITE_CODE.TRANSECT.VISIT_DATE
Fixed model: Constant + Hedge + Adjacent + Ditch + CROP + DISTANCE + SOIL_CATEGORY + Hedge.Adjacent + CROP.DISTANCE + DISTANCE.SOIL_CATEGORY

Dispersion parameter estimated

Estimated variance components

Random term	component	s.e.
SITE_CODE	0.332	0.081
SITE_CODE.TRANSECT	0.000	bound
SITE_CODE.TRANSECT.VISIT_DATE	0.308	0.047

Residual variance model

Term	Model(order)	Parameter	Estimate
	s.e.		

Dispersn	Identity	Sigma2	2.724	0.171

Estimated variance matrix for variance components

SITE_CODE	1	0.006627		
SITE_CODE.TRANSECT	2	0.000000	0.000000	
SITE_CODE.TRANSECT.VISIT_DATE	3	-0.000582	0.000000	0.002184
Dispersn	4	-0.000108	0.000000	-0.002130
		1	2	3

Dispersn	4	0.029082
		4

Wald tests for fixed effects

Sequentially adding terms to fixed model

Fixed term	Wald statistic	d.f.	Wald/d.f.	chi pr
Hedge	0.21	1	0.21	0.645
Adjacent	11.59	5	2.32	0.041
Ditch	3.43	1	3.43	0.064
CROP	6.00	3	2.00	0.111
DISTANCE	8.46	2	4.23	0.015
SOIL_CATEGORY	1.62	3	0.54	0.656
Hedge.Adjacent	12.51	4	3.13	0.014
CROP.DISTANCE	55.21	6	9.20	<0.001
DISTANCE.SOIL_CATEGORY	23.00	6	3.83	<0.001

Dropping individual terms from full fixed model

Fixed term	Wald statistic	d.f.	Wald/d.f.	chi pr
DISTANCE.SOIL_CATEGORY	23.00	6	3.83	<0.001
CROP.DISTANCE	58.58	6	9.76	<0.001
Hedge.Adjacent	12.60	4	3.15	0.013
Ditch	4.05	1	4.05	0.044

Bembidion lampros

Generalized linear mixed model analysis

Method:	c.f. Schall (1991) Biometrika
Response variate:	XX2326
Distribution:	poisson
Link function:	logarithm
Random model:	SITE_CODE + SITE_CODE.TRANSECT + SITE_CODE.TRANSECT.VISIT_DATE

```
Fixed model:                Constant + Hedge + Water + Adjacent + Verge + DISTANCE + SOIL_CATEGORY +
Hedge.DISTANCE + Water.DISTANCE + Adjacent.DISTANCE + Verge.DISTANCE


Dispersion parameter estimated
```

Estimated variance components

```
Random term                                     component          s.e.
SITE_CODE                                           0.216         0.074
SITE_CODE.TRANSECT                                  0.000         bound
SITE_CODE.TRANSECT.VISIT_DATE
                                                    0.382         0.067
```

Residual variance model

```
Term                              Model(order)      Parameter            Estimate
                                  s.e.
Dispersn                          Identity          Sigma2                  3.089
0.221
```

Estimated variance matrix for variance components

```
                  SITE_CODE    1       0.005522
         SITE_CODE.TRANSECT    2       0.000000       0.000000
SITE_CODE.TRANSECT.VISIT_DATE  3      -0.001311       0.000000       0.004518
                   Dispersn    4       0.000096       0.000000      -0.003294
                                              1              2              3


                   Dispersn    4       0.048905
                                              4
```

Wald tests for fixed effects

```
Sequentially adding terms to fixed model

Fixed term                       Wald statistic      d.f.      Wald/d.f.    chi pr
Hedge                                      2.05         1           2.05     0.152
Water                                      0.05         1           0.05     0.830
Adjacent                                   1.00         5           0.20     0.963
Verge                                      1.30         1           1.30     0.254
DISTANCE                                   5.28         2           2.64     0.071
SOIL_CATEGORY                             12.93         3           4.31     0.005
Hedge.DISTANCE                            13.25         2           6.62     0.001
Water.DISTANCE                             9.90         2           4.95     0.007
```

```
Adjacent.DISTANCE                              31.25        10          3.13    <0.001
Verge.DISTANCE                                  7.43         2          3.71     0.024

Dropping individual terms from full fixed model

Fixed term                            Wald statistic      d.f.     Wald/d.f.    chi pr
Verge.DISTANCE                                  7.43         2          3.71     0.024
Adjacent.DISTANCE                              34.30        10          3.43    <0.001
Water.DISTANCE                                  7.91         2          3.95     0.019
Hedge.DISTANCE                                 15.57         2          7.78    <0.001
SOIL_CATEGORY                                  13.43         3          4.48     0.004


Table of effects for Constant

 0.5261   Standard error: 0.19981


Table of effects for Hedge


 Hedge          Absent        Hedge
               0.00000     -0.13868


Standard error of differences: 0.1840


Table of effects for Water


 Water     FALSE      water
          0.0000     0.5456


Standard error of differences: 0.4129


Table of effects for Adjacent


  Adjacent          Crop         Grass      Ploughed      Semi-Nat         Urban
                  0.0000        0.1494        0.0799       -0.3692        0.4179


  Adjacent          Wood
                 -0.0490


Standard errors of differences

Average:                    0.4221
Maximum:                    0.6120
Minimum:                    0.1974
```

```
Average variance of differences: 0.1916


Table of effects for Verge


 Verge     Absent       Verge
           0.0000      0.4366


Standard error of differences: 0.1854


Table of effects for DISTANCE


 DISTANCE             2           8          32
                 0.0000      0.4198      0.1932


Standard errors of differences

Average:                             0.1691
Maximum:                             0.1785
Minimum:                             0.1583

Average variance of differences: 0.02866


Table of effects for SOIL_CATEGORY


 SOIL_CATEGORY          Heavy          Light        Medium        Organic
                       0.0000         0.2966        0.6478        -0.0966


Standard errors of differences

Average:                             0.3795
Maximum:                             0.5399
Minimum:                             0.1866

Average variance of differences: 0.1638


Table of effects for Hedge.DISTANCE


         DISTANCE           2           8          32
            Hedge
           Absent      0.0000      0.0000      0.0000
            Hedge      0.0000      0.1636      0.6957
```

```
Standard errors of differences

Average:                          0.1795
Maximum:                          0.1834
Minimum:                          0.1754

Average variance of differences: 0.03225


Table of effects for Water.DISTANCE


     DISTANCE              2              8             32
        Water
        FALSE         0.0000         0.0000         0.0000
        water         0.0000        -1.4818        -1.1078


Standard errors of differences

Average:                          0.6755
Maximum:                          0.8383
Minimum:                          0.5597

Average variance of differences: 0.4677


Table of effects for Adjacent.DISTANCE


     DISTANCE              2              8             32
     Adjacent
         Crop         0.0000         0.0000         0.0000
        Grass         0.0000        -0.4400        -0.9435
     Ploughed         0.0000        -0.3194        -0.7220
     Semi-Nat         0.0000        -0.0689         0.4751
        Urban         0.0000        -1.3001        -1.2286
         Wood         0.0000        -0.3011        -0.3028


Standard errors of differences

Average:                          0.4084
Maximum:                          0.7498
Minimum:                          0.1955

Average variance of differences: 0.1893


Table of effects for Verge.DISTANCE


     DISTANCE              2              8             32
        Verge
       Absent         0.0000         0.0000         0.0000
```

```
              Verge          0.0000         -0.4091         -0.4984


Standard errors of differences

Average:                        0.1953
Maximum:                        0.2061
Minimum:                        0.1828

Average variance of differences: 0.03826
```

Pterostichus niger

*******************model inestimable**

Agonum dorsale

```
Generalized linear mixed model analysis

Method:                  c.f. Schall (1991) Biometrika
Response variate:        X3503
Distribution:            poisson
Link function:           logarithm
Random model:            SITE_CODE + SITE_CODE.TRANSECT + SITE_CODE.TRANSECT.VISIT_DATE
Fixed model:             Constant + Water + DISTANCE + Water.DISTANCE


Estimated variance components

Random term                                         component            s.e.
SITE_CODE                                              0.1131          0.0325
SITE_CODE.TRANSECT                                     0.0000           bound
SITE_CODE.TRANSECT.VISIT_DATE
                                                       0.2304          0.0334


Residual variance model

Term                                     Model(order)       Parameter                Estimate
                                         s.e.
Dispersn                                 Identity           Sigma2                      0.909
0.0623


Estimated variance matrix for variance components


                        SITE_CODE    1      0.0010567
               SITE_CODE.TRANSECT    2      0.0000000       0.0000000
    SITE_CODE.TRANSECT.VISIT_DATE    3     -0.0002483       0.0000000       0.0011182
```

```
                                   Dispersn      4          0.0000276            0.0000000            -0.0006392
                                                                    1                    2                     3


                                   Dispersn      4          0.0038847
                                                                    4
```

Wald tests for fixed effects

Sequentially adding terms to fixed model

```
Fixed term                              Wald statistic        d.f.          Wald/d.f.      chi pr
Water                                             2.08           1               2.08       0.149
DISTANCE                                         26.18           2              13.09      <0.001
Water.DISTANCE                                    9.91           2               4.96       0.007
```

Dropping individual terms from full fixed model

```
Fixed term                              Wald statistic        d.f.          Wald/d.f.      chi pr
Water.DISTANCE                                    9.91           2               4.96       0.007
```

Trechus quadristriatus

Generalized linear mixed model analysis

```
Method:                 c.f. Schall (1991) Biometrika
Response variate:       X2105
Distribution:           poisson
Link function:          logarithm
Random model:           SITE_CODE + SITE_CODE.TRANSECT + SITE_CODE.TRANSECT.VISIT_DATE
Fixed model:            Constant + Adjacent + RoadTrack + Verge + DISTANCE + SOIL_CATEGORY +
Adjacent.DISTANCE + RoadTrack.DISTANCE + Verge.DISTANCE + DISTANCE.SOIL_CATEGORY
```

Dispersion parameter estimated

Estimated variance components

```
Random term                                    component            s.e.
SITE_CODE                                          0.144           0.053
SITE_CODE.TRANSECT                                 0.000           bound
SITE_CODE.TRANSECT.VISIT_DATE
                                                   0.284           0.052
```

Residual variance model

```
Term                                   Model(order)      Parameter              Estimate
                                       s.e.
Dispersn                               Identity          Sigma2                    1.164
0.102
```

Estimated variance matrix for variance components

```
                   SITE_CODE    1      0.002770
          SITE_CODE.TRANSECT    2      0.000000      0.000000
SITE_CODE.TRANSECT.VISIT_DATE   3     -0.000752      0.000000      0.002675
                    Dispersn    4      0.000006      0.000000     -0.001407
                                              1             2             3

                    Dispersn    4      0.010495
                                              4
```

Wald tests for fixed effects

Sequentially adding terms to fixed model

```
Fixed term                 Wald statistic   d.f.   Wald/d.f.   chi pr
Adjacent                             2.34      5        0.47    0.800
RoadTrack                            1.38      2        0.69    0.501
Verge                                4.56      1        4.56    0.033
DISTANCE                            29.30      2       14.65   <0.001
SOIL_CATEGORY                        2.65      3        0.88    0.449
Adjacent.DISTANCE                   27.58     10        2.76    0.002
RoadTrack.DISTANCE                   3.47      4        0.87    0.482
Verge.DISTANCE                       3.25      2        1.63    0.197
DISTANCE.SOIL_CATEGORY              42.96      6        7.16   <0.001
```

Dropping individual terms from full fixed model

```
Fixed term                 Wald statistic   d.f.   Wald/d.f.   chi pr
DISTANCE.SOIL_CATEGORY              42.96      6        7.16   <0.001
Verge.DISTANCE                       2.30      2        1.15    0.317
RoadTrack.DISTANCE                   2.54      4        0.64    0.637
Adjacent.DISTANCE                   17.74     10        1.77    0.059
```

Calathus fuscipes

Generalized linear mixed model analysis

```
Method:              c.f. Schall (1991) Biometrika
Response variate:    X2903
Distribution:        poisson
Link function:       logarithm
Random model:        SITE_CODE + SITE_CODE.TRANSECT + SITE_CODE.TRANSECT.VISIT_DATE
Fixed model:         Constant + Hedge + Adjacent + Verge + CROP + DISTANCE + SOIL_CATEGORY +
Hedge.DISTANCE + Adjacent.DISTANCE + Verge.DISTANCE + CROP.DISTANCE + DISTANCE.SOIL_CATEGORY
```

```
Dispersion parameter estimated
```

Estimated variance components

```
Random term                                    component           s.e.
SITE_CODE                                          0.327          0.108
SITE_CODE.TRANSECT                                 0.000          bound
SITE_CODE.TRANSECT.VISIT_DATE
                                                   0.365          0.062
```

Residual variance model

```
Term                            Model(order)      Parameter              Estimate
                                s.e.
Dispersn                        Identity          Sigma2                    2.005
0.162
```

Estimated variance matrix for variance components

```
                     SITE_CODE    1       0.011657
            SITE_CODE.TRANSECT    2       0.000000        0.000000
 SITE_CODE.TRANSECT.VISIT_DATE    3      -0.001042        0.000000        0.003830
                      Dispersn    4      -0.000117        0.000000       -0.002214
                                                 1               2               3


                      Dispersn    4       0.026317
                                                 4
```

Wald tests for fixed effects

```
Sequentially adding terms to fixed model

Fixed term                       Wald statistic        d.f.      Wald/d.f.     chi pr
Hedge                                      0.28           1           0.28      0.594
Adjacent                                   3.43           5           0.69      0.634
Verge                                      0.14           1           0.14      0.706
CROP                                       6.19           2           3.09      0.045
DISTANCE                                   4.59           2           2.30      0.101
SOIL_CATEGORY                              2.07           3           0.69      0.559
Hedge.DISTANCE                             5.30           2           2.65      0.071
Adjacent.DISTANCE                         31.99          10           3.20     <0.001
Verge.DISTANCE                             7.99           2           3.99      0.018
CROP.DISTANCE                             11.67           4           2.92      0.020
DISTANCE.SOIL_CATEGORY                    15.17           6           2.53      0.019

Dropping individual terms from full fixed model
```

```
Fixed term                              Wald statistic    d.f.     Wald/d.f.   chi pr
DISTANCE.SOIL_CATEGORY                           15.17       6          2.53    0.019
CROP.DISTANCE                                    10.03       4          2.51    0.040
Verge.DISTANCE                                    9.20       2          4.60    0.010
Adjacent.DISTANCE                                37.12      10          3.71   <0.001
Hedge.DISTANCE                                   11.70       2          5.85    0.003
```

Nebria brevicollis

```
Generalized linear mixed model analysis

Method:                 c.f. Schall (1991) Biometrika
Response variate:       X801
Distribution:           poisson
Link function:          logarithm
Random model:           SITE_CODE + SITE_CODE.TRANSECT + SITE_CODE.TRANSECT.VISIT_DATE
Fixed model:            Constant + Verge + CROP + DISTANCE + Verge.DISTANCE + CROP.DISTANCE


Dispersion parameter estimated


Estimated variance components

Random term                                  component            s.e.
SITE_CODE                                        0.572           0.139
SITE_CODE.TRANSECT                               0.000           bound
SITE_CODE.TRANSECT.VISIT_DATE
                                                 0.525           0.080

Residual variance model

Term                              Model(order)      Parameter            Estimate
                                  s.e.
Dispersn                          Identity          Sigma2                  3.317
0.242


Estimated variance matrix for variance components


                    SITE_CODE   1      0.019422
           SITE_CODE.TRANSECT   2      0.000000      0.000000
SITE_CODE.TRANSECT.VISIT_DATE   3     -0.001870      0.000000      0.006386
                     Dispersn   4     -0.000391      0.000000     -0.003370
                                              1             2             3
```

```
                              Dispersn      4              0.058490
                                                                  4
```

Wald tests for fixed effects

```
Sequentially adding terms to fixed model

Fixed term                            Wald statistic      d.f.        Wald/d.f.     chi pr
Verge                                           0.96         1             0.96      0.328
CROP                                            3.51         3             1.17      0.320
DISTANCE                                      268.09         2           134.05     <0.001
Verge.DISTANCE                                 37.51         2            18.75     <0.001
CROP.DISTANCE                                  80.81         6            13.47     <0.001

Dropping individual terms from full fixed model

Fixed term                            Wald statistic      d.f.        Wald/d.f.     chi pr
CROP.DISTANCE                                  80.81         6            13.47     <0.001
Verge.DISTANCE                                  6.95         2             3.48      0.031
```

Bembidion tetracolum

Generalized linear mixed model analysis

```
Method:                  c.f. Schall (1991) Biometrika
Response variate:        X2355
Distribution:            poisson
Link function:           logarithm
Random model:            SITE_CODE + SITE_CODE.TRANSECT + SITE_CODE.TRANSECT.VISIT_DATE
Fixed model:             Constant + Hedge + Adjacent + RoadTrack + DISTANCE + Hedge.DISTANCE +
Adjacent.DISTANCE


Dispersion parameter estimated
```

Estimated variance components

```
Random term                                     component              s.e.
SITE_CODE                                           0.386             0.175
SITE_CODE.TRANSECT                                  0.000             bound
SITE_CODE.TRANSECT.VISIT_DATE
                                                    0.673             0.132
```

Residual variance model

```
Term                                  Model(order)       Parameter                Estimate
                                      s.e.
```

```
Dispersn                        Identity        Sigma2              4.585
0.455
```

Estimated variance matrix for variance components

```
                       SITE_CODE   1      0.03049
              SITE_CODE.TRANSECT   2      0.00000      0.00000
    SITE_CODE.TRANSECT.VISIT_DATE   3     -0.00456      0.00000      0.01752
                        Dispersn   4     -0.00210      0.00000     -0.00962
                                                1            2            3


                        Dispersn   4      0.20718
                                                4
```

Wald tests for fixed effects

Sequentially adding terms to fixed model

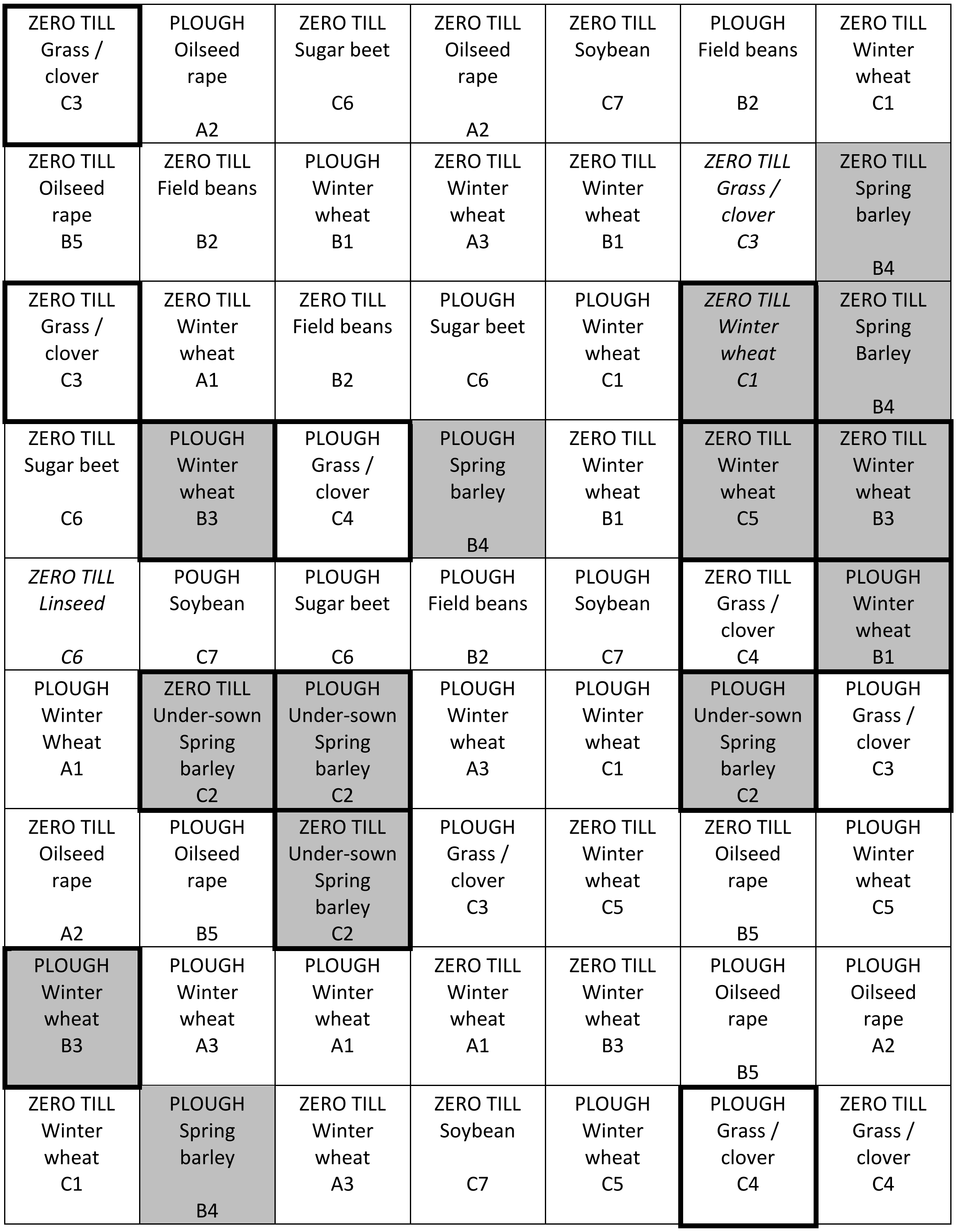
```
Fixed term                    Wald statistic     d.f.      Wald/d.f.    chi pr
Hedge                                   3.47        1           3.47     0.063
Adjacent                                1.29        4           0.32     0.863
RoadTrack                               5.85        2           2.93     0.054
DISTANCE                                2.27        2           1.13     0.322
Hedge.DISTANCE                         13.73        2           6.86     0.001
Adjacent.DISTANCE                      45.63        8           5.70    <0.001
```

Dropping individual terms from full fixed model

```
Fixed term                    Wald statistic     d.f.      Wald/d.f.    chi pr
Adjacent.DISTANCE                      45.63        8           5.70    <0.001
Hedge.DISTANCE                         11.94        2           5.97     0.003
RoadTrack                               6.23        2           3.12     0.044
```

*Verge in the code refers to the term Margin in the paper

Appendix 2 (chapter 3)



ZERO TILL Grass / clover C3	PLOUGH Oilseed rape A2	ZERO TILL Sugar beet C6	ZERO TILL Oilseed rape A2	ZERO TILL Soybean C7	PLOUGH Field beans B2	ZERO TILL Winter wheat C1
ZERO TILL Oilseed rape B5	ZERO TILL Field beans B2	PLOUGH Winter wheat B1	ZERO TILL Winter wheat A3	ZERO TILL Winter wheat B1	*ZERO TILL* *Grass / clover* *C3*	ZERO TILL Spring barley B4
ZERO TILL Grass / clover C3	ZERO TILL Winter wheat A1	ZERO TILL Field beans B2	PLOUGH Sugar beet C6	PLOUGH Winter wheat C1	*ZERO TILL* *Winter wheat* *C1*	ZERO TILL Spring Barley B4
ZERO TILL Sugar beet C6	PLOUGH Winter wheat B3	PLOUGH Grass / clover C4	PLOUGH Spring barley B4	ZERO TILL Winter wheat B1	ZERO TILL Winter wheat C5	ZERO TILL Winter wheat B3
ZERO TILL *Linseed* *C6*	POUGH Soybean C7	PLOUGH Sugar beet C6	PLOUGH Field beans B2	PLOUGH Soybean C7	ZERO TILL Grass / clover C4	PLOUGH Winter wheat B1
PLOUGH Winter Wheat A1	ZERO TILL Under-sown Spring barley C2	PLOUGH Under-sown Spring barley C2	PLOUGH Winter wheat A3	PLOUGH Winter wheat C1	PLOUGH Under-sown Spring barley C2	PLOUGH Grass / clover C3
ZERO TILL Oilseed rape A2	PLOUGH Oilseed rape B5	ZERO TILL Under-sown Spring barley C2	PLOUGH Grass / clover C3	ZERO TILL Winter wheat C5	ZERO TILL Oilseed rape B5	PLOUGH Winter wheat C5
PLOUGH Winter wheat B3	PLOUGH Winter wheat A3	PLOUGH Winter wheat A1	ZERO TILL Winter wheat A1	ZERO TILL Winter wheat B3	PLOUGH Oilseed rape B5	PLOUGH Oilseed rape A2
ZERO TILL Winter wheat C1	PLOUGH Spring barley B4	ZERO TILL Winter wheat A3	ZERO TILL Soybean C7	PLOUGH Winter wheat C5	PLOUGH Grass / clover C4	ZERO TILL Grass / clover C4

Figure S1 Experimental plan for Large Scale Rotation Experiment at Brooms Barn in harvest year 2018. Rotation A: 1. winter wheat, 2. oilseed rape, 3. winter wheat; Rotation B: 1. winter wheat, 2. field beans, 3. winter wheat, 4. spring barley, 5. oilseed rape; Rotation C: 1. winter wheat, 2. spring barley under-sown with grass / clover, 3. grass / clover, 4. grass / clover, 5. winter wheat, 6. sugar beet, 7. soybean. Each phase of every rotation is part of both a zero till and a ploughed system, replicated twice. Three extra plots are included in the design (in italics) in 'Zero till Rotation C' but replacing sugar beet with linseed as it is not possible to completely avoid soil disturbance in a rotation that includes sugar beet. Each plot is 24 x 24 m and divided into two sub-plots; in future years, organic amendments are added to one sub-plot. Shaded plots were included in the invertebrate trapping Run 1 and plots with a solid border in Run 2.

Table 2- Run 1 and Run 2 trap species totals. S-T= subterranean, Pitfall= Standard pitfall traps. Damaged unidentifiable carabids were grouped by size; small 2-4mm; small-med 4-9mm, medium 9-14mm.

	Run 1			Run 2		
	S-T	Pitfall	Total	S-T	Pitfall	Total
Pterostichus melanarius	826	1151	1977	731	362	1093
Harpalus rufipes	1233	700	1933	133	59	192
Ocys harpaloides	72	2	74	0	0	0
Calathus fuscipes	19	52	71	21	42	63
Pterostichus niger	22	16	38	7	1	8
Poecilius cupreus	7	20	27	0	0	0
Trechus quadristriatus	25	0	25	235	9	244
Nebria salina	17	2	19	9	6	15
Carabus violaceus	10	8	18	3	2	5
Bembidion lampros	11	1	12	2	7	9
B. quadrimaculatum	6	0	6	0	0	0
Anchomenus dorsalis	3	2	5	1	0	1
Calathus melanocephalus	5	0	5	4	11	15
Amara eurynota	2	0	2	0	0	0
Bembidion tetracolum	2	0	2	3	0	3
Agonum muelleri	1	0	1	0	0	0
Elaphorus parvulus	1	0	1	1	0	1
Notiophilus biggutatus	1	0	1	0	1	1
Tachys micros	0	0	0	4	0	4
Bembidion tetracolum	0	0	0	0	0	0
Harpalus affinis	0	0	0	1	0	1
Brachinus crepitans	0	0	0	1	0	1
Demetrius atricaillus	0	0	0	1	0	1
Pterostichus madidus	0	0	0	1	0	1
Carabid larvae granivores	-	-	-	12	5	17
Carabid larvae predators/omnivores	-	-	-	27	1	28
Carabid larvae total	5	0	5	39	6	45
Unidentified damaged small	22	0	22	0	0	0
Unidentified damaged small-medium	6	13	19	0	0	0
Unidentified damaged medium	14	371	385	0	0	0
Total Carabidae	2309	2338	4647	1197	506	1703

Table 2- Individual species LMM outputs for Run 2 species with significant terms *Pterostichus melanarius, Trechus quadristriatus, Harpalus rufipes Pterostichus niger, Calathus fuscipes, Bembidion lampros, Calathus melanocephalus,* and *Carabus violaceus*

Species Model terms retained	d.d.f	F	P
Pterostichus melanarius			
Crop type	9.0	41.78	<0.001
Trap type	60.7	0.18	0.672
Crop type.trap type	60.6	5.22	0.008
Trechus quadristriatus			
Crop type	11.6	2.39	0.135
Trap type	60	110.50	<0.001
Crop type.trap type	60	6.04	0.004
Harpalus rufipes			
Crop type	10.7	15.46	<0.001
Pterostichus niger			
Crop type	11.1	4.38	0.04
Trap type	63.7	1.96	0.167
Crop type and trap type	63.6	3.73	0.029
Calathus fuscipes			
Trap type	66.4	9.15	0.004
Bembidion lampros			
Tillage	11.4	6.02	0.031
Trap type	65.6	5.09	0.027
Calathus melanocephalus			
Crop type	7.8	7.39	0.016
Tillage	8.3	7.26	0.026
Trap type	65.5	3.48	0.067
Crop type and tillage	6.48	8.5	0.019
Carabus violaceus			
Tillage	10.6	12.89	0.004

Appendix 3 (chapter 4)

Table 1- Details of experimental margin seed mix. Starred species = tussock forming grasses

Common name	**Scientific name**	**Percentage composition**
Grass margin seed mix		
Common bent	*Agrostis capillaris*	10%
Crested dogstail*	*Cynosurus cristatus*	50%
Slendercreeping red-fescue*	*Festuca rubra*	35%
Smaller cat's-tail *	*Phleum bertolonii*	5%
Wildflower margin seed mix		
Common bent	*Agrostis capillaris*	8%
Crested dogstail*	*Cynosurus cristatus*	40%
Slendercreeping red-fescue*	*Festuca rubra*	28%
Smaller cat's-tail *	*Phleum bertolonii*	4%
Yarrow	*Achillea millefolium*	1.2%
Common knapweed	*Centaurea nigra*	3%
Wild carrot	*Daucus carota*	1%
Field scabious	*Knautia arvensis*	0.6%
Oxeye daisy	*Leucanthemum vulgare*	1.6%
Birdsfoot trefoil	*Lotus corniculatus*	2%
Musk mallow	*Malva moschata*	0.8%
Cowslip	*Primula veris*	0.4%
Selfheal	*Prunella vulgaris*	3%
Meadow buttercup	*Ranunculus acris*	3.2%
Red campion	*Silene dioica*	2%
Wild red clover	*Trifolium pratense*	0.2%
Tufted vetch	*Vicia cracca*	1%

Table S1- Fitted model for spatial factors on total carabid abundance

Model	Fixed Effects	c_0	c_1	a	Effective range
Total abundance standard pitfall traps					
Null model	Run	0.74	0.63	39.17	117.51
REML fitted	Run + Vegetation + Easting + Northing + Easting.Northing + Adjacent	0.6886	0.3056	14.6251	43.81
Total abundance subterranean pitfall traps					
Null model	Run	1.0533	0.5255	105.8535	317.5605
REML	Run + Easting + Northing + Easting.Northing + Adjacent	0.0	1.0662	1.5173	5.18

Table S2- Fitted model for spatial factors on *Pterostichus melanarius* abundance in pitfall traps

Model	Fixed Effects	c_0	c_1	a	Effective range
Pterostichus melanarius abundance					
Null model	Run	0.5380	1.3148	68.6916	206.0748
REML fitted	Run + Vegetation + Easting + Northing + Easting.Northing + Adjacent	0.5532	0.4988	36.9738	110.7638
Harpalus rufipes abundance					
Null model	Run	0.8248	0.2568	580.7363	1,742.2089
REML fitted	Run + Vegetation + Easting + Northing + Easting.Northing	0.7743	5.6890	28954.2484	86739.18
Pterostichus madidus abundance					
Null model	Run	0.5146	0.6067	103.0439	309.131
REML fitted	Run + Vegetation + Easting + Northing + Easting.Northing	0.4939	0.2507	22.1171	110.2304
Amara eurynota abundance					
Null model	Run	0.2133	0.0861	62.3313	186.9939
REML fitted	Run + Vegetation + Adjacent	0.1956	0.0000	0.0000	0.0001159668
Poecilius cupreus abundance					
Null model	Run	0.3115	0.1322	504.5521	1,513.6563
REML fitted	Run + Vegetation + Easting + Northing + Easting.Northing	0.3013	0.0130	31.6369	94.77579
Total carabid larvae abundance					
Null model	Run	0.2710	0.0505	286.5109	859.5327
REML fitted	Run + Vegetation	0.2728	0.0428	366.8379	1098.948

Appendix 4 (Chapters 6 and 7)

Participant recruitment

Requests included in newsletters and social media communications of agricultural organisations: Linking the Environment and Farming (LEAF), Agricology, Biodiversity Agriculture Soil and Environment (BASE), Championing the Farmed Environment (CFE), The Farming and Wildlife Advisory Group (FWAG), Agri-Tech- east, The Agriculture and Horticulture Development Board (ADHB), and the National Farmers Union (NFU).

Articles: in agricultural magazine Practical Farm Ideas [print issued] available from https://www.farmideas.co.uk/, and Farm wildlife UK [online blog] Available at: https://farmwildlife.info/2020/07/12/case-study-carabid-beetles-for-natural-enemy-pest-control/.

Podcasts: Farmers weekly episode 4 available at https://www.fwi.co.uk/news/farmers-weekly-podcast-episode-4-covid-19-loans-and-red-tractor-inspections , and Wellies and Labcoats available at https://soundcloud.com/mandy-stoker-414270483/wellies-and-labcoats-getting-started

Feature in institutional news story, available at https://www.rothamsted.ac.uk/news/researcher-makes-internet-appeal-after-covid-19-stymies-her-research

Presented at the online 'Cereals' agricultural show 9-11 June 2020, in the Rothamsted Research site area.

Researcher and institute social media promotion on twitter #BeneficialBeetlesSurvey

Engagement materials

Educational video (https://youtu.be/vNyTzU96yYA)

Carabid ID quiz (https://readingagriculture.eu.qualtrics.com/jfe/form/SV_byGTrOfFP9TG2Ud)

Monitoring factsheet (https://www.rothamsted.ac.uk/sites/default/files/How%20to%20pitfall%20trap%20on%20your%20farm.pdf)

Table 1- Online carabids in farmland Talk events conducted as part of the engagement treatment

Event	Date and time	Access and follow-up
Arden Farm Wildlife Network. Incorporating Warwickshire Rural Hub	Jun 17, 1pm	Attendees by invite of organisers only. Around 40 farmers. Follow-up by email reminders of organisers
BASE farmers talk Available to BASE member farmers. Video available on BASE website.	9th July, 7pm	Attendees by invite of organisers only. Around 30 farmers. Follow-up by email reminders of organisers. Follow-up on fertiliser and pesticide questions on BASE website.
BASIS talk Talk with BASIS accreditation points for attendees, organised by Rothamsted.	14th July, 12.30pm	Attendance open by link promoted on Rothamsted media. Around 30 farmers. Follow-up by email and social media.

Table 2- Full questionnaire content

Question Description	**Response type**
Section 1 Carabids	
Statement on carabids: "*Carabids (sometimes called ground beetles) have been shown to be effective predators of crop pests such as aphids, slugs, caterpillars, grubs and mites. They also feed on weed seeds such as dandelion, shepherds purse and chickweed. This type of pest control is termed "natural-enemy pest control".* *In this survey we are interested in your opinions on natural enemy pest control provided by carabid beetles, and the management of habitats on farms that may promote their abundance."* [picture of Pterostichus sp. Showing jaws open]	
Filter question for K-E treatment only- verification that participants have viewed all of the materials: animation; quiz; and factsheet	
Q1 Before today were you aware that the beetles inhabiting your agricultural fields included carabid beetles?	Tickbox response, one could be selected of *Yes* or *No*
Q2 Do you believe you could identify a carabid beetle?	Tickbox response, one could be selected of *(i) Yes - many species; (ii) Yes- a few species and families (iii) Yes- as distinct from other types of beetle; (iv) Not sure; (v) Probably not; (vi) Definitely not*

Q3a Before today were you aware that carabid beetles eat crop pests such as aphids, slugs, caterpillars, grubs and mites?	Tickbox response, one could be selected of *Yes* or *No*
Q3b Before today were you aware that carabid beetles eat crop weed seeds such as dandelion, shepherds purse and chickweed?	Tickbox response, one could be selected of *Yes* or *No*
Q4a Do you believe that carabid beetles can make a significant contribution to Crop insect pest control?	Tickbox response, one could be selected of *Yes, No*, or *Not sure*
Q4b Do you believe that carabid beetles can make a significant contribution to Crop weed control?	Tickbox response, one could be selected of *Yes, No*, or *Not sure*
Section 2 The farm environment and conservation	
Statement on farm measures: *"There are many measures that may help to increase the overall abundance and number of different predatory species of carabid beetles.* *Some of these involve including natural habitat in proximity to crop areas so that carabids have resources over time; some encourage their increased movement into the crop area; and some reduce the mortality associated with farm operations."*	
Q5 Have you implemented the following farm management? (AES= agri-environment schemes)	The response was in the form of a table with rows associated with the FMPs listed in Table 2 and the columns associated with the responses *(i) In the past, through AES, (ii) In the past, voluntarily (iii) Currently, through AES, (iv) Currently, voluntarily (v) No/Not applicable.* Multiple columns could be selected for each FMP.
Q6 Do you carry out any of the above [FMPs] particularly with the aim of increasing the abundance of carabid beetles and their associated natural-enemy pest control? If so could you indicate which and provide some details please.	*Yes* or *No* with Qualitative response facilitated by a text entry box.
Q7 Which, if any, of the above options would you consider carrying out, or increasing the amount you do, in order to boost the abundance of carabid beetles	Qualitative response facilitated by a text entry box

and their associated natural-enemy pest control?	
Q8 Is there any reason you would be apprehensive about implementing any of the above options?	Qualitative response facilitated by a text entry box
Q9a How important in your opinion is the following FMP to improving the control of crop pests by natural-enemies such as carabids?	The response was in the form of a table with rows associated with the FMPs listed in Table 2 and the columns associated with the responses *(i) Extremely important; (ii) Very important (iii) Moderately important-* *Slightly important (iv) Not at all important (v) Not sure*
Q9b How difficult would you rate the following farm management, in terms of implementing it on your farm (in terms of cost, labour, knowledge, equipment, and time)?	The response was in the form of a table with rows associated with the FMPs listed in Table 2 and the columns associated with the responses *(i) Extremely difficult; (ii) Moderately difficult; (iii) Slightly difficult (iv)* *Not at all difficult; (v) Not sure (vi) Impossible due to soil or landscape constraints (vii) Impossible due to legal or tenancy constraints.*
Section 3 Farmer attributes	
Information statement: *"To put your answers in context we would like to know about your farm enterprise. All answers are confidential and you will not be identifiable by your response."*	
Q10 What is your farm type? Please tick the box that most accurately describes your farming enterprise.	Tickbox response, one could be selected of 10 options, from Defra categories (Defra 2020a): *(i) Dairy; (ii) LFA/upland Grazing Livestock; (iii) Lowland Grazing Livestock; (iv) Cereals; (v) General cropping; (vi) Pigs; (vii) Poultry; (viii) Mixed; (ix) Horticulture; (x) Not applicable* Classified for analysis as: Cereals; Livestock; General cropping; and Mixed
Q11 What is the size of your farm?	Tickbox response, one could be selected of *(i) Under 20 hectares; (ii) 21 to 50 hectares; (iii) 51- 100 hectares; (iv) 101 - 500 hectares; (v) Over 500 hectares; (vi) Not applicable*

	Classified for analysis as: Under 50 ha; 50-100ha; 100-500ha; and Over 500ha
Q12 What are the sources of your farming experience and knowledge? Please tick all that apply (multiple boxes can be checked)	Tickbox response, one could be selected of *(i) Farming background;* *Farm work from childhood/ leaving school; (ii) College course/further education (agricultural); (iii) University level education (agricultural); (iv) Agricultural industry qualification- e.g. BASIS* Classified for analysis as: Non-formal education; Formal education; and Industry qualification
Q13 Do you receive advice on farm management from any of the following? Please tick all that apply *(*multiple boxes can be checked)	Tickbox response, one could be selected of *(i) Agricultural groups/bodies; (ii) Conservation organisations; (iii) Governmental organisations; (iv)Agronomists /professional advisors; (v) Industry representatives; (vi) Farm events/ training; (vii) Farmer networks/farming colleagues* Classified for analysis as: top-down advice *(i)-(v)*, and participatory advice *(vi)* and *(vii)*

Table 3- Farm management practices included in the questionnaire

Farm management practice (FMP)	Literature citing significance to carabid abundance or distribution
Habitat provision on un-cropped land	
Hedgerow maintenance	5, 6, 9, 14, 40, 41
Hedgerow establishment	4, 5, 6, 9, 14, 40
Beetle banks	9, 14, 40, 42
Field margins/ buffer strips	5, 6, 9, 41, 43, 44, 45
Ditch maintenance	6, 9, 14, 40, 41
Ponds/ wet areas/ waterbody creation	5, 6, 9, 41
Fallow land	9, 14
Natural area retention (e.g. woods, grassland)	4, 6, 9, 13, 46, 47
Crop management	
Cover cropping	14, 40, 48
Under sowing /companion crop	14, 49, 50, 51
Extensive (low) grazing	5, 52, 53
Low fertiliser input	5, 6, 14, 43, 40
Reduced tillage	7, 14, 43, 48, 54, 55, 56
Diverse cropping/rotations	14, 40, 57, 58
Low herbicide use	40, 59
Low pesticide/ antihelminth use	5, 6, 40, 60