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THE EFFECT OF *SINAPIS ALBA* COVER CROPS ON ABOVE- AND BELOW-GROUND CARABIDAE COMMUNITY STRUCTURE

BY

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Abstract

Efforts to alleviate pressure on food security have resulted in agricultural expansion, reliance on synthetic inputs and a multitude of unsustainable farming practises, all of which have contributed to sharp biodiversity decline and environmental degradation. In response, UK Governments have developed agri-environments schemes incentivising sustainable farming practises, including the cultivation of winter cover crops. Many cover crop species have been documented to enhance crop-pest predator populations, thus facilitating integrated pest management strategies and thereby minimising reliance on pesticides. Yet, numerous cover crop species remain understudied; there is no pre-existing literature exploring the impact of *Sinapis alba* on invertebrate communities. This study assessed the effect of *S. alba* cover crops, in relation to fallow plots, on the community structure of carabid beetles (Carabidae), the primary crop-pest predator group in farmland ecosystems. Above- and below-ground invertebrate communities, comprised of adult and larval specimens, were sampled across plots of arable farmland with surface-pitfalls and subterranean traps, respectively. Analysis through Bayesian Hierarchal Modelling found that *S. alba* had no significant effect on carabid abundance, richness nor Shannon-Weiner diversity. *S. alba* also had no effect on community evenness or below-ground composition. However, the cover crops did affect above-ground carabid community composition and there was strong evidence to suggest that *S. alba* increased above-ground carabid abundance. The findings begin to illuminate the potential of *S. alba* in supporting carabid communities and therefore should inform agri-environment schemes to heighten their efficacy in tackling both food insecurity and biodiversity decline.

Key Words: Carabidae, Sinapis alba, cover crops, Bayesian Hierarchal Modelling, agri-environment schemes, agro-ecology

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Contents

Abbreviations

AES – Agri-environment scheme

CI – Credibility interval

IPM - Integrated pest management

NMDS - Non-metric multidimensional scaling

SRUC - Scotland's Rural University College

1. Introduction

1.1 The Current Agricultural Space

Biodiversity loss, one of the Anthropocene's most pressing challenges, often appears to be an inevitable by-product of agricultural expansion. Owing to a growing human population forecasted to reach 9.7 billion by 2050 (United Nations, 2019), efforts to attain food security have intensified and resulted in large-scale dependence on synthetic inputs (Watson *et al.*, 2002; Lamichhane *et al.*, 2016), monocultures (Grant, 2006) and disruptive soil cultivation techniques (Bocchi & Orlando, 2021), all of which have contributed to catastrophic declines in biodiversity (Geiger *et al.*, 2010; Woodcock *et al.*, 2016; Bocchi & Orlando, 2021; Mancini *et al.*, 2023). Yet, the apparent mutual exclusivity between agricultural- and biodiverse-land is being increasingly exposed through sustainable farming techniques.

Today, emerging agricultural practices that afford a greater emphasis to optimising biodiversity in parallel with yield are being implemented. These include intercropping as opposed to monoculture (Malézieux *et al.*, 2009; Li *et al.*, 2023), the use of bio-pesticides in the place of harmful artificial pesticides (Khan & Rahman, 2017), and conservative tillage techniques rather than deep-soil ploughing (Cooper *et al.*, 2020). Many land owners are adopting these practises, largely because they are being incentivised by government agri-environment schemes (AESs) including those from the UK (UKGOV, 2O24) and the EU (Kleijn *et al.*, 2003). The schemes encompass a number of strategies thought to be effective in minimising the environmental degradation and biodiversity loss associated with conventional agriculture and poor land management, one of which is use of cover crops.

1.2 Cover Crops and Fallow Practices in Modern Farming

Traditional agricultural practices in the United Kingdom, and many other parts of the world, have seen arable land be designated as fallow between cash-crop growing seasons. Over this period, the ground is left bare to rebalance soil nutrients and to disrupt crop-pest and disease cycles (Nielsen & Calderón, 2011). However, the sustainability of this land-use strategy has been scrutinised for its negative impact on biodiversity, soil erosion (Nielsen & Calderón, 2011) and nitrate leaching rates which cause eutrophication in adjacent watercourses (Sainju *et al.*, 2006). To combat these negative effects and reduce reliance on synthetic inputs, the cultivation of cover crops in place of fallow land has gained momentum as an alternative approach.

The practice of cover cropping involves sowing 'cover' crops between the growing seasons of major commercial crops. Research demonstrates that cover crops can offer a multitude of ecosystem services. They have been shown to reduce soil erosion rates (Bommarco *et al.*, 2018), suppress agricultural weeds (Favarato *et al.*, 2014; Osipitan *et al.,* 2018), increase arbuscular mycorrhizae root associations (Boles *et al.*, 2017), elevate nutrient cycling rates (Hallama *et al.*, 2019) and promote biodiversity (Jowett *et al.*, 2021).

Promoting farmland biodiversity is a particularly important ecosystem service, not only because of the current rates of rapid biodiversity decline, but also because it encourages multi-trophic communities encompassing secondary and/or tertiary consumers (Therond *et al.*, 2017). Global yield losses caused by crop-pests and pathogens are estimated to be between 17 – 41% for each of the 5 five major crops (wheat, rice, maize, potato and soybean) (Savary *et al.*, 2019) and are forecasted to increase under the catalyst of climate change (Skendžić *et al.*, 2021). Therefore, by enhancing the abundance and diversity of species that predate crop-pests, weeds and the vectors of crop pathogens, cover crops could enhance the biodiversity of invertebrates while simultaneously serving as a mode of integrated pest management (IPM) that excludes the application of harmful pesticides (Barzman *et al.*, 2015). These prospects have encouraged the uptake of cover cropping, with the expectation that it will boost the populations of crop-pest predators. In farmland ecosystems, the major group of invertebrate predators are Carabidae (carabids or ground beetles).

1.3 Carabidae

Carabids are one of the most diverse beetle families with over 40,000 described species, including 2700 European species, 350 of which reside in Britain and Ireland (Luff, 2007). The majority of the taxon are polyphagous, meaning they consume a number of food sources including the populations of damaging crop-pests such as aphids (Hemiptera) and slugs (Gastropoda) (Kromp *et al.*, 1999; Reich *et al.*, 2020). Their ability to regulate these populations has been noted in a number of studies (Kromp *et al.*, 1999; Bianchi *et al.*, 2006; Kotze *et al.*, 2011) which makes carabid presence an indicator of active biological pest control (Barzman *et al.*, 2015). However, the large-scale declines in invertebrate biodiversity have extended to carabid populations (Brooks *et al.*, 2012). Consequently, efforts to understand the effect of cover crops on carabid populations have intensified in recent years (Jowett *et al.*, 2021) to preserve and heighten their ecosystem services.

Carabid abundance and diversity are thought to be a factor of, predominantly, resource availability (Muneret *et al.*, 2023). Already, a number of cover crop species are attributed to have caused increases in food resources such as prey species abundance and, in turn,

carabid abundance and diversity relative to communities of fallow land. These include, but are not limited to, hairy vetch (*Vicia villosa* Roth), triticale (x *Triticosecale* Wittmack), rye (*Secale cereale* L.) (Rivers *et al.*, 2017), as well as ray grass (*Lolium multiflorum* Lam.), Crimson clover (*Trifolium incarnatum* L.) (Triquet *et al.*, 2023) and Sorghum-sudangrass (*Sorghum × drummondii* Nees ex Steud.) (Meagher *et al.*, 2023). For example, three years after cycling with vetch cover crops began, Rivers *et al.* 2017 found that carabid communities became more even and exhibited elevated abundance, species richness, and diversity, all of which are indicative of more resilient and effective agents of pest biocontrol (Bianchi *et al.*, 2006; Bommarco *et al.*, 2018; Jowett *et al.*, 2021). Cover crops are also thought to provide more ecological niches for invertebrate species, meaning they can host indicator species (Duyck *et al.*, 2011). However, knowledge surrounding the effect of many other cover crop species on carabid communities remains sparse.

Sinapis alba L. (mustard) is a winter cover crop included in the UK Governments' AESs (HMGOV, 2024). Farmers are afforded grants for sowing mustard between cash-crop growing seasons in the hope that it mirrors the positive ecosystems services exhibited by other cover crop species. Studies have found mustard to be effective in thwarting weed propagation and survival (Brust *et al.*, 2011; Schappert *et al.*, 2019). Yet, no previous literature has explored the relationship between mustard cover crops and carabid community structure. In particular, few studies have attempted to sample both the above- and below-ground invertebrate communities of arable land sown with cover crops. Therefore, the effect of cover crops on soil dwelling invertebrates including carabid larvae remains a wide knowledge gap (Jowett *et al.*, 2021). In turn, attempts to explore these relationships are crucial for developing more efficacious and economical AESs which currently cost European governments tens of billions of pounds (Kleijn *et al.*, 2003).

1.4 Study Objectives

This study's primary objective is to quantify the effect mustard cover crops on carabid abundance and diversity, in relation to plots of fallow, across arable farmland. Above- and below-ground invertebrate communities will be sampled over a 3-month, autumn period (September - November). Then, variation in carabid abundance, species richness, Shannon-Weiner (Shannon's) diversity and community evenness and composition between the plot types will be analysed. Following this, the presence of carabid indicator species (those showing an affiliation to a specific plot type) will be tested for. Finally, the study will also quantify and assess variation in slug abundance between the plot types given that they are the most relevant crop-pest group during the autumn/winter period (Reich *et al.*, 2020).

1.5 Research Questions and Hypotheses

In light of the aforementioned ecological theory and existing literature, above- and below-ground carabid abundance, species richness and diversity are expected to be highest across plots sown with mustard, primarily due to increases in resource availability. Carabid community composition is anticipated to differ significantly between the plot types, with mustard plots expected to harbour more even carabid communities. Within their communities, mustard plots are also hypothesised to host indicator species whereas fallow plots are not. Finally, mustard plots are expected to contain fewer slugs than fallow plots, owing to the predicted increase in predatory carabids.

2. Methods

2.1 Study Site

The study site was located within Boghall Farm, Edinburgh, which encompasses a number of arable fields (Fig. 1) with mineral sandy loam soils. The exact field site was situated at an elevation of ~197 m on a south-easterly facing slope exposed to westerly winds (Fig. 1). The average annual temperature and precipitation is 12.1 °C and 690 mm, respectively (SRUC, 2024).

As a SRUC-owned site, agro-ecological research is conducted in parallel with working agriculture. The farm operates on an annual agricultural cycle, whereby between February and September the field sites' dominant vegetation type is a *Hordeum vulgare* L. (spring barley) monoculture. Historically, outside of this period, the fields have been left as fallow. However, for two years prior to the study, the field sites' dominant October - January vegetation has been mustard, radish and vetch cover crop monocultures in addition to areas of fallow.

Three sampling events, each lasting seven days, were conducted over a period of three months (October – November 2023). The sampling events commenced on the 22nd and ended on the 29th of their respective months. Over this timeframe, air temperatures fluctuated between -4.2 and 19.1 °C with varied cloud cover and rainfall. The most extreme weather event occurred during October when Storm Babet brought exceptional rainfall to the United Kingdom, including Eastern Scotland which experienced up to 200 mm of rainfall over 4 days (18th – 21th) (Met Office, 2023).
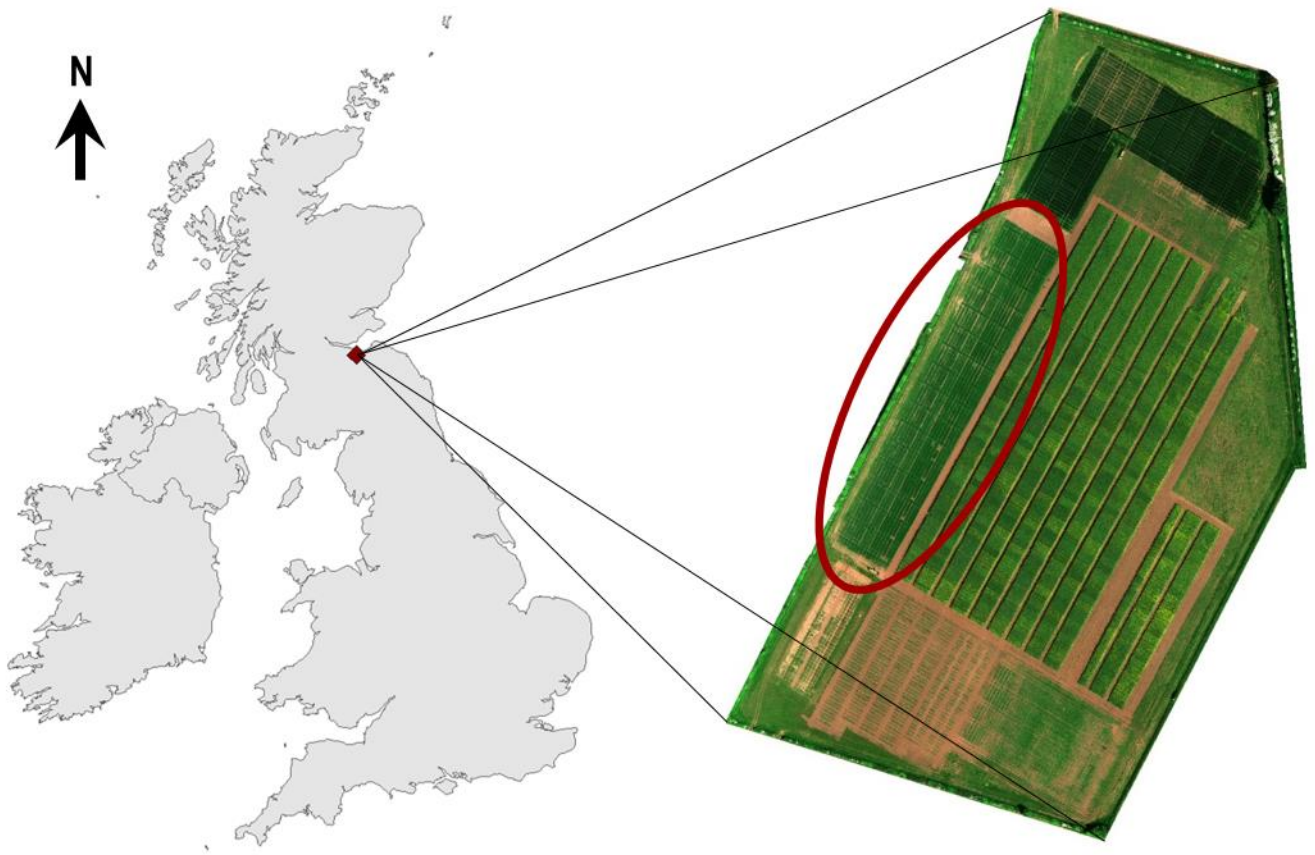
Figure 1. Study site: Boghall Farm, Edinburgh (55°52'44.5″N 3°12'11.4″W). The drone imagery shows the farm's layout (August 2023). The exact field site (circled) is adjacent to the farm's Western perimeter. UK map scale = 1: 1,250,000. Boghall Farm Scale = 1:1500. Drone image credit: Simon Gibson-Poole (SRUC).

2.2 Data Collection

Data was collected across a 194 m x 30 m field on the western edge of Boghall Farm (Fig. 2a). As the site of multiple ecological studies, the field had been divided into 32, 10 m x 10 m plots prior to this experiment. These were grouped by soil cultivation regime (minimum tillage or ploughed, n = 4). Each plot was sowed with either mustard, radish, vetch, or left as fallow. The plots were further divided into 5, 10 m x 2 m sub-plots each with a distinct fungicide/biological treatment type, one of which was a control (untreated). This is relevant as it dictated the sampling strategy; the plots followed an interspersed layout while the untreated subplots were randomly distributed (Fig. 2b). The fully randomised arrangement of treatments within the interspersed plots minimised the systematic pseudoreplication commonly associated with ecological studies (Hurlbert, 1984).
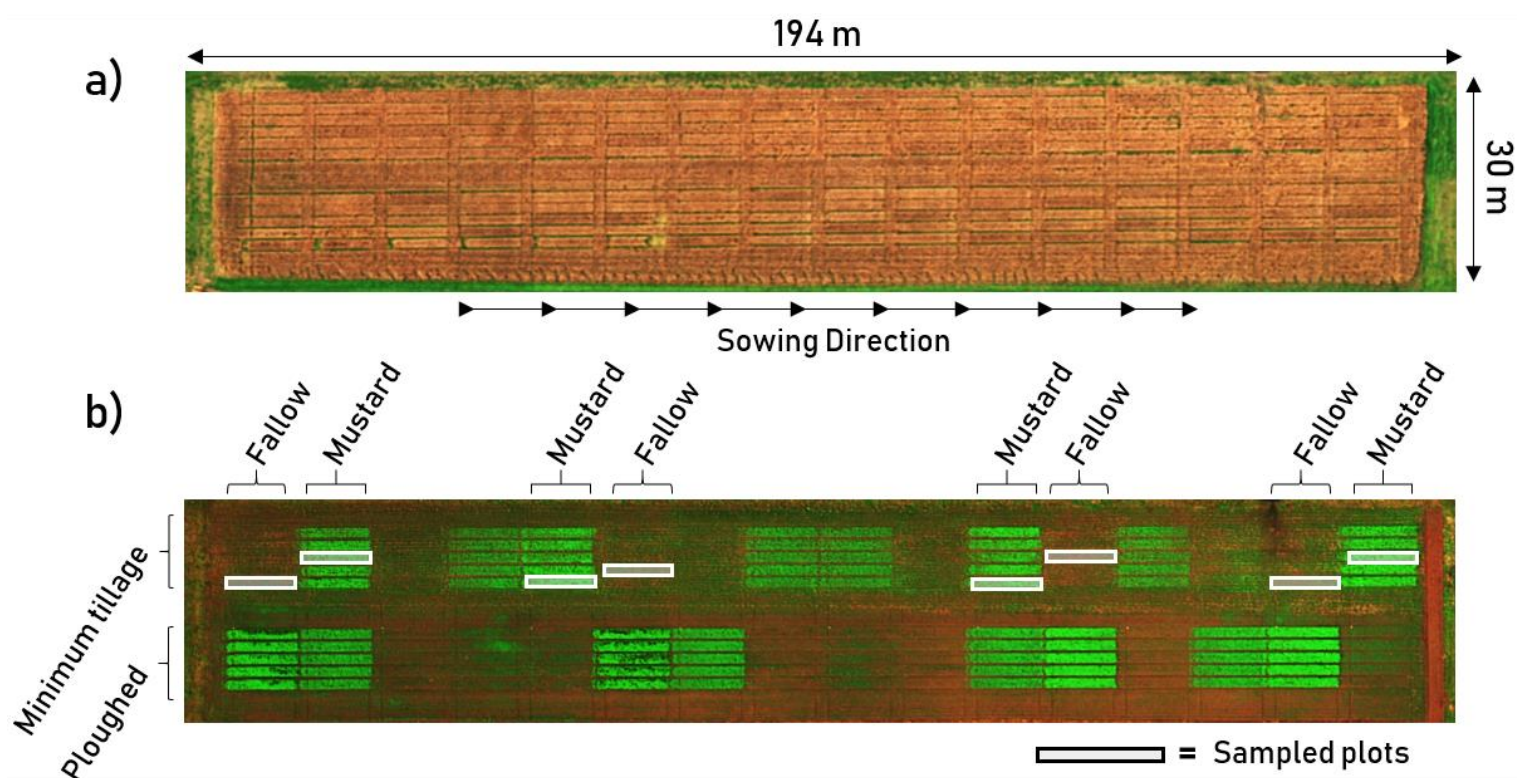
Figure 2. Labelled drone images of the field site during the first (a) and final (b) months of sampling (September and November 2023, respectively). The first diagram notes the field's dimensions and direction of cover crop sowing. The second shows the distribution of soil cultivation regimes and the interspersed layout of fallow and mustard plots. The locations of the sampled subplots (n = 8), all from minimum tillage plots, are highlighted. Drone image credit: Simon Gibson-Poole (SRUC).

Invertebrate populations were measured across 8 subplots (Fig. 2b) at each sampling event. The subplots were split equally between those sown with mustard and those left as fallow. Within each subplot, the above- and below-ground invertebrate populations were sampled using 3 pitfalls and 2 subterranean traps, respectively. This amounted to 72 pitfalls and 48 subterranean samples over the three sampling events.

Both traps types were installed one week prior to the first sampling event which allowed them to settle into the soil, thus increasing their stability and functionality. This settling period also allowed invertebrates to become more accustomed to the traps presence which, once sampling has begun, results in a greater catch rate (Jowett *et al.*, 2021).

2.3 Trap Types

2.3.1 Pitfall Traps

Standard pitfall-trapping has been used to sample invertebrate populations for decades, owing to arthropods' mobile nature (Greenslade, 1964; Leather, 2005). This widely used method was adopted to measure the above-ground invertebrate communities of fallow and mustard plots (Fig. 3a). The pitfalls were set into the ground so that the rim ran parallel to the substrate surface. The traps' physical characteristics were selected and standardised based on research that identified them as relevant or impactful for invertebrate catch efficacy. Plastic cups with a diameter of 90 mm and depth of 140 mm were used. This was informed by Luff (1975) who found carabid catches to increase with diameters above 25 mm. We did not exceed 90 mm because he also cites that much larger pitfall diameters are associated with reduced catch rates of smaller British carabid species. Moreover, Work *et al.* (2002) note that pitfall circumference and carabid catch rates are not directly proportional, which also informed the decision to opt for this pitfall size. Pitfall colour was also standardised to be white; research shows that white pitfalls make for more effective carabid traps than darker traps such as those that are green or brown (Buchholz *et al.*, 2010).

At the beginning of each sampling event, each pitfall was filled with 100 mL of trapping fluid. This consisted of salt dissolved in water (30 g/L) which simultaneously killed and preserved catch without repelling invertebrates (as alternative trapping fluids can (Kwon *et al.*, 2022)). A drop of detergent agent was also added to break the surface water tension and enhance the immersion, retention and preservation of catch (Schmidt *et al.*, 2006). Each pitfall was covered and fixed with a 12 mm x 12 mm malleable metal mesh to prevent small mammals and birds from entering and/ or predating the invertebrate catch while also allowing small invertebrates, including slugs to be caught. Between sampling events, the pitfalls were covered with parafilm, thus rendering them inactive.

2.3.2 Subterranean Traps

Carabid larvae generally account for <1 % of pitfalls' total catch (New, 1998; Hyvarinen *et al.*, 2006). Therefore, specialised 'subterranean traps' (Fig. 3b) were used to sample the below-ground invertebrate communities (Jowett *et al.*, 2021). Similarly to the pitfalls, the subterranean traps were set in the ground a week prior to the first sampling event. Each trap comprised of a cylindrical plastic tube with a diameter of 70 mm and a height of 34 mm. Three central 150 mm x 40 mm cuttings, covered by a coarse 10 mm x 10 mm wire mesh allowed mobile, soil-dwelling invertebrates to permeate through and fall into a central trapping

container containing 50 mL of trapping fluid. The trapping containers (diameter = 55 mm, height = 50 mm) were wrapped with string to increase their diameter and mitigate loose fits within the central cylinders. This prevented invertebrates from being lost to the sides of the trapping cylinders, thus increasing catch retention rate. The containers were lowered to the base of the trap at the beginning of each sampling event and collected at the end with a hook. The top of the trap was covered with parafilm to prevent above-ground invertebrates and soil from being collected.
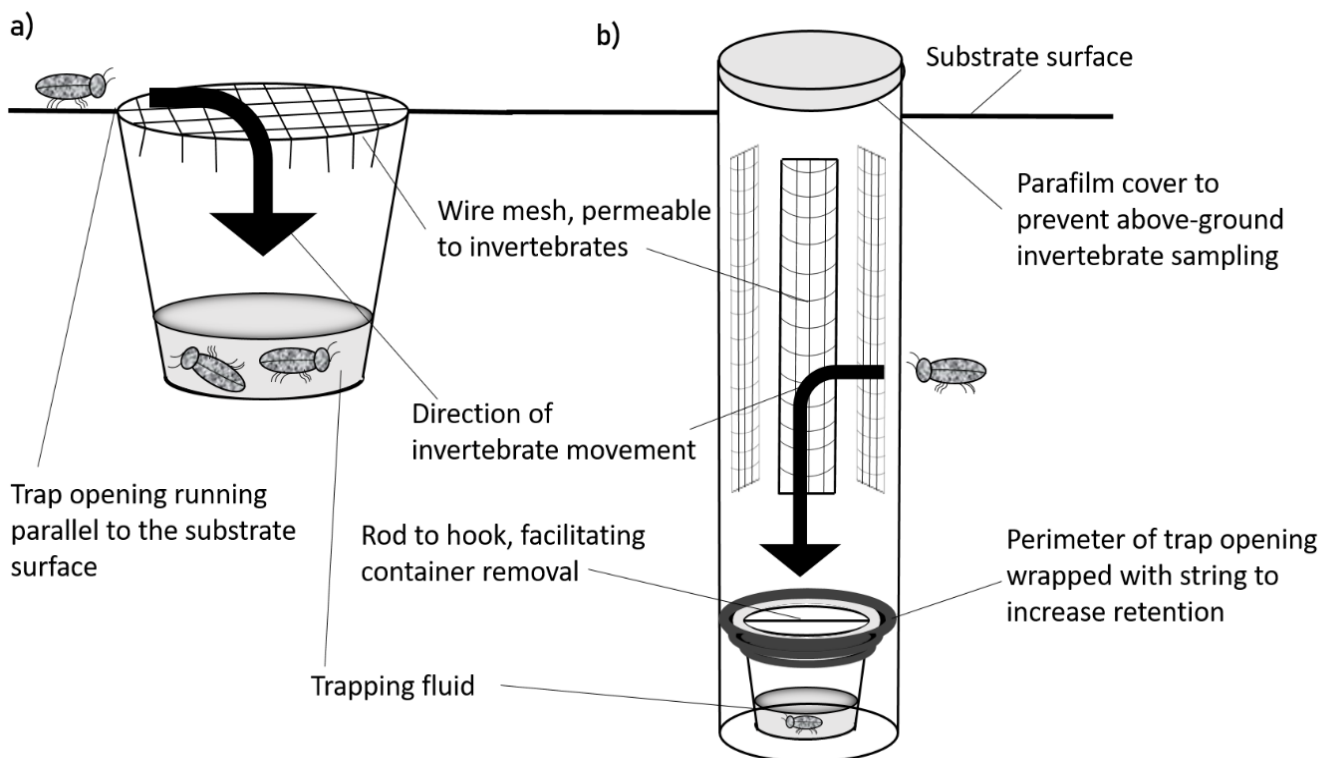
Figure 3. Not-to-scale labelled diagrams of the traps used to sample a) above-ground (standard pitfalls) and b) below-ground (subterranean traps) invertebrate communities.

2.4 Abiotic Data: Data Loggers

A number of environmental variables were recorded using the TMS-4 soil data logger probes (Wild *et al.*, 2019). The entire below-ground section of each probe was inserted into the soil to a depth of 10 cm. They measured soil, surface and air (19 cm above the substrate) temperature (°C), as well as soil moisture content (raw values) at 15 minute intervals for the duration of each sampling event (n = 6 (3 mustard, 3 fallow)). This data logger was chosen in particular because of its capability to measure soil moisture; this is cited as the most influential abiotic component as many carabid species are limited to a narrow moisture range (Luff, 2007; Kirichenko-Babko *et al.*, 2020).

The data was extracted and cropped to the relevant timeframe using the TOMST Lolly software (Version 1.47) (Wild *et al.*, 2019). Then the raw soil moisture data values were calibrated using the accompanying R package 'myClim' (Kopecký *et al.*, 2021) to give the soil-volumetric water contents (%).

2.5 Subplot Layout

3 pitfall traps and 2 subterranean traps were installed in each subplot. The pitfalls were installed at regular intervals (4 m) along the centre of each plot's lateral margin (Fig. 4). Aside from avoiding bias and encouraging subplot-wide sampling, this interval distance was selected based on research finding pitfall capture rates to be largely influenced by sampling intervals, even at small scales. For example, Ward *et al.*, (2001) found that beetle catch diversity to be significantly greater at intervals of 5 m compared to 1 m. In turn, the sampling intervals were increased but limited to 4 m. This was so that the peripheral pitfalls could be installed 1 m from the subplot edge (Fig. 4). This decision was taken to reduce the effect of external conditions on the subplots (Ng *et al.*, 2018) which was further mitigated by a 2 m buffer zone between adjacent plots (Fig. 2). Similarly, the subterranean traps were separated by 4 m and evenly interspersed with pitfalls. The soil probes were used across 6 of the 8 plots (3 fallow, 3 mustard) and were inserted into the soil 0.5 m from south-facing edge of their subplot, parallel to the central pitfall (Fig. 4).
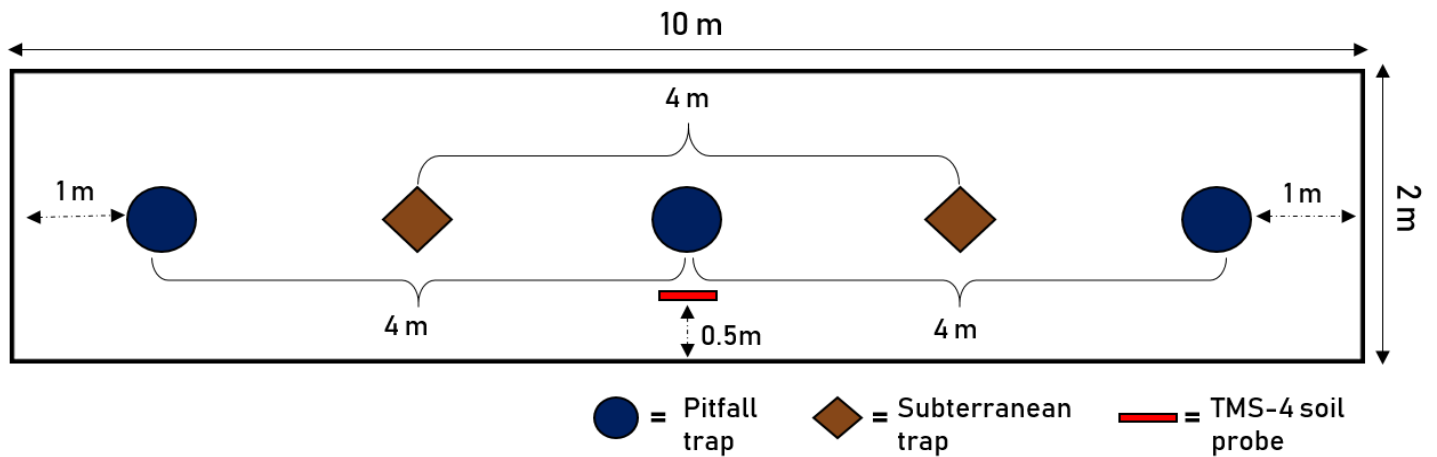

Figure 4. Diagram illustrating the dimensions and trap layout of an example subplot. Traps and probe not drawn to scale.

2.6 Invertebrate Identification

After each sampling event, all invertebrates were collected from their respective traps and stored in plastic containers with corresponding labels. The samples were then transported to the lab, filtered to remove water, and preserved in containers containing 100 mL of ethanol and water (0.7:1).

To begin identification, the contents of each preserved trap were emptied onto a plastic dish. Each specimen was individually transferred to the stage of a dissecting microscope illuminated with diffuse light. The different invertebrate groups were identified to pre-determined, varying taxonomic ranks. Carabids and their larvae were identified using dichotomous keys in *'The Carabidae (Ground Beetles) of Britain and Ireland'* (Luff, 2007) and *'The Carabidae (Coleoptera) Larvae of Fennoscandia and Denmark'* (Luff, 1993), respectively, to species level (Fig. 5). All other invertebrates were identified to order using the '*Insects of Britain & Northern Europe'* (Chinery, 1993) identification guide.

Equivocal specimens were left to dry on tissue paper for 10 minutes before attempts to re-identify them. This was to perceive finer morphological traits such as setae (hair-like bristle structures), pores and elytra (outer-wing casing) more clearly to facilitate identification. Unidentifiable specimens were recorded as such.
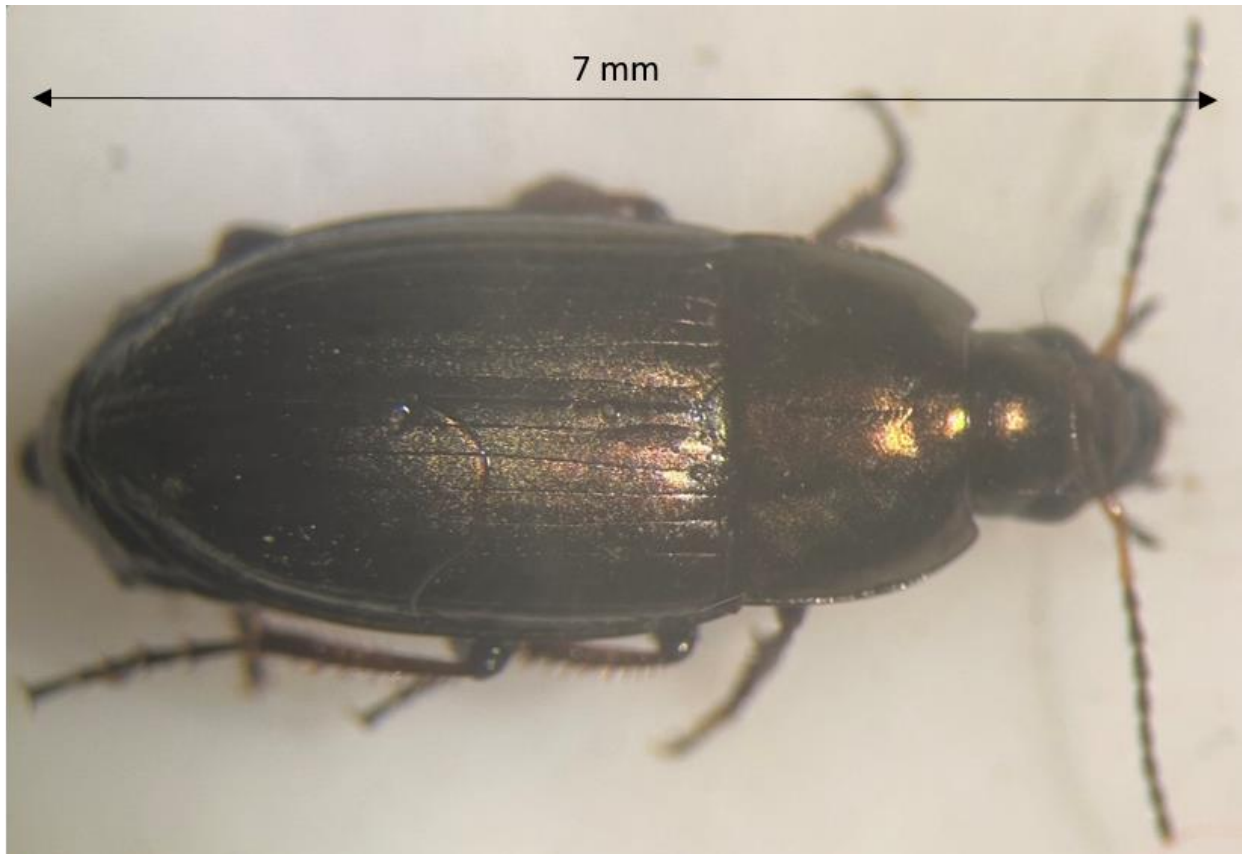
Figure 5. *Amara aenea,* an example of an adult above-ground carabid sampled in September. 16x magnification.

2.7 Pre-data Analysis

Prior to analysis, the counts of individuals belonging to the same species in different life-cycle stages were pooled. For example, if a trap caught 1 adult and 1 larval *Nebria brevicollis* Fabricius, the total *N. brevicollis* count for that trap would be 2. This was to ensure accurate calculations of above- and below-ground carabid species richness, Shannon's diversity (H') and mean relative abundances (n = 72 and 48, respectively) using the 'vegan' package (Dixon, 2003). Relative abundances were calculated after being grouped by plot type i.e. mustard/fallow.

Richness was chosen as a measure of diversity as it negates the effect of disproportionately high populations. Shannon's was also chosen over alternative indices of diversity as it affords greater statistical power to rarer species in comparison to Simpson's index of diversity, for example (Roswell *et al.*, 2021). This was necessary as one species (*N. brevicollis)* dominated

the majority of the samples. Above- and below-ground slug abundances were pooled to increase sample size (n = 120) and, in turn, model validity.

2.8 Data Analysis

All data analyses and visualisations were performed using R, version 4.3.3 (R Core Team, 2022), the code for which can be accessed freely on Github and in Appendix 1. Using the 'brms' package (Buerkner, 2017), Bayesian Hierarchical Statistical Modelling was used to analyse the effect of mustard cover crops on carabid abundance and diversity (richness and Shannons's diversity (H')), as well as pooled slug abundance. This statistical framework incorporates existing knowledge (or a lack of) into analysis in the form of (informative or non-informative) prior distributions in combination with the raw data. As a function of these factors, the model outputs included posterior distributions and credibility intervals which permit a more nuanced interpretation of the data in comparison to the dichotomous outputs of frequentist statistics (Halsey, 2019). This also renders Bayesian models less susceptible to type I and II errors, which research shows is commonplace in ecological studies (Colquhoun, 2014; 2019).

2.9 Carabid Abundance and Diversity Metrics

Carabid analyses were divided into above- and below-ground communities. This was to compare variation in the impact of mustard cover cropping across these distinct, ecologically variable microhabitats, hence the two separate sampling methods. To be conservative in analysis, all 'non-identifiable carabid larvae' (n = 8) were treated as a single species. Because no up-to-date British carabid larvae guide exists, morphological variation between unidentifiable specimens was insufficient evidence for grouping them as distinct species. Such differences could merely be a function of intraspecific phenotypic variation or sexual dimorphism which is commonplace in the carabid taxon (Benitez, 2013; Baranovská & Knapp, 2014; Komlyk & Brygadyrenko, 2019). The effect of mustard cover cropping on pooled slug abundance was also modelled.

2.10 Fixed and Random Effects

2.10.1 Fixed Effects

For each model, in addition to the primary variable of interest (abundance, richness and Shannon's diversity), sampling event ('month') was treated as a secondary fixed effect. Month

was incorporated as opposed to the abiotic data because firstly, there was an incomplete dataset in that only 6 of the 8 plots had data loggers which reduced statistical power. Secondly, adding multiple environmental variables (soil, surface and air temperature and soil moisture) risked overfitting the model, resulting in poor convergence and more unreliable conclusions. Thirdly, by treating month as a fixed effect, the model accounted for temporal variations in the data stemming from carabid life cycles. For example, individuals may have completed their adult life-cycle over the course of the sampling period. This is characteristic of many of the sampled carabid species including *N. brevicollis* and *Trechus obtusus* Erichson whose adult populations peak during September before diminishing by November following egg laying (Luff, 2007). Therefore, 'month' acted as a proxy for the effect of the seasonal and biological variables while simultaneously circumnavigating the issue of analysing an incomplete dataset. Finally, given the explanatory variables accounted for within month, it has been treated as a fixed effect rather than a random effect. Additionally, 'month' has <5 levels (3 sampling events) and is therefore unsuitable to be treated as a random effect.

2.10.2 Random Effects

Critically, to avoid violating the assumption of independence (committing pseudoreplication), 'plot' was included as a random effect in the models. This was because adjacent plots were likely to be spatially autocorrelated in their invertebrate communities owing to heterogeneity in environmental conditions, soil composition and/ or historical land management practises between different plots, all of which could be reflected in the response variables. 'Plot' was not necessarily omitted from models if it resulted in a better cross-validation information criterion value as doing so, solely for this reason, would be statistical malpractice (Appendix 2).

Consideration was also given to treating 'trap' as a nested effect within 'plot' but in spite of the data's hierarchical structure, this was avoided. While it makes logical sense to nest 'trap' within 'plot' owing to the correlated environmental conditions and/or community compositions, ultimately, the relatively low number of levels for pitfalls and subterranean traps (3 and 2, respectively) is inadequate for estimating variance precisely (Appendix 2).

2.11 Meeting Model Assumptions

Each Bayesian Hierarchal Model ran 3000 iterations (1000 warm-up) to output accurate posterior distributions and probabilities, with a thorough and comprehensive estimation of uncertainty. Prior to analysis, the data's raw distributions were visualised to inform model assemblage i.e. choice of 'family' argument. All count data had poisson distributions which is

characteristic ecological counts. The richness and Shannon's diversity data were normally distributed resulting in the use of the 'Gaussian' family argument (Appendix 2).

The predictive ability of posterior distributions were assessed using (pp_check) plots, the model-data fit with trace plots, and 'Leave-One-Out' (LOO) cross-validation information criterions were consulted to compare the fit (expected log pointwise predictive density (ELPD)) of prospective models (Vehtari *et al.*, 2017). This was used to inform model selection to balance the trade-offs between model rationality, complexity and compatibility with the data (Appendix 2). All models converged successfully (Rhat = 1). All bulk and tail effective sample sizes exceeded 1000.

Only non-informative priors were used for this study given that it is the first of its kind. The creation of a unique, informative prior could not be justified; there are no previous studies measuring carabid diversity across mustard and fallow plots in tandem. Models that incorporated a poisson distribution had their outputs back-transformed into the original units. Explanatory variables were deemed 'significant' if the 95% credibility interval for the respective parameter did not span 0.

2.12 Community Composition and Indicator Species

Variation in above- and below-ground carabid community composition was assessed with non-metric multidimensional scaling (NMDS) plots and, subsequently, PERMANOVA. Traps where carabid populations equalled 0 were removed to create Bray-Curtis dissimilarity matrices (n = 71 and 44 for above- and below-ground communities, respectively). As before, both plot type and month were treated as explanatory variables. The data's fit was gleaned to be adequate using stress plots/scores. Homogeneity in multivariate dispersion was also checked using the 'betadisper()' and 'permutest()' vegan package functions (Dixon, 2003).

Finally, a species indicator analysis was performed using the 'indicspecies' R package (Cáceres & Legendre, 2009) to identify above- and below-ground carabid species associated with particular plot types.

3. Results

A total of 4146 invertebrates were collected over the sampling period. This included 1788 carabids, 1780 of which were identified to species level (Appendix 3).

Mustard-sown plots had no significant effect on above-ground carabid abundance (Bayesian Hierarchal Model, β = 0.32, 95% CI = −0.04 to 0.69, standard error = ± 0.18; see Fig. 6) nor below-ground carabid abundance (Bayesian Hierarchal Model, β = 0.28, 95% CI = −0.25 to 0.74, standard error = ± 0.26; see Fig. 7).

Mustard-sown plots had no significant effect on above-ground carabid species richness (Bayesian Hierarchal Model, β = 0.22, 95% CI = −1.97 to 1.40, standard error = ± 0.59; see Fig. 8) nor below-ground carabid species richness (Bayesian Hierarchal Model, β = 0.13, 95% CI = −0.67 to 0.96, standard error = ± 0.41; see Fig. 9).

Mustard-sown plots had no significant effect on above-ground carabid Shannon's diversity (Bayesian Hierarchal Model, β = -0.10, 95% CI = −0.39 to 0.19, standard error = ± 0.15; see Fig. 10) nor below-ground carabid Shannon's diversity (Bayesian Hierarchal Model, β = 0.14, 95% CI = −0.16 to 0.45, standard error = ± 0.15; see Fig. 11).

Above-ground carabid community composition varied between fallow and mustard-sown plots (PERMANOVA, $F_{1, 67}$ = 2.98, R^2 = 0.025, p = 0.024; see Fig. 12), but not in below-ground communities (PERMANOVA, $F_{1, 40}$ = 0.73, R^2 = 0.016, p = 0.634; see Fig. 13).

There were no significant associations between any carabid species and particular plot types for above-ground communities (Multilevel pattern analysis, $F_{1, 21}$ > 1, p-values > 0.05) nor below-ground communities (Multilevel pattern analysis, $F_{1, 21}$ > 1, p-values > 0.05; see Appendix 4).

Species rank-abundance curves revealed that carabid community evenness was similar between fallow and mustard-sown plots across both above- (Fig. 14) and below-ground communities (Fig. 15).

Mustard-sown plots had no significant effect on pooled slug abundance (Bayesian Hierarchal Model, β = 0.11, 95% CI = −0.78 to 1.08, standard error = ± 0.46; see Fig. 16).

Finally, each of the aforementioned relationships were exposed to highly variable environmental conditions including fluctuations in soil-volumetric water content (%) (Fig. 17) and soil, surface and air temperature (°C) (Fig. 18)
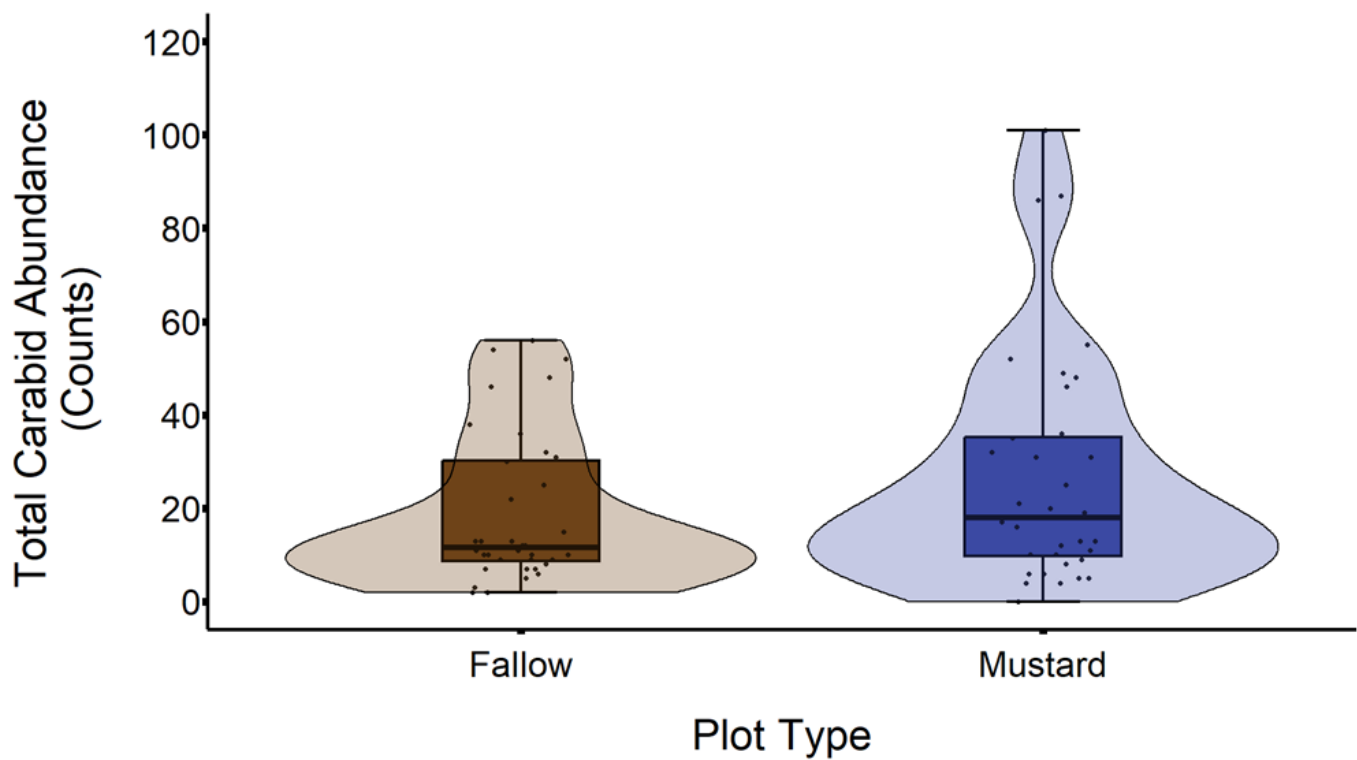
Figure 6. Box, dot and violin plot displaying above-ground carabid abundance (adult and larvae counts) collected in pitfall traps across arable farmland subplots sown with mustard (n = 36, standard deviation = ± 24.9) or left as fallow (n = 36, standard deviation = ± 16.1). The box-and-whisker plots demonstrate the median, interquartile range (boxes) as well as minima and maxima (whiskers). The dot-plot displays the raw data while the violin plot represents the distribution densities.

Figure 7. Box, dot and violin plot displaying below-ground carabid abundance (adult and larvae counts) collected in subterranean traps across arable farmland subplots sown with mustard (n = 24, standard deviation = ± 3.2) or left as fallow (n = 24, standard deviation = ± 2.3). The box-and-whisker plots demonstrate the median, interquartile range (boxes) as well as minima and maxima (whiskers). The dot-plot displays the raw data while the violin plot represents the distribution densities.

Figure 8. Box, dot and violin plot displaying above-ground carabid species richness collected with pitfall traps across arable farmland subplots sown with mustard (n = 36, standard deviation = ± 2.1) or left as fallow (n = 36, standard deviation = ± 1.4). The box-and-whisker plots demonstrate the median, interquartile range (boxes) as well as minima and maxima (whiskers). The dot-plot displays the raw data while the violin plot represents the distribution densities.
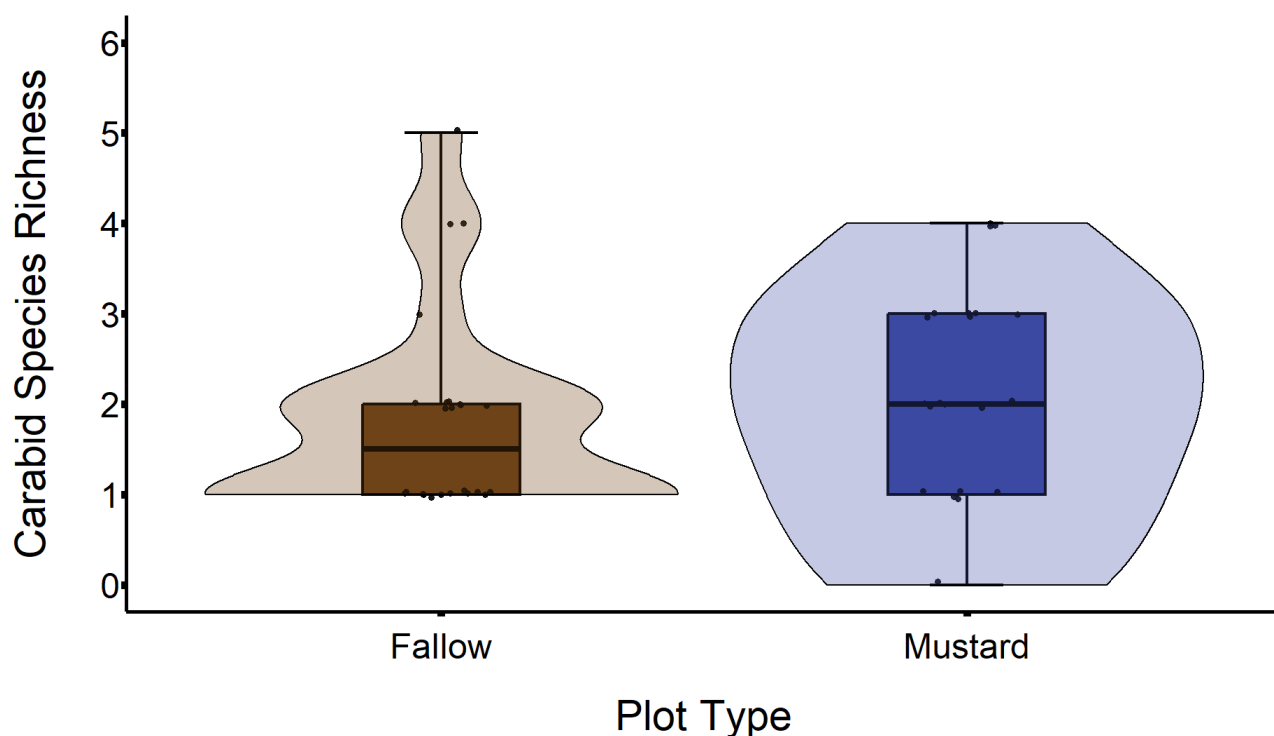
Figure 9. Box, dot and violin plot displaying below-ground carabid species richness collected with subterranean traps across arable farmland subplots sown with mustard (n = 24, standard deviation = ± 1.3) or left as fallow (n = 24, standard deviation = ± 1.1). The box-and-whisker plots demonstrate the median, interquartile range (boxes) as well as minima and maxima (whiskers). The dot-plot displays the raw data while the violin plot represents the distribution densities.
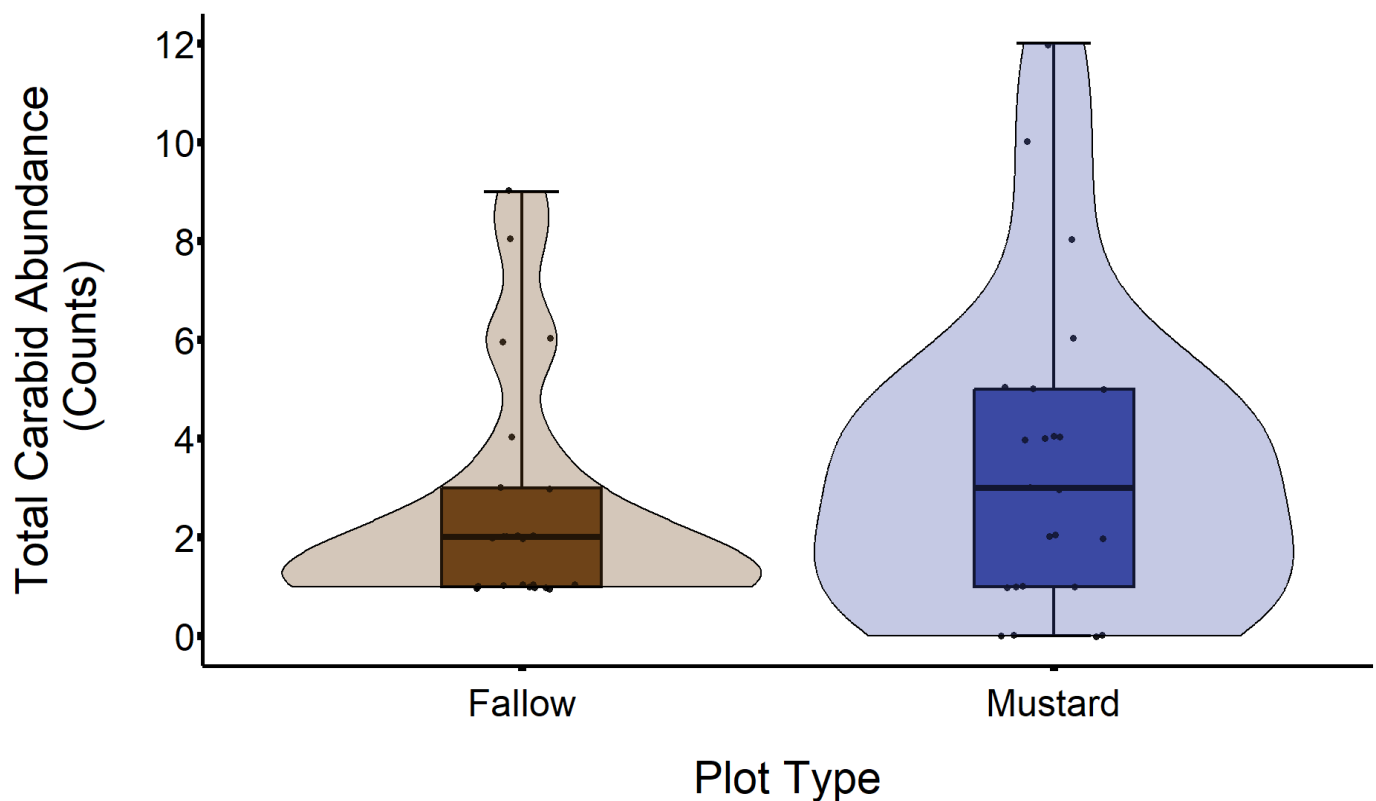
Figure 10. Box, dot and violin plot displaying above-ground carabid community Shannon's diversity (H') collected with pitfall traps across arable farmland subplots sown with mustard (n = 36, standard deviation = ± 0.44) or left as fallow (n = 36, standard deviation = ± 0.4). The box-and-whisker plots demonstrate the median, interquartile range (boxes) as well as minima and maxima (whiskers). The dot-plot displays the raw data while the violin plot represents the distribution densities.
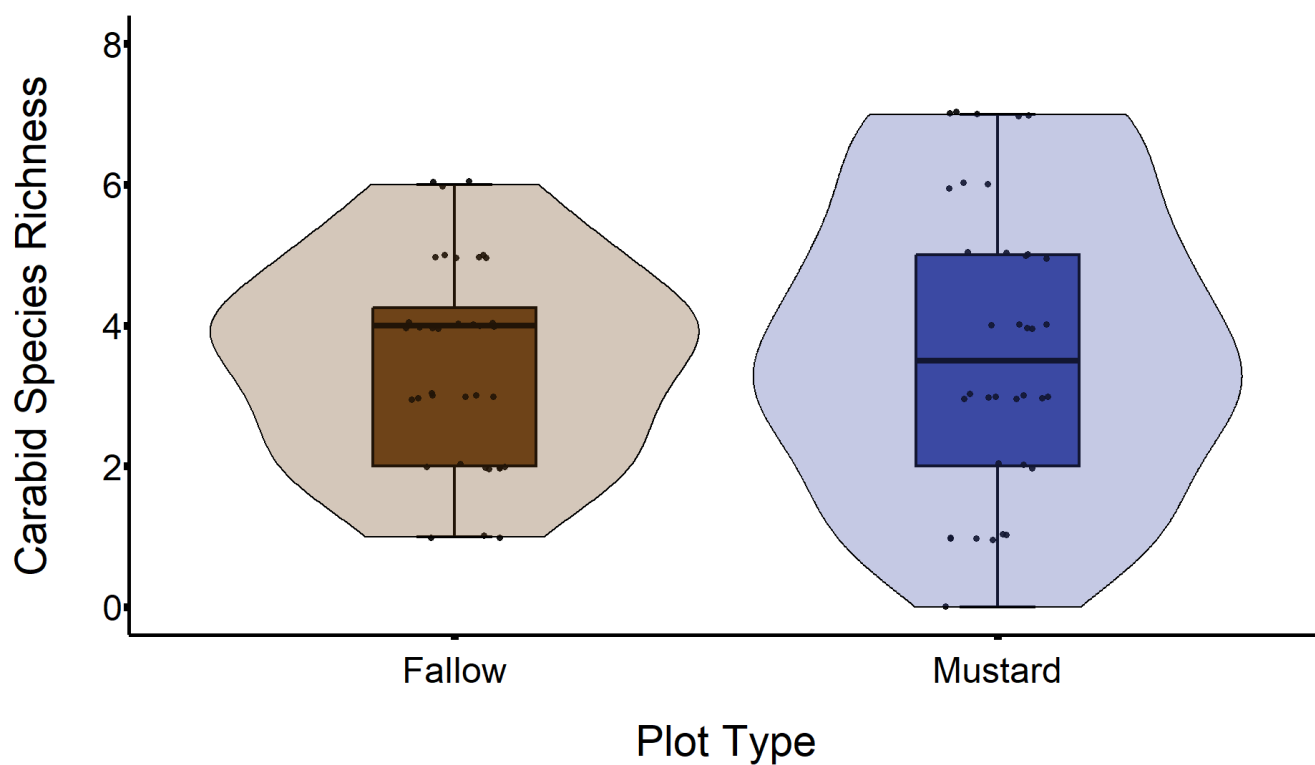

Figure 11. Box, dot and violin plot displaying below-ground carabid community Shannon's diversity (H') collected with subterranean traps across arable farmland subplots sown with mustard (n = 24, standard deviation = ± 0.50) or left as fallow (n = 24, standard deviation = ± 0.48). The box-and-whisker plots demonstrate the median, interquartile range (boxes) as well as minima and maxima (whiskers). The dot-plot displays the raw data while the violin plot represents the distribution densities.
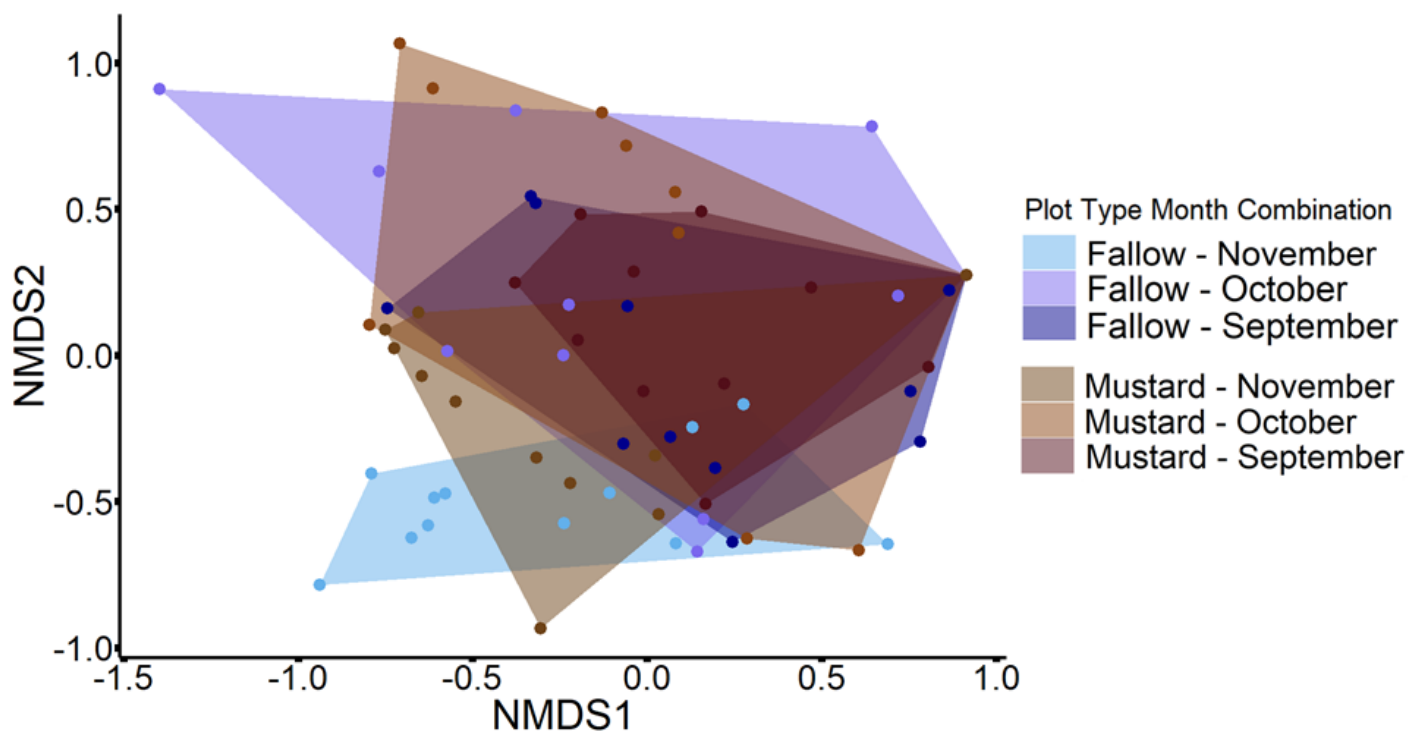
Figure 12. Non-metric multidimensional scaling (NMDS) plots for above-ground carabid community compositions across arable farmland subplots sown with mustard or left as fallow over three distinct sampling events in September (n = 12 and 12), October (n = 12 and 12) and November (n = 11 and 12), respectively. 2-D stress = 0.18.
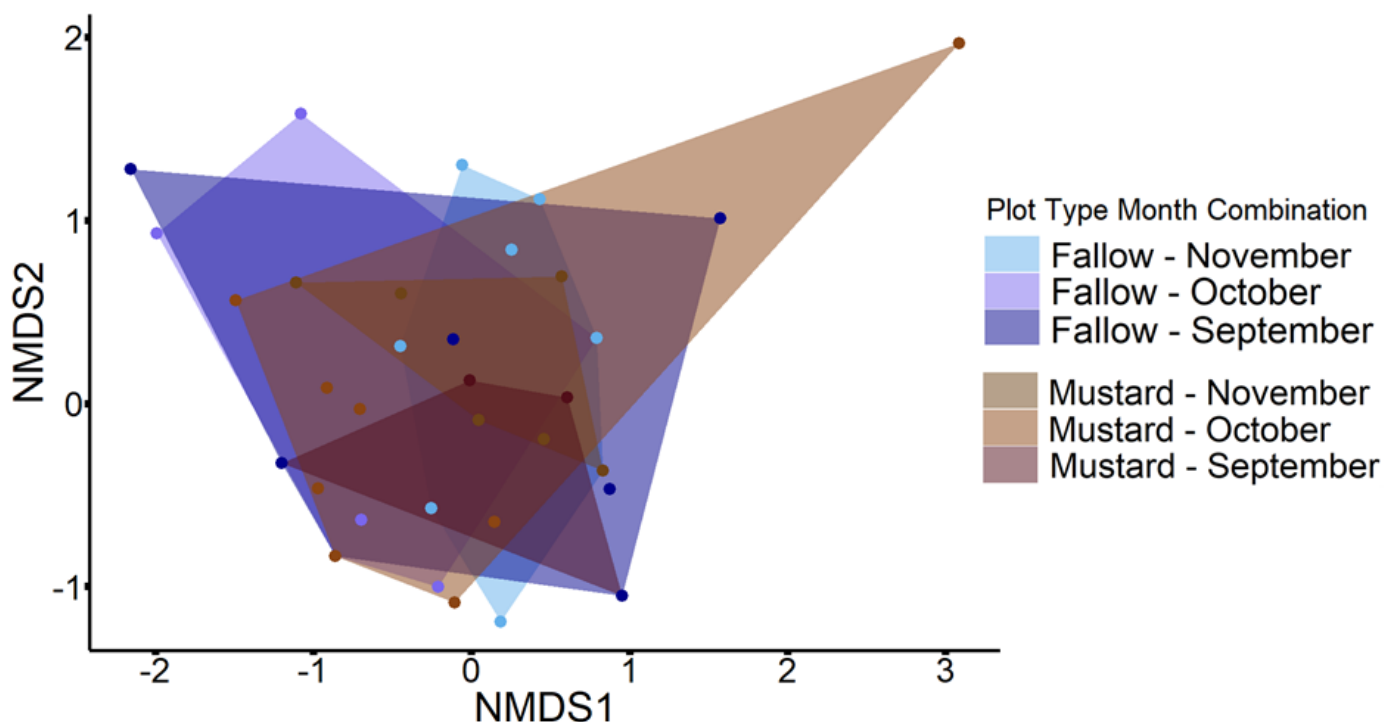
Figure 13. Non-metric multidimensional scaling (NMDS) plots for below-ground carabid community compositions across arable farmland subplots sown with mustard or left as fallow over three distinct sampling events in September (n = 5 and 8), October (n = 8 and 8) and November (n = 7 and 8), respectively. 2-D stress = 0.07.
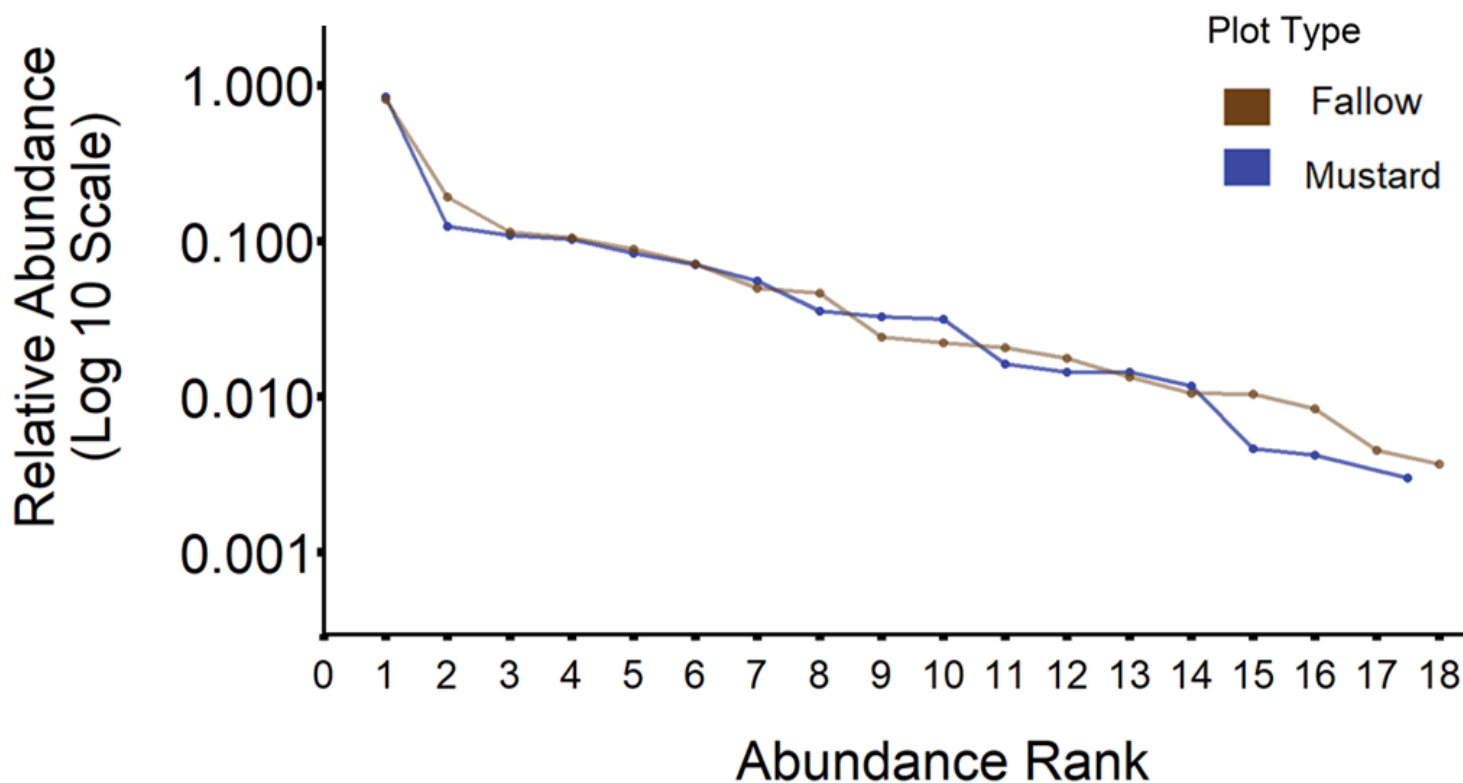
Figure 14. Mean above-ground carabid species rank-abundance curves for mustard sown subplots (n = 36) and those left as fallow (n = 36). Relative abundance scale = log 10. The standard deviations for each species' relative abundance can be found in Appendix 5.1
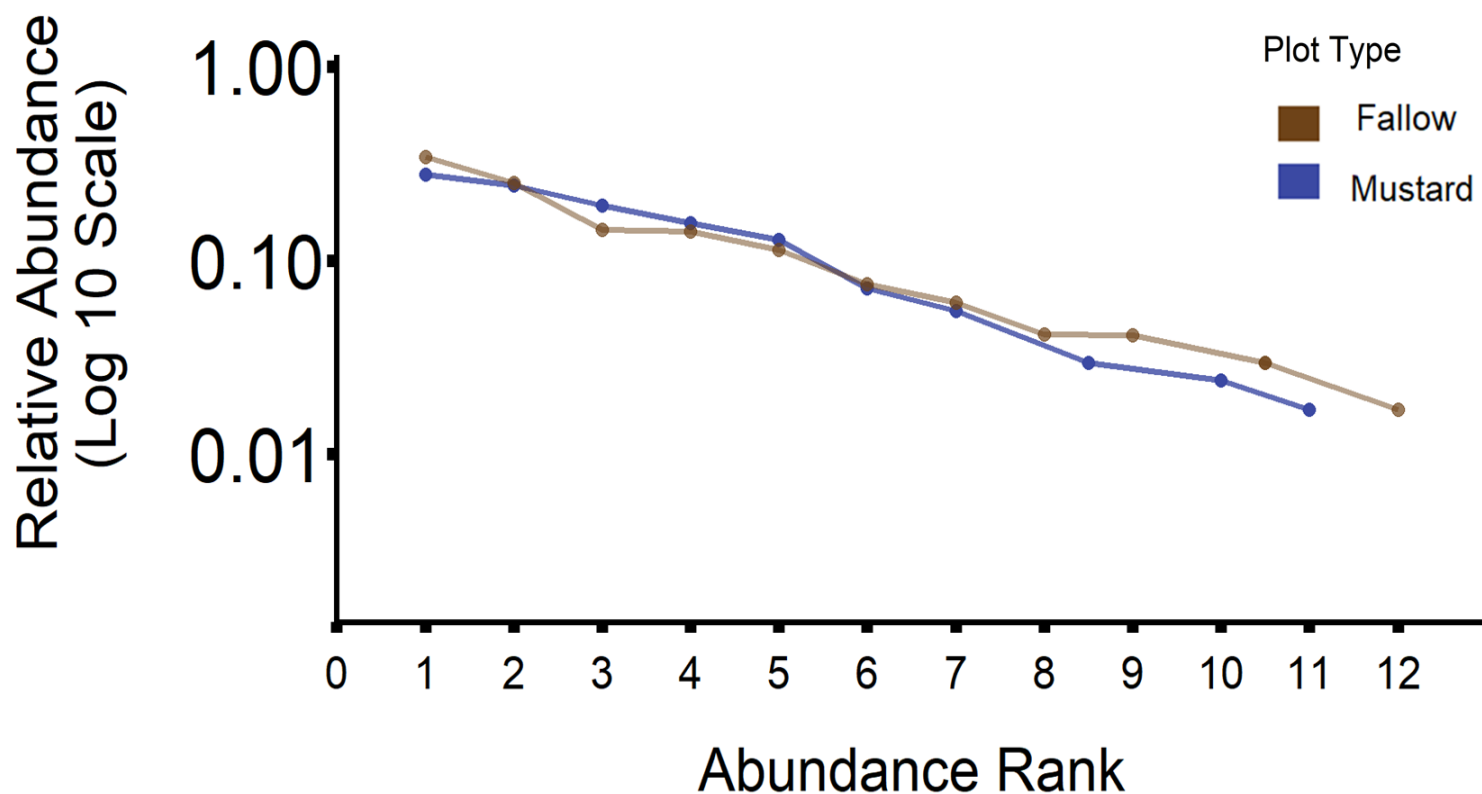
Figure 15. Mean above-ground carabid species rank-abundance curves for mustard sown subplots (n = 24) and those left as fallow (n = 24). Relative abundance scale = log10. The standard deviations for each species' relative abundance can be found in Appendix 5.2
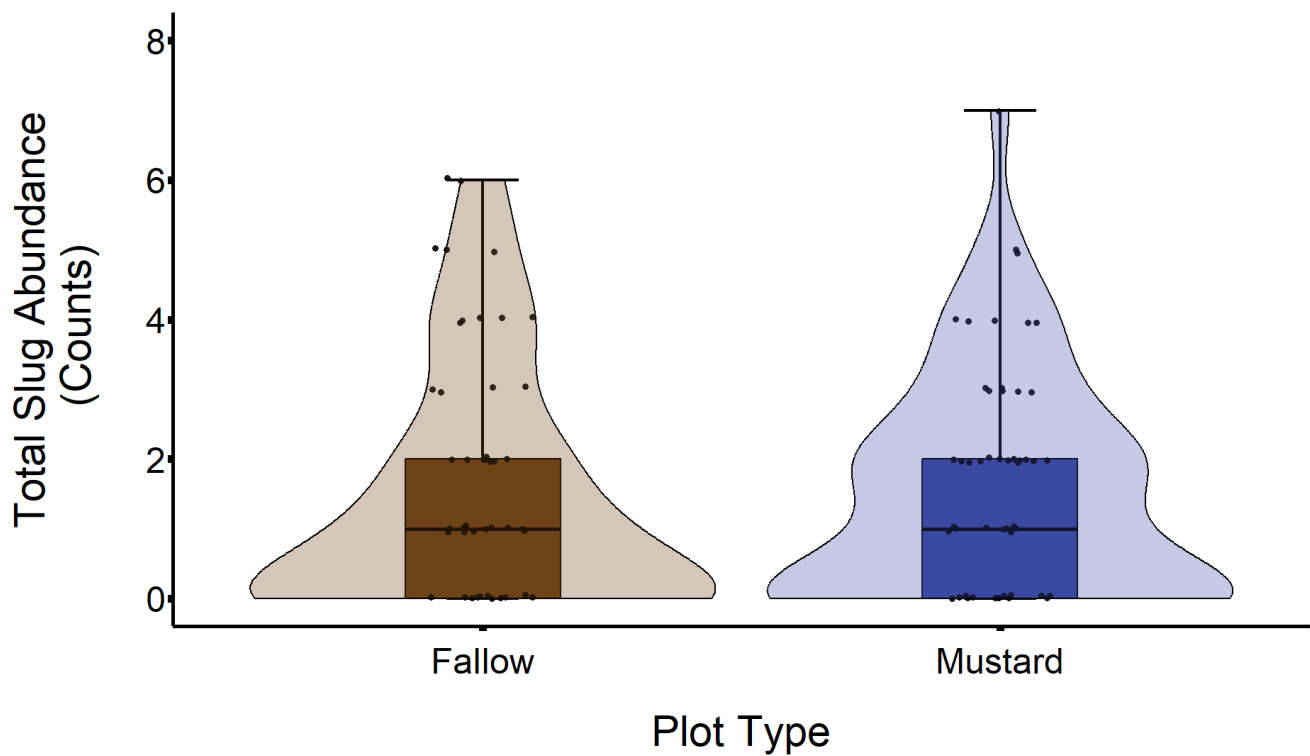
Figure 16. Box, dot and violin plot displaying pooled above- and below-ground slug abundance (counts) collected in pitfall and subterranean traps across arable farmland subplots sown with mustard (n = 60, standard deviation = ± 1.6) or left as fallow (n = 60, standard deviation = ± 1.8). The box-and-whisker plots demonstrate the median, interquartile range (boxes) as well as minima and maxima (whiskers). The dot-plot displays the raw data while the violin plot represents the distribution densities.
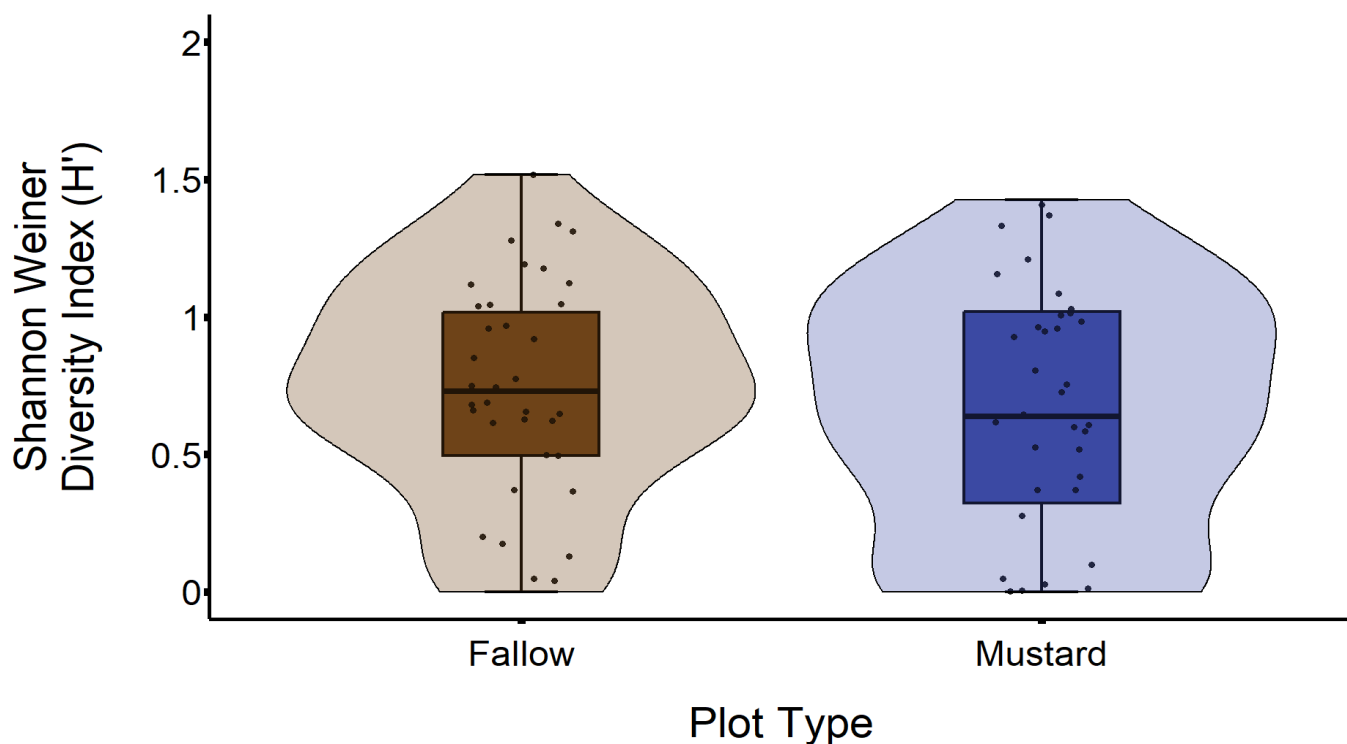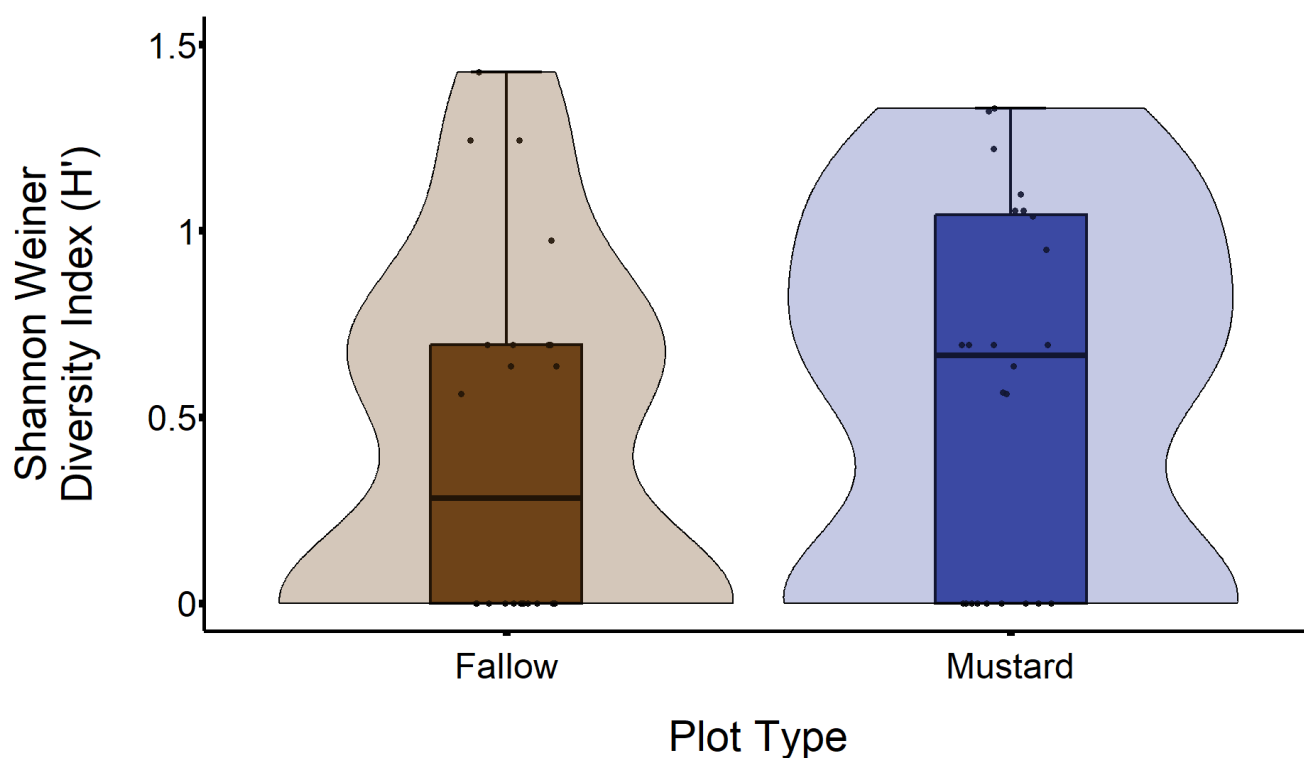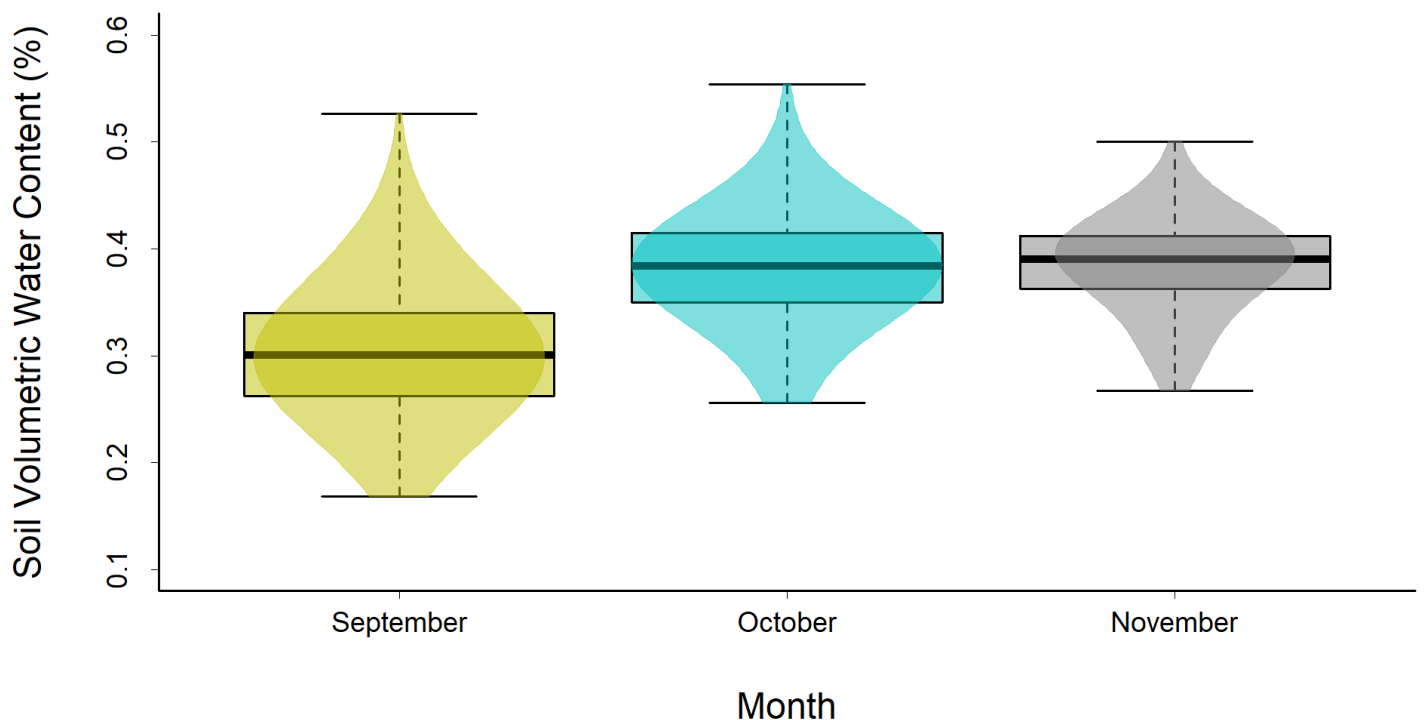

Figure 17. Box- and violin-plot displaying the selected plots' soil-volumetric water contents (%) at Boghall Farm. Measurements were taken across 3 fallow and 3 mustard plots with TMS-4 data loggers during September (n = 6 standard deviation = ± 0.06), October (n = 6, standard deviation = ± 0.05) and November (n = 6, standard deviation = ± 0.04). The box-and-whisker plots demonstrate the median, interquartile range (boxes) as well as minima and maxima (whiskers). The dot-plot displays the raw data while the violin plot represents the distribution densities.
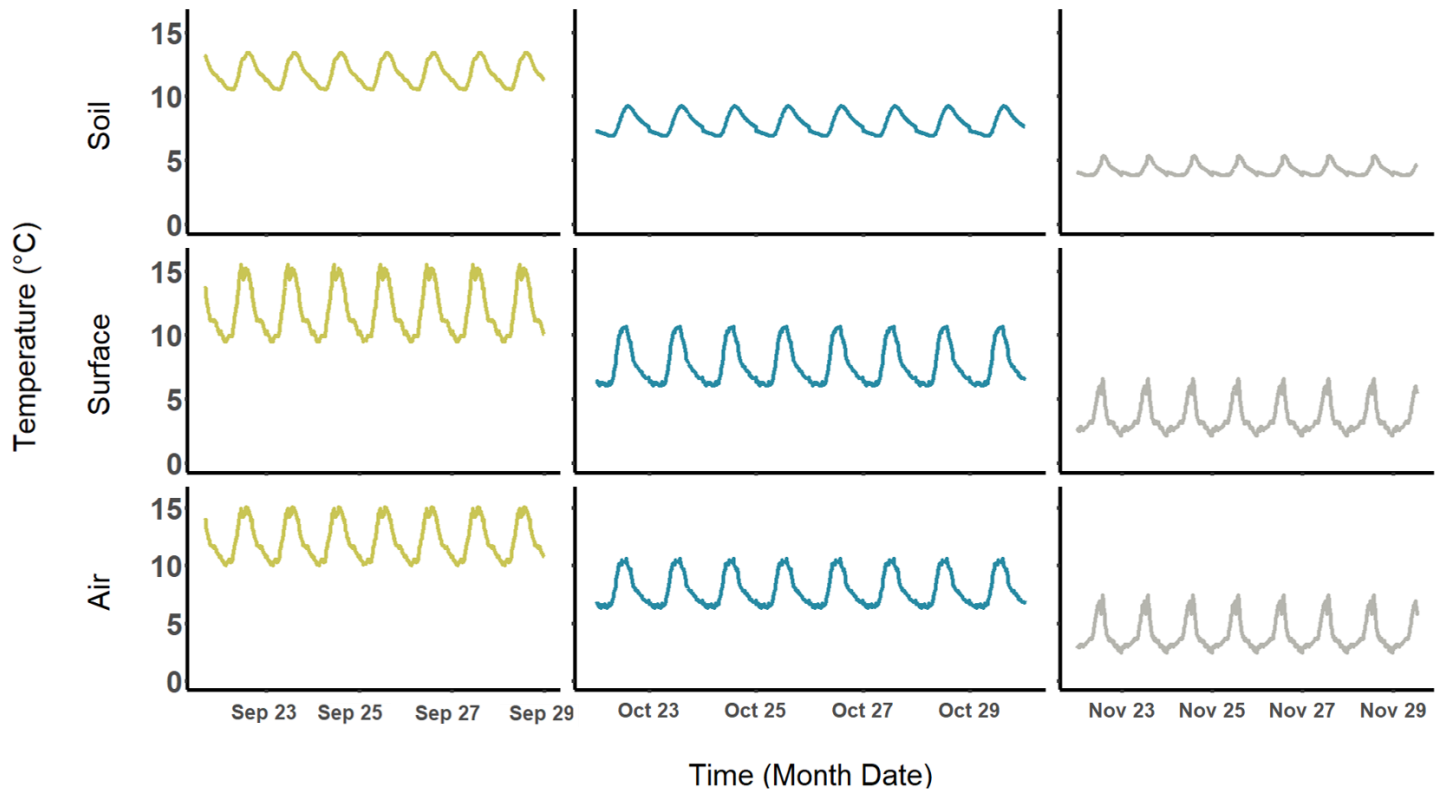
Figure 18. Line plots portraying the average temperatures across 6 subplots (3 fallow, 3 mustard) during each sampling event at 15-minute intervals. Over the three sampling events taking place in September, October and December, the data loggers recorded the temperature of soil (n = 6, standard deviations = ± 1.28, ± 1.44, ± 2.60), substrate surface (n = 6, standard deviation = ± 2.66, ± 2.47, ± 3.96) and air (n = 6, standard deviation = ± 2.51, ± 2.37, ± 4.02, respectively).

4. Discussion

4.1 Summary

The study's primary objective was to assess the impact of mustard cover crops on the abundance, diversity, and composition of both above- and below-ground carabid communities, in comparison to fallow plots. No significant relationships were discovered between mustard-sown plots and carabid abundance (Fig. 6 & 7), richness (Fig. 8 & 9) and Shannon's diversity (H') (Fig. 10 & 11) (CIs spanned 0). While above-ground carabid community composition varied significantly between fallow and mustard-sown plots (p = 0.024; Fig. 12), there was no significant effect detected for below-ground communities (p = 0.634; Fig. 13), nor did the communities appear to differ in their evenness (Fig. 14 & 15). Finally, pooled slug abundance also showed no variation between mustard and fallow plots (CI spanned 0).

4.2 Carabid Community Structure

4.2.1 Carabid Abundance

Although the majority of the tested relationships were insignificant, defying the initial hypotheses and literature, the results provide a number of vital insights into the relationships between mustard cover crops and carabid community structure. Most interestingly, perhaps, is the marginally insignificant effect of mustard cover cropping on above-ground carabid abundance (CI = −0.04 to 0.69). Coupled with the higher mean and maximum carabid abundances observed in mustard plots (27 and 101) in comparison to fallow (18 and 56, respectively), this result brings attention to the possibility of an underlying effect.

The general scientific consensus is that cover crops alter microclimates and provide a greater volume of shelter and feeding resources than fallow plots which, subsequently, gives rise to larger carabid abundances (Jowett *et al.*, 2021; Meagher *et al.*, 2023; Triquet *et al.*, 2023). Therefore, mustard plots were theorised to host a greater abundance of above- and below-ground carabids. The borderline insignificance of the above-ground abundance analysis strongly hints towards an effect of mustard and its validity in supporting IPM. A range of factors may have suppressed the perceived strength of mustard's effects. First, a number of contextual and climatological aspects of the study which are discussed in full in *'4.2.4 Contextual Impacts and Time'* and *'4.2.5 The Impact of Climatological Variation and Storm Babet'*. Secondly, their impact could be limited by the way in which they were sown. For example, Chapagain *et al.* (2020) found that the ecosystem services offered by cover crops are amplified by sowing multi-species mixtures; the extent of mustard cover crops' influence

could have been limited by using them as a monoculture. Additionally, multi-species cover crop mixtures encompassing under-sown crops are known to diversify canopy structure which is a proven method for optimising carabid abundance (Armstrong & McKinlay, 1997; Scopel *et al.*, 2013; Jowett *et al.*, 2021). Nevertheless, this result provides encouraging evidence to suggest that mustard may be driving increases in carabid abundance. In addition to abundance, the presence of specific carabid species also permits inferences into mustard's ability to facilitate pest biocontrol.

The most abundant species in mustard plots was *Nebria Brevicollis*; there were 269 more individuals in mustard plots (827) than there were in fallow (558). *N. brevicollis* predates a range of invertebrate crop-pests including aphids (Kromp *et al.*, 1999) which are responsible for transmitting almost 300 insect-borne viruses, including barley yellow dwarf disease which is attributed to yield losses of up to 80% (Dedryver *et al.*, 2010). Another key finding was the presence of *Pterostichus madidus* Fabricius and *P. niger* Schaller, which, in above-ground communities, were found exclusively in mustard plots (Appendix 4.1). These species are predators of aphids as well as snails and slugs (Winder *et al.*, 2005; Jowett *et al.*, 2021). The latter are particularly relevant pests, projected to cost the UK more than £100 million in annual agricultural losses (Barua *et al.*, 2021). While the *P. madidus* and *P. niger* individuals were too few to be deemed indicator species (n = 9, p = 0.1 and n = 6, p = 0.5, respectively; Appendix 4.1), the findings offer valuable evidence to suggest that mustard plots can accommodate a wider range of predatory carabid species capable of controlling some of the most notorious crop-pests.

4.2.2 Carabid Species Richness and Diversity

Although some carabid species were exclusive to specific plot types, overall, species richness showed little variation (Fig. 8 & 9). The total carabid species richness of mustard and fallow above-ground communities was 17 and 16, and in below-ground communities it was 11 and 12, respectively. This contrasts the initial hypotheses informed by research citing cover crops' ability to provide more resources than fallow land (Jowett *et al.*, 2021; Muneret *et al.*, 2023). The higher resource availability was expected to manifest in a higher number of ecological niches and, in turn, species (Rivers *et al.* 2017). However, there are multiple possible explanations as to why the results contrasted these expectations. One theory is that the while mustard crops may offer more resources for prey and carabid species, these are not necessarily partitionable. This may have prevented specialised carabid prey species and, in turn, carabid species from colonising prospective ecological niches. Thus, mustard may have

simply increased the ecosystems' carrying capacity i.e. the maximum carabid population size able to be supported by mustard plots.

A second, more probable hypothesis however, is that regardless of mustard's effect on prey species richness, it was unlikely to be reflected in carabid species richness because of carabids' generalist nature (Symondson *et al.*, 2020). British carabids are mostly polyphagous, and so it is plausible that an increased carrying capacity across mustard plots only caused the populations of pre-existing species to expand. This would explain why carabid species richness showed little variation in spite of the elevated above-ground abundance across mustard plots (albeit statically insignificant), and why no indicator species were detected (Appendix 4). This theory could also be applied to interpret mustard's lack of effect on carabid Shannon's diversity.

Given the homogeneity in species richness across plot types, interspecific competition within communities is likely to be similar (Connell *et al.*, 1983). Therefore, the contribution each carabid species makes towards their respective community is likely to remain proportionate across plots, notwithstanding changes in abundance. This is confirmed by the Shannon's diversity analyses for both above and below-ground communities (CIs = −0.39 to 0.19, and -0.16 to 0.45, respectively). Furthermore, the similarity in above-ground carabid Shannon's diversity between plot types is made evident by the comparable ranges, interquartile ranges, and medium values displayed by Figure 10's boxplots and the data distributions as illustrated by the violin plots. Furthermore, while Figure 11 depicts a higher medium below-ground Shannon's diversity for plots sown with mustard, the data is highly variable with a large interquartile range (0.69 H'). The interquartile ranges were inflated across the below-ground communities of both plot types by numerous diversity scores of 0 H' (n = 9 and 11 for mustard and fallow, respectively). This score represents samples that contained 1 or 0 carabid species which undoubtedly contributed towards the insignificant effect of mustard on carabid diversity. That said, the results provide conflicting evidence surrounding the effect of cover cropping on community composition.

4.2.3 Carabid Community Composition

Originally, it was thought that mustard plots would significantly influence both above- and below-ground carabid community composition. This was informed by the works of Brooks *et al.*, (2008) whose national assessment of carabid community structure found composition to be, primarily, a factor of crop type. The R^2 value for the above-ground community composition PERMANOVA implies that mustard presence explained ~2.5% of the variation in carabid community composition (Fig. 12; p = 0.024). This is likely to be a culmination of the above-

ground carabid abundance and diversity trends. As discussed, there is evidence to suggest that mustard cover crops cause a greater abundance of above-ground carabids, which extends to the populations of species exclusive to mustard plots such as *P. niger* and *P. madidus*. Therefore, as a function of these factors, the PERMANOVA's significant result provides more evidence in support of an effect of mustard cover crops on above-ground community structure.

Likewise, the uniformity in carabid abundance and diversity for below-ground communities was mirrored in the insignificant effect of mustard on below-ground carabid community composition (Fig. 13; $p = 0.634$). This casts some doubt over the validity of using mustard as a cover crop, at least in isolation. As discussed, the impact of mustard on community assemblages could be suppressed by using it as a monoculture (Chapagain *et al.*, 2020) or due to carabids' generalist nature (Symondson *et al.*, 2020). Yet, the lack of evidence in support of the initial hypotheses for below-ground carabid community structure should not be used to invalidate the use of mustard cover crops. This is because these results are unlikely to be affirmed by long-term trends. In fact, broader contextual aspects of the study are hypothesised to be the primary catalysts for each of the insignificant findings.

4.2.4 Contextual Impacts and Time

At the time of data collection, Boghall farm had only practised cover cropping for two years. Critically, however, it can take multiple years for the effects of cover crops to be reflected in invertebrate communities. For example, Rivers *et al.* (2017) found that carabid community evenness only changed in response to cover cropping after three annual cycles. Likewise, Sabais *et al.* (2011) propose that a minimum of four years are required for invertebrate populations to stabilise in response to planting. This is clear evidence to suggest that the study's results may not reflect future long-term trends. This is also the most likely explanation as to why some models revealed clear trends but were insignificant, such as the above-ground carabid abundance model.

Equally, the migration of new species to the plots may take time. Many studies show that the effects of agricultural ecosystem restoration on invertebrate communities can take decades to be realised due to lags in the time it takes for invertebrates to colonise newly improved habitats (Parkhurst *et al.*, 2022). This could explain the lack of variation in carabid richness and Shannon's diversity among plot types. In fact, this proposed delay in habitat could be exacerbated by external factors, namely nearby anthropogenic infrastructure.   .

There is a main road (A702) that runs directly adjacent to the West of the plots (Fig. 1). Studies have identified roads as dispersal barriers for many invertebrates, including carabids, whose communities can experience abundance and functional diversity loss in response (Deppe & Fischer, 2023). The magnitude of effect is exacerbated for flightless carabids which show an aversion to crossing roads and are susceptible to being killed by vehicles, thus resulting in lower migration and gene-flow rates (Remon *et al.*, 2022). This could also reduce the viability of existing carabid populations, including the plots' most abundant species, *N. brevicollis* which has poor flight potential (Nelemans, 1987). Again, this concept could be applied to explain why analyses for carabid richness, diversity and community composition and evenness were all deemed to contrast the original hypotheses.

Conversely, the close proximity of the plots to the road may be amplifying carabid biodiversity, potentially owing to roadside vegetation serving as supplementary habitats. The grassy hedge margins between the road and field site (Fig. 1) could have driven increases in carabid diversity (Boetzl *et al.,* 2018). This habitat type was responsible for a positive correlation found between carabid community functional richness and proximity to motorways in Rebrina *et al.'s* (2022) recent study. These opposing theories, both of which may be true of the ecosystem, underline the characteristic complexity of farmland habitats. Regardless, the influence of the road and the field margins have been largely controlled for by the random distribution of plot types and, inadvertently, by the approximate distance between the road and each plot which run parallel to one another (Fig. 1).

4.2.5 The Impact of Climatological Variation and Storm Babet

A primary source of variation in the data stemmed from the monthly sampling events. This is illustrated most obviously in Figure 12 by the lack of overlap between the NMDS polygons representing fallow communities in September and November. Furthermore, there was a notable decline of 833 carabids caught between September (1156) and October (273). The natural progression of carabid life cycles likely contributed towards these findings; carabid activity declines during October (in the northern hemisphere) (Jaskula & Soszynska, 2011). This included some of the study's most commonly observed species such as *N. Brevicollis* and *T. obtusus* which lay eggs and complete their univoltine life cycle over this period (Penney 1966; Thiele, 1977; Luff, 2007). However, there was an increase of 86 carabids sampled between October (273) and November (359) which casts doubt over the validity of this argument in explaining all the variance. In spite of the ecological explanations offered to interpret the trends in carabid community structure, climatological conditions and a severe weather event, namely Storm Babet, undeniably impacted the results.

Storm Babet brought exceptional rainfall (up to 200 mm) to the United Kingdom, including Eastern Scotland (18th – 21th October) (Met Office, 2023) and could have been a primary determinant of the insignificant results. Research shows that severe storms such as Babet have severe consequences for invertebrate populations due to inundation and high winds (Plum, 2005). October sampling began one day after Storm Babet officially ended (22nd), and the abiotic data shows that soil-volumetric water content peaked in October (0.55 %; Fig. 17) which further highlights how the extreme weather conditions experienced at Boghall may have been responsible for the carabids' waning counts.

While the effects of Storm Babet were likely to be distributed evenly across all subplots, the declines in carabid counts reduced the analyses statistical power and, in turn, increased the risk of a type I error. Although this hypothesis is difficult to test given the complexity and uncertainty surrounding carabid lifecycles, nevertheless, this aspect of the study illuminates the need to understand the influence of weather events on the invertebrate communities. This is exceptionally relevant considering the UK's climatic trends which are forecasted to bring higher frequencies of severe storms (Alexander *et al.*, 2005) as well as warmer temperatures which are predicted worsen the impact crop-pests (Skendžić *et al.*, 2021).

4.3 Slug Abundance

The final aspect of the study focused on the effect of mustard cover crops on pooled slug abundance. The lack of effect (CI = −0.78 to 1.08) defied the initial hypotheses, but in light of mustard's insignificant effect on carabid abundance and diversity (which was predicted to drive differences in slug abundance) this finding is unsurprising. Figure 16 clearly represents the similarity in slug abundances across fallow and mustard plots which had identical means of 0.5 (0 or 1 slug). Slug abundances across mustard plots were larger than expected, potentially resulting from increased resources in mustard plots (Wezel *et al.*, 2014), which was also theorised for carabid populations. In fact, a multitude of complex community dynamics could have induced slug abundance increase (e.g. higher resource availability) and decrease (e.g. carabid community structure change) (Le Gall & Tooker *et al.*, 2017). In turn, the results warrant a deeper exploration of the predator-prey dynamics within mustard plots including those related to pests active during other times of the year such as aphids in spring/summer (Kromp *et al.*, 1999). Nevertheless, as discussed, some carabid species that are prolific predators of slugs appeared to show a propensity for inhabiting mustard plots such as the aforementioned *P. madidus* and *P. niger* which heightens the evidence surrounding mustard's ability to facilitate IPM and carabid conservation.

4.4 Important Considerations

4.4.1 Above- and Below-ground Communities

A conservative approach was taken during data analysis to minimise the risk of type II errors from being realised. However, it should be noted that the prudent approach towards analysis could have allowed type I errors to arise. Firstly, analysis was divided into above- and below-ground carabid communities. While pooling above- and below-ground community data before analysis may have increased the perceived effect of cover cropping, it is important to acknowledge that the two distinct microhabitats have unique ecological dynamics and processes. Analysing them independently allows for a more representative and statically sound assessment of mustard's influence on farmland microhabitats' invertebrate communities.

However, it could also explain why the perceived effect of mustard of on carabid abundance was stronger in above-ground communities than in below-ground communities. The accumulative above-ground carabid abundance was 1643, more than ten times that of below-ground communities (145) (Appendix 3). In turn, the statistical power of the below-ground models was significantly lower, potentially culminating in a type I error. Therefore, each of the below-ground analyses would have benefitted from a larger sample size of individuals which could be attained by sampling over a larger timeframe.

4.4.2 Prior selection

Secondly, the lack of informative priors used during model selection could have also contributed towards to a type I error. Bayesian Hierarchal Models are an emerging statistical practise in ecology (Halsey, 2019) and the study's exclusive use of non-informative priors reflects many models in the field (Banner *et al.*, 2020). This aspect of model selection was justified by a lack of pre-existing research on mustard cover crops. However, this study's data should be incorporated into the (informative) priors of future research to offer a more comprehensive assessment of mustard's impact on carabid community structure.

4.4.3 Unidentifiable Carabids

Thirdly, the unidentifiable carabids (8 larvae) were grouped and treated as a single species for analysis which introduced some uncertainty. However, this conservative feature of the methodology was justified given the widespread phenotypic variation and sexual dimorphism within the Carabidae taxon (Benitez, 2013; Baranovská & Knapp, 2014; Komlyk &

Brygadyrenko, 2019), which could have otherwise been misleading. In addition, the 8 unidentifiable carabids composed just 0.4% of the total carabid population and so their effect was likely negligible. That said, there are more relevant shortcomings of the study that limit its applicability in informing policy and AESs to a greater extent.

4.5 Limitations & Future Directions

4.5.1 Temporal Range of Data Collection

This study presents a robust rationale to evidence that mustard cover crops could increase, at the very least, above-ground carabid populations. While these findings could begin to inform the validity of incorporating mustard cover crops into agri-environment schemes, they would offer a more well-informed and reliable verdict upon being combined with the results of a longer carabid population monitoring programme. It is standard practise for studies such as this to span decades; Parkhurst *et al.*'s (2022) meta-analysis found that 57% of studies (on invertebrate community response to agricultural restoration) recorded data for between 11 and 50 years. However, winter cover cropping has only been practised at Boghall Farm for two years. In light of the wide timeframe over which cover crops' effect on invertebrate communities can take to be expressed (Rivers *et al.*, 2017), it would be an oversight to dismiss mustard as ineffective in enhancing carabid communities based solely on the study's insignificant results. Instead, priority should be given to monitoring the effects of mustard over a larger temporal range. This would especially benefit the below-ground monitoring aspect of the study; these analyses' small sample sizes inhibit their statistical power and make them vulnerable to type I errors.

In addition, the proposed long-term carabid population monitoring programme should collect a wider range of abiotic soil data. Soil moisture data was collected, informed by literature citing it as the primary determinant of carabid community structure (Luff, 2007; Kirichenko-Babko *et al.*, 2020). However, invertebrate community structure is also a factor of soil pH (Duddigan *et al.*, 2021), organic carbon (Flores-Rios *et al.*, 2020) and NPK content (Nessel *et al.*, 2021) so monitoring them in future studies would allow for a more complete assessment of the elements influencing the response variables.

4.5.2 Soil Cultivation Regime

For this study, collecting data from Boghall's ploughed subplots in addition to min-till subplots (Fig. 2) would have required double the sampling effort, rendering it infeasible. However,

investigating the relationship between mustard and invertebrate community characteristics on ploughed soil (in addition to minimum tillage) could reveal an interaction effect between cover crop presence and soil cultivation regime. The relationship between ploughing intensity and carabid community structure is complex. For example, the effect of ploughing can be especially severe during carabid breeding seasons (Marrec *et al.*, 2015) and for larval communities (Baguette & Hance, 1997). Therefore, it is logical to postulate that the extent of cover crops' effect on invertebrate communities could be a function of soil cultivation intensity. Interestingly, this hypothesised cover crop – tillage interaction effect has already been documented for soil microbiome diversity (Nakian *et al.*, 2020) which additionally points towards the possibility of an interaction effect on carabid community structure. Understanding these relationships would offer more nuanced, practical and holistic perspectives on how cover crops should be implemented in parallel with other farming practises and land management strategies.

4.5.3 Functional Diversity

Finally, this study assessed carabid abundance which, given their polyphagous nature, is a particularly important metric for understanding carabid community pest-control efficacy. However, the concept of functional diversity remained unexplored. Functional diversity is the number of functions served by ecosystem communities, which extends to the diversity of feeding groups (Petchey & Gaston, 2006). The functional diversity of carabid community feeding groups offers useful insights into their effectiveness as modes of pest-control; a community comprised of more feeding groups is likely to predate a wider range of crop-pests (Baulechner *et al.*, 2020). While abundance, species richness and functional richness can be positively correlated they are not proportional and the relationships are complicated (Suárez-Castro *et al.*, 2022). Some cover crop species are known to shape the distribution of carabid communities' ecological traits (Triquet *et al.*, 2023) but the effects of mustard are unknown. Therefore, future studies should seek to quantify the effect of mustard cover crops on the functional diversity of carabid feeding groups. The findings could have important implications for policy by permitting a more balanced interpretation of how mustard cover crops support successful IPM that simultaneously combats carabid biodiversity decline (Kotze & O'Hara, 2003; Brooks *et al.*, 2012).

5. Conclusions

The study assessed the effect of *S. alba* cover crops on above- and below-ground Carabidae community structure and, as the first of its kind, illuminates extremely valuable trends. The primary finding was the difference in above-ground carabid abundance between plots sown with *S. alba* and plots left as fallow. Although marginally insignificant, the higher abundances observed across *S. alba* plots support the literature documenting the positive impacts of cover crops on carabid communities. The ability of *S. alba* to facilitate effective IPM is further evidenced by the exclusive presence of particularly prolific slug predators in above-ground carabid communities, and by the significant effect of *S. alba* on above-ground carabid community composition. Finally, the study also sheds light on the community structure of below-ground carabids in the immature stages of their life-cycle which is a vastly understudied topic throughout the field of agro-ecology.

The findings could be used in isolation to advise policy makers and land owners, but equally, they also offer an invaluable foundation for the long term impacts of *S. alba* cover crops to be monitored. Achieving food security without compromising biodiversity should remain a primary objective of governments and farmers alike to rewrite the existing narrative of assumed mutual exclusivity between productive, high yield agriculture and biodiverse land. In an agricultural era characterised by the excessive use of pesticides and catastrophic biodiversity decline, studies such as these should not only begin to inform more efficacious farming policies and AESs, but also set a precedent for a changing mind-set. A set of principles focused on rectifying the longstanding, unsustainable practices of conventional farming to build more biodiverse and resilient food systems.

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7. Appendices

All code can be found in the following GitHub repository:

https://github.com/mattprill/dissertation_code.git

```r
# Libraries ----

library(tidyverse)  # Range of functions.

library(vegan)  # Multitude of diversity functions

library(brms)  # Bayesian Modelling

library(loo)  # Assessing model fit

library(indicspecies)  # Indicator Species Analysis
```

```r
# Data ----

# Above ground carabid abundances

above_ground_carabids <-
read.csv("Dissertation/Data/invertebrates/above_ground_carabids.csv"
)


# Below ground carabid abundances

below_ground_carabids <-
read.csv("Dissertation/Data/invertebrates/below_ground_carabids.csv"
)


# Below ground carabid richness and shannons

above_carabid_diversity_indicies <-
read.csv("Dissertation/Data/invertebrates/above_carabid_diversity_in
dicies")


# Below ground carabid richnnes and shannons

below_carabid_diviersit_indcies <-
read.csv("Dissertation/Data/invertebrates/below_carabid_diversity_in
dicies")


# Above ground carabid NMDS data

above_nmds <- read.csv("Dissertation/Data/invertebrates/above_nmds")
```

```
# Below ground carabid NMDS data

below_nmds <- read.csv("Dissertation/Data/invertebrates/below_nmds")


# Pooled slug abundances

slugs <-  read.csv("Dissertation/Data/invertebrates/slugs.csv")
```

Bayesian Analysis Example

The following code was repeated for all Bayesian Analyses (Below-ground abundance and above- and below- richness and Shannon's diversity), substituting in the respective data/response variables as well as the 'gaussian' family argument for richness and Shannon's diversity models.

```
# Above ground carabid abundances ----


# Data distribution - Histogram & Distribution Curve

ggplot(above_ground_carabids, aes(x = trap_total)) +

    geom_histogram(binwidth = 5, color = "darkblue",

    fill= "lightblue") +

    ylab("Count\n") +

    xlab("\n\n Pitfall carabid total ") +

    theme(axis.text=element_text(size = 20),

        axis.title=element_text(size = 20))) +

    geom_density(aes(y=8.1*..count..))


# Bayesian analysis

above_abundance_mbrms <- brm(trap_total ~ plot_type + month +
(1|plot), data = above_ground_carabids, family = poisson(), chains =
3, iter = 3000, warmup = 1000)


# Assessing model fit

plot(above_abundance_mbrms)  # Plot the model

pp_check(above_abundance_mbrms) # Showing posterior distribution (y)
and 10 random 10 random distributions created by the model (yrep)
```

```
summary(above_abundance_mbrms)   # Summarises model outputs

loo(above_abundance_mbrms)    # Leave-one-out cross validation
```

NMDS and PERMANOVA

The following code was repeated for all below-ground NMDS, substituting in the respective data/response variables.

```
# NMDS

set.seed(123)

above_nmds <- metaMDS(above_ground_carabids_matrix, distance =
"bray", k = 3, autotransform = TRUE, trymax = 300, group =
above_ground_carabids[, c("Plot_Type", "Month")])


plot(above_nmds)

stressplot(above_nmds)

above_nmds$stress  # Stress is < 0.2 which is good


# Checking assumption of homogeneity in multivariate dispersion

above.inv.dist <- vegdist(above_nmds, method = "bray")   #

above.inv.dispersion <- betadisper(above.inv.dist, group = above
_nmds_rows$plot_type_month) # Grouping factors

permutest(above.inv.dispersion)


# Analysis

# Analysis grouping factors

above_nmds_plot_type <- above_ground_carabids$plot_type

above_nmds_month <- above_ground_carabids$month


above_merged_permanova <- adonis2(as.matrix(above_nmds) ~
above_nmds_plot_type + above_nmds_month, permutations = 999, method
= "bray")


above_permanova   # Summary
```

45

Indicator Species Analysis

```r
# Indicator Species Analysis ----


plot_type_groups_above <- above_ground_carabids$plot_type

plot_type_groups_below <- below_ground_carabids$plot_type


# Above-ground

above_merged_indval <-  multipatt(above_merged_abundances_only,
plot_type_groups_above, control = how(nperm=999))


summary(above_merged_indval)


# Below-ground

below_merged_indval <-  multipatt(below_merged_abundances_only,
plot_type_groups_below, control = how(nperm=999))


summary(below_merged_indval)
```

Appendix 2: LOO information criterion model tables

Abbreviations

A – Carabid abundance

P – Plot type/ treatment (mustard/ fallow)

M - Month

ID – Plot Number

T – Trap

R – Richness

D – Diversity (Shannon's)

S – Slug abundance

Table 2.1 Above-ground model selection table for above-ground carabid abundances. The elected model is highlighted in green.

Model	Rhat (1 = Successful Convergence)	Bulk and Tail Effect Size Samples > 1000	Expected Log Pointwise Predictive Density (ELPD)	Difference in ELPDs	Primary Critique
A ~ P + M	1	Yes	-329.2	-10	Prone to spatial pseudoreplication
A ~ P + M (1|ID)	1	Yes	-319.2	0	N/A
A~ P + M (1|ID/T)	1	Yes	-326.8	-7.6	Insufficient no. of 'T' levels

Table 2.2. Below-ground model selection table for below-ground carabid abundances. The elected model is highlighted in green.

Model	Rhat (1 = Successful Convergence)	Bulk and Tail Effect Size Samples > 1000	Expected Log Pointwise Predictive Density (ELPD)	Difference in ELPDs	Primary Critique
A ~ P + M	1	Yes	-116.8	0	Prone to spatial pseudoreplication
A ~ P + M (1|ID)	1	Yes	-119.5	-2.7	ELPD < First model's
A~ P + M (1|ID/T)	1	Yes	-117	-0.2	Insufficient no. of 'T' levels

Table 2.3. Above-ground model selection table for above-ground carabid richness. The elected model is highlighted in green.

Model	Rhat (1 = Successful Convergence)	Bulk and Tail Effective Size Samples > 1000	Expected Log Pointwise Predictive Density (ELPD)	Difference in ELPDs	Primary Critique
R ~ P + M	1	Yes	-35.0	0	Prone to spatial pseudoreplication
R ~ P + M (1|ID)	1	Yes	-35.2	-0.2	ELPD < First model's (marginally)
R~ P + M (1|ID/T)	1	Yes	-36.2	-1.2	Insufficient no. of 'T' levels

Table 2.4. Below-ground model selection table for below-ground carabid richness. The elected model is highlighted in green.

Model	Rhat (1 = Successful Convergence)	Bulk and Tail Effective Size Samples > 1000	Expected Log Pointwise Predictive Density (ELPD)	Difference in ELPDs	Primary Critique
R ~ P + M	1	Yes	-77.0	-0.1	Prone to spatial pseudoreplication
R ~ P + M (1|ID)	1	Yes	-77.9	-1	ELPD < Other models'
R~ P + M (1|ID/T)	1	Yes	-76.9	0	Insufficient no. of 'T' levels

Table 2.5. Above-ground model selection table for above-ground carabid Shannon's Diversity. The elected model is highlighted in green.

Model	Rhat (1 = Successful Convergence)	Bulk and Tail Effective Size Samples > 1000	Expected Log Pointwise Predictive Density (ELPD)	Difference in ELPDs	Primary Critique
D ~ P + M	1	Yes	-35.0	0	Prone to spatial pseudoreplication
D ~ P + M (1|ID)	1	Yes	-35.2	-0.2	ELPD < First model's (marginally)
D ~ P + M (1|ID/T)	1	Yes	-36.2	-1.2	Insufficient no. of 'T' levels

Table 2.6. Below-ground model selection table for below-ground carabid Shannon's Diversity. The elected model is highlighted in green.

Model	Rhat (1 = Successful Convergence)	Bulk and Tail Effective Size Samples > 1000	Expected Log Pointwise Predictive Density (ELPD)	Difference in ELPDs	Primary Critique
D ~ P + M	1	Yes	-31.7	0	Prone to spatial pseudoreplication
D ~ P + M (1|ID)	1	Yes	-32.8	-1.1	ELPD < Other models'
D ~ P + M (1|ID/T)	1	Yes	-32.7	-1	Insufficient no. of 'T' levels

Table 2.7. Model selection table for pooled slug abundance. The elected model is highlighted in green.

Model	Rhat (1 = Successful Convergence)	Bulk and Tail Effective Size Samples > 1000	Expected Log Pointwise Predictive Density (ELPD)	Difference in ELPDs	Primary Critique
S ~ P + M	1	Yes	-205.2	-11.8	Prone to spatial pseudoreplication
S ~ P + M (1|ID)	1	Yes	-200.8	-7.3	ELPD < Third models'
S ~ P + M (1|ID/T)	1	Yes	-193.4	0	Insufficient no. of 'T' levels

Appendix 3: Monthly and Total Carabid Abundance Data

Table 3.1 Monthly and accumulative above-ground carabid species abundance.

Species	Month			Total
	November	October	September	
Agonum muelleri	0	0	1	1
Amara aenea	2	2	5	9
Amara plebeja	0	3	1	4
Anchomenus dorsalis	0	1	7	8
Bembidion lampros	11	7	13	31
Calathus fuscipes	0	0	3	3
Carabus coriaceus	1	0	0	1
Clivina fossor	0	0	2	2
Harpalus rufipes	0	3	1	4
Loricera pilicornis	8	14	8	30
Nebria brevicollis	175	176	991	1342
Nebria rufescens	41	7	3	51
Notiophilus biguttatus	2	1	3	6
Oodes helopioides	2	0	0	2
Oxypselaphus obscurus	2	6	18	26
Poecilus cupreus	0	1	2	3
Pterostichus madidus	2	1	6	9
Pterostichus niger	0	0	6	6
Pterostichus strenuus	19	3	12	34
Trechus obtusus	23	5	37	65
Non-identifiable carabids	3	1	2	6
				Accumulative total = 1643

Table 3.2 Monthly and accumulative below-ground carabid species abundance.

Species	Month			Total
	November	October	September	
Agonum muelleri	4	0	0	4
Amara aenea	1	1	0	2
Amara plebeja	0	0	0	0
Anchomenus dorsalis	0	0	0	0
Bembidion lampros	7	7	4	18
Calathus fuscipes	0	0	0	0
Carabus coriaceus	0	0	0	0
Clivina fossor	0	1	0	1
Harpalus rufipes	0	1	1	2
Loricera pilicornis	1	1	0	2
Nebria brevicollis	20	6	17	43
Nebria rufescens	16	1	1	18
Notiophilus biguttatus	0	0	0	0
Oodes helopioides	0	0	0	0
Oxypselaphus obscurus	1	10	2	13
Poecilus cupreus	0	0	0	0
Pterostichus madidus	3	3	0	6
Pterostichus niger	0	0	0	0
Pterostichus strenuus	1	7	0	8
Trechus obtusus	13	4	9	26
Non-identifiable carabids	1	0	1	2
				Accumulative total = 145

Table 4.1. Above-ground indicator species analysis results. P values indicate level of significance; NA values are indicative of species that present in both plot types (non-indicator species by default).

Species	Present in fallow plots	Present in mustard plots	N	Standard Deviation (±)	F-value	P -value
Nebria brevicollis	Yes	Yes	1342	19.67	0.99	NA
Calathus fuscipes	Yes	No	3	0.26	0.24	0.48
Loricera pilicornis	Yes	Yes	30	0.69	0.56	NA
Pterostichus strenuus	Yes	Yes	34	0.84	0.54	NA
Pterostichus niger	No	Yes	6	0.40	0.26	0.50
Poecilus cupreus	Yes	Yes	3	0.20	0.20	NA
Harpalus rufipes	No	Yes	4	0.23	0.33	0.14
Anchomenus dorsalis	Yes	Yes	8	0.32	0.33	NA
Bembidion lampros	Yes	Yes	31	0.7	0.55	NA
Oxypselaphus obscurus	Yes	Yes	26	0.92	0.44	NA
Notiophilus biguttatus	Yes	Yes	6	0.28	0.29	NA
Trechus obtusus	Yes	Yes	65	1.63	0.61	NA
Agonum muelleri	No	Yes	1	0.12	0.17	1
Amara plebeja	Yes	Yes	4	0.29	0.20	NA
Amara aenea	Yes	Yes	9	0.33	0.35	NA
Clivina fossor	No	Yes	2	0.24	0.17	1
Nebria rufescens	Yes	Yes	51	1.22	0.61	NA
Pterostichus madidus	No	Yes	9	0.44	0.39	0.10
Oodes helopioides	Yes	No	2	0.17	0.24	0.47
Carabus coriaceus	Yes	No	1	0.12	0.17	1
Non identifiable carabids	Yes	No	6	0.33	0.30	0.27

Table 4.2. Below-ground indicator species analysis results. P values indicate level of significance; NA values are indicative of species that present in both plot types (non-indicator species by default).

Species	Present in fallow plots	Present in mustard plots	N	Standard Deviation (±)	F-value	P -value
Nebria brevicollis	Yes	Yes	43	1.64	0.66	NA
Loricera pilicornis	Yes	No	2	0.20	0.29	0.50
Pterostichus strenuus	Yes	Yes	8	0.56	0.32	NA
Harpalus rufipes	Yes	Yes	2	0.20	0.20	NA
Bembidion lampros	Yes	Yes	18	0.70	0.52	NA
Oxypselaphus obscurus	Yes	Yes	13	0.54	0.48	NA
Trechus obtusus	Yes	Yes	26	0.97	0.58	NA
Agonum muelleri	Yes	No	4	0.58	0.20	1
Amara aenea	Yes	Yes	2	0.20	0.20	NA
Clivina fossor	No	Yes	1	0.14	0.20	1
Nebria rufescens	Yes	Yes	18	0.89	0.46	NA
Pterostichus madidus	Yes	Yes	6	0.39	0.32	NA
Non identifiable carabids	Yes	Yes	2	0.20	0.20	NA

Appendix 5: Standard Deviations for Carabid Relative Abundances

Table 5.1. Above-ground plots carabid relative abundances and standard deviations (n = 72).

| | Standard Deviation (±) | |
Species	Mustard	Fallow
Nebria brevicollis	0.19	0.19
Calathus fuscipes	0.00	0.04
Loricera pilicornis	0.16	0.17
Pterostichus strenuus	0.16	0.14
Pterostichus niger	0.05	0.022
Poecilus cupreus	0.05	0.02
Harpalus rufipes	0.10	0.00
Anchomenus dorsalis	0.04	0.07
Bembidion lampros	0.15	0.16
Oxypselaphus obscurus	0.12	0.11
Notiophilus biguttatus	0.06	0.07
Trechus obtusus	0.16	0.17
Agonum muelleri	0.02	0.00
Amara plebeja	0.03	0.09
Amara aenea	0.08	0.04
Clivina fossor	0.03	0.00
Nebria rufescens	0.16	0.21
Pterostichus madidus	0.08	0.06
Oodes helopioides	0.00	0.07
Carabus coriaceus	0.00	0.05
Non identifiable carabids	0.02	0.15

Table 5.2. Below-ground plots carabid relative abundances and standard deviations (n = 48).

Species	Standard Deviation (±)	
	Mustard	Fallow
Nebria brevicollis	0.35	0.41
Calathus fuscipes	0.00	0.00
Loricera pilicornis	0.00	0.14
Pterostichus strenuus	0.21	0.26
Pterostichus niger	0.00	0.00
Poecilus cupreus	0.00	0.00
Harpalus rufipes	0.14	0.14
Anchomenus dorsalis	0.00	0.00
Bembidion lampros	0.30	0.29
Oxypselaphus obscurus	0.30	0.32
Notiophilus biguttatus	0.00	0.00
Trechus obtusus	0.37	0.38
Agonum muelleri	0.00	0.14
Amara plebeja	0.00	0.00
Amara aenea	0.08	0.08
Clivina fossor	0.14	0.00
Nebria rufescens	0.23	0.28
Pterostichus madidus	0.21	0.17
Oodes helopioides	0.00	0.00
Carabus coriaceus	0.00	0.00
Non identifiable carabids	0.12	0.20