

1 Beneficial arthropod habitat useage changes within-season: implications
2 for pest control services in croplands

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7 **Abstract**

Ground-dwelling arthropods can be important generalist predators in agro-ecosystems, and can use non-crop features as overwintering habitats. However, it is unclear which types of landscape features constitute useful non-crop habitat, and at what spatial scale organisms gather resources. Additionally, the same landscape feature may act as source of arthropod spillover at different times of the year, but this is rarely considered. We modeled the activity-density of four highly-abundant species of Canadian prairie arthropods, and used functional regression to simultaneously consider both their habitat preferences and the timing of sources and sinks. *Pterostichus melanarius* (Coleoptera: Carabidae) and *Pardosa moesta* (Arachnida: Lycosidae) appear to be attracted to canola (*Brassica napus* L.) during the early summer, then disperse to grasslands, wetlands, and grassy road margins during the end of the summer. This suggests that grasslands and wetlands act as reservoir habitats for predatory arthropods, and that farmers should consider preserving existing habitat in order to maintain pest-control services across the season.

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1. Introduction

Arthropods are one of the most influential groups of animals in agricultural systems. Pest arthropods can cause large reductions in crop yield (Oerke 2005), which can result in negative downstream economic effects and food insecurity. On the other hand, spillover of beneficial arthropods from adjacent non-crop patches can deliver increased crop yields by providing ecosystem services such as extra pollination or pest suppression (Losey & Vaughan 2006; Klein *et al.* 2007; Garibaldi *et al.* 2013). Seasonal “pulses” of food resources from crop fields act as a bottom-up driver of their associated arthropod communities, meaning that agricultural land can act as a source of nutrients and individuals for adjacent non-crop land (Diekötter *et al.* 2010; Galpern *et al.* 2017). These important fluxes of mobile arthropods, both to crops and away from them, are key for managing both crop yield and biodiversity in agroecosystems. Finding “win-win” practices is of particular importance to land managers and conservationists; that is, practices that result in better conservation outcomes while maintaining or improving crop yields.

Uncultivated semi-natural land (SNL) can act as important habitat for beneficial arthropods (Duelli & Obrist 2003), which may spill over into adjacent cropland. Therefore, landscape management is a strategy to increase beneficial arthropod abundance in crops (Landis *et al.* 2000; Albrecht *et al.* 2010; Martin *et al.* 2020; but see Tscharncke *et al.* 2016; Karp *et al.* 2018). For example, wild bee abundance in agricultural landscapes is largely driven by flower and nest availability (Roulston & Goodell 2011), and the effect of SNL on bee abundance and diversity is generally positive. Predatory arthropods such as beetles or spiders can be limited by water, food, and egg-laying sites (Lövei & Sunderland 1996; Purtauf *et al.* 2005; Gardiner *et al.* 2010), but the effect of SNL on their abundance and diversity is less consistent (Macfadyen & Muller 2013; Shackelford *et al.* 2013) as some taxa may use SNL as a travel corridor or overwintering site, but are not completely dependent on it for reproduction. Some taxa are not dependent on SNL at all, and thrive in cultivated landscapes, while others exclusively inhabit SNL and do not venture beyond the edge of cultivated fields. For example, carabid beetles are thought to reproduce in field margins, while the adults feed in fields (Desender & Alderweireldt 1988). Habitat preference also depends on the life history of the organisms in question, such as the seasonal timing of emergence, feeding, and reproduction, as well as their traits such as dispersal capability. Non-adjacent cropland can also influence arthropod abundance if the organisms are long-distance dispersers (Öberg *et al.* 2008). In this way, the spillover of beneficial arthropods into crops depends not only on the amount of adjacent SNL, but the specific habitat type, the time of the year, and the spatial scale at

which an organism gathers resources.

Despite what is known about the spatial and temporal aspects of beneficial arthropod spillover, these are rarely considered together. First, some non-crop habitat may act as sources of arthropods during some times of the year, but as sinks during other times, meaning that the timing of spillover from non-crop habitat may not align with important periods in crop development. Arthropods can migrate from managed crops back into adjacent SNL at the end of the season (Desender & Alderweireldt 1988; Tscharntke *et al.* 2005), but this is seldom considered. Second, the spatial “grain” of the landscape that is relevant to an organism depends on their traits and life history (Ahrenfeldt *et al.* 2015). For instance, bumblebee abundance can be influenced by both nearby and far-away SNL abundance (Westphal *et al.* 2006), but this is poorly studied for other groups of beneficial organisms (but see Sander *et al.* 2006). Finally, the feeding and life-history characteristics of many predatory ground beetles and spiders are often poorly-documented, especially in North America. This makes it difficult to make generalizations of which habitat types harbour beneficial arthropods, making it even more difficult to provide accurate information to farmers about land management practices.

In this study, we used pitfall traps to determine how landscape composition affects the seasonal abundance of arthropods across a large Canadian prairie agroecosystem. We considered the following hypotheses: 1. Untilled semi-natural land provides egg-laying and feeding areas for predatory arthropods, meaning that it should act as a source of arthropods during the early part of the season, and a sink during the later part of the season. 2. Crops act as sources of food (pest insects) for predatory arthropods during the growing season. This should result in agricultural land becoming a sink for predators in the early part of the season as they migrate into the crop, and a source at the end of the season as they migrate out of the crop. 3. Crops may act as a temporary feeding site for predators. Therefore, crops may act as a local sink for arthropods, but will also be negatively associated at larger (landscape-level) scales. Using a large pitfall trapping dataset, we related seasonal changes in arthropod abundance to landscape composition at multiple spatial scales.

2. Methods

2.1. Data collection

We used a set of 198 pitfall traps installed in road margins (minimum of 5 m away from the road edge, 85 traps) and in-field locations (113) across southern Alberta, Canada in 2017 (Figure 1). The sites spanned a west-to-east gradient of four natural subregions, including foothills parkland, foothills

69 fescue, mixedgrass, and dry mixedgrass (Natural Regions Committee 2006). Traps were placed starting
70 on May 16, and collections ended on August 28, with collection occurring continuously and traps being
71 emptied every 14 days on average (SD: 3). This resulted in 850 unique collection events, taking place
72 across a total of 11614 trapping days. In-field traps were placed in canola crops (68), wetlands (16),
73 grassy field edges (11), and remnant prairie grasslands (18). Traps in canola were installed at 25, 75,
74 and 200 m along a transect heading away from the nearest non-crop feature (wetland, grassy field
75 edges, or remnant prairie), while the trap at 0 m was installed in the non-crop feature itself. We used
76 582 mL Solo® cups buried up to the rim and partially filled with propylene glycol, with 2 cm wire mesh
77 mounted over the rim to prevent vertebrates from falling into the traps. Specimens were identified
78 to species using appropriate taxonomic literature (Dondale & Redner 1990; Edgar 1990; Vogel 2004;
79 Yigit *et al.* 2007).

80 We used counts of organisms in our pitfall traps as proxies of ecosystem service provision. However,
81 increased counts of organisms in pitfall traps can represent higher activity levels (same number of
82 organisms but more mobile) or higher abundances in the vicinity of the trap. This makes it impossible
83 to disentangle arthropod activity from density using single traps (Lang 2000; Zhao *et al.* 2013),
84 meaning that counts in the traps represent the “activity-density” of a given organism. Despite this
85 drawback, activity-density is generally positively related to ecosystem services, at least in carabids
86 (Trichard *et al.* 2014; Boetzel *et al.* 2018; González *et al.* 2020), making it acceptable for our study.

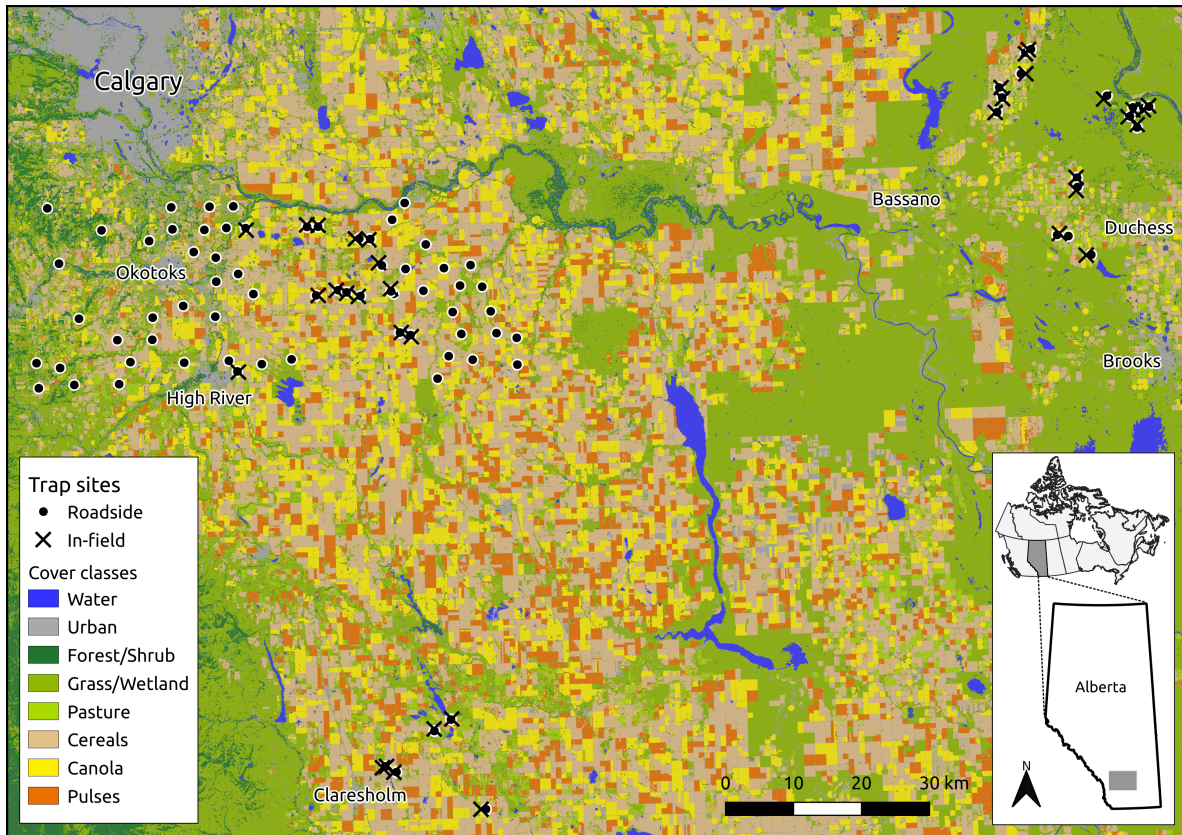


Figure 1: Classified land cover and location of pitfall traps during 2017. Inset map shows study location within Alberta provincial boundaries. Roadside traps were installed in road margins, while in-field traps were installed directly in canola fields, wetlands, or grassy field edges.

We used four highly-abundant species of predatory arthropods found in the pitfall traps, as common species are often more important for ecosystem service provision than rare species (Winfree *et al.* 2015). *Pterostichus melanarius* is an introduced predatory ground beetle (Coleoptera: Carabidae) that is a wide-ranging generalist known to prey upon crop pests (Cárcamo & Spence 1994; Larsen *et al.* 2003; Busch 2016). It is commonly found in untilled grasslands (Purtauf *et al.* 2005) and may use grassy field edges as larval habitat (Desender & Alderweireldt 1988). *Pardosa* are a genus of wolf spiders (Araneae: Lycosidae) that use an active wandering predation strategy (Young & Edwards 1990), and are common across the Canadian prairies. Both *Pardosa distincta* and *Pardosa moesta* are found in a wide variety of habitats, but are common in ungrazed pastures (Dondale & Redner 1990; Cárcamo *et al.* 2014). *P. distincta* is also commonly found in disturbed environments (Collins *et al.* 1996; Wade & Roughley 2010), while *P. moesta* appear to prefer less frequent disturbances (Graham *et al.* 2003; Kowal & Cartar 2011; but see Dondale & Redner 1990). Other *Pardosa* are known to use

road margins and wooded areas as habitat (Buddle 2000; Drapela *et al.* 2011). Finally, *Phalangium*
opilio is an introduced harvestman (Opiliones: Phalangidae) that is found in drier disturbed areas
(Bragg & Holmberg 2009). Juveniles hatch from eggs during the spring, becoming adults during the
summer, and eggs are laid during the fall (adults do not overwinter; Bragg & Holmberg 2009). They
are commonly found in human-altered landscapes (Muster & Meyer 2014; Van de Poel 2015) and are
nocturnal generalist hunters and scavengers (Halaj & Cady 2000; Allard & Yeargan 2005b, a), mainly
eating small soft-bodied invertebrates (Acosta & Machado 2007).

To characterize landscape composition surrounding the traps, we used publicly available classified
landscape data (30 m resolution; Agriculture and Agri-Food Canada 2018). AAFC cropland landscape
classifications from 2017 were very accurate for cultivated fields (~90%), but were less accurate for non-
crop areas (~70%). We combined functionally similar landscape categories (cereals: *Triticum aestivum*
and *Hordeum vulgare*, pulses: *Pisum sativum* and *Lens culinaris*, forest: coniferous and broadleaf).
At each site, we extracted the proportion of each cover class within 30m annuli (rings), with the
inner radius of each annulus ranging from 30 to 1470m in increments of 30m (total of 49 annuli, 1.5
km maximum). The ten most-common cover classes surrounding our sites represented 98% of the
total land cover in our study region: grassland, cereal, canola, pasture, pulses, wetland, urban (road
margins), shrubland, flax, and forests (Figure S2); flax was removed, as only a single site had nearby
flax cover.

2.2. Analysis

Functional regression (Ramsay & Silverman 2004; Yen *et al.* 2014) was used to incorporate land-
scape information at different distances, allowing assessment of both local and regional landscape
composition (Galpern & Gavin 2020). Scalar-on-function regression is a special type of linear regres-
sion model ($y = X\beta + e$), where the columns of the model matrix X contain some continuous predictor
of the scalar y , and the values of the coefficients (β) are modeled as a smooth function $f(x)$ of the
predictors. In our case, the proportion of landscape cover (X) within each annulus surrounding the
trap is a function of distance away from the trap, meaning that the coefficients are a smoothed function
of distance ($\beta_i = f(\text{distance}_i)$), and represent the additive effect of a given type of landscape cover at
distances away from the trap (i.e. $X\beta$). This allows for the possibility that the size of the landscape
“grain” relevant to a given organism may change over the course of its life stages (Addicott *et al.* 1987;
Lima & Zollner 1996; Gardiner *et al.* 2010). It also allows for the possibility that certain land cover
types may be locally beneficial, but detrimental at large scales, indicating that the cover type may

130 not constitute a completely usable habitat.

131 Scalar-on-function regression of activity-density was fit using generalized additive models (*mgcv*
132 version 1.8.33; Wood 2017). Count data of arthropods were modeled using a negative binomial distri-
133 bution with a log-link function and a single dispersion parameter (θ). To account for different lengths
134 of trap exposure, log-days since trap placement were used as a fixed effect with their slope held at 1
135 (“offset” variable). Trapping location was included as a fixed effect with 5 levels (canola, field edge,
136 grassland, road margin, and wetlands) to account for the effect of local cover independent of the sur-
137 rounding landscape composition. Day of year was included as a 1-dimensional smooth, and easting and
138 northing (km east and north of the trap extent centre point) were included as 2-dimensional smooths,
139 in order to account for underlying spatial and temporal autocorrelation in the data.

140 For each landscape cover class, we used three scalar-on-function terms. First, we used the propor-
141 tion cover in the annuli surrounding each trap location (spatial effect of cover class). Second, we used
142 the average proportion cover across days of the year (temporal effect of cover class). Finally, we used
143 a tensor-product interaction of landscape cover and day of year (spatio-temporal interaction of cover
144 class). We used 10 basis dimensions for the spatial and temporal landscape smoothers, and 16 basis di-
145 mensions for the spatio-temporal interaction. The effective degrees of freedom for all smoothing terms
146 were far below the number of basis dimensions, indicating that no additional basis dimensions were
147 needed (see Tables S2, S4, S6, S8). To remove unimportant terms from the model, we used thin-plate
148 regression splines with shrinkage, a continuous analog to stepwise model selection where weaker terms
149 are completely removed from the model rather than reduced to a line (Marra & Wood 2011). The
150 deviance residuals from each model were visually inspected for normality and equal variance (Hilbe
151 2011; Wood 2017). Finally, we calculated the proportion of explained variance (R^2) for each set of
152 terms (Nakagawa *et al.* 2013, 2017).

153 Preliminary model fits revealed that some of the landscape terms in our model were strongly
154 concurred with each other, so we removed them from the model or combined them. Concurvity is
155 a nonlinear analogue of multicollinearity which can bias estimates of standard errors (Buja *et al.*
156 1989). There is no agreed-upon threshold of “unacceptable” concurvity, but 0.5 is commonly used
157 (Dominici 2002; Ramsay *et al.* 2003). Forests and shrubland were combined into a single “woodland”
158 category, and grassland and wetland were combined into a single “grassland” category, as they were
159 strongly positively correlated at all distances, indicating similar feature classes. Cereal was removed
160 from the model, as it was negatively correlated with canola cover at distances less than 200m and

161 was positively correlated at distances over 500m, reflecting the most common crop rotations (canola
 162 \rightarrow wheat \rightarrow barley) and the commonly-used 800 m block structure of farmland in our study region
 163 (quarter-sections). This resulted in a reduced set of landscape terms, none of which were strongly
 164 concurred with each other (cropland: canola, pulses; SNL: grassland, pasture, woodland, roadside; see
 165 Figure S1).

166

167 **Box 1: Interpreting Functional Regression Plots**

168 Functional linear regression is a special case of linear regression, where both the independent
 169 variable is predicted by a functional dependent variable, meaning that the slope is a function (vector)
 170 rather a fixed (scalar) value (Ramsay & Silverman 2004; Yen *et al.* 2014). Therefore, the interpretation
 171 of a functional regression plot is very different from that of a simple linear regression plot. Figure 2a
 172 shows a simple linear regression plot of a hypothetical relationship between trap *activity-density* (y)
 173 and a single predictor, *proportion cover* (x), which is measured in a circle of a fixed radius surrounding
 174 each trap. If we suppose that the relationship between x and y is similar at all radii at which x is
 175 measured, then Figure 2b shows the resulting functional linear regression plot, where the slope (β) is
 176 the same at all distances (we avoid the problem of overlapping concentric circles by using concentric
 177 *annuli*). In reality, it is more likely that nearby cover will be more influential on activity-density than
 178 far-away cover, which could result in a relationship similar to Figure 2c. As functional regression takes
 179 any continuous predictor of y , it is also possible to use proportion cover (measured within an annulus of
 180 a fixed radius) as a predictor of measurements taken across time, allowing the effect of proportion cover
 181 to vary over the course of the season (Figure 2d). Finally, the effect of proportion cover over distance
 182 and time may be modeled as a smoothed surface, representing the joint spatio-temporal influence of
 183 landscape cover on activity-density.

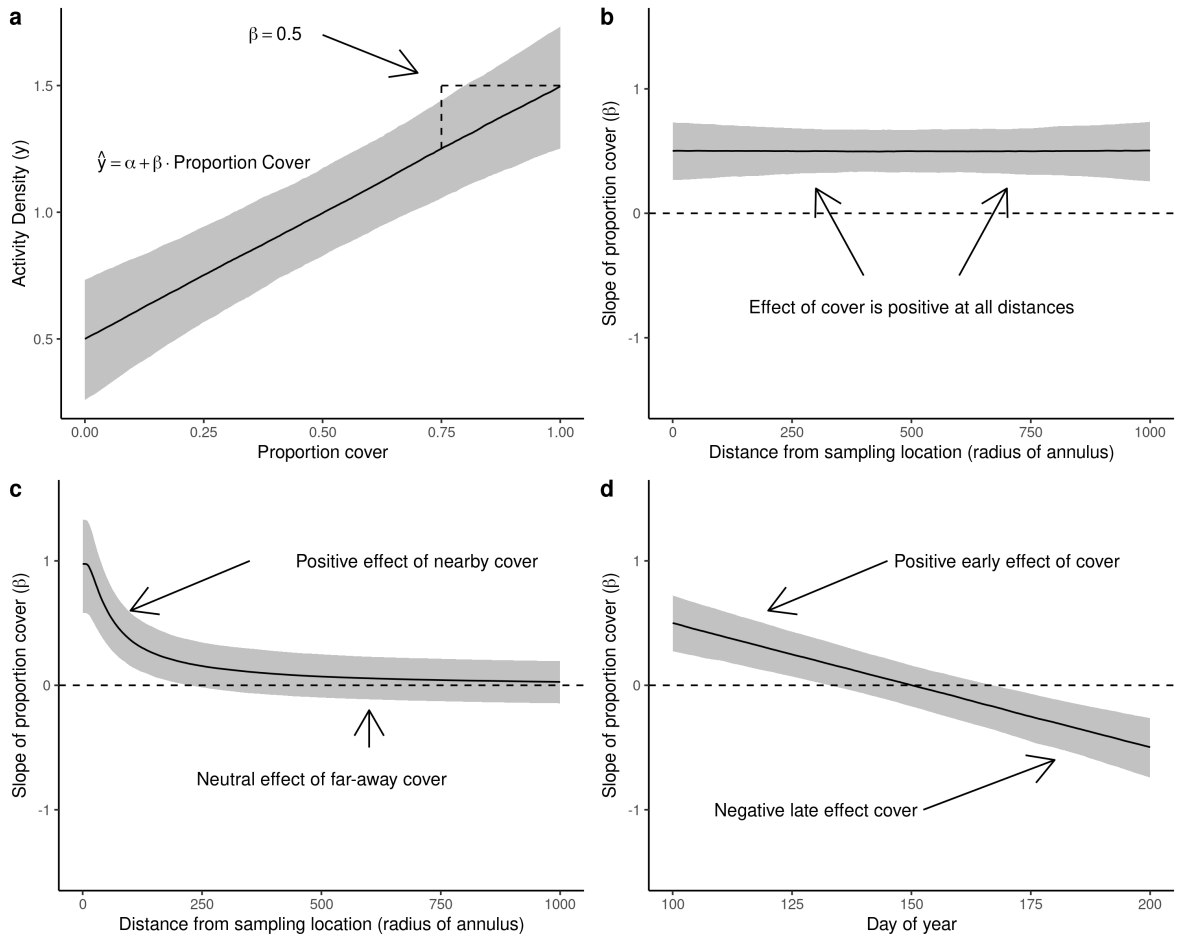


Figure 2: Examples of (functional) linear regression plots. **a)** shows a simple linear regression plot, with a single slope value for a single regressor. **b)** shows the equivalent plot in functional regression form, where the slope is a smoothed function that maps onto a function-valued regressor. **c)** and **d)** show functional linear regression plots where the slope varies with the location of the regressor.

184

185 Functional regression plots of landscape composition reveal which cover classes are acting as
 186 spillover sources or sinks of a given arthropod, and at what spatial scale. Positive effects of nearby
 187 landscape cover classes indicate that arthropods are spilling over *from* it. However, negative responses
 188 to nearby landscape cover classes can indicate one of two things: 1) It may indicate that arthropods are
 189 spilling over *into* it (i.e. net sink for spillover) or 2) it may indicate that no arthropods are available
 190 to spill over *from* it. We consider 1) to be the more likely scenario, as it is unlikely that any one
 191 cover class is *completely* unoccupied. For example, a cover class with low-quality habitat could act
 192 as an ecological trap (Galpern *et al.* 2017) if it acts as a net sink but never acts as a source of spill

over. Alternatively, a cover class could act as a sink by providing high-quality habitat at certain times of the year (e.g. egg laying/feeding), but act as a source at other times (e.g. during emergence). In the Results section, we refer to local- and landscape-level effects, where local indicates the effects of landscape composition at scales of <500 m, whereas landscape indicates scales >500 m. Similarly, we refer to early- and late-season effects, where landscape composition affected activity-density on June 20th or August 20th, respectively.

3. Results

3.1. Landscape composition and trap catches

Grassland, cereal, and canola were the three most-abundant landcover classes surrounding our traps, accounting for 77% of land cover (Figure S2). Several landscape “fingerprints” were evident in the landscape annuli, with cereal cover increasing with distance away, along with a corresponding decrease in canola cover. Study sites were originally chosen for sampling arthropods surrounding canola agroecosystems, so canola was a dominant signal in the landscape, but there was also a large amount of variation in grassland and pasture surrounding each site (Figure S2). Grassland cover was largely constant with distance, but a cluster of sites had uniformly high or low cover of grassland with distance. The pitfall traps caught a total of 18968 *Pterostichus melanarius*, 5397 *Pardosa distincta*, 2350 *Pardosa moesta*, and 34090 *Phalangium opilio* (mean trapping rates per day: 1.58, 0.49, 0.22, 2.92, SD: 5.69, 1.08, 1.09, 5.48, respectively).

3.2. Ground beetle: *Pterostichus melanarius*

P. melanarius activity-density was strongly influenced by trap location and landscape composition (Tables S1, S2). Canola crops had a marginally higher activity-density of *P. melanarius* than other trap locations (Figure 3a). Grassland cover was the most important land cover type in explaining activity-density (R^2 : 0.104, Table 1), and local grassland had a negative effect late in the summer (Figure 3b), suggesting that *P. melanarius* may move into grasslands later in the year. Local canola had a positive effect in the early season, but landscape-level canola had a negative effect, indicating that areas with widespread canola coverage had lower *P. melanarius* activity-density (Figure 3c). Pulses acted as a late-season source, indicating that *P. melanarius* may migrate out of the crop after (or during) harvest (Figure 3d). Finally, *P. melanarius* activity-density had a strong temporal and spatial component (both $p < 0.001$), indicating that phenology and local geographic factors were important drivers of

ground beetle activity-density (Figure S3). Landscape composition and trap location explained 22% of the variance in activity-density, while the spatial and temporal smoothers accounted for 41% (Table 1).

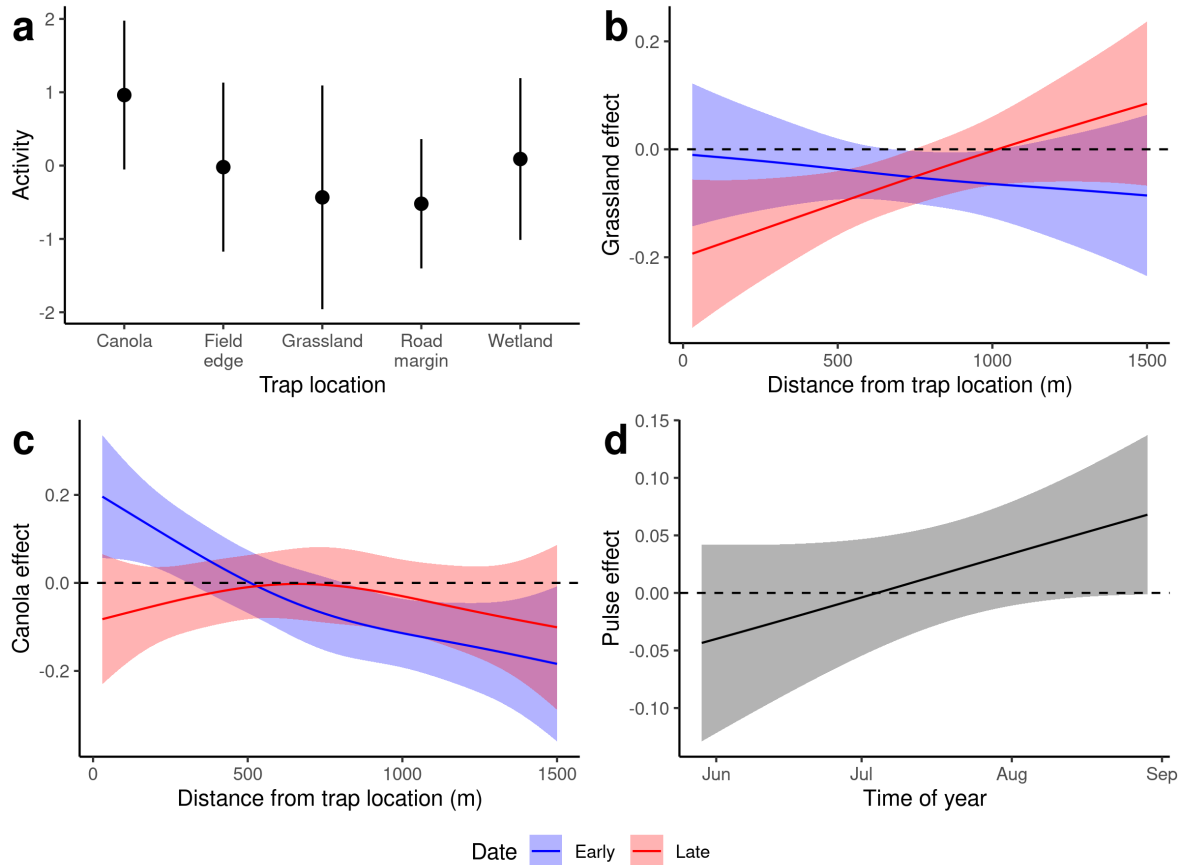


Figure 3: Landscape influence on *Pterostichus melanarius* activity-density. a) shows the effect of local trap location, and b-c) are functional regression plots of the proportion grassland and canola at distances away from each trap. d) is a functional regression plot over time, showing the effect of pulses at different times of the year. Lines and dots represent means, and bars and shaded regions represent 95 % confidence regions ($1.96 \times \text{SE}$). Coloured regions represent early- and late-season effects (blue = June, red = August).

3.3. Wolf spiders: *Pardosa distincta* and *Pardosa moesta*

Activity-density of *P. distincta* and *P. moesta* was influenced by trap location and landscape composition (Tables S3, S4, S5, S6), but landscape composition had relatively weak effects on both species (R^2 : 0.0446, 0.0963). Unlike *P. melanarius*, both *Pardosa* species had far lower activity-density in canola than any other cover type (Figures 4a, 5a). Activity-density of both *Pardosa* species had a strong temporal and spatial component, although the temporal component was dominant for *P. distincta*, whereas the spatial component was dominant for *P. moesta* (Figures S4 and S5; both

232 $p < 0.001$).

233 *P. distincta* activity-density was negatively affected by landscape-level pasture (Figure 4b), while
234 woodlands had a negative effect late in the season (Figure 4c). This suggests that large amounts
235 of pasture are unsuitable habitat for *P. distincta*, and that they migrate into woodlands later in the
236 season. However, trap location and the temporal random effect (Figure S4a) explained roughly 10 times
237 more variance than landscape composition (R^2 : 0.45 versus 0.045), meaning that while *P. distincta*
238 may be locally abundant in certain cover types, it is highly general in its overall habitat preferences.

239 *P. moesta* activity-density responded to grassland, canola, and road margins. Grasslands had a
240 local negative effect, but a positive landscape-level effect, indicating that while these cover types act
241 as a local sink, the general amount of grassland in the area had a positive effect (Figure 5b). Local
242 canola cover had a positive early effect on activity-density, but a negative local effect later in the season
243 (Figure 5c). Local road margins also had a similar effect, acting as an early source and a late sink
244 (Figure 5d). Pulses also had a positive effect at the landscape level (Figure 5e), but this explained very
245 little variance in *P. moesta* activity-density (Table 1, R^2 : 0.004). Similar to *P. distincta*, trap location
246 and an East-West spatial random effect (Figure S5b) explained roughly 5 times more variance in *P.*
247 *moesta* activity-density than landscape composition (R^2 : 0.5 versus 0.096), meaning that *P. moesta*
248 is also fairly general in its overall habitat preferences, and is influenced more heavily by larger-scale
249 abiotic factors.

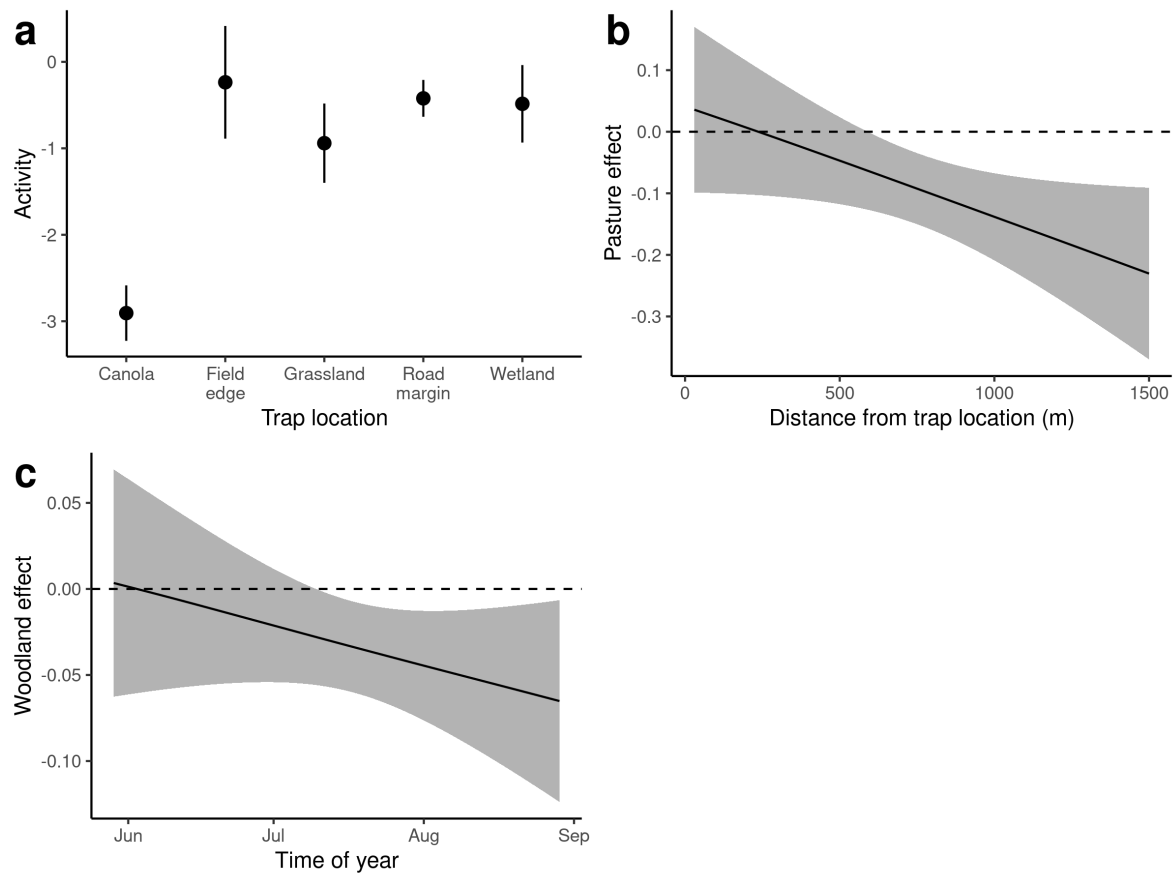


Figure 4: Landscape influence on *Pardosa distincta* activity-density. a) shows the effect of local trap location, b) is a functional regression plot of the proportion pasture at distances away from each trap, and c) is a functional regression plot over time, showing the effect of woodland at different times of the year. Lines and dots represent means, and bars and shaded regions represent 95 % confidence regions ($1.96 \times \text{SE}$).

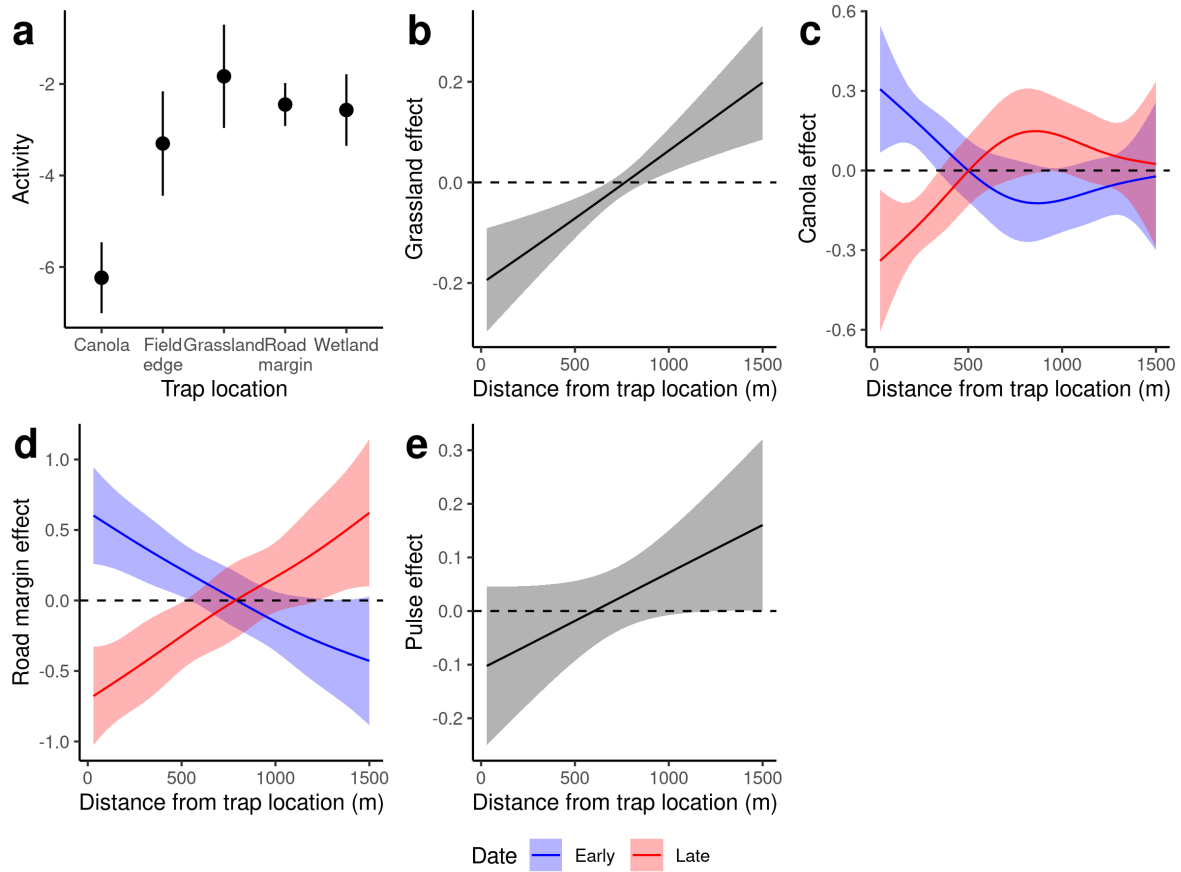


Figure 5: Landscape influence on *Pardosa moesta* activity-density. a) shows the effect of local trap location, and b-e) are functional regression plots of the proportion grassland, canola, road margins, and pulses at distances away from each trap. Lines and dots represent means, and bars and shaded regions represent 95 % confidence regions ($1.96 \times SE$). Coloured regions represent early- and late-season effects (blue = June, red = August).

3.4. Harvestman: *Phalangium opilio*

P. opilio activity-density was somewhat influenced by trap location, with field edges and wetlands having the highest activity-density (Figure 6a), but this effect was swamped by the effect of landscape and the spatiotemporal random effects (Table 1), meaning that *P. opilio* activity-density is only mildly influenced by local cover type. Nearby grassland and woodland both had negative effects on *Phalangium opilio* activity-density, but only early in the season (Figures 6b,c), suggesting that *P. opilio* may preferentially migrate to these cover classes. The temporal random effect was overwhelmingly the most important predictor of *P. opilio* activity-density (R^2 : 0.44), showing that activity-density increased during the spring, and showed very little decline during the rest of the season (Figure S6a). Similar to *P. moesta*, *P. opilio* also showed a distinct East-West spatial random effect (Figure S6b),

260 indicating that their activity-density is also influenced by larger-scale abiotic factors.

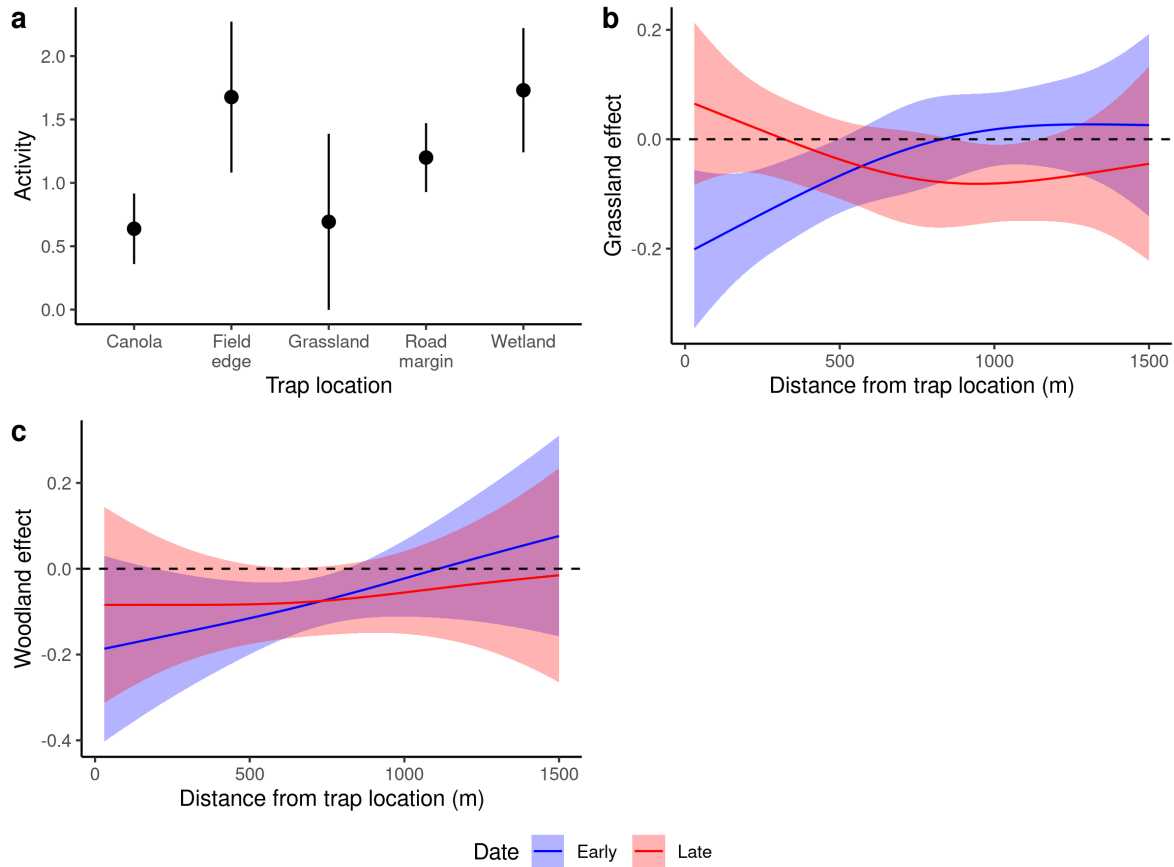


Figure 6: Landscape influence on *Phalangium opilio* activity-density. a) shows the effect of local trap location, and b-c) are functional regression plots of the proportion grassland and woodland at distances away from each trap. Lines and dots represent means, and bars and shaded regions represent 95 % confidence regions (1.96 x SE). Coloured regions represent early- and late-season effects (blue = June, red = August).

261 4. Discussion

262 Our prediction of SNL having late-season effects on beneficial arthropods was supported (Table
 263 2). Specifically, grassland had a negative effect on *P. melanarius* activity-density, woodlands on *P.*
 264 *distincta* activity-density, and road margins on *P. moesta* activity-density, all during late summer
 265 (August - September). This suggests that these arthropods migrate to these habitats at the end of the
 266 summer to prepare for oviposition or overwintering. However, *P. opilio* showed no evidence of this,
 267 instead showing a negative effect of grassland *early* in the season, suggesting that a) they aggregate in
 268 grasslands or b) grasslands do not constitute suitable habitat for *P. opilio*, resulting in low spillover.

Table 1: R^2_{GLMM} for model components, representing the proportion of total variance explained by each term. R^2 was calculated using methods from Nakagawa et al. 2013 and Nakagawa et al. 2017.

Term	<i>Pterostichus melanarius</i>	<i>Pardosa distincta</i>	<i>Pardosa moesta</i>	<i>Phalangium opilio</i>
Trap Location	0.080	0.294	0.379	0.026
Day of Year	0.040	0.160	0.000	0.436
Spatial Location	0.373	0.000	0.125	0.085
Grassland	0.104	0.000	0.017	0.086
Canola	0.030	0.002	0.037	0.000
Pasture	0.000	0.032	0.002	0.000
Woodland	0.000	0.009	0.001	0.017
Pulses	0.005	0.000	0.004	0.001
Road margins	0.000	0.001	0.034	0.002
Residual	0.369	0.502	0.400	0.348

Table 2: Synthesis of model results. Bio-control potential is based on likely early-season aggregation to canola crops.

Species	Summary	Bio-control potential
<i>Pterostichus melanarius</i>	<ul style="list-style-type: none"> · Aggregates in canola during early season · Disperses to grassland during late season 	High
<i>Pardosa distincta</i>	<ul style="list-style-type: none"> · Negative effect of pasture · May locally aggregate in field edges 	Low
<i>Pardosa moesta</i>	<ul style="list-style-type: none"> · Aggregates in canola during early season · Disperses to road margins and grassland during late season · Aggregates in grasslands across the season. 	Medium
<i>Phalangium opilio</i>	<ul style="list-style-type: none"> · Aggregates to grassland early in the season 	Low

There was little evidence of SNL acting as early-season sources, aside from road margins having a positive early effect on *P. moesta* activity-density. However, some cover classes had a positive effect at the landscape level (grassland and road margins on *P. moesta*), suggesting earlier or larger-scale dispersal away from these cover classes. Canola had a positive effect on *P. melanarius* and *P. moesta* in the early season, suggesting that these organisms aggregate to canola crops and disperse at the end of the season (mass effects *sensu* Shmida & Wilson 1985). Canola also had negative landscape-level effects on *P. melanarius* while pasture had negative effects on *P. distincta*, meaning that these cover types likely represent only partial habitat for these arthropods. Finally, the influence of landscape composition tended to be limited to a radius of about 500m, indicating that large-scale *and* local land cover can be important to beneficial arthropod abundance. There was also a strong temporal component to most of the landscape effects, meaning that it is important to consider how sinks and sources may change over the season.

The predatory ground beetle *Pterostichus melanarius* responded to landscape composition, primarily to canola, pulses, and grass and wetland cover. Grassland and wetland cover had a negative late-season effect, suggesting that *P. melanarius* migrates into it at the end of the summer. Other studies have found similar results, suggesting that untilled land is important off-field habitat for carabids (Desender & Alderweireldt 1988; Fournier & Loreau 2002; but see Hatten *et al.* 2007). In particular, Purtauf *et al.* (2005) found that carabid density increased with proportion of nearby grasslands, so our negative late-season effect of grasslands may represent *P. melanarius* moving to overwintering habitat at the end of the season. However, *P. melanarius* is also found in a wide variety of habitats, and tends to prefer agricultural fields (Larsen *et al.* 2003). Our models confirmed this, as they showed that canola and pulse crops had positive effects on *P. melanarius* activity-density early in the season. Early in the season, canola crops had a local positive effect, but a landscape-level negative effect, which may indicate that they provide only temporary feeding habitat. The effect of pulse crops on carabid abundance is not well-studied, but our results suggest that pulses may represent a potential food resource for *P. melanarius*, albeit a weak one (Table 1). Carabids are predators of pea-leaf weevils (*Sitona lineatus*) on other Fabaceae (Hamon *et al.* 1990), and *P. melanarius* can prey upon other carabids that are predators of *S. lineatus*, such as *Bembidion quadrimaculatum* (Vankosky *et al.* 2011), so this effect may be direct or indirect. We did not consider the influence of previous years' crops, although carabids tend to be more abundant in areas of high crop rotation (Bertrand *et al.* 2016; Busch 2016). Finally, *P. melanarius* has long- and short-winged morphs with very different dispersal

abilities (Niemelä & Spence 1999; Bourassa *et al.* 2011), which may influence the degree to which landscape-level proportion cover impacts activity-density.

The wolf spiders *Pardosa distincta* and *Pardosa moesta* both responded to landscape composition, but it explained only a small fraction of their activity-density (R^2 : 0.045, 0.096). This means that both species of *Pardosa* appear to have very general habitat preferences, but may be somewhat influenced by certain cover types. Pasture had a negative effect at the landscape scale, and woodland had a late-season negative effect, suggesting that *P. distincta* move to woodlands for overwintering or winter foraging (Aitchison 1984; Buddle 2000). *Pardosa* are found in areas close to disturbed roadside strips (Drapela *et al.* 2008, 2011; Kowal & Cartar 2011), but *P. distincta* appears to be less sensitive to disturbances than *P. moesta* (Collins *et al.* 1996; Wade & Roughley 2010). Moring & Stewart (1994) showed that *P. distincta* were active in grassy habitats, which we found partial evidence of, as *P. distincta* tended to have higher activity-density in trap locations with higher grass cover (Figure 4a). Canola had an early-season positive effect on *P. moesta*, indicating that *P. moesta* and *P. melanarius* may both use canola as foraging grounds. We also found that road margins had a positive early-season and a negative late-season effect (similar to Drapela *et al.* 2008). Grassland and pulses also had a local negative effect but a positive landscape-level effect; this suggests that they may constitute suitable habitat for *P. moesta* and attract them away from other cover types. Wolf spiders (Lycosidae) employ a wandering-active predation strategy (Young & Edwards 1990), meaning that nearby landscape composition may be more influential to *Pardosa* than large-scale composition (Öberg *et al.* 2007, 2008). While trapping location explained a large proportion of variance for both species (0.29 and 0.38), several landscape features were also important at large spatial scales, including grass and wetland, pasture, pulses, and road margins. Therefore, *Pardosa* dispersal distances may be further than previously thought, either through ballooning as juveniles (Richter 1970; Greenstone 1982) or through other long-distance travel.

Phalangium opilio activity-density responded to grass and wetland cover, as well as wooded landscapes. Other studies have found that *P. opilio* is mostly found in human-altered landscapes with a large proportion of farming (Muster & Meyer 2014; Van de Poel 2015). Since most of our study area was in or near farmed land, the lack of variation is understandable, but there were a few notable landscape-level patterns that emerged. *P. opilio* activity-density was higher in grassy field edges and wetlands, but grasslands and wetlands had a local negative effect on *P. opilio* until late in the season. These indicate that while grass and wetlands could act as a reservoir, spillover into other land cover

types may be limited, as *P. opilio* avoids heavily grazed areas, possibly due to low humidity (Šajna *et al.* 2011). *P. opilio* is also found in large numbers at the edges of forests, and may migrate from forests into farmlands (Van de Poel 2015). We found the opposite pattern: forests had a weak negative effect on *P. opilio*, at least early in the year. Unlike the other arthropods, most of the variation in activity-density for *P. opilio* was explained by day of year ($R^2 = 0.44$), indicating strong seasonal emergence cues. However, there was also a strong East-West spatial random effect in both *P. opilio* and *P. moesta*, meaning that larger-scale geographic patterns (possibly related to rainfall or temperature) also influence their activity-density.

Many other studies have considered the overall effect of SNL on ecosystem service provision, but we have highlighted the different spatial and temporal aspects of ecosystem service provision. We have shown how a relatively straightforward statistical technique can be used to consider multiple spatial scales of landscape composition, providing richer inference about the processes acting on beneficial arthropods. Our results show empirical evidence of arthropod migration between cover types at different times of year, which is rarely considered beyond single-field studies. Since we did not directly track individual movements, future studies should directly examine arthropod movement and life-history within matrices of cover types, with the goal of integrating landscape ecology and behavioural processes into a single model (Lima & Zollner 1996). This would also allow direct inference about landscape categories that were combined in our dataset, allowing us to consider different landscape categories independently. Finally, future work should explicitly link landscape structure, arthropod abundance, and ecosystem services (Gagic *et al.* 2017).

5. Applications

Our work has three main applications. First, it adds to the basis of scientific evidence showing that SNL can act as reservoir habitats in intensely-managed agroecosystems. Based on our findings, farmers and land managers should consider preserving existing grassland and wetland habitat to act as a background source of arthropods for pest-control in crops. While local habitat appears valuable, even landscape-level habitat can be valuable, as it can increase the number of beneficial arthropods at larger spatial scales (e.g. Figures 3, 5). Secondly, our work suggests that *P. melanarius* and *P. moesta* should be investigated for their role as predators in canola crops (Table 2). They appear to aggregate in canola crops early in the season, meaning that they have the potential to provide valuable pest-control services to growers. Finally, we demonstrate that timing and spatial scale of spillover

361 should be considered in future landscape studies of ecosystem services. We show important differences
362 in the timing of landscape effects on activity-density (early-season vs. late-season spillover) that are
363 typically ignored, but should be considered when assessing how SNL can deliver ecosystem services.

	Trap location	s(day)	s(E,N)	s(Distance):Grassland	s(Time):Grassland	ti(Distance,Time):Grassland	s(Distance):Canola	s(Time):Canola	ti(Distance,Time):Canola	s(Distance):Pasture	s(Time):Pasture	ti(Distance,Time):Pasture	s(Distance):Woodland	s(Time):Woodland	ti(Distance,Time):Woodland	s(Distance):Pulses	s(Time):Pulses	ti(Distance,Time):Pulses	s(Distance):Urban	s(Time):Urban	ti(Distance,Time):Urban
Trap location	1	0.01	0.01	0.04	0.01	0.01	0.44	0.11	0.07	0.17	0.05	0.01	0.01	0	0	0.07	0.01	0	0.04	0.01	0
s(day)	0.07	1	0.06	0.01	0.4	0.02	0.02	0.43	0.23	0.01	0.21	0.02	0.04	0.21	0.02	0.02	0.28	0.03	0.03	0.42	0.22
s(E,N)	0.25	0.08	1	0.43	0.18	0.05	0.29	0.14	0.05	0.53	0.22	0.07	0.75	0.31	0.07	0.47	0.22	0.04	0.4	0.18	0.03
s(Distance):Grassland	0.24	0.02	0.14	1	0.36	0.02	0.29	0.1	0.02	0.21	0.1	0.01	0.27	0.09	0.01	0.12	0.04	0.01	0.34	0.13	0.01
s(Time):Grassland	0.05	0.6	0.11	0.97	1	0.01	0.1	0.13	0.04	0.09	0.14	0.01	0.17	0.24	0.03	0.06	0.07	0.01	0.29	0.39	0.13
ti(Distance,Time):Grassland	0.07	0.09	0.01	0.04	0.13	1	0.05	0.09	0.25	0.04	0.06	0.03	0.02	0.13	0.08	0.01	0.04	0.05	0.02	0.11	0.04
s(Distance):Canola	0.72	0.02	0.1	0.14	0.07	0.01	1	0.39	0.1	0.29	0.09	0.03	0.03	0.01	0	0.34	0.12	0.01	0.34	0.12	0
s(Time):Canola	0.47	0.67	0.04	0.1	0.13	0.03	0.93	1	0.35	0.21	0.23	0.02	0.02	0.02	0.01	0.28	0.39	0.02	0.24	0.28	0.11
ti(Distance,Time):Canola	0.54	0.27	0.03	0.05	0.07	0.15	0.36	0.38	1	0.19	0.15	0.09	0.01	0.02	0.02	0.07	0.15	0.06	0.06	0.09	0.07
s(Distance):Pasture	0.33	0.02	0.09	0.13	0.06	0.02	0.28	0.09	0.05	1	0.41	0.1	0.05	0.03	0	0.08	0.02	0.02	0.16	0.06	0.01
s(Time):Pasture	0.21	0.34	0.06	0.12	0.22	0.03	0.21	0.16	0.14	0.8	1	0.06	0.06	0.16	0.03	0.07	0.06	0.02	0.14	0.19	0.06
ti(Distance,Time):Pasture	0.14	0.24	0.04	0.02	0.1	0.05	0.08	0.09	0.18	0.33	0.57	1	0.02	0.09	0.03	0.01	0.03	0.03	0.03	0.09	0.06
s(Distance):Woodland	0.04	0.02	0.14	0.33	0.14	0.01	0.06	0.03	0.01	0.04	0.03	0	1	0.37	0.05	0.02	0.01	0	0.25	0.11	0.01
s(Time):Woodland	0.02	0.26	0.04	0.21	0.26	0.05	0.04	0.05	0.01	0.03	0.06	0.01	0.92	1	0.27	0.02	0.03	0.01	0.2	0.24	0.14
ti(Distance,Time):Woodland	0.01	0.08	0.04	0.06	0.09	0.05	0	0.04	0.02	0.01	0.03	0.01	0.11	0.41	1	0	0.01	0.04	0.01	0.08	0.06
s(Distance):Pulses	0.18	0.01	0.08	0.08	0.04	0.01	0.35	0.16	0.02	0.12	0.05	0.01	0.03	0.02	0	1	0.37	0.06	0.22	0.09	0
s(Time):Pulses	0.09	0.35	0.02	0.05	0.06	0.01	0.23	0.31	0.08	0.07	0.08	0.01	0.01	0.02	0	0.8	1	0.02	0.14	0.16	0.07
ti(Distance,Time):Pulses	0.05	0.19	0.02	0	0.04	0.04	0.04	0.13	0.15	0.02	0.06	0.02	0.01	0.03	0.01	0.05	0.38	1	0.01	0.07	0.03
s(Distance):Urban	0.36	0.03	0.11	0.36	0.16	0.01	0.45	0.19	0.05	0.22	0.1	0.02	0.21	0.09	0.01	0.26	0.09	0.01	1	0.36	0.02
s(Time):Urban	0.1	0.62	0.04	0.27	0.39	0.01	0.27	0.32	0.08	0.14	0.16	0.01	0.18	0.26	0.02	0.14	0.21	0.02	0.88	1	0.47
ti(Distance,Time):Urban	0.03	0.62	0.04	0.03	0.29	0.03	0.04	0.24	0.06	0.03	0.16	0.04	0.03	0.26	0.07	0.02	0.23	0.04	0.07	0.55	1

Figure S1: Concurvity estimates for reduced cover classes used in models.

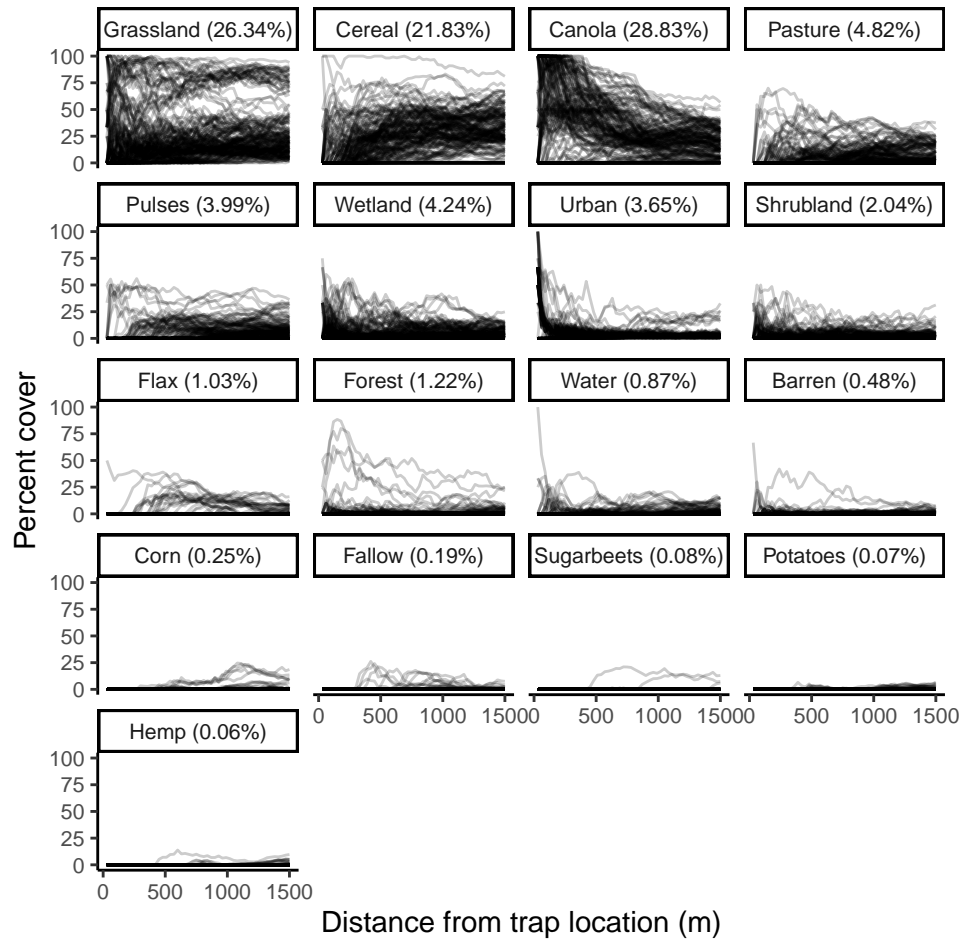


Figure S2: Percent cover of landscape cover classes in annuli surrounding each trap location. Sites are represented by individual lines. Mean cover for each class is listed in each sub-heading.

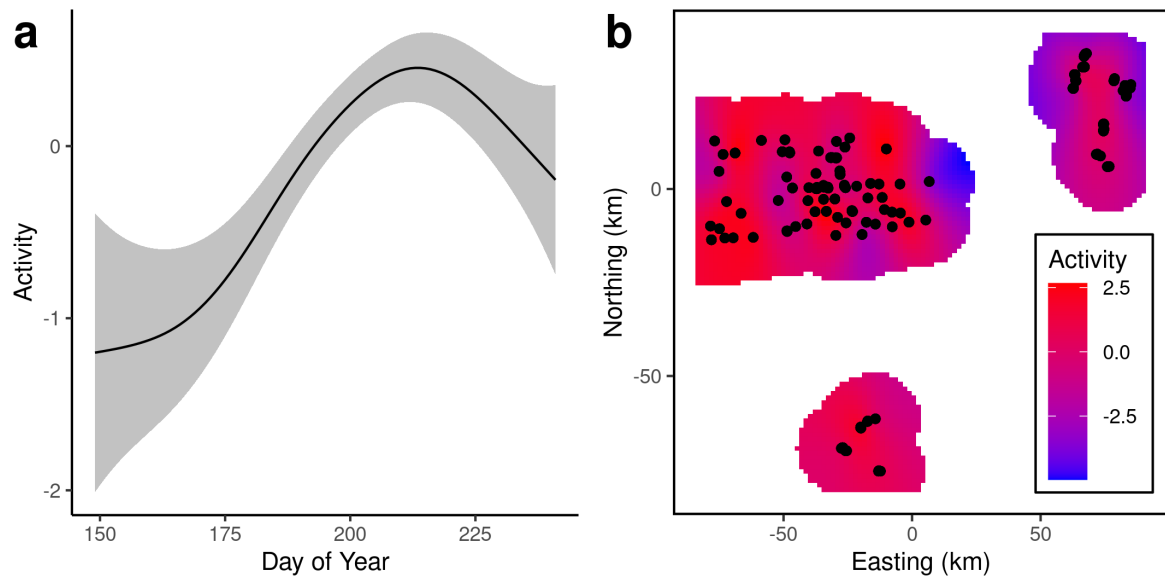


Figure S3: Temporal and spatial components of *Pterostichus melanarius* activity-density (after accounting for landscape composition and trap location). a) shows the effect of day of year, and b) shows the spatially smoothed effect of site location.

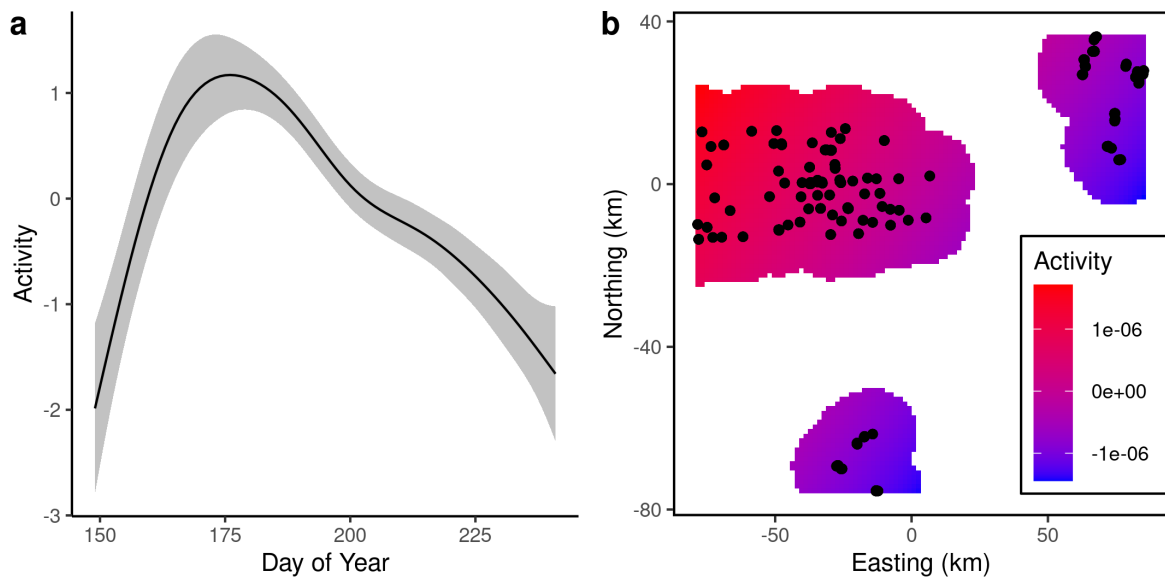


Figure S4: Temporal and spatial components of *Pardosa distincta* activity-density (after accounting for landscape composition and trap location). a) shows the effect of day of year, and b) shows the spatially smoothed effect of site location.

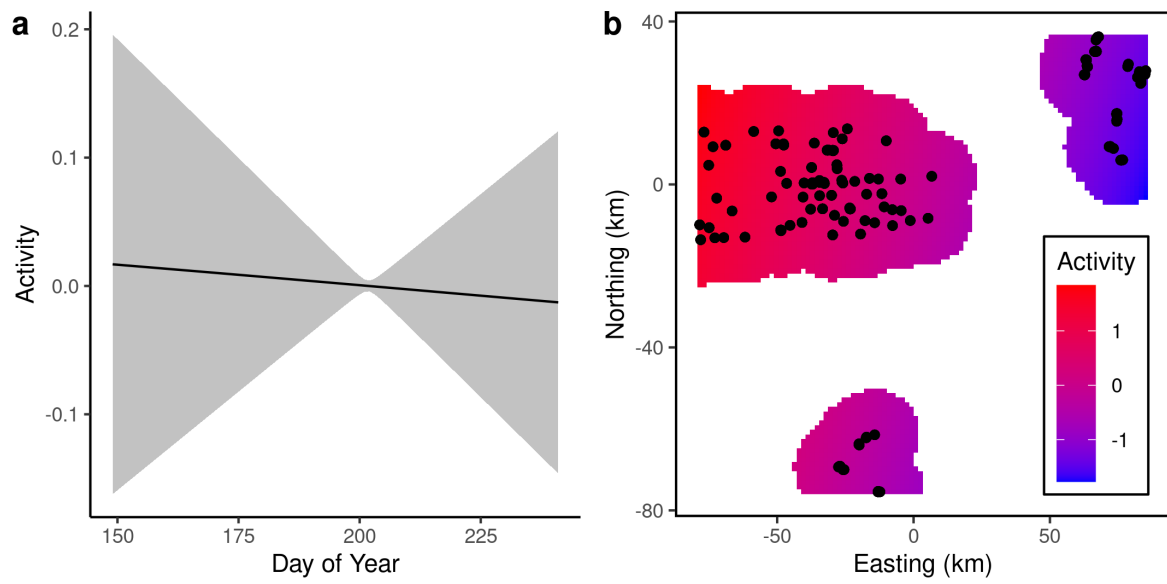


Figure S5: Temporal and spatial components of *Pardosa moesta* activity-density (after accounting for landscape composition and trap location). a) shows the effect of day of year, and b) shows the spatially smoothed effect of site location.

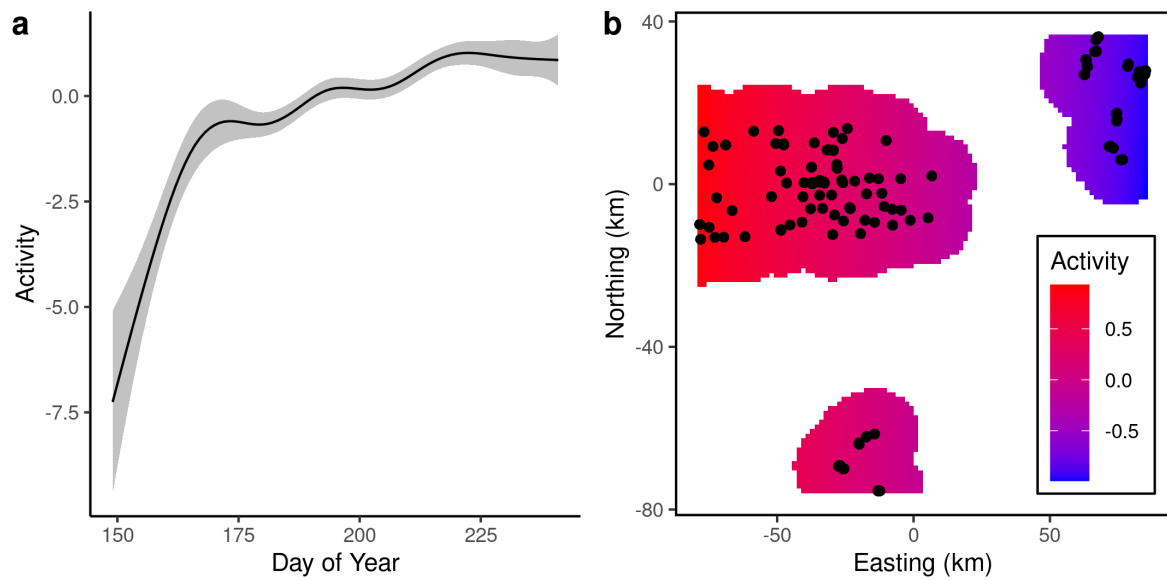


Figure S6: Temporal and spatial components of *Phalangium opilio* activity-density (after accounting for landscape composition and trap location). a) shows the effect of day of year, and b) shows the spatially smoothed effect of site location.

Table S1: Trap location (cover type that trap was located in) intercept estimates for *Pterostichus melanarius*

Trap location	β	S.E.	Z	p
Canola	0.96	0.52	1.86	0.063
Road margin	-0.52	0.45	-1.16	0.247
Grassland	-0.43	0.78	-0.56	0.578
Field edge	-0.02	0.59	-0.04	0.972
Wetland	0.09	0.56	0.16	0.874

Table S2: Smooth terms for *Pterostichus melanarius*. *s* indicates a thin-plate spline, *ti* indicates a tensor-product interaction. All terms except for day and (E,N) are functional regression fits.

Smoothing term	E.d.f.	χ^2	p
s(Day)	3.48	31.11	<0.001
s(E,N)	39.47	309.8	<0.001
s(Distance):Grassland	1.51	11.24	<0.001
s(Day):Grassland	<0.01	<0.01	0.769
ti(Distance,Day):Grassland	0.93	3.87	0.026
s(Distance):Canola	1.71	7.36	0.004
s(Day):Canola	<0.01	<0.01	0.824
ti(Distance,Day):Canola	1.64	8.86	0.002
s(Distance):Pasture	<0.01	<0.01	0.979
s(Day):Pasture	0.67	0.92	0.23
ti(Distance,Day):Pasture	<0.01	<0.01	0.907
s(Distance):Woodland	<0.01	<0.01	0.439
s(Day):Woodland	<0.01	<0.01	0.939
ti(Distance,Day):Woodland	<0.01	<0.01	0.983
s(Distance):Pulses	<0.01	<0.01	0.498
s(Day):Pulses	1.27	3.96	0.033
ti(Distance,Day):Pulses	1.4	2.24	0.16
s(Distance):Urban	<0.01	<0.01	0.277
s(Day):Urban	<0.01	<0.01	0.582
ti(Distance,Day):Urban	<0.01	<0.01	0.591

Table S3: Trap location (cover type that trap was located in) intercept estimates for *Pardosa distincta*

Trap location	β	S.E.	Z	p
Canola	-2.91	0.16	-17.77	<0.001
Road margin	-0.42	0.11	-3.88	<0.001
Grassland	-0.94	0.23	-4.02	<0.001
Field edge	-0.24	0.33	-0.71	0.477
Wetland	-0.49	0.23	-2.12	0.034

Table S4: Smooth terms for *Pardosa distincta*. *s* indicates a thin-plate spline, *ti* indicates a tensor-product interaction. All terms except for day and (E,N) are functional regression fits.

Smoothing term	E.d.f.	χ^2	p
s(Day)	5.59	120.42	<0.001
s(E,N)	<0.01	<0.01	0.958
s(Distance):Grassland	<0.01	<0.01	0.966
s(Day):Grassland	<0.01	<0.01	0.94
ti(Distance,Day):Grassland	<0.01	<0.01	0.616
s(Distance):Canola	<0.01	<0.01	0.927
s(Day):Canola	<0.01	<0.01	0.645
ti(Distance,Day):Canola	0.75	2.18	0.077
s(Distance):Pasture	1.76	14.9	<0.001
s(Day):Pasture	0.46	0.66	0.202
ti(Distance,Day):Pasture	<0.01	<0.01	0.799
s(Distance):Woodland	0.01	0.01	0.098
s(Day):Woodland	1.61	7.74	0.005
ti(Distance,Day):Woodland	0.56	0.98	0.153
s(Distance):Pulses	<0.01	<0.01	0.693
s(Day):Pulses	<0.01	<0.01	0.921
ti(Distance,Day):Pulses	<0.01	<0.01	0.43
s(Distance):Urban	<0.01	<0.01	0.725
s(Day):Urban	0.7	1.03	0.224
ti(Distance,Day):Urban	<0.01	<0.01	0.919

Table S5: Trap location (cover type that trap was located in) intercept estimates for *Pardosa moesta*.

Trap location	β	S.E.	Z	p
Canola	-6.24	0.40	-15.76	<0.001
Road margin	-2.45	0.24	-10.22	<0.001
Grassland	-1.83	0.58	-3.18	0.001
Field edge	-3.30	0.58	-5.67	<0.001
Wetland	-2.57	0.40	-6.44	<0.001

Table S6: Smooth terms for *Pardosa moesta*. *s* indicates a thin-plate spline, *ti* indicates a tensor-product interaction. All terms except for day and (E,N) are functional regression fits.

Smoothing term	E.d.f.	χ^2	p
s(Day)	0.05	0.04	0.349
s(E,N)	1.96	50.7	<0.001
s(Distance):Grassland	1.87	14.39	<0.001
s(Day):Grassland	<0.01	<0.01	0.944
ti(Distance,Day):Grassland	<0.01	<0.01	0.976
s(Distance):Canola	<0.01	<0.01	0.341
s(Day):Canola	<0.01	<0.01	0.627
ti(Distance,Day):Canola	2.22	21.63	<0.001
s(Distance):Pasture	<0.01	<0.01	0.936
s(Day):Pasture	<0.01	<0.01	0.835
ti(Distance,Day):Pasture	1.6	2.96	0.109
s(Distance):Woodland	<0.01	<0.01	0.646
s(Day):Woodland	0.95	2.23	0.085
ti(Distance,Day):Woodland	<0.01	<0.01	0.414
s(Distance):Pulses	1.48	3.94	0.039
s(Day):Pulses	0.4	0.5	0.221
ti(Distance,Day):Pulses	<0.01	<0.01	0.984
s(Distance):Urban	<0.01	<0.01	0.846
s(Day):Urban	0.63	0.8	0.252
ti(Distance,Day):Urban	3.15	20.23	<0.001

Table S7: Trap location (cover type that trap was located in) intercept estimates for *Phalangium opilio*

Trap location	β	S.E.	Z	p
Canola	0.64	0.14	4.49	<0.001
Road margin	1.20	0.14	8.64	<0.001
Grassland	0.69	0.35	1.95	0.051
Field edge	1.68	0.30	5.52	<0.001
Wetland	1.73	0.25	6.92	<0.001

Table S8: Smooth terms for *Phalangium opilio*. *s* indicates a thin-plate spline, *ti* indicates a tensor-product interaction. All terms except for day and (E,N) are functional regression fits.

Smoothing term	E.d.f.	χ^2	p
s(Day)	7.2	141.89	< 0.001
s(E,N)	1.95	59.8	< 0.001
s(Distance):Grassland	1.69	50.17	< 0.001
s(Day):Grassland	<0.01	<0.01	0.685
ti(Distance,Day):Grassland	1.39	5.79	0.013
s(Distance):Canola	<0.01	<0.01	0.466
s(Day):Canola	<0.01	<0.01	0.882
ti(Distance,Day):Canola	<0.01	<0.01	0.675
s(Distance):Pasture	0.36	0.42	0.291
s(Day):Pasture	<0.01	<0.01	0.436
ti(Distance,Day):Pasture	<0.01	<0.01	0.585
s(Distance):Woodland	1.44	14.8	< 0.001
s(Day):Woodland	<0.01	<0.01	0.601
ti(Distance,Day):Woodland	1.81	4.06	0.073
s(Distance):Pulses	<0.01	<0.01	0.716
s(Day):Pulses	<0.01	<0.01	0.713
ti(Distance,Day):Pulses	1.23	1.88	0.187
s(Distance):Urban	0.79	1.94	0.088
s(Day):Urban	<0.01	<0.01	0.419
ti(Distance,Day):Urban	0.36	0.53	0.224

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