Differential effects of soil conservation practices on arthropods and crop yield

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Abstract

1. Various agricultural practices aim to promote biodiversity and ecosystem services by increasing habitat availability and diversity. However, responses to such practices are context dependent, differentially impacting functional groups of service-providing organisms and crop yields.
2. Low and no tillage are promoted as sustainable management practices that increase soil heterogeneity and habitat. Here we (a) investigated whether soil tillage practices in canola crop fields altered arthropod biodiversity or yield, and (b) compared effects of field-scale management to landscape-scale habitat context. We focused on effects of full (multiple tillage passes that leave soil surface bare), intermediate (tilled once and some stubble remains), or no (seed planted directly into last year's stubble) tillage on five functional groups with unique diets and reproductive strategies: (i) herbivores, (ii) kleptoparasites, (iii) parasitoids, (iv) pollinators, and (v) predators.
3. Effects of habitat context on arthropod abundance and diversity varied across functional groups. Pollinators responded to on-farm soil management, benefiting from intermediate tillage. Predators and herbivores responded most strongly to landscape-scale habitat composition and were more abundant in landscapes with more semi-natural habitat. Our results indicate that natural history differences among arthropod functional groups mediate how habitat availability affects biodiversity. However, variation in arthropod communities had little effect on canola crop yield, which was lowest in fields with no tillage.
4. *Policy implications:* Our research highlights that soil management impacts on aboveground arthropods are complex, and that practices thought to increase agricultural sustainability do not necessarily achieve this goal. While reducing tillage intensity may increase soil quality

and habitat availability, our results show that tillage can negatively impact arthropods and crop yields. This highlights the increasingly-documented disconnect between biodiversity conservation and enhancing crop yield. Truly sustainable agriculture requires finding and implementing practices that benefit both biodiversity and human wellbeing.

Keywords: sustainable agriculture, biodiversity, functional groups, crop yield, canola, tillage, pollinators, natural enemies, soil habitat

Introduction

Enhancing crop yield while supporting biodiversity and ecosystem services is a challenge in agroecosystems. Management practices like intercropping and reduced tillage (here referred to as sustainable agriculture) aim to support biodiversity and ecological services by increasing habitat availability and diversity, although responses to such practices vary among unique service-providing functional groups (Lefcheck et al., 2015; Mitchell et al., 2015). Indeed, there has been a call to determine simultaneous impacts of habitat change on multiple ecosystem services such as soil quality, pollination, and pest control (Bommarco et al., 2013; Tamburini et al., 2020). These impacts cannot necessarily be extrapolated from studies of single services due to interactions among organisms. It is thus key to determine how organisms in unique functional groups, that provide separate ecosystem services, differentially respond to sustainable agriculture practices.

Reducing tillage is a practice that can support biodiversity by increasing soil habitat availability and heterogeneity (de Graaff et al., 2019; Tamburini et al., 2020). Reduced tillage was originally implemented to limit soil erosion and conserve soil moisture. It can also improve in-field habitat through reduced soil disturbance frequency, improved soil physical and chemical profiles (Kennedy & Schillinger, 2006), and increased prevalence of flowering plants that feed beneficial insects (e.g., He et al., 2021; Rowen et al., 2020). However, effects of soil management on ecosystem service providers likely depend on how animal functional groups interact with soil. For example, tillage harms ground-nesting bees (Ullmann et al., 2016) and predators that shelter among weeds (Cranshaw, 2004), but often has little impact on herbivorous pests (Tooker et al., 2020). Impacts of soil management on distinct functional groups may also depend on landscape context. Semi-natural habitat near farms can facilitate dispersal via habitat

corridors or provide patches of suitable habitat amidst less hospitable matrixes (Kremen et al., 2007; Tscharntke et al., 2012). However, prior studies find that organisms can benefit from field-level sustainable agriculture practices mainly in relatively simple (Scheper et al., 2013; Tscharntke et al., 2012) or complex (Kennedy et al., 2013; Lichtenberg et al., 2017) landscapes. These complexities show that there is an urgent need to study effects of sustainable agriculture practices, including soil management, on multiple functional groups at various scales.

Sustainable farming must also generate high crop yields. Because yield captures the total contribution of biotic communities and farming practices, it can be difficult to ascribe yield changes to single factors (Tamburini et al., 2019). Studies that use a single analytical framework to measure habitat availability and diversification impacts on biodiversity enable assessing how multiple elements of the biotic system, and farming practices, directly and indirectly alter crop production (Birkhofer et al., 2015; Byrnes et al., 2014; Weekers et al., 2022).

Here, we assessed how soil management through reduced tillage, and landscape context, affected arthropods in unique functional groups, and how habitat and arthropod communities affected canola yield. Canola provides floral resources for pollinators and natural enemies, but attracts pests like aphids and flea beetles (Delaplane & Mayer, 2000; Morandin & Winston, 2005; Reddy, 2017). Yield may be altered by interactions among such beneficial and harmful arthropods (Lundin et al., 2020; Morandin & Winston, 2005; Ouvrard & Jacquemart, 2019; Reddy, 2017). Specifically, we asked:

(1) Do effects of tillage on abundance and diversity of arthropods vary based on functional group? While negative impacts of tillage on soil-dwelling animals are well documented (de Graaff et al., 2019; Rowen et al., 2020), tillage impacts on insects that visit leaves, stems, and flowers remain poorly studied. However, we can reasonably hypothesize that functional groups

with higher dependence on soil are more strongly impacted by high-intensity tillage (Rowen et al., 2020). Thus, we predicted that pollinators (mainly ground-nesting bees in our study region) and the kleptoparasites that depend on them would be harmed by tillage (as in Ullmann et al., 2016). Conversely the directly of tillage impacts on herbivores, parasitoids, and predators varies widely (e.g., Jasrotia et al., 2021; Rowen et al., 2020; Serée et al., 2021; Wichura et al., 2022).

(2) Which habitat scales do various functional groups respond most strongly to? Many vegetation-visiting arthropods are highly mobile, and thus likely to be influenced by both field-scale management and the surrounding landscape (Lichtenberg et al., 2017; Marja et al., 2022). The relative importance of local and landscape habitat can vary by functional group (e.g., Lichtenberg et al., 2017; Sánchez et al., 2022), although multiple mechanisms likely drive these differences (Sirami et al., 2019), and results published to date are not consistent enough to predict differential effects for our study system.

(3) How do arthropods and habitat context affect crop yield? Reduced tillage often decreases yield, including for oilseed crops like canola (e.g., Lundin, 2019; Tamburini et al., 2020). This could potentially be counteracted if reduced tillage enhances pest control and pollination by promoting abundance or biodiversity of predators and pollinators.

Materials and methods

Study sites

We sampled arthropod abundance and diversity in canola (*Brassica napus* and *B. rapa*) fields in eastern Washington and northern Idaho during the summers of 2013 and 2014 (Fig. S1; Table S1). This heavily agricultural region has only scattered patches of semi-natural habitat. The primary crops grown are grains and legumes, but canola production has increased from 5K

to over 75K acres in the last decade because it promotes soil quality and grower profits (Painter et al., 2006; USDA NASS, 2020). As a mass-flowering crop that blooms for up to a month, canola attracts diverse flower-feeding arthropods such as pollinators and natural enemies like predators and parasitoids (Delaplane & Mayer, 2000; Morandin & Winston, 2005). Canola fields are thus an effective model system for studying multiple ecosystem service providers.

We selected 15 canola fields each year with sizes from 0.7 to 142 ha (mean ± SD = 44.4 ± 41.0). Most fields were maintained by local farmers, but four were on research farms maintained by local universities or seed companies. All seed was treated with a neonicotinoid (mainly thiamethoxam) prior to planting, and some farmers applied a pyrethroid insecticide one time at the end of or after bloom as needed to keep flea beetles and cabbage seed pod weevils below the economic threshold. Most farmers also treated their fields with an herbicide (mainly glyphosate) early in the year, well before bloom. Because farmers rotate canola with other crops, no field was sampled both years. Fields were sufficiently far apart (nearest neighbor distance of 5.4 ± 2.9 (min 1.9) km in 2013 and 6.8 ± 6.0 (min 2.8) km in 2014), relative to insect flight distances and the scale at which we measured the landscape (1 km radius), to be considered spatially independent.

Arthropod sampling

To target diverse arthropods that associate with canola flowers, we used two collection techniques: (i) traps typically used to sample bees and (ii) sweep netting. All sampling occurred along one field edge on days where daytime temperatures were above 13 ˚C and the wind speed below 4.5 m s-1. Sampling locations were haphazardly selected along accessible field edges, where we could work without damaging crops and where traps on the ground would not be

covered in vegetation. At 10:00, we conducted 100 spatially continuous sweeps at the level of the canola canopy, immediately emptied net contents into a plastic bag, and stored them on ice. In the lab, we freeze-killed arthropods, then removed them and sorted to morphospecies (see below for sorting details). Bees were pinned, while specimens in other taxa were stored in ethanol.

Around noon at each site, we set out a line of bee traps that stayed in place for 24 h. This line included two blue vane traps (SpringStar) and six pan traps painted in colors that attract bees (Kearns & Inouye, 1993; Leong & Thorp, 1999). We used two each of white, fluorescent yellow, and fluorescent blue pan traps, randomizing color order within the line. Each trap contained unscented soapy water. We separated traps by 5 m, and located them ~0.5 m from the edge of the field. Traps and sweep netting began at the same spot. The following day, we collected trapped arthropods using a strainer, washed off excess soap, and stored the specimens in ethanol. In the lab, we washed and dried bees, and all specimens were sorted to genus and morphospecies based on morphological characteristics (Arnett et al., 2002; Arnett, 2000; Arnett & Thomas, 2000; Boyle & Philogène, 1983; Derraik et al., 2002, 2010; Michener, 2000; Stehr, 1987a, 1987b). Both adults and immature forms were considered.

To aid interpretation, specimens were assigned to functional groups based on literature and information from local species (Arnett, 2000; Michener, 2000; Stehr, 1987a, 1987b). We found five common functional groups: (i) pollinators, (ii) herbivores, (iii) predators, (iv) parasitoids, and (v) kleptoparasites (Table S2). This classification considers both diet and reproductive strategy. Herbivores included major regional canola pests (thrips, aphids, flea beetles, cabbage seedpod weevils, and *Lygus* bugs; Reddy, 2017). Kleptoparasites are important regulators of bee

communities, and may be valuable indicators of pollinator biodiversity (Sheffield et al., 2013). We also considered predators and parasitoids pooled together as “natural enemies”.

Field and landscape variables

We assessed several agronomic and weather-related variables for each field: (i) field size, (ii) tillage, (iii) growing degree days, and (iv) cumulative precipitation. We determined field size in ArcGIS by creating a polygon that traced each field’s boundary, and subtracting the areas of all uncultivated patches. These patches were typically remnant prairie vegetation, and occurred both within and adjacent to fields. We determined these uncultivated patches by walking through fields and drawing patches on a map, ensuring that we covered sufficient area to see the entire field. We later converted these maps to ArcGIS polygons. To categorize each site’s tillage regimen, we asked farmers about their practices. We categorized each field as having (i) full (4 to 7 passes that produce bare soil with no remaining stubble before seeding; 6 fields), (ii) intermediate (field tilled once and then planted into remaining stubble; 13 fields), or (iii) no (seed planted directly into the previous year’s stubble; 11 fields) tillage. These represent the three main tillage regimes used in the study region. Because canola is planted very shallow, spring tillage in the region is recommended to be limited to 2 to 5 cm (Brown et al., 2009).

We incorporated temperature and precipitation variables into analyses because our sites spanned a mild precipitation and temperature gradient (PRISM Climate Group, 2020), and because weather can influence insect biodiversity (e.g., Forcella et al., 2021; Skellern et al., 2017). To measure weather variables, we gathered daily temperature and precipitation estimates from PRISM (PRISM Climate Group, 2020). We calculated growing degree days and cumulative precipitation through the day before we sampled arthropods at a field. Growing degree days

indicate accumulated heat units that are likely to affect growth of a given taxonomic group. Temperatures below 5 ˚C can hinder canola growth (Dickson, 2014). We thus calculated growing degree days as the cumulative amount of heat above 5 ˚C since January 1.

We calculated landscape composition as the amount of semi-natural habitat within a 1 km radius of each field. This radius is ecologically relevant for pollinators, herbivores, and natural enemies (Greenleaf et al., 2007; Rusch et al., 2016). We determined land cover using CropScape data (USDA SARS, 2014a, 2014b, 2015a, 2015b) and ArcGIS to calculate the areas of each land cover type around each site. Semi-natural habitat included deciduous forest, evergreen forest, grassland, shrubland, and wetlands, while crop habitats were classified as agricultural. Landscape composition around our sites ranged from 0% to 36% semi-natural habitat, and was independent of tillage regime (Kruskal-Wallis test: $X^2_2 = 2.47$, $P = 0.29$).

Data analysis

To assess how each functional group responded to local- and landscape-scale habitat, we used a regression and model selection framework. We first calculated three common community metrics – abundance, richness, and evenness (E_{var}, Smith & Wilson, 1996) – for each functional group at each site as our response variables. Evenness describes how sampled individuals are distributed across taxa, and can provide valuable insights into the degree that rare taxa are contributing to taxonomic richness and to ecosystem service functioning (Crowder et al., 2010; Winfree et al., 2015). We ran separate linear regressions for each functional group that included tillage, the proportion of semi-natural habitat within 1 km, their interaction, year, degree days through the day before sampling, cumulative precipitation through the day before sampling, and field size as fixed effects. These variables were not collinear (Table S4). It was necessary to

control for year, weather, and field size because all are known to affect insect abundance and biodiversity (e.g., Aldercotte et al., In press; Forcella et al., 2021; Fragoso et al., 2021; Skellern et al., 2017; Smith et al., 2020). Because abundance data were overdispersed, we used negative binomial regressions (MASS package, Venables & Ripley, 2002). We analyzed richness and evenness data with linear models (identity link), although herbivore evenness had to be log-transformed due to heteroscedasticity. We then used information-theoretic model selection to determine the best fit models for each metric and functional group (MuMIn package, Barton, 2014), selecting models with AICc values within 2 of the smallest value (Burnham & Anderson, 1998). Low richness values, and thus lack of variation, prevented us from analyzing kleptoparasite and parasitoid evenness, but all other metrics were assessed. This resulted in 13 models (one for each functional group and abundance/diversity metric), each with 30 observations (28 observations for predator evenness).

We next assessed how arthropod biodiversity, as well as local- and landscape-level habitat factors, affected canola yields. We ran separate linear regressions for each community metric (abundance, richness, evenness; three models total) that included tillage, the proportion of semi-natural habitat within 1 km, their interaction, year, and abundance or diversity of each arthropod functional group. All equations used linear regression (identity link), and met assumptions of this modeling approach. As with assessment of how functional groups responded to habitat context, we selected models with AICc values within 2 of the smallest value.

Ethics

This study did not require ethical approval.

Results

Overall, we collected 22,879 individuals across 131 taxa. This included 15,256 herbivores (20 taxa, 82% of individuals were pest species), 154 kleptoparasites (8 taxa), 1,080 parasitoids (6 taxa), 4,217 pollinators (64 taxa), and 739 predators (31 taxa). The most abundant taxonomic groups were thrips (7,184 individuals; herbivores, major canola pests), aphids (4,078; herbivores, major canola pests), sciaroid flies (2,041 individuals; herbivores), two halictid bee morphotaxa (813 and 581 individuals; pollinators), chalcidoid wasps (727 individuals; parasitoids), and chrysomelid beetles (576 individuals; herbivores, major canola pests). The most common predators were melyrid beetles (229 individuals).

Effects of tillage and landscape on arthropod communities

Effects of habitat context on arthropod abundance and diversity varied across functional groups. Broadly, pollinators and kleptoparasites were affected by tillage while herbivores and predators responded most strongly to landscape composition. Tillage and landscape composition never had an interactive effect. This pattern did not reflect a correlation between field- and landscape-scale habitat measures, as semi-natural habitat did not differ based on tillage regimen (Kruskal-Wallis test: $X^2_2 = 2.47$, $P = 0.29$). Overall, tillage and landscapes impacted arthropod abundance and richness more than evenness.

Pollinator richness was higher in fields with intermediate tillage than fields with no tillage (Fig. 1a; Tables S5, S6). Kleptoparasite abundance was higher in fields with either form of conservation tillage (intermediate or no tillage) than in heavily-tilled fields in one of four best models (and significant at $\alpha < 0.10$ in a second model; Fig. 1b; Tables S6, S7). Pollinator abundance and evenness, and kleptoparasite richness, were not affected by local or landscape

habitat context (Tables S5, S7, S8). There were too few kleptoparasite species (median 2 per site) to assess evenness.

Landscapes with more semi-natural habitat promoted greater herbivore (Fig. 2a) and predator (Fig. 2b) abundance regardless of tillage regime (Table S7). Herbivore diversity and predator richness were unaffected by either tillage or landscape composition (Tables S5, S8). These results did not qualitatively change if the site in the landscape with the most semi-natural habitat was removed (Table S7). Parasitoids were unaffected by habitat context at either local or landscape scale (Tables S5, S7, S8).

Environmental variables had mixed effects on arthropod abundance and diversity (Tables S5, S7, S8). As expected, all functional groups except predators showed inter-annual variation in abundance, richness, or evenness, typically with lower abundance and richness, but higher evenness, in 2013 than 2014. Cumulative precipitation had stronger impacts than degree days at time of insect sampling. Detritivore abundance, kleptoparasite abundance and richness, pollinator abundance, and predator richness were higher at sites with less precipitation, while parasitoid abundance and pollinator evenness showed the opposite pattern. Detritivore abundance, kleptoparasite richness, parasitoid abundance, and predator richness were higher at cooler sites. Field size affected only a few metrics. Kleptoparasites were more abundant and speciose, and pollinator communities were less even, at larger fields.

Differential responses of arthropod functional groups could potentially indicate trade-offs when aiming to manage for multiple functional groups. However, our results show stronger evidence of synergies than trade-offs. Functional groups with known trophic relationships had correlated metrics (Table S3). We found positive correlations in abundance and diversity of (i) pollinators and kleptoparasites, and (ii) parasitoids, predators, and herbivores (and between

natural enemies and herbivores). Additionally, abundance and evenness of pollinators versus predators and parasitoids (and of pollinators and natural enemies as a group) were positively correlated (Table S3).

Effects of tillage, landscape and arthropod communities on crop yields

Field-scale habitat management directly impacted canola yield. In all analyses, yield was lower in fields with no tillage than in fields with full or intermediate tillage (Fig. 3a, Tables S6, S9). Landscape composition did not impact canola yield, however.

We found minimal evidence for effects of habitat context on crop yield, via arthropod communities (Tables S6, S9; variance inflation factors in Table S10). Higher landscape-scale habitat availability did promote more diverse herbivore communities, which lowered crop yields (Fig. 3b; Tables S6, S9). However, arthropod abundance and evenness, and richness of other functional groups, did not impact yield.

Discussion

Soil management can affect arthropod biodiversity, with impacts varying by functional group or landscape context, due to differences in resource needs or dispersal among taxa (Bommarco et al., 2013; Harmon-Threatt, 2020). Because many of these arthropods provide ecosystem services or are pests, biodiversity impacts are predicted to affect crop yield. However, impacts of soil-management on above-ground arthropods are poorly studied. We found that agricultural landscapes can simultaneously support pollinators and predators, but that different functional groups respond to habitat context at separate scales. Pollinators were affected by field-scale availability and diversity via reduced tillage, while landscapes with more semi-natural

habitat promoted herbivores and predators. Although habitat context affected arthropod biodiversity, arthropods did not strongly impact crop yield. Our results show that sustainable agriculture practices can impact crop yield directly, but not always indirectly by promoting higher arthropod biodiversity (as in Ricketts et al., 2016, but contrary to Dainese et al., 2019).

We found that pollinator and kleptoparasite, but not herbivore, predator, or parasitoid guilds responded to tillage intensity. We expected reduced tillage would promote pollinators, and kleptoparasites that depend on them, by destroying fewer ground-nesting bee nests and improving soil quality (Kennedy & Schillinger, 2006; Ullmann et al., 2016). Intriguingly, we found that intermediate tillage supported a more diverse pollinator community than no tillage. One potential explanation is that untilled soil contains too thick a layer of decaying crop stems for bees to dig through (Stinner & House, 1990). However, tillage impacts, and presence of kleptoparasites that are typically found in the vicinity of bee nests, do suggest that bees are nesting in canola crop fields or nearby grain or legume fields, which is often assumed to not occur (Kleijn et al., 2011).

Effects of tillage on natural enemies and herbivores are more well studied than for bees, although results have been mixed for each group (Furlan et al., 2021; Rowen et al., 2020; Tooker et al., 2020). When reduced tillage promotes natural enemies, likely mechanisms are increased availability of weeds that provide nectar, or surface mulch that provides shelter and prey (Clark et al., 1993; Stinner & House, 1990). The first mechanism is likely not operating in our system because canola provides abundant nectar and weeds were controlled with glyphosate. The second mechanism may also not be relevant because crops rotated with canola do not contribute much mulch (Hammel, 1996). When reduced tillage promotes herbivores, it mainly does so due to less soil disturbance or by promoting larger or more diverse weed communities (Rowen et al., 2020).

Neither mechanism applies to our study, since we mainly sampled herbivores that reside near the tops of plants rather than in soil, and weeds were controlled. Thus, it is not surprising that tillage intensity did not affect natural enemies or herbivores. This highlights the importance of studying mechanisms underlying habitat-biodiversity relationships, including how species' natural histories relate to both food and shelter resources within a habitat (Carvalheiro et al., 2021).

We found that landscapes with more semi-natural habitat promoted predators and herbivores. Heterogeneous landscapes offer opportunities for mobile consumers to exploit patchy resources (Tscharntke et al., 2012). Predators and our main herbivores (aphids and thrips) routinely travel long distances in search of suitable habitat patches (Loxdale & Lushai, 1999; Schellhorn et al., 2014). In contrast, most of our pollinators (bees) are central place foragers that repeatedly return to a single nest and visit food patches only within their flight range of this nest. Indeed, bees visiting canola flowers in Alberta tended to travel only a few meters from their nest when surrounded by canola flowers (Robinson, 2019). Thus, most of the bees we collected likely were nesting in or near the fields we sampled, and were affected more by tillage than landscape composition. This result mirrors meta-analyses that suggest that highly mobile organisms are more likely to respond to landscape-scale habitat patterns than less mobile organisms (Lichtenberg et al., 2017; Schneider et al., 2014).

While we show local and landscape habitat patterns affected arthropod communities, these communities minimally impacted crop yields, similar to studies that have found no relationship between multi-diversity and multifunctionality (Birkhofer et al., 2018). We did find that yield was lower in fields with higher herbivore richness. Inspection of herbivore abundances at each site (Table S11) suggests two potential drivers. First, sites with higher herbivore richness could have higher pest abundance (Table S3). Second, sites with higher herbivore richness could be

more likely to contain a specific damaging pest. Our data shows high-herbivore-richness fields contained large numbers of aphids, a key canola pest (Reddy, 2017). We also found more chrysomelids, curculionids, meloids, scraptiids, pentatomids, and yponomeutids in sites with higher herbivore richness. However, the only canola pests in these groups are seedpod weevils (Curculionidae), which damage a later crop stage than we sampled (Reddy, 2017).

Abundance and diversity of "beneficial" pollinators and predators also did not affect canola yield. Canola has high variability in pollinator dependence (Ouvrard & Jacquemart, 2019), and the ≥ 15 varieties in our study may not be pollinator dependent (as in Perrot et al., 2018), or the study region is windy enough to ensure high pollen dispersal. Variation in pollinator dependence may explain the difference between our results and other studies that find increased yield of oilseed crops with higher pollinator abundance (Catarino et al., 2019). Benefits from pollinators and predators may have also been limited by insecticide use, as farmers grow insecticide-coated seeds that provide plants with systemic insecticide coverage. This may effectively control herbivore pests, or reduce pollinator abundance (Catarino et al., 2019). It is also possible that pollinators or predators correlate with common measures of single ecosystem services, such as pollen deposition or consumption of sentinel pests on a small subset of plants. If such patterns were present, they did not scale up to the entire field (as found by Birkhofer et al., 2018; Sutter et al., 2018; Tamburini et al., 2020), and thus are unlikely to affect farmer decisions.

Tillage intensity did affect crop yields. Reduced tillage has previously been found to reduce yield for crops including oilseed rape (Lundin, 2019; Tamburini et al., 2020). Indeed, multiple sustainability-oriented farming practices (e.g., organic farming) sometimes result in lower yield than their conventional counterparts (Smith et al., 2020; Tamburini et al., 2020). Despite the yield loss seen here, reduced tillage can provide other benefits such as improving soil infiltration,

reducing erosion, decreasing evaporative water loss from soil, and improving soil quality (Hammel, 1996; Kennedy & Schillinger, 2006). These factors might ultimately increase yield of other crops or reduce farmers' costs. This highlights the complex decisions that underlie farm management decisions.

Overall, our study highlights the need to understand how biodiversity patterns and crop yields are simultaneously affected by multiple mechanisms, including via soil management, at various scales. We showed that field-scale soil habitat management impacted pollinators, while landscape-scale habitat availability promoted predators and herbivores. These differences likely reflect natural history differences among these functional groups. However, these habitat impacts on biodiversity only minimally impacted yield. It is often assumed that enhancing biodiversity promotes ecosystem services, although evidence from arthropod-mediated ecosystem services such as pollination and pest control is mixed (e.g., Birkhofer et al., 2018; Dainese et al., 2019; Ricketts et al., 2016). Without clear evidence that a conservation action such as reduced tillage is likely to increase crop yield, adoption by farmers will likely remain low (Kleijn et al., 2019). Thus, data-driven management of agricultural landscapes to simultaneously support natural biodiversity and boost crop yield requires much more research to determine the contexts in which given management practices, and soil diversification practices in particular, do or do not meet this multi-faceted goal.

Author contributions

EML and DWC conceived the ideas and designed methodology; EML collected and analyzed the data; IM identified arthropods; EML and AJC led the writing of the manuscript; All authors contributed critically to the drafts and gave final approval for publication.

Statement on inclusion

Our study design and results interpretation incorporated local knowledge from stakeholders, and results were communicated with stakeholders through outreach.

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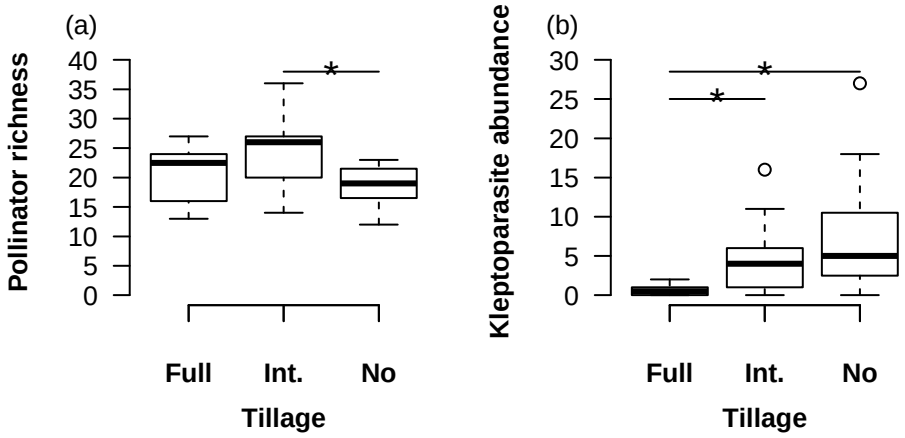

Fig. 1: Box and whisker plots of (a) pollinator richness and (b) kleptoparasite abundance as a function of tillage intensity. "Int." is intermediate tillage. Lines with asterisks indicate groups that are statistically different from each other.

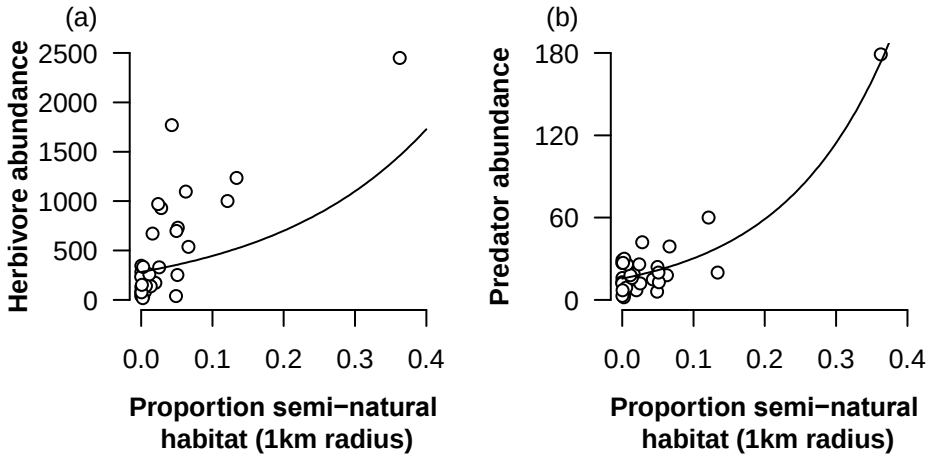

Fig. 2: (a) Herbivore and (b) predator abundance increase with landscape-scale habitat availability (proportion of semi-natural habitat in a 1 km radius around a site). Curves show best-fit lines from negative binomial regressions.

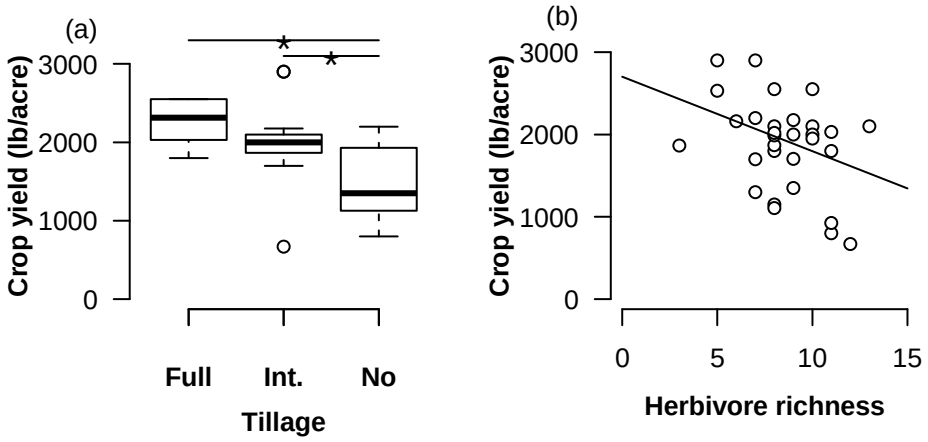

Fig. 3: Canola yield (a) was lowest with no tillage and (b) decreased as herbivore richness increased. “Int.” is intermediate tillage. Lines with asterisks (a) indicate groups that are statistically different from each other. The curve (b) shows the best-fit line from linear regression.