Differential effects of soil conservation practices on arthropods and crop yield

Running title: Tillage impacts on arthropods and crop yield

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Abstract

1. Many agricultural management tactics, such as reduced tillage, aim to promote biodiversity and ecosystem services. Responses to such tactics can be context dependent, however, and differentially impact (i) functional groups of service-providing organisms and (ii) crop yields.
2. In canola (*Brassica napus* Linnaeus, *B. rapa* L) crop fields we assessed how soil tillage and landscape context affected arthropod biodiversity and crop yield. We assessed 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 functional groups with unique diets and reproductive strategies: (i) herbivores, (ii) kleptoparasites, (iii) parasitoids, (iv) pollinators, and (v) predators.
3. Effects of tillage and landscape context on arthropod abundance and diversity varied across functional groups. Pollinators responded strongest to tillage, benefitting from intermediate tillage. Predators and herbivores responded strongly to landscape context, as both were more abundant in landscapes with more semi-natural habitat. Our results suggest natural history differences among functional groups mediate effects of landscape context on biodiversity. However, variation in arthropod communities had little effect on canola crop yield.
4. *Policy implications:* The effects of soil management practices on aboveground arthropods are complex, and practices thought to increase some aspects of agricultural sustainability may not be beneficial in other contexts. Identifying practices such as intermediate tillage that may increase soil quality and arthropod diversity is key to designing agricultural ecosystems that will effectively benefit both biodiversity and human wellbeing.

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

Introduction

Agricultural management tactics such as intercropping and reduced tillage are implemented in an effort to support biodiversity and ecological services in agroecosystems without sacrificing yield. Reduced tillage, for example, supports biodiversity by creating soil habitat availability and heterogeneity (de Graaff et al. 2019; Tamburini et al. 2020). However, responses of organisms to practices such as tillage often vary among service-providing functional groups (Lefcheck et al. 2015; Mitchell et al. 2015). This has led to calls to better assess impacts of habitat change on multiple ecosystem services such as soil quality, pollination, and crop yield (Bommarco et al. 2013; Tamburini et al. 2020). Given the complexity of agricultural food webs, studies should also assess how organisms in unique functional groups respond to management.

Effects of in-field soil management practices on ecosystem service providers likely depend on how animal functional groups interact with soil. For example, tillage can harm ground-nesting bees (Ullmann et al. 2016) and predators that shelter among weeds (Cranshaw 2004), but often has little to no impact on herbivorous pests that feed on crops (Tooker et al. 2020). While reduced tillage is implemented to limit soil erosion and conserve soil moisture, it can also affect soil chemical and physical profiles, and availability of flowering plants that feed beneficial insects (Kennedy and Schillinger 2006). However, impacts of soil management practices on distinct functional groups may also depend on the landscape context. Semi-natural habitat near farms can facilitate dispersal of organisms to crops (Kremen et al. 2007; Tscharntke et al. 2012) and responses of organisms to particular practices may depend on the landscape context. Indeed, some studies show benefits of sustainable agricultural practices accrue most strongly in relatively simply landscapes, while others show the greatest benefits in complex landscapes (Tscharntke et al. 2012; Kennedy et al. 2013; Scheper et al. 2013; Lichtenberg et al. 2017).

While supporting biodiversity is often a goal of agricultural production systems, crops must also generate high yield. Because yield captures the total contribution of biotic communities and farming practices, it can be difficult to ascribe yield to single factors (Tamburini et al. 2019). Studies are thus needed that use a single analytical framework to assess how habitat availability and diversification affect biodiversity and yield, both directly and through indirect interactions among organisms and management practices (Byrnes et al. 2014; Birkhofer et al. 2015; Weekers et al. 2022). Such studies may be particularly useful when conducted at field-level scales that involve commercial production and representative growing practices for a given region.

Here we assessed how soil tillage affected arthropod functional groups in canola (*Brassica napus* Linnaeus, *B. rapa* L) crops of the Pacific Northwest USA, and how landscape context and tillage interacted with arthropods to affect yield. Canola provides floral food for pollinators and natural enemies, but attract pests like aphids (Aphididae) and flea beetles (Chrysomelidae). We first asked if effects of tillage on arthropod abundance and diversity varied by functional group. We hypothesised functional groups with soil dependence, like pollinators and kleptoparasites, would be most strongly impacted by tillage (Rowen et al. 2020). Second, we asked if responses of functional groups to tillage depended on landscape context, given variation in mobility and habitat needs of unique organisms (Lichtenberg et al. 2017; Marja et al. 2022). Third, we asked whether variation in arthropod communities interacted with tillage and landscape context to affect yield (Delaplane and Mayer 2000; Morandin and Winston 2005; Reddy 2017). Reduced tillage often decreases crop yield (e.g., Lundin 2019; Tamburini et al. 2020), but enhanced pest control or pollination could counteract this. This allowed us to assess how agricultural practices directly and indirectly affected multiple ecosystem services and biodiversity across landscapes.

Materials and Methods

Study sites

We sampled arthropods in spring canola fields in eastern Washington and northern Idaho during 2013 and 2014 (Fig. S1; Table S1). This heavily agricultural region has patches of semi-natural habitat amidst considerable acreage of grains, legumes, and canola (Painter et al. 2006; USDA NASS 2020). As a mass-flowering crop that blooms for up to a month, canola attracts flower-feeding arthropods such as pollinators and natural enemies like predators and parasitoids (Delaplane and Mayer 2000; Morandin and Winston 2005). Canola fields are thus an effective model system for studying multiple ecosystem service providers across unique functional groups.

We selected 15 fields each year ranging from 0.7 to 142 ha (mean ± SD = 44.4 ± 41.0). The short canola bloom period and relatively small number of spring canola fields in the region limited further sampling. Most fields were maintained by local farmers with four maintained by local universities or seed companies. All seed was treated with a neonicotinoid, and some sites applied a pyrethroid insecticide once after bloom to control flea beetles and cabbage seed pod weevils (*Ceutorhynchus obstrictus* [Marsham]). Most farmers also applied an herbicide treatment (glyphosate) before bloom. Fields were spaced at least 2 km apart, which was sufficiently far relative to insect flight distances to consider them spatially independent.

Arthropod sampling

We used two collection techniques to sample diverse arthropods that associate with canola: (i) traps typically used to sample bees and (ii) sweep nets. All sampling occurred along one field edge on days with daytime temperatures above 13 ˚C and wind speed below 4.5 m/s. 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 continuous sweeps in the canola canopy, emptied net contents into a plastic bag, and stored them on ice. In the lab, we freeze-killed arthropods, then sorted them to morphospecies. Bees were pinned and specimens in other taxa were stored in ethanol.

Around 12:00, 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 colours that attract bees (white, fluorescent yellow, fluorescent blue; Kearns and Inouye 1993; Leong and Thorp 1999). We separated traps by 5 m and located them ~0.5 m from the field edge. 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 (Boyle and Philogène 1983; Stehr 1987a, 1987b; Arnett 2000; Arnett and Thomas 2000; Michener 2000; Arnett et al. 2002; Derraik et al. 2002, 2010). Both adults and immature forms of all arthropod groups were considered.

Specimens were also assigned to five functional groups using literature and information from local species (Stehr 1987a, 1987b; Arnett 2000; Michener 2000): (i) pollinators, (ii) herbivores, (iii) predators, (iv) parasitoids, and (v) kleptoparasites (Table S2). This classification considered both diet and reproductive strategy. Herbivores included major regional canola pests (thrips [Thysanoptera], aphids, flea beetles, cabbage seedpod weevils, and *Lygus* bugs Hahn; Reddy 2017). Kleptoparasites are regulators of bee communities, and may reflect overall levels of pollinator biodiversity (Sheffield et al. 2013). We also considered predators and parasitoids pooled together as “natural enemies”.

Field and landscape variables

For each site we assessed agronomic and weather factors that can affect insects: (i) tillage, (ii) field size, (iii) growing degree days, and (iv) cumulative precipitation (e.g., Skellern et al. 2017; Smith et al. 2020; Forcella et al. 2021; Fragoso et al. 2021; Aldercotte et al. 2022). We asked farmers directly to categorise each site's tillage regime. A field had either (i) full (4 to 7 passes producing bare soil with no stubble before seeding; n = 6), (ii) intermediate (field tilled once with some stubble remaining before seeding; n = 13), or (iii) no (soil not tilled and seed planted directly into the previous year's stubble; n = 11) tillage. These represent the three main tillage regimes used in the 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 determined field size in ArcGIS by creating a polygon tracing the boundary and subtracting the areas of all uncultivated patches (typically remnant prairie within and adjacent to fields; originally mapped by hand). We gathered daily temperature and precipitation values from PRISM (PRISM Climate Group 2020) and calculated growing degree days and cumulative precipitation through the day before we sampled arthropods. These environmental measures can cause inter-annual variation in arthropod populations (Skellern et al. 2017; Forcella et al. 2021). Growing degree days were calculated as the cumulative amount of heat above 5 ˚C since January 1 (Dickson 2014).

We also calculated the amount of semi-natural habitat within 1 km of each field, a radius that 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) to calculate area of each land cover type around each site. Semi-natural habitat included forests, grassland, shrubland, and wetlands, while crop habitats were classified as agricultural. Landscapes 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

We used model selection to test how functional groups responded to tillage and landscape context. We calculated three community metrics – (i) abundance, (ii) richness, and (iii) evenness (E_{var}, Smith and Wilson 1996) – for each functional group at each site. Evenness captures how individuals are distributed across taxa and indicates the degree that rare taxa affect ecosystem functioning (Crowder et al. 2010; Winfree et al. 2015). We ran linear regressions for each functional group with tillage, proportion semi-natural habitat, their interaction, year, degree days, cumulative precipitation, and field size as fixed effects. These variables were not collinear (Table S4). As abundance data were overdispersed, we used negative binomial regressions (MASS package, Venables and Ripley 2002). We analysed richness and evenness with linear models (identity link), but herbivore evenness was log-transformed due to heteroscedasticity. All analyses met model assumptions. We used information-theoretic model selection to assess model fit for functional group metrics (MuMIn package, Barton 2014), and selected models with AICc values within 2 of the lowest value (Burnham and Anderson 1998). Low richness, and thus lack of variation, prevented us from analysing kleptoparasite and parasitoid evenness; all other metrics were assessed. There were 13 total models, one for each functional group and community metric, each with 30 observations (28 for predator evenness).

We next assessed how arthropod biodiversity, tillage, and landscape context affected canola crop yield; farmers provided yield data for their sites directly. We ran separate linear regressions with abundance, richness, or evenness that also included tillage, proportion semi-natural habitat, their interaction, and year. For each set of models, we selected the best fit models as those with AICc values within 2 of the smallest value.

Results

We collected 22,879 individuals across 131 taxa, with 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 herbivores were thrips, aphids, sciaroid flies, and chrysomelids (7,184, 4,078, 2,041, and 576 individuals, respectively). The most common pollinators were two halictid bee morphospecies (813 and 581 individuals). The most common natural enemies were chalcidoid wasps (727 individuals, parasitoid) and melyrid beetles (229 individuals, predator).

Effects of tillage and landscape on arthropod communities

Overall, pollinators and kleptoparasites were affected by tillage while herbivores and predators responded most strongly to landscape composition. 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 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 tillage or landscape context (Tables S5, S7, S8). In contrast, more semi-natural habitat promoted herbivore and predator abundance regardless of tillage regime (Fig. 2; Table S7). Herbivore diversity and predator richness were unaffected by tillage or landscape context (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 tillage or landscape context (Tables S5, S7, S8). Tillage and landscape composition never had an interactive effect.

Environmental variables had mixed effects on arthropod abundance and diversity (Tables S5, S7, S8). Precipitation generally had stronger impacts on arthropod communities than degree days. Greater detritivore abundance, kleptoparasite abundance and richness, pollinator abundance, and predator richness occurred at sites with lower precipitation. Parasitoid abundance and pollinator evenness had the opposite pattern. Detritivore abundance, kleptoparasite richness, parasitoid abundance, and predator richness were highest at cooler sites. Larger fields were associated with greater kleptoparasite abundance and richness but lower pollinator evenness.

Differential responses of arthropod functional groups may indicate trade-offs when aiming to manage biodiversity, but we found stronger evidence for synergies than trade-offs. Functional groups with known trophic relationships often had correlated metrics (Table S3). For example, we found positive correlations in abundance and diversity between pollinators and kleptoparasites, and among parasitoids, predators, and herbivores. Abundance and evenness of pollinators was also positively correlated with abundance and evenness of natural enemies, as well as individual natural enemy groups (predators or parasitoids) (Table S3).

Effects of tillage, landscape and arthropod communities on crop yields

Tillage strongly affected canola yield, and yield was lower in fields with no tillage than with full or intermediate tillage (Fig. 3a, Tables S6, S9). Landscape composition did not impact canola yield, however. We found little evidence for effects of landscape context or arthropod communities on yield (Tables S6, S9; S10). Higher landscape-scale habitat availability promoted more diverse herbivore communities, which lowered yield (Fig. 3b; Tables S6, S9). However, arthropod abundance and evenness, and richness of other functional groups, did not impact yield.

Discussion

Soil management may differentially affect functional groups 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 can affect crop yield. We found that agricultural landscapes can simultaneously support pollinators and predators, but different functional groups respond to habitat variability at different scales. Pollinators were most affected by tillage within fields, while landscape context most strongly affected herbivores and predators. Yet, no arthropod group strongly impacted crop yield. Our results show that agriculture practices alter crop yield directly, but not always indirectly by affecting arthropods (as in Ricketts et al. 2016).

We found that pollinator and kleptoparasite, but not herbivore, predator, or parasitoid taxa responded to tillage. Reduced tillage may promote pollinators and kleptoparasites by destroying fewer ground-nesting bee nests (Kennedy and Schillinger 2006; Ullmann et al. 2016), but we found intermediate tillage supported a more diverse pollinator community than no tillage. One potential explanation is that untilled soil contains a thick layer of crop stems that prevent ground nesting (Stinner and House 1990). However, our observed impacts of tillage along with the presence of kleptoparasites suggests that many bee species nest in canola crop 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 (Rowen et al. 2020; Tooker et al. 2020; Furlan et al. 2021). Reduced tillage can benefit natural enemies by promoting weeds that provide nectar or surface mulch that provides shelter and prey (Stinner and House 1990; Clark et al. 1993). These mechanisms are likely not operating in our system as canola provides abundant nectar, farmers controlled weeds, and crops in the region do not contribute much mulch (Hammel 1996). When reduced tillage promotes herbivores, it mainly does so due to less soil disturbance or by promoting weeds (Rowen et al. 2020). Neither mechanism applies here, since we mainly sampled herbivores that reside near the tops of plants rather than in soil, and farmers manged weeds. Thus, it is not surprising that tillage did not affect natural enemies or herbivores. This highlights the necessity of studying mechanisms mediating how species' life histories relate to food and shelter resources (Carvalheiro et al. 2021).

Heterogeneous landscapes provide opportunities for consumers to exploit patchy resources (Tscharntke et al. 2012), and landscapes with more semi-natural habitat had more predators and herbivores. Predators and our main herbivores (aphids and thrips) routinely travel long distances in search of suitable habitat (Loxdale and Lushai 1999; Schellhorn et al. 2014). In contrast, most pollinators are central place foragers that repeatedly return to a single nest. Indeed, bees visiting canola flowers tend to travel only a few metres from their nest (Robinson 2019). Thus, most of the bees we collected likely were nesting in or near the canola fields we sampled, and were thus 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 (Schneider et al. 2014; Lichtenberg et al. 2017).

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 pollinators and predators also did not affect yield. Canola has high variability in pollinator dependence (Ouvrard and Jacquemart 2019), and the varieties in our study may not be pollinator dependent (Perrot et al. 2018), or the study region is windy enough to ensure pollen dispersal. Variation in pollinator dependence may explain differences between our results and 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 (neonicotinoid treated seeds) that may control pests and may reduce pollinator abundance. 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.

Tillage intensity did affect crop yields, similar to studies showing reduced tillage reducing yield for oilseed rape and other crops (Lundin 2019; Tamburini et al. 2020). Indeed, multiple sustainability-oriented farming practices sometimes result in lower yield than their conventional counterparts (Smith et al. 2020; Tamburini et al. 2020). Despite 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 and

Schillinger 2006). These factors might ultimately increase yield of other crops or reduce farmers' costs. This highlights the complex decisions that underlie farm management.

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 tillage impacted pollinators, while landscape context strongly affected predators and herbivores. These differences likely reflect natural history differences among functional groups. However, these habitat impacts on biodiversity 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., Ricketts et al. 2016; Birkhofer et al. 2018; Dainese et al. 2019). 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.

Conflict of Interest Statement

We declare no conflict of interest.

Author Contribution

EML and DWC conceived research. EML conducted experiments. IM identified arthropods. EML analysed data and conducted statistical analyses. EML, AJC and DWC wrote the manuscript. DWC secured funding. All authors read and approved the final manuscript.

Data Availability Statement

Data will be published via SCAN and Zenodo.

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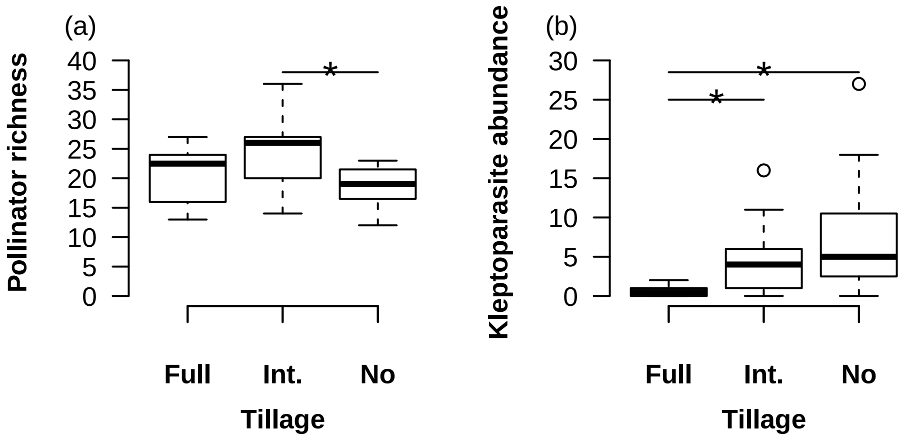

Fig. 1: Box and whisker plots of (a) pollinator richness and (b) kleptoparasite abundance as a function of tillage intensity. “Int.” is intermediate tillage. Lines with asterisks indicate groups that are statistically different from each other.

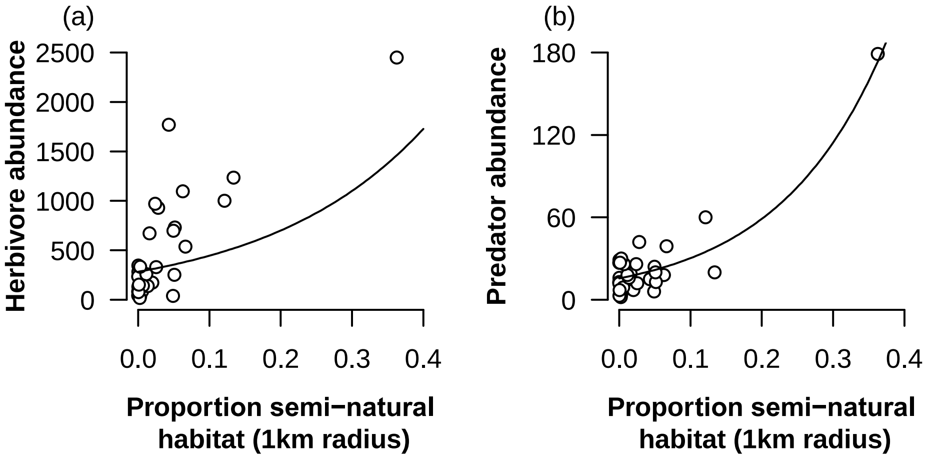

Fig. 2: (a) Herbivore and (b) predator abundance increase with landscape-scale habitat availability (proportion of semi-natural habitat in a 1 km radius around a site). Curves show best-fit lines from negative binomial regressions.

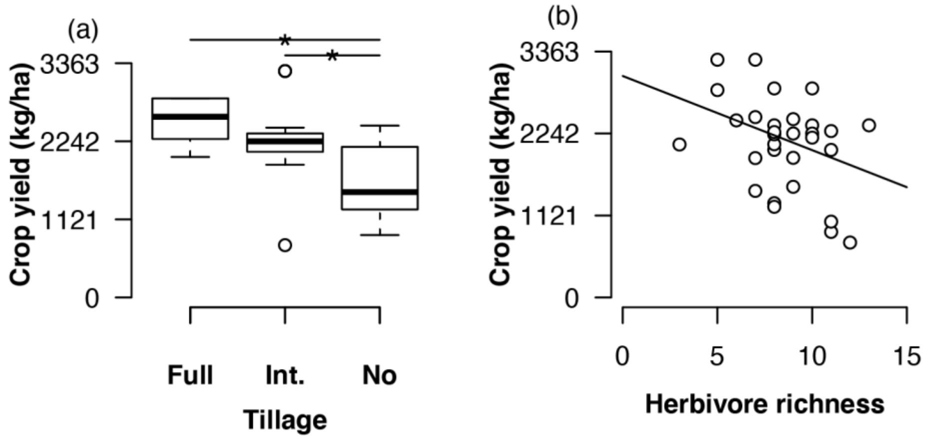

Fig. 3: Canola yield (a) was lowest with no tillage and (b) decreased as herbivore richness increased. “Int.” is intermediate tillage. Lines with asterisks (a) indicate groups that are statistically different from each other. The curve (b) shows the best-fit line from linear regression.