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Research article

Arthropod removal in wheat fields enhanced yield regardless of natural habitat patch proximity

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ABSTRACT

Natural habitat patches can be essential in conserving biodiversity and providing ecosystem services for agro-ecological systems. However, adopting a land-sharing approach requires a deep understanding of the agricultural costs and benefits associated with the existence of adjacent natural habitat patches. We used 17 paired natural habitat patch-wheat field replicates to test the effects of distance from the natural patches and removal of ground-dwelling arthropods from the field on the wheat yield. Removing ground-dwelling arthropods increased wheat yield. Community compositions of ground-dwelling arthropods in the natural habitat patches and wheat fields varied significantly, irrespective of the distance from the natural patch. In April and May, near the wheat harvest, predator abundance was higher in the natural habitat patches than in the wheat fields, whereas the abundance of potential pests was much higher in the wheat fields. This reduced predator-pest ratio in the wheat fields may explain why removing ground-dwelling arthropods increased wheat yield. Future research should focus on developing effective methods for managing ground-dwelling and vertical wheat pest populations while preserving their natural enemies' integrity within the fields and adjacent natural habitat patches.

1. Introduction

Agricultural practices are necessary for sustaining the ever-expanding global human population (Khan et al., 2021). However, agriculture utilizes 40% of the Earth's land surface (Ramankutty et al., 2008), primarily contributing to global changes and accelerated environmental degradation (Clark and Tilman, 2017). Agroecology aims to address such conflicts between biodiversity and food production by implementing ecological principles in agricultural systems, referred to as wildlife-friendly agriculture, which can simultaneously benefit conservation and food production (Wezel et al., 2009; Duru et al., 2015; Gallardo-López et al., 2018). Many agricultural ecosystems comprise a continuous landscape mosaic formed by natural habitat patches (hereafter, natural patches) and farming areas. These agroecosystems provide and rely on ecosystem services, defined as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life" (Lawton, 1998). Consequently, agroecology aims to optimize ecosystem services for agriculture, which rely on the surrounding landscape's diversity and functioning (Tilman, 1999; Barrios et al., 2020).

Several previous studies show positive influences of natural and semi-natural areas in agroecological landscapes (e.g., grass and wildflower strips, uncultivated field edges, and natural patches) on agricultural yield (Duelli et al., 1990; Holland et al., 2012; Boetzl et al., 2019). Such areas may host wild predatory invertebrates that play an essential role in supporting ecosystem services in arable crops (Woodcock et al., 2016), providing them with alternative energy resources and habitats for over-wintering and nesting (Tscharntke et al., 2005; Blitzer et al., 2012; Tschumi et al., 2016), as was shown for predatory invertebrates, including spiders (Griffiths et al., 2008) and ground beetles (Bilde and Topping, 2004; Fournier and Loreau, 2001). For example, Holland et al. (2012) reported increased aphid control in wheat fields with expanded grass strips. In another study, Rand and Tscharntke (2007) discovered a significant rise in the ratio of natural enemies to prey in

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wheat-dominated patches. A meta-analysis by Dainese et al. (2019) found clear evidence that the richness of natural enemies positively influenced service delivery.

The functional implications of natural enemy spillover to crops and the impact of natural habitats on pests remain inconclusive (Veres et al., 2013; Karp et al., 2018). Martin et al. (2013) showed in a field exclusion experiment that landscape complexity can have diverse effects on trophic interactions among natural enemies, potentially limiting ecosystem services and cabbage yield. Plant diversity in natural patches can benefit both the pest and natural enemy populations, complicating the identification of biological control benefits. (Tscharntke et al., 2016). Furthermore, natural patches can serve as winter shelters for pests, leading to spillover into agricultural fields (Blitzer et al., 2012; Sivakoff et al., 2013; Laterza et al., 2023). Growers are concerned that increased biodiversity from natural patches may adversely affect agricultural yield and production quality. Overall, understanding these interactions is crucial for effective pest management, balancing farmer needs and environmental considerations (Tscharntke et al., 2016).

Previous works suggested that host ranges in many insects that promote spillover effects are likely widespread (Blitzer et al., 2012), but only a few included yield quantifications as a function of distance. Raatz et al. (2019) measured the impact of semi-natural habitats on wheat yield and showed that wheat yield losses were relevant directly adjacent to natural landscape elements (5 and 10 m). Furthermore, the same study group found an increase in wheat yield with distance from the semi-natural habitat (Raatz et al., 2021). Still, these losses are putatively reduced by conventional farming practices (Raatz et al., 2021). Arable weeds were the most promising biotic cause of wheat yield losses only at the 1-m and 5-m distance from the natural patches (Raatz et al., 2019, 2021). However, herbivory rates greater than 10% of the leaf surface, caused by cereal leaf beetle larvae (*Oulema* spp.), did not affect wheat yield (Raatz et al., 2021). Also, Mei et al. (2021) showed that wheat yield, at a 5 m distance from the field margins, was 15% higher in fields with flower strips than in fields without flower strips. However, this difference was no longer apparent at 20 m from the margins (Mei et al., 2021).

In contrast, Rodenwald et al. (2023) assessed the impact of two field margin types, grassy strip versus flower strip, and found that wheat yield did not vary with distance to any field margin. The abundance of cereal leaf beetles was significantly higher in the field interior than in the field edge (Rodenwald et al., 2023). Gras et al. (2016) showed that removing predatory ants from cocoa tree trunks, known to feed on herbivores such as caterpillars and beetles, reduced cocoa yields from 600 to 300 kg ha^{-1}. A net exclusion experiment in apple orchards in Washington, USA, illustrated that fruits obtained from caged plants exhibited significantly lower overall damage than conventional and control treatments (Marshall and Beers, 2022). Consequently, the net effect of arthropod removal on yield is contingent upon its impact on the abundance of pests and natural enemies within the ecosystem, which can compensate for each other (Bianchi et al., 2006).

The present study aimed to empirically examine the complex interplay between wheat fields and natural patches in an agroecosystem using a large-scale field experiment. We hypothesized that removing ground-dwelling arthropods has a negative, positive, or neutral effect on wheat yield, depending on how much pests versus natural enemies are affected. Alternatively, if ground-dwelling arthropod removal decreases pest species while having little effect on natural enemies, it may positively contribute to crop productivity. To address these hypotheses, we explored how removing ground-dwelling arthropods from the agricultural matrix influenced wheat yield at different distances from the natural patches. Ground-dwelling arthropods were experimentally excluded from the wheat fields at varying distances from the natural patches to assess the yield's response. This approach, notably underutilized (Holland, 1998), addresses three key questions: (i) If and to what extent does the removal of arthropods influence wheat yield? (ii) How does wheat yield change as a function of distance from natural patches? (iii) How does the composition of arthropod communities in the wheat fields change with proximity to natural patches? Our working hypothesis for the first question is that wheat yield changes with arthropod removal following the change in the ratio between natural enemies and pests. For our second question, our working hypothesis is that wheat yield either increases (Raatz et al., 2019) or decreases (Woodcock et al., 2016) with increasing distance because of spillover effects of pest populations or natural enemies from the adjacent natural habitat patches, respectively. Finally, for the third question, we hypothesize that ground-dwelling arthropod community composition within wheat fields gradually changes with distance from the natural patches.

2. Materials and methods

2.1. Research area

The topography of the Southern Judea Lowlands (SJL) features gentle, rolling limestone hills interspersed with loessal valleys (Ben-Yosef, 1980). It is located in a semi-arid climatic zone, experiencing an average annual precipitation of 425 mm during winter (October–March), calculated over the last 30 years (IMS-Israel Meteorologic Service, https://ims.gov.il/he/ClimateAtlas), with an average minimum temperature of 8.5° in January and an average maximum temperature of 34.3° in August. Over the past five thousand years, human development has led to habitat fragmentation, and modern agricultural practices have created a mosaic of isolated and semi-isolated limestone hills within the agricultural matrix (Ben-Yosef, 1980). These natural patches, characterized by native vegetation ranging from scrubland and garrigue to batha on thin, rocky soils (Waizel, 1984), are economically unsuitable for cultivation. Despite this, they exhibit high biodiversity, making the area an excellent model system for studying agroecological processes (Yaacobi et al., 2007; Giladi et al., 2011; Rotem, 2014; Gavish and Ziv, 2016; Chase et al., 2018).

2.2. Wheat pests

Various insect species, such as aphids (e.g., *Sitobion avenae, Rhopalosiphum padi*, and *Schizaphis graminum*), wheat mites (*Petrobia latens* and *Penthaleus* major), wheat flukes (*Sitodiplosis mosellana* and *Contarinia tritici*), Hessian fly (*Mayetiola destructor*), wheat stem sawfly (Cephidae), and wheat midge (*Sitodiplosis mosellana*, family: Ceccidomyidae), are known wheat pests, causing substantial yield reduction (Willocquet et al., 2008; Savary et al., 2019). Farmers typically use various pest control measures to minimize damage to wheat crops (Tilman, 1999; Liu et al., 2016; Schmid et al., 2018). However, growing concern over these methods' long-term sustainability and environmental impact has increased interest in more sustainable pest management strategies, such as biological control and integrated pest management. (Griffiths et al., 2008; Gavish-Regev et al., 2009; Raatz et al., 2021).

2.3. Experimental design

The study was conducted in the wheat fields surrounding Kibbutz Beit Nir, Israel (31.640°-31.669°N, 34.829°-34.878°E; Fig. 1). The elevation at the study area ranges between 157 and 244 m above sea level. Annual precipitation in the year of the study, 2021, was 476 mm from November through May (rains ended in March: https://rain.cabri.org.il/Beit-Nir/Season). Minimum and maximum temperatures during the study period ranged between 3.2° and 41.4 °C. Seventeen wheat fields and adjacent natural patch pairs, called patch-field arrays, were selected with a distance of at least 100 m between arrays. We chose to focus less on edge effects and more on within-field effects. Therefore, each array included three treatment levels extending into the field from the border with the natural patch at distances of 20, 40, and 60 m to assess the impact of distance on wheat yield. A 1m × 1m sampling plot

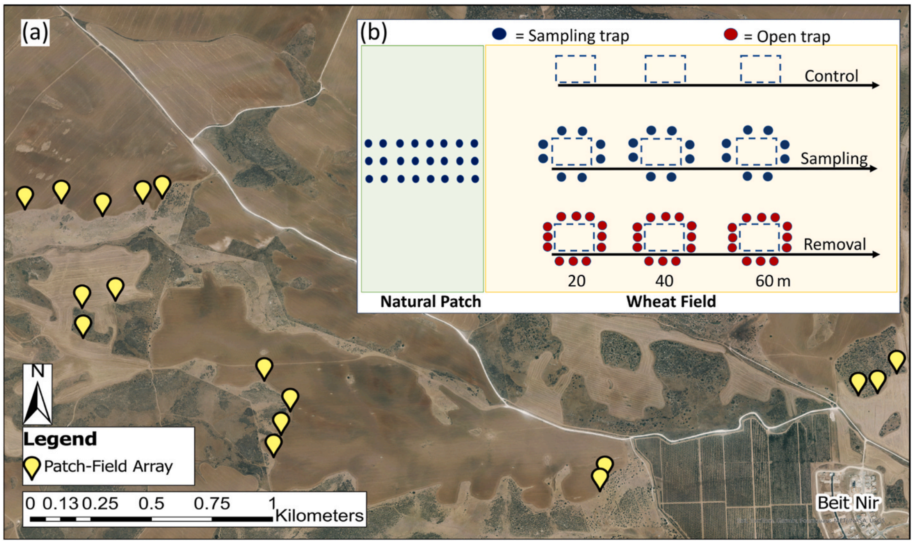

Fig. 1. Study area. (a) Map of the study area in Southern Judea Lowlands around the Beit Nir area site. Each round pin represents a patch-field area with nine wheat plots and a sampling grid in the natural patch. (b) A schematic representation of the field patch arrays in each of the 17 replicates.

was designated within each distance, totaling nine plots per patch-field array. The first treatment level, labeled "control," aimed to measure wheat yield without intervention. In the second treatment level, "sampling," eight pitfall traps were set up around each plot to monitor spatiotemporal changes in the arthropod community. These traps were opened once a month for 72 h only (a total of 24 traps within each wheat field). The third treatment level, "removal," involved setting up 12 wet pitfall traps with ethylene glycol around each plot, accompanied by plastic barriers (20 cm in height) that were sunk at least 10 cm into the ground, further preventing ground-dwelling arthropod entrance into the wheat plots (Holland, 1998; Schmidt et al., 2004; Martin et al., 2013). Such plastic barriers were used in other studies and found to have negligible effects on yield (Martin et al., 2013) or on the microclimate within the experimental plot (Schmidt et al., 2003). Therefore, we inferred that they had minimal impact on wheat yield in the current study. In the natural patch, situated 5 m from the field, a grid of 30 pitfall traps was set up in three rows of 10 traps each. Overall, the sampling effort in the natural patches and the wheat fields was relatively close, so the catch per trap was comparable. Metal posts, 2 m in height, were erected at the corners of the sampling plots in each field-patch array to collect specimens from the flying arthropod community. One pole was placed beside the pitfall traps in the natural patch, and the remaining three were positioned within the wheat field, one at each corner of the wheat sampling plots in the "sampling" treatment.

2.4. Sampling

Throughout the wheat growing season, pitfall traps in the sampling treatment and the natural patch were opened for 72 h once a month, and yellow sticky traps were installed on poles. Sampling dates in 2021 (day of trap opening) were Feb 14, Mar 7, Apr 11, and May 2. Collected samples were brought to the laboratory for later sorting and identification. Arthropods were identified to the lowest taxonomic level possible by expert entomologists from The Steinhardt Museum of Natural History (TAU) and The Institutes for Desert Research (BGU) to the lowest possible taxonomic level.

2.5. Yield assessment

In late May, wheat was manually harvested in the nine plots of each patch-field array using secateurs. Twenty kernels from each plot were individually dried and weighed separately. In the laboratory, following a dry plant biomass protocol (60 °C for 48 h), we counted Grains Per Spike (GPS) and measured grain mass (g) for each kernel.

2.6. Data analysis

All statistical analyses were performed using R (Team RC, 2021) with the following main packages: lme4 v. 1.1.35.3 (Bates et al., 2015), nlme v. 3.1.163 (Pinheiro and Bates, 2000), plyr v. 1.8.9 (Wickham, 2011), tidyverse v. 2.0.0 (Wickham et al., 2019), and vegan v. 2.6.6.1 (Oksanen et al., 2024). The complete list of all packages used can be found in Appendix A. Wheat yield differences among the three treatment levels (i. e., control, sampling, and removal) and as a function of distance from the natural patches into the wheat fields were assessed using linear mixed-effects models with control and distance of 20 m into the field as the reference level of each explanatory variable, respectively.

To control for possible arthropod sampling effects associated with varying trap numbers, we first computed median and mean values for 1000 randomly rarefied arthropod communities based on the wheat field's average sample size. Next, Poisson distribution was applied for count-based variables, and normal distribution was applied for predator-phytophagous ratios. Fixed factors included distance and time, with replicate nested within the field as a random factor to address natural variability between fields and reflect the relative proximity of some patch-field pairs. For arthropod species richness and abundance, generalized linear mixed models were employed, with Poisson distribution, incorporating distance and time as fixed factors and 'replicate' nested within the field as a random factor. To assess the impact of time and distance from the natural patches on arthropod community composition, we used nMDS ordinations and PERMANOVAs. A SIMPER analysis was performed to examine the relative contribution of observed taxonomic groups to the observed variance in arthropod community composition (Similarity Percentages, Clarke, 1993). Then, the delta of abundances between the natural patches and the wheat fields was calculated for these influential groups for each distance every month (Figs. A.11-A.22).

3. Results

The number of grains per spike (GPS) and the total grain mass per kernel (g) varied significantly with distance and treatment (Fig. 2, Tables 1 and 2). Specifically, GPS at a distance of 40 m into the field was significantly higher than at 20 m ($z = 4.16$, $p < 0.001$); however, no

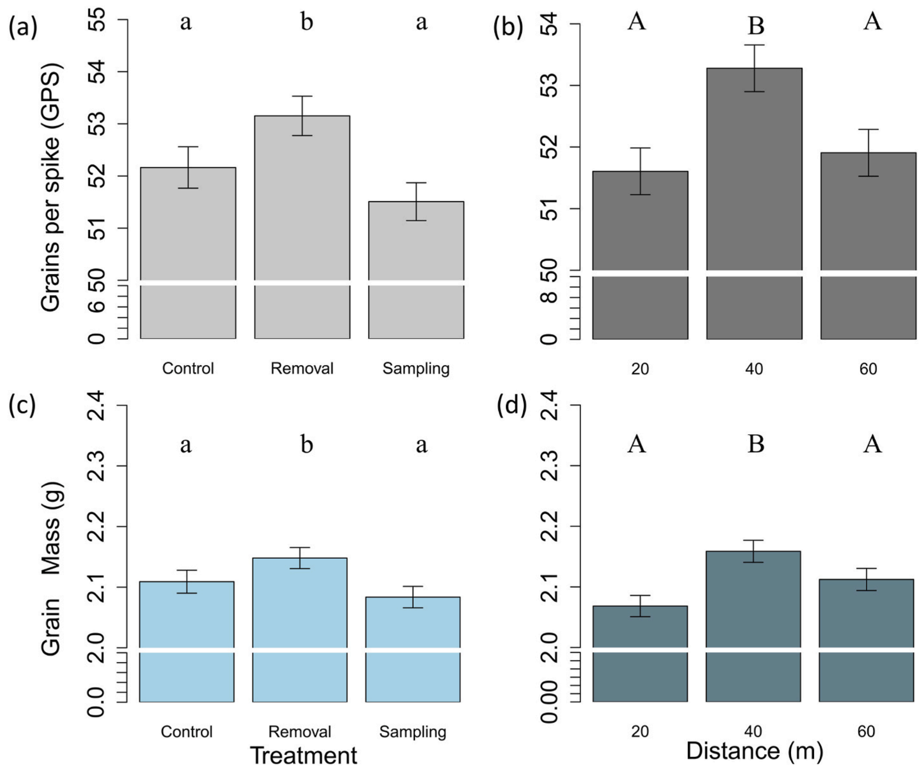

Fig. 2. Number of Grains per Spike (GPS) and Grain Mass for each kernel in the different experimental arrays (a and c) and at three distances from the natural patches into the wheat fields (b and d). Bars represent the Mean±1SE, with different letters indicating significant differences based on Tukey's Honest Significant Difference (HSD) post-hoc test.

Table 1
Results of a generalized linear mixed effects model, fitted by maximum likelihood (Family: Poisson), for Grains per Spike (GPS).

Effects	Estimate	Std. Error	z value	*p*-value
Distance 40 m Vs. Distance 20	0.026	0.006	4.16	<0.001
Distance 60 m Vs. Distance 20	0.005	0.006	0.77	0.442
Removing Vs. Control	0.026	0.006	4.15	<0.001
Sampling Vs. Control	−0.008	0.006	−1.27	0.204

Table 2
Results of a linear mixed-effects model, fitted by REML, for Grain Mass (g).

Effects	Estimate	Std. Error	t value	*p*-value
Distance 40 m Vs. Distance 20	0.070	0.023	3.06	0.002
Distance 60 m Vs. Distance 20	0.039	0.023	1.73	0.085
Removing Vs. Control	0.068	0.023	2.95	0.003
Sampling Vs. Control	−0.008	0.023	−0.33	0.742

significant differences were detected between distances of 20 and 60 m ($z = 0.77$, $p = 0.442$). Arthropod removal caused a significant increase in GPS relative to control ($z = 4.15$, $p < 0.001$). However, GPS did not differ significantly between the sampling and control plots ($z = -1.27$, $p = 0.204$).

The same trends were found for total grain mass per kernel (g). Specifically, grain mass at a distance of 40 m into the field was significantly higher than at 20 m ($t = 3.06$, $p = 0.002$). Although there was a trend of increasing yield from a distance of 20–60 m into the field, it was marginally non-significant ($t = 1.72$, $p = 0.084$). Arthropod removal significantly increased grain mass relative to the control ($t = 2.95$, $p = 0.003$). In contrast, grain mass did not differ significantly between the sampling and control plots ($t = -0.33$, $p = 0.742$).

The net difference in grain mass detected in removal plots was 0.068 g per kernel. The estimated number of wheat kernels in a 1m × 1m plot is ~400. To extrapolate the data on a larger scale, we calculated the net effect for a 1 m^2 plot by multiplying 400 with 0.0682 g. This equals 27.28 g per 1 m^2, i.e., 272.8 kg per 1 ha. Assuming an average yield of two tons per 1 ha in Israel (Israel Plant Gene Bank, https://igb.agri.gov.il/web/?page=47&lang=he), this difference may translate into an increase of ~13.64% in wheat yield per 1 ha.

Ground-dwelling arthropod richness was slightly higher in natural patches than in wheat fields, with non-significant differences across the four months ($z = -1.71$, $p = 0.086$; Fig. B.1; Table B.1). Arthropod abundance varied with time ($z = 7.88$, $p < 0.001$) and distance ($z = -3.96$, $p < 0.001$), with a significant time by distance interaction ($z = 2.36$, $p = 0.018$). Generally, arthropod abundance was significantly higher in natural patches than in the wheat fields only in May. Specifically, arthropod abundance in May in the natural patches was significantly higher from the 20 and 60m into the wheat fields but not from the 40 m. For a complete description of the ground-dwelling arthropod community, see Appendix B, Figs. B.1-B.23.

Ground-dwelling arthropod community composition differed significantly between the natural patches and the wheat fields, irrespective of the distance from the natural patches ($F_{1,245} = 10.12$, $p = 0.001$; Fig. 3, Table 3). In addition, community composition varied with time ($F_{1,245} = 36.38$, $p = 0.001$). Furthermore, from February to May, there was a discernible trend of increasing similarity in arthropod community composition between the natural habitat patches and the wheat fields (illustrated by the convergence of green communities in the natural patch with blue communities in the wheat field, Fig. 3). The significant interaction between time and distance ($F_{1,245} = 2.98$, $p = 0.001$) indicated that the similarity in community composition between the natural patches and wheat fields increased over time. ($p < 0.001$; Fig. 3; Table 3). During February, the dissimilarity in community composition of ground-dwelling arthropods was generated mainly by *Bembidion* sp. 18%, Spiders (Arachnida: Araneae) 11%, Malacostraca

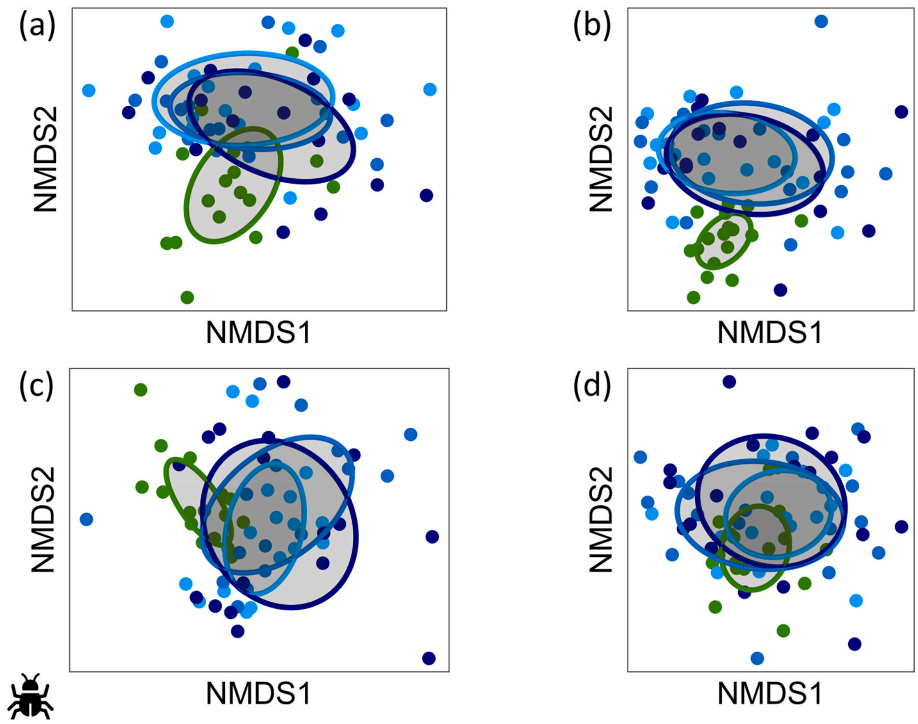

Fig. 3. Non-metric multi-dimensional ordination of ground-dwelling arthropod community composition for (a) February (stress: 0.207), (b) March (stress: 0.195), (c) April (stress: 0.208), and (d) May (stress: 0.208). Community samples were taken from the natural patch (green) and at three distances into the wheat field: 20 m in light blue, 40 m in blue, and 60 m in dark blue. Ellipses represent a confidence interval for each group centroid.

Table 3
Results of a Permutational Multivariate Analysis of Variance (PERMANOVA) of ground-dwelling arthropod community composition.

Effects	df	Species groups				Functional groups				
		SS	R^2	F	*p*-value	df	SS	R^2	F	*p*-value
Distance	1	2.26	0.030	10.32	0.001	1	1.21	0.032	11.89	0.001
Date	1	7.95	0.104	36.39	0.001	1	4.38	0.115	43.15	0.001
field	5	6.93	0.091	6.34	0.001	5	4.36	0.114	8.59	0.001
Distance: Date	1	0.65	0.009	2.98	0.001	1	0.15	0.004	1.47	0.224
field: block	12	5.19	0.068	1.98	0.001	12	3.27	0.086	2.69	0.001
Residual	245	53.55	0.700			245	24.86	0.650		
Total	265	76.53	1			265	38.22	0.032		

14% and Diplopoda 9%. However, in May, the equivalent dissimilarity was driven by other groups: Messor ant species (*Messor semirufus*) 23%, Malacostraca 10%, and *Zophosis punctata* 10%. Out of 22 species found in the natural patches, only seven were mutual to all other distances into the wheat fields (Fig. B.23).

Flying arthropod richness did not vary significantly with distance ($z = -0.329$, $p = 0.742$; Fig. C.1; Table C.1) but varied over time ($z = -1.96$, $p = 0.0502$) while peaking in April. Flying arthropod abundance increased through time ($z = 34.08$, $p < 0.001$), with significant effects for both the distance ($z = 6.97$, $p < 0.001$) and time-by-distance interaction ($z = -8.261$, $p < 0.001$). The flying arthropod community composition overlapped between the natural patches and wheat fields ($F_{1,148} = 1.32$, $p = 0.25$; Fig. C.2; Table C.2), varied over time ($F_{1,148} = 3.51$, $p = 0.005$), but with a marginally nonsignificant interaction effect ($F_{5,148} = 3.36$, $p = 0.062$). Two leading groups showing significant changes with distance were Thripidae and Cecidomyiidae (gall midges), which are wheat potential pests. In March, at a distance of 60 m into the wheat fields, Thripidae became the most abundant group, showing a substantially higher abundance compared to natural patches (Fig C.3). Gall midges abundance in March was higher in the wheat fields than in the natural patches (Fig. C.4). For a complete description of the flying arthropod community see Appendix C, Figs. C.1-C.14.

Next, we focused on ground-dwelling predators, such as Araneae, *Bembidion* sp., *Calathus* sp., and *Scarites Saxicola*. Predator abundance varied significantly with time, distance from the natural patches, and time-by-distance interaction effect ($z = -6.65$, $p < 0.001$; $z = 2.95$, $p = 0.003$; $z = -5.40$, $p < 0.001$, respectively; Fig. 4a; Table 4). Specifically, predator abundance was high in February and March, with no discernible variation between the natural patches and wheat fields. However, predator numbers declined as April and May progressed, with a notable reduction within the wheat fields. Similarly, phytophagous species, including *Amara* sp. and Messor ants, varied significantly with time and distance from the natural patches, with the interaction between both being significant ($z = 14.12$, $p < 0.001$; $z = -7.52$, $p < 0.001$; $z = 7.39$, $p < 0.001$; Fig. 4b; Table 4). *Amara* and *Messor* sp. are potential wheat pests (Anjos et al., 2022; Bukejs and Balalaikins, 2008). The phytophagous abundance remained relatively low from February through April but increased drastically in May. March through May showed increased phytophagous abundance at a distance of 40 m into the wheat fields. The calculated predator-phytophagous ratio varied significantly over time ($t = -4.44$, $p < 0.001$; Fig. 4c; Table 5) but not with the distance from natural patches into the wheat fields ($t = 1.71$, $p = 0.112$). The predator-phytophagous ratio decreased in April and May. This latter month showed a ratio close to one, especially at a distance of 40 m into

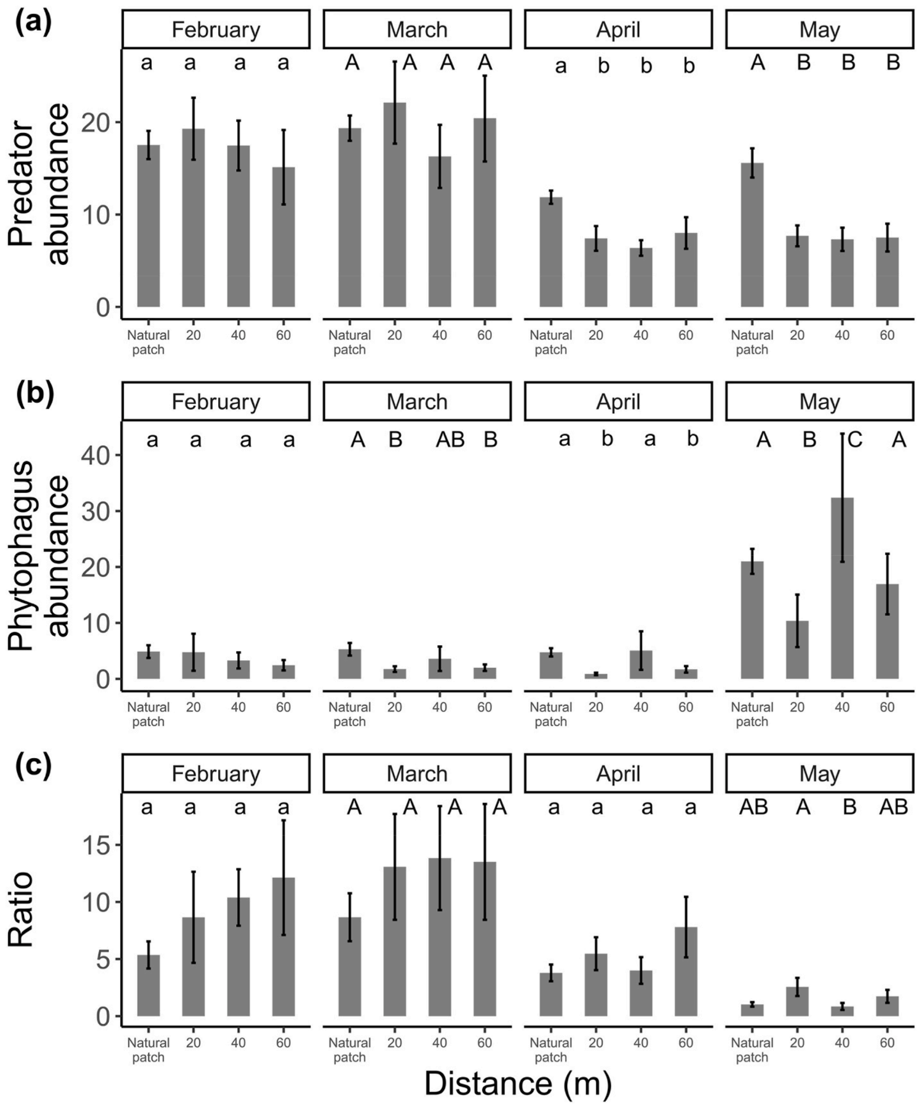

Fig. 4. Mean±1SE of (a) abundance of ground-dwelling predators, (b) phytophagous species, and (c) predator-phytophagous ratio in natural patches and at three distances from the natural patches into the wheat fields by sampling months, with different letters indicating significant differences based on Tukey's Honest Significant Difference (HSD) post-hoc test.

Table 4
Results of a generalized mixed model, fitted by maximum likelihood (Family: Poisson), for ground-dwelling predator species (left) and phytophagous species (right).

	Predators				Phytophagous			
	Estimate	Std. Error	z-value	*p*-value	Estimate	Std. Error	z-value	*p*-value
Date	−0.158	0.024	−6.65	<0.001	0.522	0.037	14.12	<0.001
Distance	0.007	0.002	2.95	0.003	−0.037	0.005	−7.52	<0.001
Distance × Date	−0.004	0.001	−5.40	<0.001	0.008	0.001	7.34	<0.001

Table 5
Results of a linear mixed-effects model, fitted by REML, for the log-transformed predator-phytophagous ratio.

Effects	Estimate	Std. Error	t value	*p*-value
Time	−0.034	0.008	−4.44	<0.001
Distance	0.019	0.011	1.71	0.112

the wheat fields.

4. Discussion

The use of removal studies in various systems has become increasingly important in assessing the influence of critical taxa on community composition and ecosystem processes (Denmead et al., 2017). We show that removing ground-dwelling arthropods increased wheat yield to the extent that it can be extrapolated on a larger scale to as much as 135.4–338.5 kg per ha. We also found significant differences in ground-dwelling community composition between the natural patches and the wheat fields, which may indicate weak species spillover to the wheat fields. Also, the predator-prey ratio decreased significantly toward the harvest time. Based on the goal and findings, we emphasize the need to develop more targeted methods for integrated pest management (IPM).

Our study quantified changes in wheat yield in response to ground-dwelling arthropod exclusion at distances of 20, 40, and 60 m from the natural patches into the wheat fields. We found that the effect of distance on the number of grains per spike (GPS) and grain mass was significant. In Segre et al. (2020), measurements were taken from the field margins at 1, 10, and 50 m into the arable crop. Their results indicated decreased yield at the first meter from the field margin. However, yield was higher further into the field, and no significant differences were found between the other distances. Therefore, if there is any effect of the natural patches on the wheat fields, it is within a very short distance, which might not be very effective given the large scale of the landscape. However, losses at field borders seem insignificant and are reduced by conventional farming practices (Raatz et al., 2021).

Our results contrast a removal study by Holland and Thomas (1997), showing that arthropod exclusion reduced wheat yield. Furthermore, when Liere et al. (2015) examined the effects of isolating soybean plants from arthropod natural enemies, they found a 37% decrease in soybean yield. We interpret this to mean that the increase in wheat yield observed in our study resulted from the effective removal of ground-dwelling pest species rather than natural enemies.

Our study demonstrates that the sampled natural patches and wheat fields harbor significantly different ground-dwelling arthropod communities in composition. The dispute between conservation and agriculture arises from the assumption by some farmers that pests originate solely from natural patches, which are refuges for pests, undermining the contribution of natural patches according to the land-sharing agroecological approach. We suggest that the adverse effects of ground-dwelling arthropods on wheat yield are less likely caused by arthropods inhabiting the natural habitat patches. These results align with previous research (Schmidt et al., 2004) and emphasize the need for land-sharing strategies that prioritize enhancing populations of both ground-dwelling and flying predators to bolster natural pest control mechanisms in the agricultural system effectively. In addition, maintaining the diversity of potential predators, which is vital for natural pest control (Woodcock et al., 2016), can be achieved by conserving natural landscape elements.

The community composition of ground-dwelling arthropods varied significantly between the natural patches and wheat fields, irrespective of the distance from the natural patches. There were mutual species between the natural patches and wheat fields, but the composition differed irrespective of the distance from the patch to the sampling point within the wheat field. Our results align with previous studies (Lang, 2003; Segre et al., 2019; Mei et al., 2021). We show that ground-dwelling arthropod richness was higher in the natural patches than in the wheat fields (Fig. B.1). Similar results were reported in a study by Segre et al. (2019). We show that the abundance of spiders was higher in the natural patches than in the wheat fields throughout the experiment, except during April (Fig. B.3). Mei et al. (2021) illustrated that there were more spiders in the flower strip than in a distance of 20 m into the wheat fields. Mei et al. could not detect differences in the abundance of carabid beetles between the flower strips and a distance of 20 m into the wheat fields, as was evident in our study in April and May (Fig. B.4).

The dissimilarity in community composition of ground-dwelling arthropods between the natural patches and wheat fields decreased with time. This decrease results from a shift in the abundance of the main taxa between the two landscape elements. For example, the difference in the abundances of *Porcellio scaber*, *Messor* ants, and *Bembidion* sp. between the wheat fields and natural patches decreases in May (Figs. B.7-B.8, B.19-B.21). These shifts in species abundances could result from decreased vegetation contrast between the natural patches and cultivated fields as the wheat starts to dry (Yaacobi et al., 2007). Also, the weather becomes less humid (Israel Meteorological Service, 2022 https://ims.gov.il/en/ClimateAtlas).

When investigating five major taxa of flying arthropods, except for house flies, their abundances were generally higher in the wheat fields than in the natural patches (Appendix C; Figs. C.3-C.7). For example, in March, thrips were more abundant in wheat fields than in the natural patches (Fig. C.3), as was found in other studies (Roik et al., 2015; Jensen and Popay, 2022). The high abundance of these potential pests in the wheat fields may be explained by the more suitable food sources within the fields and correlate with the increase in the abundance of potential natural enemies, such as lacewings (Fig. C.6) and *Pteromalidae* wasps.

Boetzl et al. (2019) found that the proportion of predatory ground-dwelling species decreased with distance to oilseed rape field edges, indicating a beneficial role of natural landscape elements for pest control in adjacent crops. Our study found differences in the functional groups of ground-dwelling arthropods between the natural patches and wheat fields, with most sampling dates showing weak patterns (Table B.2; Fig. B.22). However, when looking into specific groups, variation as a function of distance was more apparent. In May, the abundance of phytophagous species, including *Messor* ants, was higher at a distance of 40 m into the wheat fields (Fig. 3b–s. B.20-B.21). In contrast, the abundance of predator species declined in the wheat fields (Fig. 3a), suggesting weak pest control during this month. This observation may explain the higher wheat yield values at 40 m compared to 20 and 60 m. Additionally, in line with the findings of Anjos et al. (2022), which demonstrated how ants consistently reduce the abundance of natural enemies, a similar phenomenon might be occurring here, thereby magnifying the removal effect. We infer that removal was effective, even when considering removing some of the natural enemies, resulting in a net increase in wheat yield. The origin of the phytophagous species is unclear, as the natural patches could be a refuge in months when the fields are bare or undergo intensive practices (Cullum et al., 2020; Laterza et al., 2023).

We focused on removing the ground-dwelling arthropods, which seemed to increase the wheat yield. Although several flying wheat pests were not removed in this study, removing ground-dwelling arthropods alone was sufficient to enhance the wheat yield. Various Carabid species, including *Staphylinidae* sp. and *Bembidion* sp. (Lang, 2003; Sunderland et al., 1987; Sunderland and Vickerman, 1980), known to prey on aphids, were present in our study. Previous research by Sun et al. (2022) demonstrated that over 90% of aphids are found in the lower part of flowering wheat plants throughout the day. In addition, using a field experiment, Schmidt et al. (2003) aphid populations increased by 18% when ground-dwelling predators (spiders, carabid, and staphylinid beetles) were reduced in wheat fields and by 70% when mesh cages excluded parasitoids and flying predators. These findings suggest that both ground-dwelling and flying arthropods play a significant role in pest control within wheat fields, as was also suggested by Lang (2003), demonstrating that ground-dwelling arthropod predators can reduce aphid populations in wheat fields.

It could well be that the taxonomic resolution of our study may not be sufficient to make concrete functional classifications of all the found taxa. Nevertheless, the most common species of carabids and ants identified in our research are well-documented in the literature, and their trophic functions are known. For example, carabid species such as *Scarites Saxicola* are predominantly carnivorous, while *Amara* sp. is known for its herbivorous diet. Similarly, *Messor* ants are recognized for their harvesting behavior (Plowes et al., 2013; Uhey and Hofstetter, 2022).

Many temporal environmental factors not considered in our study could potentially influence wheat yield. For example, temperature extremes during critical growing stages can adversely impact wheat production and quality (Asseng et al., 2019). Furthermore, the interaction between precipitation levels and spatial variation in soil nutrients can also affect dry matter production and grain yield (McDonald, 2006). Our field study was conducted over a single growing season, comprising a large number of replicates (i.e., 17 replicates) spatially distributed across a large area, thus providing valuable insights into arthropod-yield interactions in wheat fields. Still, we acknowledge that inter-annual variability in environmental factors could influence wheat yield and arthropod communities (Macfadyen et al., 2015; Zhao et al., 2015; Hnizil et al., 2024). Building on our methodology, future multi-year studies could further validate and expand upon these findings, accounting for potential year-to-year variations in arthropod-yield relationships.

Agroecological systems present a substantial challenge in understanding the complex interactions between natural landscape elements and the agricultural matrix. The significant increase in wheat yield observed after the removal of ground-dwelling arthropods in this study likely resulted from the disruption of local within-field arthropod communities rather than from the influence of surrounding natural habitats. These findings underscore the positive role that natural patches can play in agroecological systems, contributing to the ongoing debate about their economic value. Rather than viewing natural patches as detrimental, efforts should focus on strategies that harness their benefits while maintaining biodiversity and ecosystem services. Future research should explore additional factors influencing wheat yield, including biotic and abiotic variables such as pest population dynamics and farming practices, particularly in these dynamic landscapes.

5. Conclusions

Our study demonstrates that removing ground-dwelling arthropods from wheat fields significantly enhances yield, regardless of the proximity to natural habitat patches. This effect was evident in both the number of grains per spike and total grain mass per kernel, particularly at distances of 20 and 60 m from the natural patches into the wheat fields. These findings highlight the complex interactions between agricultural landscapes and adjacent natural habitat patches, emphasizing the need for nuanced pest management strategies. Future research should focus on developing methods to effectively manage both ground-dwelling and vertical wheat pest populations while preserving beneficial arthropods within both the wheat fields and adjacent natural patches. Such approaches could contribute to more sustainable agricultural practices that balance crop yield with biodiversity conservation in agroecosystems.

CRediT authorship contribution statement

Lital Ozeri: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Guy Rotem:** Methodology, Funding acquisition, Conceptualization. **Alfred Daniel Johnson:** Data curation. **Tomer Karni:** Software, Resources, Data curation. **Ofer Ovadia:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Yaron Ziv:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yaron Ziv and Guy Rotem reports financial support was provided by Nekudat Chen Fund. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122961.

Data availability

Data will be made available on request.

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