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Diet breadth and microhabitat mediate predator community resilience to agricultural intensification and extreme weather

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ABSTRACT

Land-use intensification and climate change have strong filtering effects on arthropod communities. Intensification increases landscape homogeneity and field-scale disturbance while extreme weather events are increasing with climate change. To disentangle their impacts, we analyzed predatory arthropod abundance and diversity across microhabitats (canopy, ground) and diet breadth (specialist, generalist, omnivore) in 58 sorghum fields in Uruguay over two years. Using a trait-based framework and Hierarchical Modelling of Species Communities, we found that double cropping negatively affected predator communities, reducing canopy predator abundance and ground predator species richness, especially ground omnivores. Larger fields decreased the proportion of canopy specialists in the community, and landscape homogeneity increased the proportion of ground omnivores. Extreme weather mainly affected ground predators, with species richness and abundance decreasing with high rainfall variability. The proportion of ground specialists decreased with both variable rainfall and more hot days. Omnivorous and generalist ground predators were more resilient to climatic stress and canopy predator abundance increased under heat extremes. Our findings suggest that land-use intensification exerts stronger negative effects on predator communities than extreme weather, though the latter can further reduce functional diversity. To enhance predator community resilience and support biological control, management strategies should prioritize reducing disturbances, such as double-cropping, and creating refuges within fields to protect against climatic extremes.

1. Introduction

Arthropod communities are radically altered by anthropogenic activities, particularly agricultural intensification (Janousek et al., 2023; Liu et al., 2023). This leads to surges in pest populations, requiring intensive management strategies that harm beneficial organisms (Gossner et al., 2016; Hendrickx et al., 2007; Sohlström et al., 2022). Simultaneously, climate change is introducing additional pressure on predator communities (Outhwaite et al., 2022; Zhang et al., 2024). The combined effects of agricultural intensification and climate stressors on beneficial arthropods, however, remain understudied (Lehmann et al., 2020; Raven and Wagner, 2021; Sohlström et al., 2022), though this has been investigated in forest systems (Michalko et al., 2023).

It is necessary to disentangle the effects of agricultural management strategies from the effects of climate change on predator communities, especially because communities naturally shift across time and space (Iuliano and Gratton, 2020; Karp et al., 2018). Sustainable agriculture research has primarily focused on enhancing biological control by increasing populations of specialist parasitoids for targeted pest management (Kapranas and Tena, 2015; Tougeron et al., 2021) or supporting diverse resident predator communities (Albrecht et al., 2020; Gurr et al., 2017). Yet, factors affecting functional diversity have rarely been studied in an integrative framework.

Agricultural intensification occurs at both landscape and local scales. Mobile arthropods link the regional landscape matrix with ecosystem services and agroecological management practices at the field scale (Gagic et al., 2012; Liere et al., 2017). Landscape intensification involves fragmented natural habitats and increasingly homogeneous land-use

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types (Margosian et al., 2009; Ramankutty et al., 2018; Sirami et al., 2019; Tscharntke et al., 2005). Landscape homogeneity increases habitat connectivity, enabling generalist, omnivorous and highly mobile insects to proliferate, while reducing the abundance of specialists and less mobile predators (Emery et al., 2021; Gardiner et al., 2009; Liu et al., 2018; Perović et al. 2010; Rand et al., 2014). At the field scale, agricultural intensification is characterized by increased pesticide use, higher cropping frequency, continuous crop rotations, and larger field sizes. Many of these practices have been shown to reduce both generalist and specialist predator abundance while increasing pest abundance (e.g., Emery et al., 2021; Heinen et al., 2024; Lee et al., 2001; Witmer et al., 2003, but see Groeneveld et al., 2015). Predator microhabitat also influences predator responses to disturbance. Canopy predators might be less affected by local disturbances due to greater mobility and dispersive capacity, while flightless and less mobile ground predators are likely more vulnerable to soil-related disturbances (Den Boer et al., 1980; Niemelä 2001; Perry et al., 2021).

In addition to the effects of land-use intensification, arthropod communities are simultaneously being exposed to shifting environmental conditions due to climate change. Little is understood about arthropod traits that confer resilience to climate change, which increases the frequency of extreme weather events, such as higher temperatures and greater oscillations in rainfall patterns (Zhang et al., 2024). Temperature extremes are often more important than temperature means in determining arthropod thermal resistance and survival (Estay et al., 2014; Lawson et al., 2015; Paaijmans et al., 2013). Homogeneous agricultural landscapes have both higher mean temperatures and larger swings in temperature variation (Alford et al., 2018; Braem.,2023). The microclimate of the occupied niche can also provide variable buffering to extreme weather events (Androcioli et al., 2018). Canopy predators are exposed to higher thermal radiation, while ground predators benefit from the buffering effects of soil and vegetation layers (Inskeep et al., 2021; Pincebourde and Woods, 2020; Unwin and Corbet, 1991). Predator diet breadth might also shape responses to climatic stressors, as organisms with broader diet breadths could be more resilient to increasingly variable conditions, though this remains poorly explored. Most research on predator responses to intensification and climate change has not considered predator microhabitat and diet breadth simultaneously, limiting our understanding of predator resilience to these environmental stressors.

This study investigates how agricultural intensification and extreme weather events shape predator communities in annual agriculture. Identifying predator groups more resistant to these stressors can inform management strategies that support resilient natural enemy communities. Using two years of data from 58 sorghum fields in western Uruguay, we applied a trait-based approach integrating both predator microhabitat and diet breadth within a Hierarchical Modelling of Species Communities framework (Ovaskainen and Abrego, 2020). Agricultural intensification was represented by long-term rotational strategy (pasture-crop rotation versus continuous crop rotation) and field management practices (insecticide use, cropping frequency, field size). We also considered the proportion of annual crops in the landscape. Extreme weather events were defined by higher rainfall variability over the season and the number of days with a maximum temperature above 34°C, both expected to increase with climate change.

We hypothesized that i) ground predators, being generally less mobile, would be negatively impacted by management intensification (either behaviourally or through direct mortality), while canopy predators would be more susceptible to extreme weather events due to reduced climatic buffering; and ii) predators with narrower diet breadths (specialists) would exhibit lower resilience to agricultural and climatic stressors compared to generalists and omnivores. We expected microhabitat and diet breadth to interact, jointly shaping predator responses to agricultural and climatic stressors.

2. Materials and methods

2.1. Study system

Over the past 20 years in western Uruguay, northeastern Argentina and southern Brazil, the landscape has become increasingly homogenized (Franzluebbers et al., 2014; Schnepf et al., 2001; Wingeyer et al., 2015), utilizing more intensive farming practices. In Uruguay the amount of land on which continuous cropping is practiced has increased together with the dominance of soybean in the landscape (Food and Agriculture Organization of the United Nations.,2023; Franzluebbers et al., 2014). From 2000–2017 total applications of N tripled, while P, K and pesticide use doubled (Food and Agriculture Organization of the United Nations.,2023). Pasture-crop rotations, in which fields are grazed for 3–4 years and then used for annual crop production for 3–4 years, used to be more common and are considered more sustainable than continuous cropping (DIEA-MGAP, 2018, Ernst et al., 2018). Pasture-crop systems have more stable soil nutrient cycling and higher C saturation, enabling faster N turnover and minimizing leaching losses (Pravia et al., 2019). They also support higher crop yields and soil organic content (Grahmann et al., 2020).

Grain sorghum is a summer crop grown in a variable landscape matrix in western Uruguay, making it an ideal system to study the effects of agricultural intensification at multiple scales. In addition to being grown on only 2–3 % of the total land allocated to annual agriculture (Food and Agriculture Organization of the United Nations.,2023), grain sorghum is also managed less intensively than soybean or maize, the more common summer crops (Chandrashekar and Satyanarayana, 2006; Staggenborg et al., 2008; Wang et al., 2024). By quantifying the trait-based responses of canopy and ground predators in grain sorghum it is possible to differentiate the effects of landscape, local and climate-driven stressors on predator communities, critical for appropriately attributing community effects to the correct driver (Rosenheim et al., 2022).

To evaluate the effects of landscape homogeneity, local agricultural intensity, and extreme weather events on canopy and ground predator communities in Paysandú, Uruguay, 58 fields planted to grain sorghum over two summers were sampled. In 2016 and 2017, 33 sorghum fields, managed under continuous crop rotation, and 25 fields managed under pasture-crop rotation, were sampled. Pasture-crop rotation fields were previously grazed for at least two years and rotated back to agriculture one year or less before sorghum planting, since legacy effects appear to be greatest in the year following conversion (Adler et al., 2018). Another annual crop was grown a maximum of one time between grazing and sorghum planting, either in the winter or previous summer. Continuous crop fields were planted with annual crops for a minimum of five years before sorghum planting. Double cropping was identified for fields in which a winter crop was grown immediately preceding the spring planting of grain sorghum. Fields in which insecticides were used only made a single application at the beginning of the season. Each field was at least 1 km from any other sampling location within a given year.

To quantify landscape homogeneity, the proportion of landscape under annual cultivation was assessed using 1 km buffers. This radius was chosen because multiple predatory taxa respond to landscape composition at this spatial scale (Abbate et al., 2022; Aguilera et al., 2020; Grez et al., 2021). The proportion of annual crop cover was classified using a combination of Google Earth satellite data, Uruguay's governmental land use plans and ground-truthing. The mean proportion of annual crop cover within a 1 km radius was 0.34, ranging from 0.01 to 0.75 (see Table A.1). Each field was categorized for local land-use intensity according to rotation intensity, insecticide use, cropping frequency, and field size (mean = 46 ha) (Table A.1).

Daily rainfall (mm) and temperatures were obtained from three weather stations; all field sites were within 50 km of one of these weather stations. Data from the Glencoe Experimental Station and the Salto weather station was provided by the National Institute of Agrofishery Research in Uruguay (INIA). Data from the Paysandú weather station was provided by the Mario A. Cassinoni Research Station (EEMAC) associated with the University of the Republic (UdelaR). The standard deviation of total rainfall (in mm) between sampling dates was used as a measure of seasonal rainfall variation (Emery et al., 2021). The number of days with a maximum temperature higher than 34 °C was used as a measure of exposure to extreme temperatures.

2.2. *Predator sampling*

All sampling was carried out in a 10 m x 10 m area within each field, located at least 8 m from the field edge. Three yellow sticky traps (Alpha Scents, 14 × 9.1 cm) were secured to 2 m wooden posts near the top of the plant height to monitor canopy predators, and three pitfall traps, at the base of each post were placed on the diagonal across the sampling area. Pitfall traps consisted of two stacked 0.95 L clear deli containers with 100 mL 30 % propylene glycol:water with four drainage holes at the top. Traps were collected and replaced every three weeks from December-March. Sticky traps were covered in cellophane and stored at -5°C, and pitfall traps were stored in 70 % ethanol. Fields had a maximum of 15 traps across five sampling weeks, but 12 traps were randomly selected to minimize variance in sampling effort due to trap missingness. If more than three traps were missing or damaged, all were selected, but a minimum of five were required for inclusion in the analysis. This resulted in the inclusion of 58 fields for the canopy predator dataset from yellow sticky traps and 53 fields for the ground predator dataset from pitfall traps. Trap catches from the same field were pooled over the season. Based on available literature, canopy predators (primarily flying adult insects) and ground predators were identified to taxa (species or morphospecies), and assigned to diet breadth categories (specialists, generalists, omnivores) (Table A.2). Predators were classified as specialists if the literature reports feeding primarily on one broader arthropod taxon (e.g., aphids, scales), and as generalists if they feed across taxa. Those feeding on both arthropods and plants were assigned to the omnivore category.

2.3. *Statistical analysis*

We estimated sample coverage using the package iNEXT to assess whether samples from pasture-crop and continuous crop systems represented communities equivalently (Hsieh et al., 2016). Sample coverage estimates the proportion of individuals from a community that belong to the taxa collected in a sample (Chao and Jost, 2012).

Canopy and ground predator communities were analyzed separately while considering species traits and accounting for study design dependencies using the Hierarchical Modelling of Species Communities (HMSC) framework, in which community responses are related to environmental covariates (Ovaskainen and Abrego, 2020). A community matrix was developed (fields × taxa) where we pooled canopy/ground predator taxa from replicate fields. An environmental matrix (fields × covariates) including landscape, local field management and climate variables, and a trait matrix (taxa × traits) classifying canopy/ground predator taxa by diet breadth (generalists, omnivores, specialists) were created. We used a hurdle approach for its greater flexibility in modelling zero-inflated data. This involved separately modelling presence-absence of taxa and abundance conditional-on-presence. In the presence-absence matrix, we transformed all non-zero values to one and used the Bernoulli distribution and probit link function. For abundance conditional-on-presence, we declared zeros as missing values, log-transformed the counts of those taxa present in a field, and fit a normal model. These data were scaled to mean zero and unit variance (Ovaskainen and Abrego, 2020). We restricted the analysis to taxa occurring in five or more fields (27 out of 66 canopy taxa, and 33 out of 78 ground taxa). We included proportion annual crop cover, rotational system ("pasture-crop" as reference), insecticide use ("no" as reference), cropping frequency ("single" as reference), field size, variability in rainfall (SD), and temperature (number days > 34°C) as model covariates. To account for differences in sampling effort due to missing traps, we added the number of traps per field as a fixed effect. Sampling year was highly negatively correlated with the number of hot days (r = -0.88). Because extreme weather events were the variables of interest and explained more variation than year alone, year was not included as a fixed effect. Instead, year and weather station were combined into a single random effect, as each had few levels (two years and three weather stations). This resulted in a *YearStation* random variable with six levels that accounted for the lack of independence among fields belonging to the same weather station, in each sampling year. No other included variables were strongly correlated (r < 0.5) (Fig. A.1).

A variance partitioning approach (Ovaskainen et al., 2017) was used to determine the proportion of variation in the occurrence and abundance attributable to fixed and random effects of all predators, generalists, omnivores and specialists. We computed species richness predictions by summing predicted occurrence probabilities over all taxa. To compute species abundance predictions, we combined both components of the hurdle model by multiplying the predicted occurrences for each species from the presence-absence model, with the abundance predictions from the abundance conditional-on-presence model (Ovaskainen and Abrego, 2020). To visualize potential shifts in the functional composition of canopy and ground predator communities, we also assessed how diet breadth influenced responses to the climate and management variables by computing community-weighted mean values of each diet breadth category. In the presence-absence model the sum of predicted occurrences of species within a diet group was divided by the total number of species occurrences. For the abundance model with combined predictions, we summed predicted abundances of species within each diet group and divided by total community abundance. When making predictions, the values of the non-focal continuous predictors were set to their mean and factors were set to their mode. We report observed differences with statistical support of > 90 % posterior probability that the plotted response variable was greater at the last value of the predictor variable than at the first. Heat maps with posterior support values of individual taxa responses were constructed. Models were run with four Markov chains for 200,000 iterations; the first 100, 000 were removed as transient. Each chain was thinned by a factor of 100, producing 1000 posterior samples per chain and resulting in a total of 4000 posterior samples. We assessed model convergence with the effective sample sizes and potential scale reduction factors of the model beta parameters (Ovaskainen and Abrego, 2020). Model convergence was good in all cases, as the effective sample sizes were generally close to the posterior sample size of 4000 and the potential scale reduction factors were close to the ideal value of one (Fig. A.2). The explanatory power of the presence-absence models was examined using Tjur's R^2 (Tjur, 2009) and Area Under the Curve (AUC; Fielding and Bell, 1997). For the abundance conditional-on-presence models we used the standard R^2 (Ovaskainen and Abrego, 2020). Models were fitted with the R-package Hmsc (Tikhonov et al., 2020) in R 4.2.1, assuming default prior distributions (Ovaskainen and Abrego, 2020).

3. Results

3.1. *Overall predator diversity and abundance*

A total of 7880 canopy predators belonging to 13 families were collected and identified to 66 taxa. Coccinellidae and Anthocoridae accounted for 87 % of canopy predators collected. For ground predators, 78 taxa from 16 families and a separate order (Scorpiones) were identified from 3364 individuals. Carabidae, Lycosidae and the order Scorpiones represented 92 % of ground predators. Sample coverage (SC) was similarly high in fields with continuous cropping (CC) and pasture-crop (PC) rotation for ground predators (SC_{cc}: 94.6 %; SC_{pc}: 89.9 %), and canopy predators (SC_{cc}: 95.5 %; SC_{pc}: 96.1 %).

Taxa present in fewer than five fields were removed for the HMSC analysis. This resulted in a total of 7788 canopy and 3166 ground predators in the analysis (Table A.2).

Canopy predator presence–absence and abundance models showed reasonable and high explanatory power, respectively (presence-absence: Tjur's $R^2 = 0.18$ and $AUC = 0.82$; abundance: $R^2 = 0.47$). Ground predators also showed similar model performance, with reasonable explanatory power for presence-absence (Tjur's $R^2 = 0.18$, $AUC = 0.82$) and strong explanatory power for abundance ($R^2 = 0.49$).

3.2. Predator responses to agricultural intensification

The agricultural predictors explained generally similar percentages of variation in canopy and ground predator occurrence and abundance (Fig. A.3), though there were some notable differences across diet breadth groups. Omnivorous canopy predators were more strongly infuenced by the proportion of annual crop cover than the other diet groups (Fig. A.3a,c). Omnivorous ground predator occurrence was more influenced by cropping frequency than generalists and specialists (Fig. A.3b).

Model predictions showed that double cropping decreased both canopy predator abundance and ground predator species richness (Figs. 1,2a,b). Diet breadth of canopy predators did not have any differential explanatory power in response to double cropping (Fig. A.4), although some common specialist taxa decreased in abundance (Fig. A.6c). The proportion of omnivorous ground predator species decreased under double cropping, while that of generalist ground predator species increased (Figs. 1,2c,d).

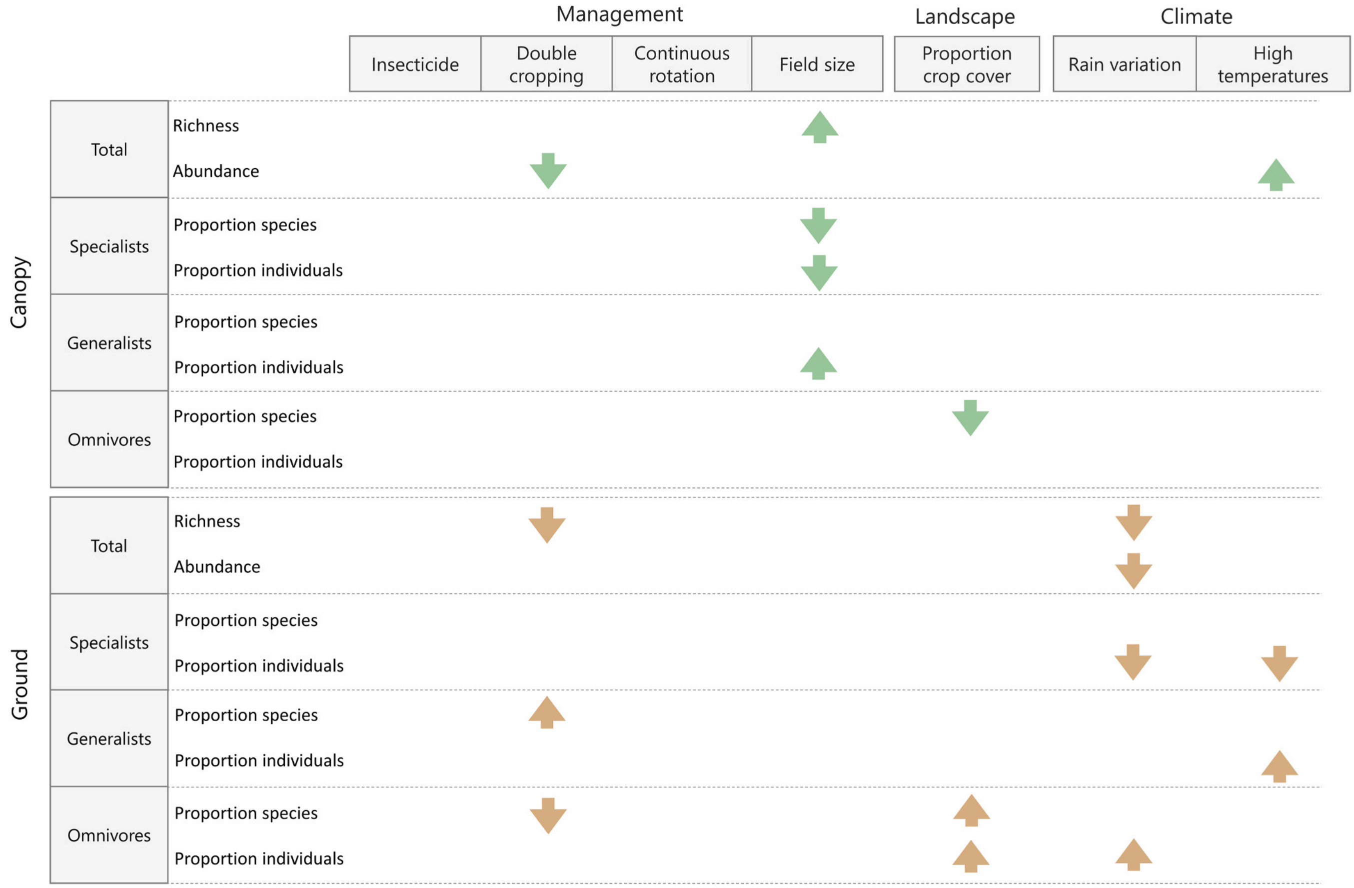
Predator responses to insecticide use and crop rotation were weak (Figs. A.4, A.5). The abundance of a few specialist canopy predator taxa showed positive responses to insecticide use (Fig. A.6c), while generalist ground predator taxa had mixed responses, and the abundance of a few omnivorous and specialist taxa were strongly negatively affected (Fig. A.6d). There were stronger positive effects of continuous rotation on the occurrence and abundance of some canopy generalist and specialist taxa, and some of the more prevalent ground omnivores (Fig. A.6a,b,c, Table A.2). A few generalist canopy taxa (Staphylinidae) were negatively affected by continuous crop rotation (Fig. A.6a).

Canopy predator species richness increased in larger fields (Figs. 1,3a), though only by approximately 2 species. Within the canopy community, the proportion of specialist species and individuals decreased while the proportion of generalist individuals increased (Figs. 1,3b-d). Ground predator responses to field size were generally weak (Fig. A.5), except for some generalist taxa that showed stronger negative responses to field size (Fig. A.6d).

Canopy predator responses to the proportion of annual crop cover were weak (Fig. A.4), with a 4 % reduction in the proportion of omnivorous canopy species (Figs. 1,4a). Ground omnivores responded more strongly to greater annual crop cover, with the proportions of species and individuals increasing (the latter by 19 %) (Figs. 1,4b,c).

3.3. Predator responses to extreme weather events

The number of hot days was more important than rainfall variability in explaining variation in canopy predator species occurrence and abundance (Fig. A.3a,c), and in ground predator species occurrence (Fig. A.3b). There were notable differences across canopy predator diet breadth groups, with generalists and specialists being more strongly influenced by the number of hot days than omnivores (Fig. A.3a,c). Ground predator species abundance was more affected by rainfall



			Management				Landscape	Climate	
			Insecticide	Double cropping	Continuous rotation	Field size	Proportion crop cover	Rain variation	High temperatures
Canopy	Total	Richness				↑			
		Abundance		↓					↑
	Specialists	Proportion species				↓			
		Proportion individuals				↓			
	Generalists	Proportion species							
		Proportion individuals				↑			
	Omnivores	Proportion species					↓		
		Proportion individuals							
Ground	Total	Richness		↓				↓	
		Abundance						↓	
	Specialists	Proportion species							
		Proportion individuals						↓	↓
	Generalists	Proportion species		↑					
		Proportion individuals							↑
	Omnivores	Proportion species		↓			↑		
		Proportion individuals					↑	↑	

Fig. 1. Summary of the statistically supported effects (> 90 % posterior probability) of local and landscape intensity and climate variables, on canopy and ground predators, and their diet breadth groups. Canopy and ground predator responses are presented in green and brown, respectively.

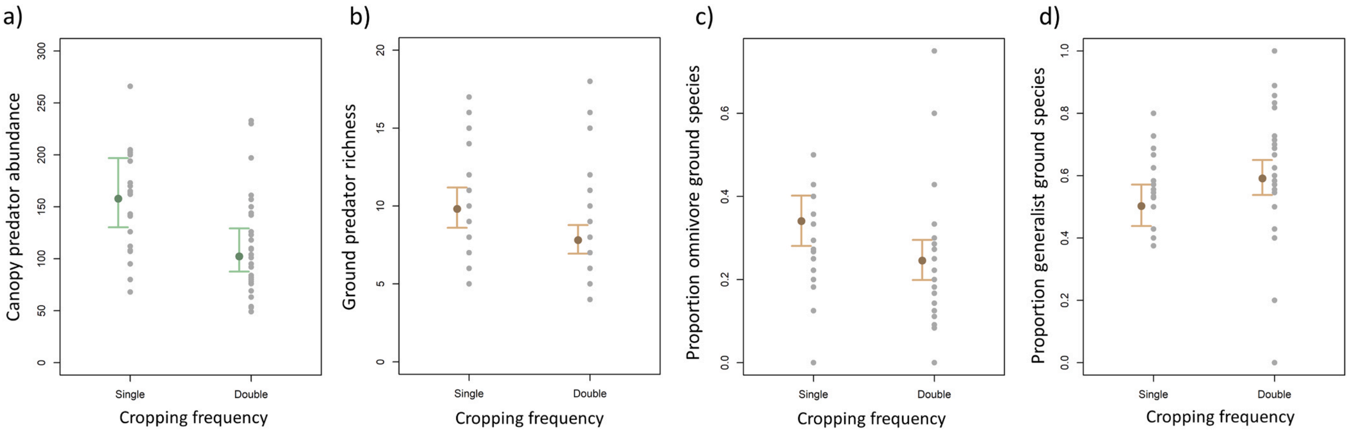


Fig. 2. Statistically supported effects (> 90 % posterior probability) of cropping frequency on canopy predator abundance (a), ground predator species richness (b), and the proportion of omnivorous and generalist ground predator species (c,d). Canopy and ground predator responses are presented in green and brown, respectively.

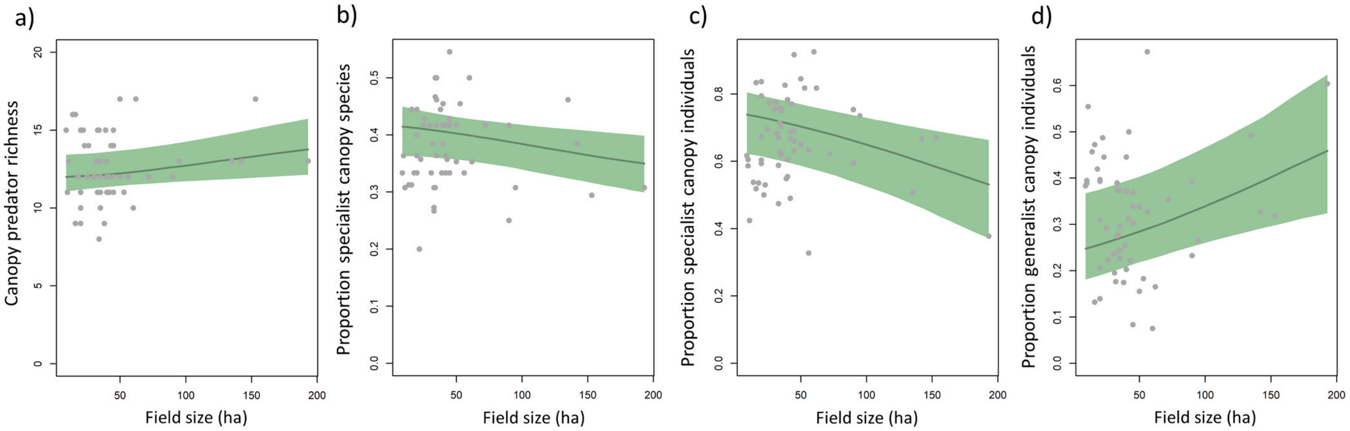


Fig. 3. Statistically supported effects (> 90 % posterior probability) of field size on canopy predator species richness (a), the proportion of specialist canopy predator species and individuals (b,c), and the proportion of generalist canopy predator individuals (d).

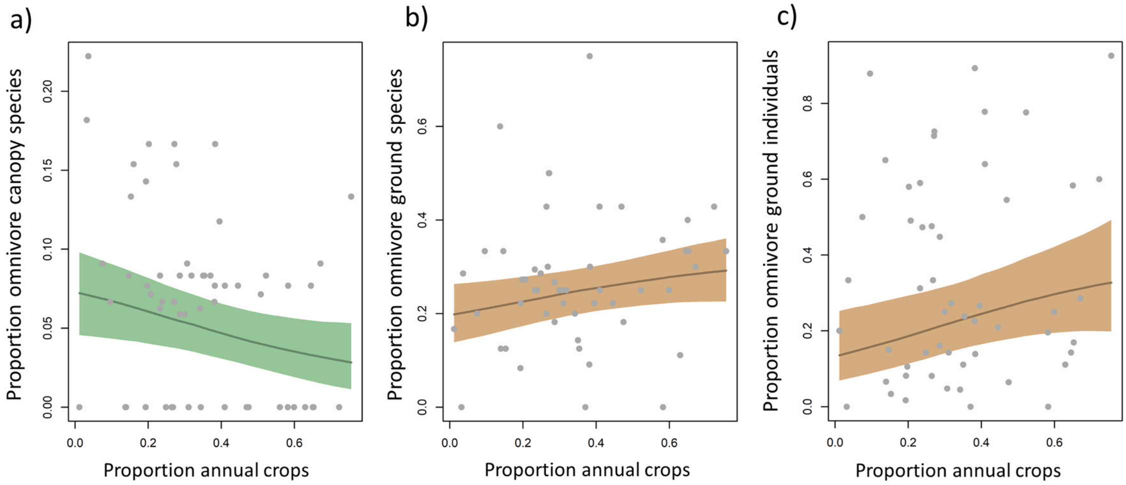


Fig. 4. Statistically supported effects (> 90 % posterior probability) of the proportion of annual crop cover in the landscape on omnivorous canopy predator species (a), and the proportion of omnivorous ground predator species and individuals (b,c). Canopy and ground predator responses are presented in green and brown, respectively.

variability than by the number of hot days, with omnivores being most influenced (Fig. A.3d).

Model predictions revealed that canopy predator abundance increased from an estimated 87–114 individuals with a greater number of hot days (Figs. 1,5a), though there were no associated shifts in diet group proportions (Fig. A.4). While neither richness nor abundance of

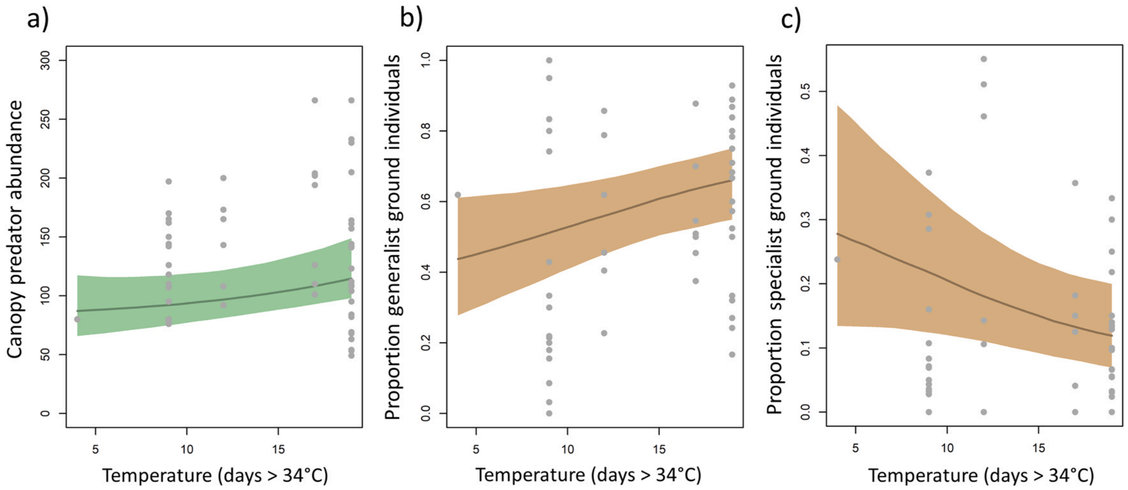


Fig. 5. Statistically supported effects (> 90 % posterior probability) of more hot days (high temperature >34 °C) on canopy predator abundance (a), and the proportion of generalist and specialist ground predator individuals (b,c). Canopy and ground predator responses are presented in green and brown, respectively.

ground predators varied with more hot days (Fig. A.5), the proportion of generalist individuals in the community increased and that of specialists decreased (Fig. 5b,c).

High rainfall variability only resulted in shifts in the ground predator community (Fig. 1). Ground predator species richness and abundance declined with increased rainfall variability, with a loss of about 3 ground predator species and 15 ground predator individuals between conditions reflecting the least variable to most variable rainfall (Fig. 6a,b). The proportion of omnivorous ground predator individuals within the community increased by 29 % with more variable rainfall (Figs. 1,6c), while the proportion of specialist individuals decreased by 13 % (Figs. 1,6d). Some specialist and generalist ground predator taxa showed stronger negative responses in occurrence and abundance to variable rainfall, especially Carabidae (Fig. A.6b,d).

4. Discussion

Predatory arthropods in subtropical grain sorghum are shaped by land-use intensification as well as extreme weather events. Across microhabitats, reductions in absolute species richness and abundance were observed in fields under double cropping. Within microhabitats, we observed shifts in the relative proportions of diet breadth groups in response to both management and extreme weather. This provides evidence of both climatic and management intensification filtering on predator communities, with potential implications for differential effects on biological control due to shifts in predator community composition (Birkhofer et al., 2022; Diehl et al., 2013; Ewald et al., 2015; Fricke et al., 2022).

Contrary to our hypothesis, both canopy and ground predators were negatively affected by the practice of double cropping. This suggests that the increased disturbance associated with two harvests per year harms predators, regardless of their occupied microhabitat, mobility or dispersive capacity. Canopy predators were less abundant in double-cropped fields, whereas ground predators experienced species losses. Although generalist ground predator species dominated the community in both single and especially double-cropped fields, possibly due to higher prey densities (Emery et al., 2021), the relative proportion of omnivorous species decreased under double cropping. This transition to a functionally less diverse community might be linked to increased disturbance in double-cropped fields, which may have reduced key plant resources for omnivorous ground predators (Rusch et al., 2013). For instance, the availability of weeds and weed seeds decreases with more intensive field management, negatively impacting omnivorous ground predators (Carbonne et al., 2022).

Insecticide use had no significant effects on the absolute richness or abundance of either canopy or ground predator communities. This stands in contrast to previous literature in which pesticide use has a consistently negative effect on higher trophic levels (Geiger et al., 2010;

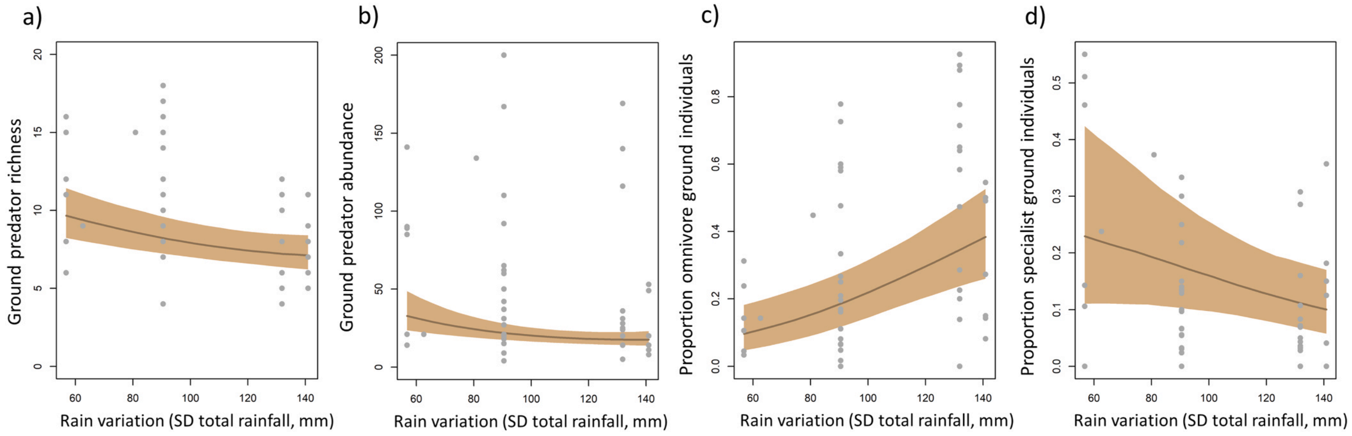


Fig. 6. Statistically supported effects (> 90 % posterior probability) of rainfall variation (standard deviation of total rainfall, in mm) on ground predator species richness and abundance (a,b), the proportion of omnivorous ground predator individuals (c), and the proportion of specialist ground predator individuals (d). In panel b the y axis is truncated to exclude a large outlier that affected visibility of the response curve.

Ewald et al., 2015). Diet breadth did not explain any differential proportional shifts in response to insecticide use either. These findings can likely be attributed to the fact that in this study, fields with insecticide use only had a single application early in the season before the sampling period began. This reflects the more extensive management approach to grain sorghum than is common in other crops (Chandrashekar and Satyanarayana, 2006; Staggenborg et al., 2008; Wang et al., 2024). Nevertheless, we found more negative impacts of insecticide use on individual ground-dwelling taxa, partially supporting our hypothesis that the generally less mobile ground predators are more sensitive to local disturbance.

No effects of rotation were observed on either the canopy or ground predator community, in contrast to our hypothesis. The generally more extensive approach to growing grain sorghum may also have resulted in a weaker contrast between the two rotational systems, though a few positive effects of continuous cropping were observed for individual canopy taxa and ground omnivores. These predatory taxa might have benefitted from higher pest densities (Emery et al., 2021).

Larger field size was associated with an increase in canopy predator species richness, though the effect was minimal (from 11.9 to 13.5). Within the canopy community, the proportion of specialist species and individuals declined in larger fields, while the proportion of generalist individuals increased. Larger fields are often more homogeneous, offering fewer resources such as refuges and non-crop habitat (Bianchi et al., 2006), which might be more limiting for specialized predators. The ground predator community appeared unaffected by field size, possibly because their lower mobility and dispersive capacity limited our ability to detect responses. Here, the effect of field size is isolated from the fraction of the surrounding landscape planted to the same crop. Since only one field was planted within 1 km of another grain sorghum field, this analysis can more confidently differentiate these variables (Rosenheim et al., 2022).

Omnivorous predator communities were affected by the amount of surrounding annual crop cover, while generalists and specialists were unaffected across microhabitats. The proportion of omnivorous canopy predator species declined with increasing annual crop cover, although they consisted of only two taxa and represented a 4 % reduction driven by the reduced occurrence of the Forficulidae, *Doru* sp. Higher annual crop cover was associated with increased proportions of omnivorous ground predator species, and especially individuals (19 % increase). This aligns with findings that omnivorous ground predators are less sensitive to landscape simplification than other trophic groups, as they can explore varied resources (Purtauf et al., 2005). Notably, this pattern contrasts with the response to management intensification, where the proportion of omnivorous ground predators decreased in fields under double cropping. A possible explanation is that while local disturbance from double cropping reduces alternative food sources early in the season, omnivores might benefit from prey in surrounding soybean crops that dominate the landscape or from higher prey abundance in sorghum in higher intensity landscapes (Cividanes, 2021; Emery et al., 2021).

Contrary to expectations, canopy predators were less susceptible to extreme heat despite their greater exposure compared to ground predators. The unexpected increase in canopy predator abundance with more hot days might be explained by the dominance of Coccinellidae in the community (74 % of individuals). These beetles are known to withstand higher temperatures by increasing aphid consumption under hotter conditions (Schwarz and Frank., 2019), through behavioral plasticity by moving to maize whorls at the hottest time of day (Pan et al., 2020), and/or decreased competition. Although the absolute richness and abundance of ground predators did not vary significantly with more hot days, the functional composition of the community shifted, with the proportion of specialist individuals decreasing and that of generalists increasing. The decreased proportion of specialist ground predators might be linked to reduced prey availability under extreme heat (Emery et al., 2021), supporting the expectation that specialists are more vulnerable to extreme weather events.

Both ground predator species richness and abundance declined with increasing rainfall variability, whereas canopy predators were largely unaffected. Periods of drought or flooding caused by erratic rainfall can disrupt soil conditions and negatively impact ground-dwelling organisms (Williams et al., 2014). Interestingly, the proportion of omnivorous ground predator individuals increased under these conditions, likely due to their dietary flexibility and diverse resource utilization, suggesting higher resilience under challenging climatic conditions (Purtauf et al., 2005).

Some limitations should be considered when interpreting our results, although they are unlikely to significantly affect our main conclusions. Despite efforts to maintain consistent sampling across fields, sampling effort had a larger effect on ground predator taxa, due to the higher number of missing pitfall traps. It also influenced the occurrence of canopy predators. Nevertheless, similarly high sample coverage estimates indicate that sampled communities were comparably represented. The large percentage of variance explained by sampling effort for omnivorous canopy predators is due to their relative scarcity in the community (2 %). Incorporating intraspecific and interspecific body size could have provided more insight into predator responses (Rusch et al., 2015; Perez-Alvarez et al.,2021), but we lacked individual measurements and some species identifications. Additionally, the use of regional weather station data on precipitation and temperature instead of within-field data loggers is a recognized limitation of this study (Braem., 2023).

4.1. Conclusions

This study advances our understanding of how agricultural intensification and extreme weather events shape beneficial arthropod communities in a subtropical agricultural system, with predator microhabitat and diet breadth playing an important role in their responses. Higher agricultural management intensity from double-cropping, resulting in greater field-scale disturbance, negatively affected both canopy and ground predators. Though generalist ground predators showed greater resilience, omnivorous ground predators declined. Climatic stressors were more harmful to ground predators, which were susceptible to increasingly variable rainfall and, to a lesser extent, heat extremes. Despite their sensitivity to local disturbances, omnivorous ground predators benefitted proportionally from erratic rainfall and landscape homogeneity, revealing adaptability and climatic resilience.

This study takes an important step by integrating the effects of local and landscape intensification with extreme weather events to identify the increased susceptibility or buffering that predator traits and microhabitat provide. To enhance predator community resilience and support biological control, management strategies should prioritize reducing disturbances, such as limiting double-cropping, and creating refuges within fields to protect against extreme weather. Additional research is needed to identify traits that confer resilience to agricultural and climatic stressors for more effective climate-adaptive agricultural management.

CRediT authorship contribution statement

Sara E. Emery: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Sasha Vasconcelos:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Nicholas J. Mills:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Horacio Silva:** Writing – review & editing, Resources, Methodology, Investigation.

Declaration of Competing Interest

The authors 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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.110100.

Data Availability

Data and R code used in this study are available from Zenodo: https://doi.org/10.5281/zenodo.17630166.

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