



Landscape-scale drivers of insect pest regulation in sugar beet

Fabian A. Boetzel^{a,*}, Nika Jachowicz^{b,c,2}, Anne Lisbet Hansen^c, Ola Lundin^{a,3}

^a Department of Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden

^b Section for Organismal Biology, Department of Plant and Environmental Sciences, University of Copenhagen, Frederiksberg, Denmark

^c Nordic Beet Research, Holeby, Denmark

ARTICLE INFO

Keywords:

Sugar beet (*Beta vulgaris*)
Black bean aphid (*Aphis fabae*)
Flea beetle (*Chaetocnema* spp.)
Integrated pest management (IPM)
Neonicotinoid insecticide ban
Pygmy mangold beetle (*Atomaria linearis*)
Scale of effect

ABSTRACT

Recent policy shifts sparked by environmental and health concerns, insecticide resistance development, and limited new registrations have caused a dwindling availability of chemical insecticides. Sugar beet, a major cash crop in temperate agricultural systems, relied on now banned neonicotinoid insecticide seed coatings for pest control, creating a need for sustainable alternatives. Using a monitoring dataset from 134 sugar beet fields in Denmark and Sweden collected over five years, we assessed landscape-scale drivers of the occurrence and damage of five dominant sugar beet pests in the region: black bean aphid, flea beetles, beet leafminers, pygmy mangold beetle and thrips. We found that insect pests generally cause limited damage to sugar beet in our study area, with damage thresholds for any of the five pests being exceeded in 20 % of the fields. Damage by thrips was more common in Denmark and damage by flea beetles and beet leafminer eggs were more common in Sweden. Pest occurrence or damage could only partly be explained by landscape-scale factors. Cropland cover was positively related to black bean aphid and thrips damage presence but negatively related to flea beetle and pygmy mangold beetle damage. Edge density was negatively related to black bean aphid occurrence but positively related to flea beetle damage. An inter-annual increase in host crop cover was positively related to flea beetle damage and crop diversity to beet leafminer infestation. We conclude that further research on the cause and countermeasures for insect pest outbreaks is needed to develop economically and environmentally sustainable insect pest regulation in sugar beet.

1. Introduction

Pests, pathogens and weeds cause considerable yield losses in agriculture (Oerke, 2006; Savary et al., 2019). Efficient pest control is essential to secure crop yields and has for decades relied heavily on the use of pesticides (Deguine et al., 2021). Concerns for biodiversity, human health and the environment have, however, caused bans of pesticides believed to be most harmful and a general policy shift away from chemical pest control in the European Union (Sánchez-Bayo, 2014; Rundlöf et al., 2015; Frank, 2024). As the future of reliable chemical pest control is no longer guaranteed, novel approaches are needed to ensure pest control in agricultural landscapes under reduced pesticide use (Deguine et al., 2021).

Sugar beet, *Beta vulgaris vulgaris* (var. *saccharifera*), is a major cash crop in more than 50 countries in the temperate regions of Europe, the

Middle East, East Asia and North America (FAO, 2024b). In 2021, 269.2 Mt of sugar beet were harvested globally which contributed approximately 20 percent to the global sugar production and highlights the importance of the crop for the global economy (FAO, 2024a, b). More than 150 pests are known to harm sugar beet globally (Lange, 1987). While most insect sugar beet pests have negligible impact on the cultivation due to their low densities, more than 40 species periodically cause significant damage (Lange, 1987). In northern Central Europe, pests can lower sugar beet yields by more than 30 percent despite chemical pest control, with nematode pests generally regarded more important than insect pests (Hanse et al., 2011). To ensure reliable sugar beet yields, pest control against insects in Europe relies heavily on prophylactic seed coatings (Hauer et al., 2017). In Northern Europe, most of the sugar beet fields used to be protected by prophylactic neonicotinoid insecticide seed coatings until recently (Hauer et al.,

* Corresponding author.

E-mail address: fabian.botzel@slu.se (F.A. Boetzel).

¹ 0000-0001-5121-3370

² 0000-0002-1290-8409

³ 0000-0002-5948-0761

2017). These seed coatings protected sugar beet seedlings against attacks by most insect pests, in northern Europe primarily beet leafminers (*Pegomya* spp.), the pygmy mangold beetle (*Atomaria linearis*), the black bean aphid (*Aphis fabae*), flea beetles of the genus *Chaetocnema* and thrips (*Thrips* spp.) (Hauer et al., 2017; Lemic et al., 2024). While the European Union banned the use of these neonicotinoid seed coatings in 2018 (Regulation (EC) No 1107/2009), temporary emergency authorisations retained their availability in several member states in the following years. In 2023, the European Court of Justice, however, ruled that these temporary exemptions violated Regulation (EC) No 1107/2009 and as a result, neonicotinoid seed coatings will no longer be available (European Court of Justice, 2023). With a lack of insecticide seed coatings providing the same level of protection as neonicotinoids and resistances against alternative insecticides used in seed coatings or applied as foliar sprays increasing, alternative means for regulation of insect pests in sugar beet are needed (Hauer et al., 2017). While negative consequences of the neonicotinoid ban are well known for the control of green peach aphid (*Myzus persicae*) transmitting viruses in sugar beet in continental Europe (Verheggen et al., 2022; Favrot et al., 2024), post-ban effects on pest pressure in sugar beet in Sweden and Denmark, where the green peach aphid only occurs sporadically, are less known.

The composition and configuration of agricultural landscapes can be utilised to predict or manage insect pest populations and crop damages, either bottom-up or indirectly top-down via beneficial effects on their natural enemies (Martin et al., 2019; Almdal and Costamagna, 2023; Boetzel et al., 2023). Whether and how different aspects of the composition and configuration of landscapes surrounding sugar beet fields can be used to predict insect pest outbreaks in sugar beet and target pest control strategies has, to date, not been investigated.

As sugar beet is an annual crop, sugar beet cover in agricultural landscapes fluctuates across years. Sugar beet pests need to locate and disperse to newly established sugar beet fields in spring and depending on the magnitude of inter-annual change in sugar beet cover, concentration and dilution effects similar to those that have been observed for insect pests in oilseed rape are likely (Schneider et al., 2015). The cover of cropland may likewise be a good predictor for insect pests of sugar beet as increasing cropland cover can increase landscape-wide management intensity and insecticide use and have been shown to decrease natural pest regulation of aphids (Meehan et al., 2011; Rusch et al., 2016). Permanent field edges have been shown to support natural enemies and thereby suppress pests (Martin et al., 2019; Boetzel et al., 2020), but margin structures often present along edges have occasionally been found to act as refugia for pests (Boetzel et al., 2025), which makes the effects of field edges on pests difficult to predict. An increased diversity of crops grown in the near surroundings in the preceding season increases the chance of the host crop or a suitable alternative host of an insect sugar beet pest to be present and thus could lead to increased pest populations in sugar beet fields in the following season. While this relation has been shown for pests of oilseed rape (Boetzel et al., 2023), crop diversity in the preceding season has also been found to support natural enemies (Raderschall et al., 2022), indicating an ambivalent role similar to field edges.

Using a dataset comprised of 134 sugar beet fields assessed weekly over 5 years in the sugar beet growing regions of eastern Denmark and southern Sweden, we aimed to assess whether insect sugar beet pest occurrence and related crop damage can be linked to the surrounding landscape context at different spatial scales. We hypothesised that (i) a decrease in sugar beet cover across years leads to pest concentration, an increase to pest dilution, especially for the more specialised pests (beet leafminers and the pygmy mangold beetle), that (ii) an increase in cropland cover, i.e. a simplification of the landscape, leads to lower natural pest regulation and thus indirectly benefits pest populations and crop damage, that (iii) permanent edges indirectly reduce pests and crop damage via fostering natural enemies and natural pest regulation, and that (iv) increasing the diversity of cultivated crops in a landscape increases the risk of insect pest problems via an increased temporal

continuity of alternate hosts (Fig. 1).

2. Materials and methods

2.1. Study region and design

Here we made use of the first five years of a monitoring program for insect pests in sugar beet that was set up in 2019 when neonicotinoid seed treatments in the crop were banned in practice. The monitoring is managed by Nordic Beet Research in collaboration with Nordic Sugar A/S Agricenter DK and SE and the Plant Protection Center at the Swedish Board of Agriculture. We included data on five sugar beet pests on 134 fields embedded in the intensive agricultural landscapes on the Danish islands Falster, Lolland, Møn and Zealand (55 fields) and the southernmost Swedish county Skåne (79 fields) across five years from 2019 to 2023, with 9–36 fields sampled per year (Fig. 2A; Supporting Information, Table S1). Sugar beet is an important cash crop in these areas of Denmark and Sweden with 2.57 Mt and 2.05 Mt harvested in 2021 which corresponds to approximately 1.7 % of the global production (FAO, 2024b).

The selected sugar beet fields ranged from 3 ha to 120 ha in size (average $\pm$ SE: 21.3 ± 1.6 ha) with comparable average field sizes in both countries (Denmark: 18.9 ± 1.6 ha; Sweden: 23.1 ± 2.5 ha). Winter cereals were the most common pre-crop in both countries with 72.4 % of all fields (96 % winter wheat), followed by spring cereals with 15.7 % of all fields (95 % spring barley). The remaining 16 fields (11.9 %) had been cultivated with maize, legumes, various vegetables or with perennial grass leys in the previous year. Sugar beet is not grown more often than every third or fourth year on the same field in the study region. One field each in Denmark and Sweden was re-monitored after three years while one field in Sweden was re-monitored after four years following the usual crop rotations (i.e. the dataset comprises 131 unique fields).

In each field one 25 m long monitoring plot was chosen where the farmer did not use any foliar insecticides but otherwise managed the crop in the same way as the rest of the field, in terms of for example fertiliser, herbicide and fungicide use. The monitoring plot was located at a distance of at least one sprayer width from the field edge, i.e. at least 24 m, and its width was adapted to the sprayer width and was typically 24–32 m. Seeds in all fields were treated with the pyrethroid seed coating Force 20CS (Syngenta; 200 tefluthrin, 120 g/unit seed) as part of standard farming practice. As a pyrethroid, tefluthrin is not systemic and provides partial but not full control of insect pests in the first weeks after sowing (Hauer et al., 2017).

2.2. Pest data collection

In the monitoring plots, pest occurrence and crop damage were recorded weekly by observers using standardised crop damage classifications. Observers were experienced agricultural consultants at Nordic Beet Research, Nordic Sugar or the Swedish Board of Agriculture. All observers received specific training each year prior to data collection and used a common protocol for data collection including example photos for the pest occurrences and damages to ensure standardised and comparable monitoring. Observers varied across countries and years, but each monitoring plot was assessed by the same observer throughout one season (often several fields in close proximity were handled by the same observer within a year).

We used recordings of pest occurrence and crop damage that were assessed on 25 plants (five clusters of five plants) in each monitoring plot, with plant clusters selected at random, but avoiding plot edges and tractor tracks. Occurrence or damage of five major sugar beet pests were assessed: (i) the share of plants with colonies of the black bean aphid, *Aphis fabae* Scopoli, 1763 (Hemiptera, Aphididae; colony defined as at least 10 individuals), (ii) the share of plants with shot damage caused by flea beetles, primarily *Chaetocnema concinna* (Coleoptera, Alticini; only

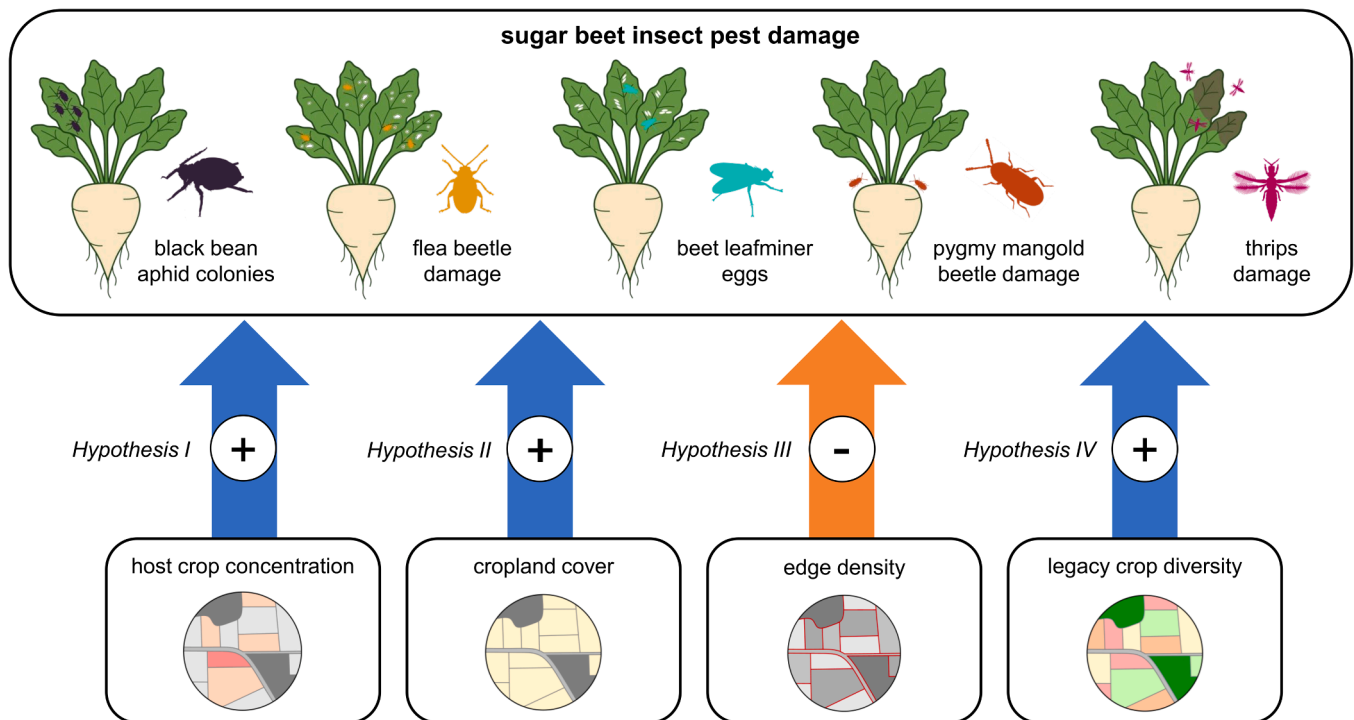


Fig. 1. Hypothesised relationships between aspects of landscape composition and configuration and sugar beet crop damage by different pests either via direct, bottom-up effects on the pests or via effects on their natural enemies and thus indirect top-down effects on the pests under the assumption that pest densities are positively related to crop damage (+ / blue: positive; - / red: negative). A concentration of host crop area between two growing seasons is supposed to result in a concentration of pests in the remaining host crop area and thus favour crop damage. Increasing cropland cover, i.e. the land on which crops are grown and a measure for the simplification of agricultural landscapes, is assumed to hamper natural enemies due to a lack of refuge habitats and high management intensity and thus indirectly benefit crop pests and increase crop damage. An increased edge density, i.e. the total length of unique edges surrounding crop fields, is expected to indirectly lower pest populations via increased pest regulation by natural enemies and thus decrease crop damage. A higher legacy crop diversity, i.e. the diversity of crop types grown in the landscape in the previous season, is assumed to foster pest populations and thus increase crop damage via an increased temporal continuity and availability of resources and host crops. The figures for pest damage patterns are symbolic, for photos see [supplementary material Fig. S1](#).

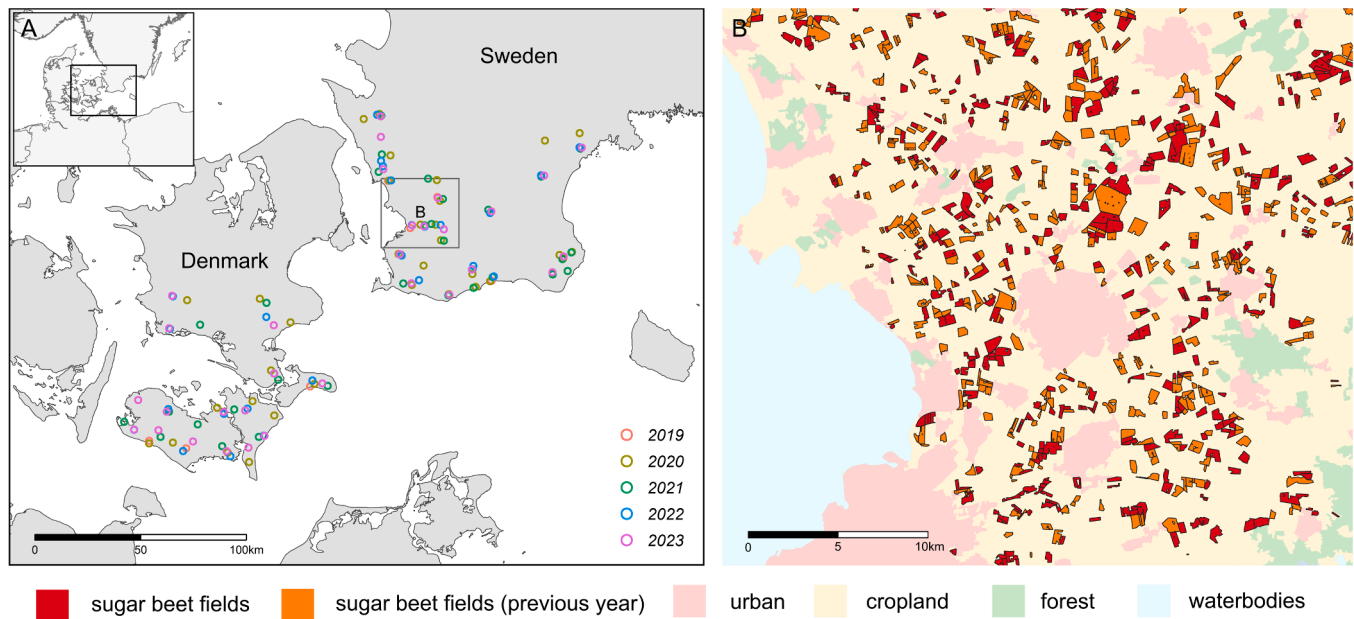


Fig. 2. Map of the study region within northern Central Europe with all 134 studied sugar beet fields (A) and a section of the study region in southernmost Sweden with sugar beet fields in 2023 highlighted in red and sugar beet fields in the previous year, 2022, highlighted in orange. In A, circles indicate selected sugar beet fields, colours indicate years; in B colours indicate land use. The background map in B was generated based on the 2018 CORINE land cover maps. Panel B is included to display in detail a representative part of the study area with respect to sugar beet cropping and general land use. Sugar beet fields are extracted from agricultural land cover maps provided by the Swedish Board of Agriculture for 2022 and 2023 ([Jordbruksverket, 2024](#)).

plants with > 5 % of the leaf area damaged by flea beetles counted as damaged), (iii) the share of plants with eggs of beet leafminers of the genus *Pegomya*, (several possible species including *P. hyoscyami* (Panzer, 1809), *P. betae* (Curtis, 1847) and *P. mixta* (Villeneuve, 1922); Diptera, Anthomyiidae), (iv) the share of plants damaged by the pygmy mangold beetle, *Atomaria linearis* Stephens, 1830 (Coleoptera, Cryptophagidae) and (v) the share of plants damaged by thrips, *Thrips* spp. (Thysanoptera; mostly *T. angusticeps*; only plants with > 50 % of the plant affected by thrips damage counted as damaged). These five groups are the most prevalent sugar beet pests in Denmark and Sweden (Hauer et al., 2017). While aphids and beet leafminer eggs were observed directly, the remaining pests were assessed indirectly through their characteristic damage to seedlings: shot hole like damage to the leaves caused by flea beetles, a distortion to seedlings caused by thrips or stem lesions and chewing damage on leaves caused by pygmy mangold beetle (Larsson 1991; Fig. S1). Pygmy mangold beetle damage was recorded as the share of plants with stem lesions out of ten dug-up plants (damaged if at least three lesions were present) and leaf damage caused by the same pest was recorded as the share of plants with leaf damage out of 25 plants. In our analyses, we used the share of plants with stem lesions as pygmy mangold beetle damage unless the share of plants with leaf damage was higher in which case it was used instead. Pest occurrence and crop damage were assessed weekly between weeks 16 and 28, from sowing ('dry seed', crop stage BBCH 0, Meier et al. 1993) until the leaves covered more than 90 % of the ground (BBCH 39), with an average of 9.4 ± 0.2 weekly observations across sites and years. All non-destructive assessments were conducted on the same five clusters of five plants throughout the season. In addition, colonies of green peach aphid, *Myzus persicae* (Sulzer, 1776) (Hemiptera, Aphididae), a potential virus vector, and damage caused by soil borne pests and the silver Y moth, *Autographa gamma* (Linnaeus, 1758) (Lepidoptera, Noctuidae) were also assessed, but recorded aphid colony numbers and damages from moths and soil borne pests were negligible and not considered further. All data was collected centrally at the servers of Nordic Beet Research (Holeby, Denmark) and cleaned by the same project coordinator.

For each of the pests, we selected the maximum value recorded (weekly average across plants assessed) during the development stage when the damage caused by the pest would have the largest economic impact for inclusion in our analyses. For damage caused by flea beetles, the pygmy mangold beetle and thrips the maximum value up until BBCH 14, and for beet leafminer eggs the maximum value up until BBCH 18 was selected. These crop stages are in line with damage thresholds by Nordic Sugar, the sugar producer in the region, in their recommended thresholds for foliar insecticide treatment (Hansen, 2023). The thresholds are illustrated in Figure S2. As black bean aphid colonies can grow until mid-summer, we avoided biases resulting from fields where monitoring was abandoned early in the year by selecting the maximum recorded occurrence after week 22 (end of May), which resembled crop stage BBCH 18 or higher in the dataset. This yielded data on black bean aphid occurrence from 120 of the 134 fields. Beet leafminer eggs were not assessed in Sweden in 2021 bringing the number of fields down to 112 for this pest.

2.3. Geospatial analyses

We used land-use maps from the Integrated Administration and Control System (IACS) of the European Union provided by the Danish Agricultural Agency (Landbrugstyrelsen, 2024) and the Swedish Board of Agriculture (Jordbruksverket, 2024) of the years 2018–2023 for the geospatial analyses. In these map layers, information about the identity and spatial extent of crops grown is given for all crop fields. Land use information was extracted using ArcGIS Pro (version 3.1.2; Esri Inc. 2023) for all the years of data collection and the respective preceding years. Prior to extracting the land-use information, we harmonised land-use categories used in both countries and categorised crop and land-use classes into 16 land use categories following Boetzel et al. (2023)

with slight adaptations. Thirteen arable land uses were included in the crop diversity measure (spring cereals, winter cereals, spring brassicas, winter brassicas, pulses, potato, maize, beets, fruits / berries, other vegetables / herbs, leys, fruit / energy trees, other; Supporting Information, Tables S2 & S3) while three non-crop land-uses were not included (permanent grassland / fallow, temporary fallow and wetlands on agricultural land). We considered all grasslands without soil disturbance as permanent grasslands. In intercropped crops, we assigned the crop category of the crop with more than 50 % cover if this was specified, otherwise it was categorised as 'other'. Cereal or brassica crops without stated seasonality, which could be grown as winter or spring crop were also designated as 'other' crops. In beets, we combined the areas covered by sugar and fodder beet as these different cultivars of the same species share a common pool of pests.

As scales of effect of landscape-features might vary, we extracted land-use information on three spatial scales using circular buffers around the monitoring plots in each field at radii of 500, 1000 and 2000 m as used in previous, comparable studies (Perez-Alvarez et al., 2018; Boetzel et al., 2023). The minimum distance between monitoring plots across all years and landscapes was 8988 m in Denmark and 2323 m in Sweden, with considerably higher average minimum distances across years and landscapes (12,008 m in Denmark and 6648 m in Sweden). This resulted in slight overlaps between two landscapes in Sweden at the 2000 m scale in 2020, 2021 and 2022 with overlaps of 30.5 %, 9.6 % and 20.3 %, respectively. Following findings of such overlap not being problematic for spatial independence (Zuckerberg et al., 2020) and due to the limited number of landscapes affected, we believe that the spatial overlap did not affect the validity of our results.

At each spatial scale, we extracted (i) the spatio-temporal isolation of the beet field as the absolute minimal distance to the nearest beet field in the previous year (edge to edge), (ii) the absolute change in host crop cover between years, (iii) the cover of permanent grasslands, (iv) the cover of arable land with regular soil disturbance as a measure of landscape-wide land-use intensity, (v) the edge density, measured as the total edge length of patches under agricultural land-use and (vi) the crop diversity in the previous year measured as the Shannon diversity of the 13 crop classes (Supporting Information, Tables S2 & S3). The change in beet cover was calculated as change in absolute cover in percentage points. The spatio-temporal isolation of sugar beet fields and the cover of permanent grasslands could not be included in the analyses as the gradients found were highly skewed. Sugar beet is one of the major crops in the region. In 60.5 % of all fields, the spatio-temporal isolation was below 100 m with a median isolation in Denmark and Sweden of only 35 m and 10 m, respectively (Fig. 2B). Permanent grasslands, the predominant open semi-natural habitats in these landscapes, were absent from 62.0 %, 34.3 % and 6.7 % of these intensive agricultural landscapes at the 500 m, 1000 m and 2000 m scales with respective median grassland covers of 0 %, 0.4 % and 0.9 %. Landscapes were overall similar in both countries across spatial scales but at 2000 m, landscapes in Sweden had on average 9.5 % longer edges and 6.9 % higher crop diversity (t-test, $p < 0.05$; Table S4).

2.4. Statistical analyses

All statistical analyses were performed in R 4.4.1 for Windows (R Development Core Team, 2024). We fitted separate generalised mixed effects models ('glmmTMB') for each of the five pests and each of the three spatial scales (package glmmTMB, version 1.1.9.9000, (Brooks et al., 2017)). Each model contained the respective pest occurrence or damage as response (proportion), and 'country' (factor, two levels), 'host crop cover change' (continuous), 'cropland cover' (continuous), 'total edge length' (continuous), and 'crop diversity' (continuous) as fixed effects as well as 'year' (factor, five levels) as random intercept. All continuous fixed effects were z-scaled to multiples of the standard deviation and mean centred using the 'scale' command to improve model fits. All responses were left-bound and zero inflated, counted

proportions. We thus fitted all models as zero-inflated gamma models with a log-link (model results for the binary part reported in [Supporting Information, Table S5](#), results for the truncated part reported in [Supporting Information, Table S6](#)). Field size was not correlated with any of the responses in initial analyses and thus not included in the models (Pearson's $|r| \leq 0.15$).

All models were checked for under- and overdispersion, zero-inflation and suitability of chosen residual distributions using the DHARMa package (version: 0.4.6, [Hartig 2022](#)) and we detected no violation of the model assumptions. Across all models fitted, ten predictors in five models (one third of all models) had variance inflation factors above 2.5 but below 5, which is regarded as indication of low to moderate correlation ([Menard, 2002; James et al., 2013](#)). These elevated VIF occurred predominantly at the 2000 m scale (eight predictors in four models), resulting in a maximum increase of the standard error by 2.2 times ([Supporting Information, Table S6](#)). This moderate collinearity is not per se a problem but rather indicates that analyses of reduced models would be biased and that the coefficient estimates obtained from the full models, albeit less precise, are more realistic and trustworthy ([Morrissey and Ruxton, 2018](#)). Model residuals were tested for spatial autocorrelation with Moran's I tests and none was detected in any of the models ($p \geq 0.062$). We obtained model outputs using type III sums of squares Wald chi-square tests with the command 'Anova' (library 'car', version 3.1–2, ([Fox and Weisberg, 2019](#))) and R^2 values with the command 'performance' (library 'performance', version 0.12.2, ([Lüdtke et al., 2021](#))).

3. Results

3.1. Pest occurrence and crop damage in Denmark and Sweden

The occurrence or damage thresholds for pest control were rarely reached across all five years in either Denmark or Sweden ([Fig. 3](#)), with 30 of the 134 fields having recorded pest occurrence or damage above the threshold for at least one pest. In Denmark, the pest most commonly

exceeding the threshold was thrips, followed by black bean aphids and the pygmy mangold beetle. In Sweden, the pests most commonly exceeding the threshold were flea beetles and black bean aphids, followed by beet leafminers and thrips ([Fig. 3](#)). While most pests were found to cause occasional damage above the threshold across the whole study region, thrips damage was especially high on the Danish island Lolland ([Fig. 3](#)).

The differences between the countries in pest occurrence and damage were also reflected in the statistical models. The probability for thrips damage was 21 % higher and its magnitude was on average 109 % higher in Denmark than in Sweden (calculation based on estimated marginal means obtained from the 1000 m scale models; [Fig. 4, Supporting Information, Tables S5 & S6](#)). Flea beetle damage was 124 % more likely and flea beetle damage and the share of plants with beet leafminer eggs were on average 104 % and 199 % higher in Sweden than in Denmark (calculation based on estimated marginal means obtained from the 1000 m and 500 m scale models, respectively; [Fig. 4, Supporting Information, Tables S5 & S6](#)). In addition, black bean aphid presence was 31 % less likely in Sweden (2000 m scale model; [Supporting Information, Table S5](#)) but when they occurred, a higher share of plants tended to have black bean aphid colonies in Sweden, but only in the 1000 m and 2000 m scale models ([Fig. 4, Supporting Information, Table S6](#)).

3.2. Pest occurrence and crop damage in relation to landscape predictors

Each landscape predictor affected at least one pest at one of the scales. The inter-annual change in sugar beet cover was positively related to flea beetle damage at the 500 m scale, which increased by 15.4 % for every ten percentage points inter-annual increase in sugar beet cover ([Fig. 4 & 5 A, Supporting Information, Table S6](#)). In black bean aphids and thrips, increasing cropland cover at the 500 m scale increased the probability of pest occurrence and crop damage, respectively ([Supporting Information, Table S5](#)). Cropland cover was negatively related to damage caused by flea beetles at the 500 m and 2000 m

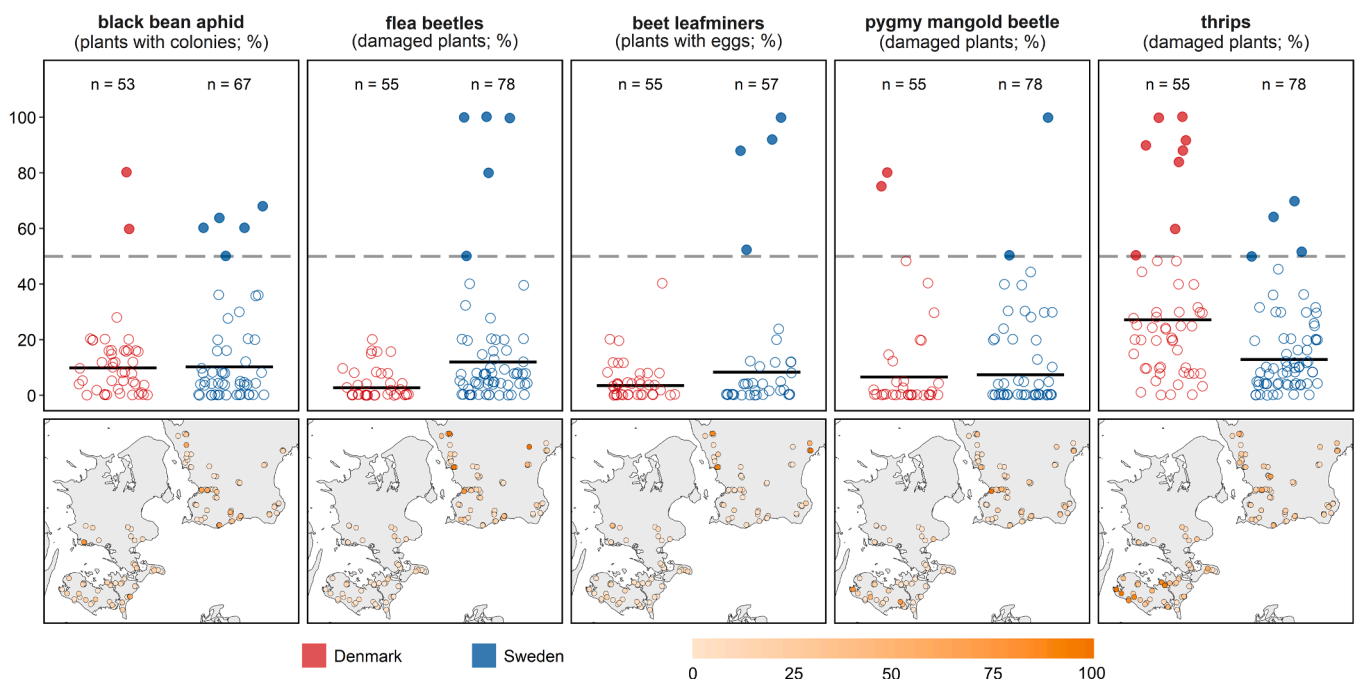


Fig. 3. The maximum occurrence or damage values measured across the five different pests in Denmark (red) and Sweden (blue) across all years (top) and the geographical distribution of pest damage with fields coloured according to the magnitude of damage recorded (bottom). In the top row, solid black lines indicate the average and dashed grey lines indicate the 50 % threshold for foliar insecticide application, with points above the 50 % threshold filled and points below the threshold open. For further explanation of the thresholds, see [2.2](#). The unit for the y-axis is stated in the respective panel titles. For an enlarged version of the maps, see [Fig. S3](#).

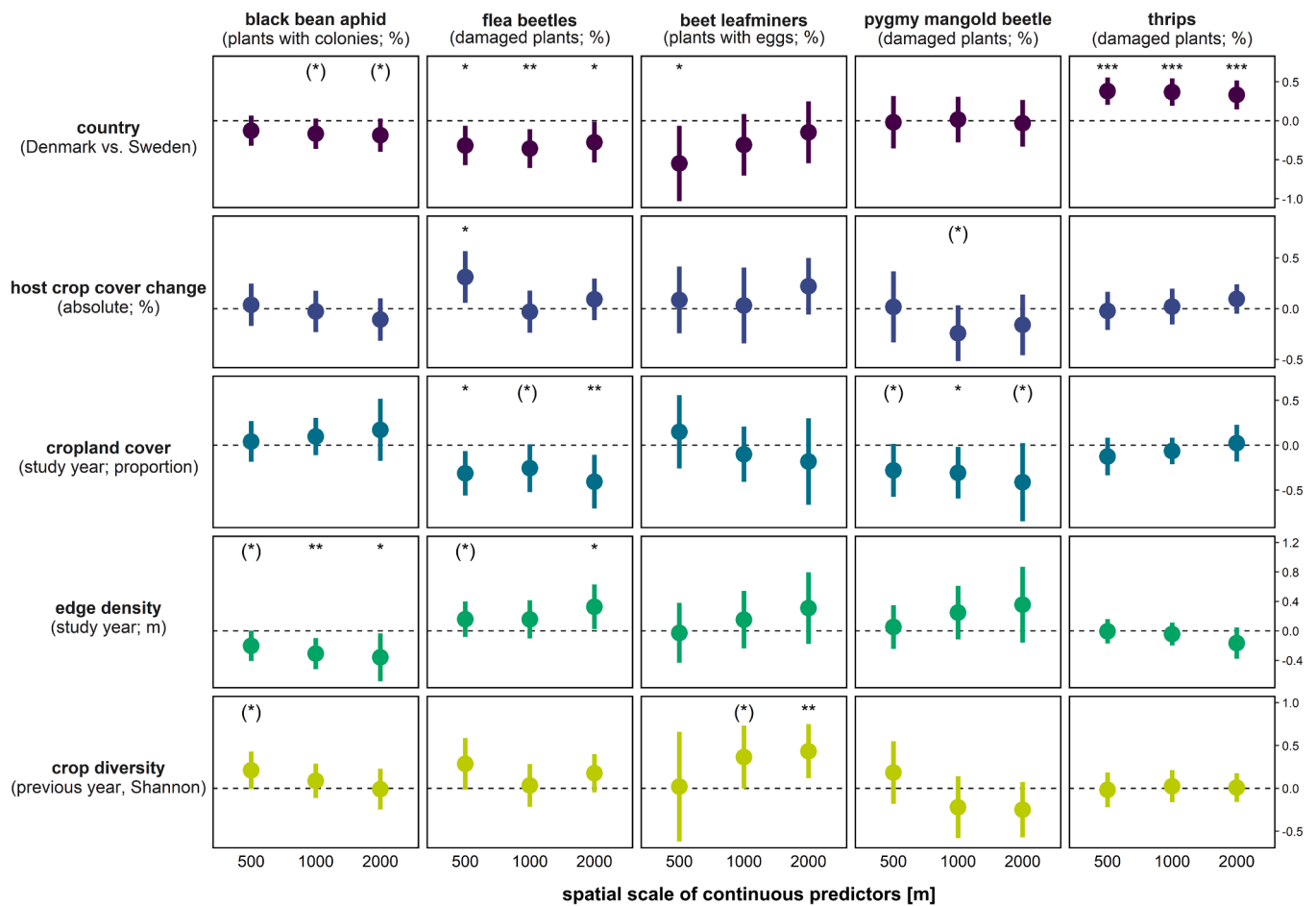


Fig. 4. Model coefficients for (panels from top to bottom) country, host crop cover change, cropland cover, edge density and Shannon crop diversity in the previous year in the three buffer radii 500 m, 1000 m and 2000 m (within each panel from left to right) for plants with black bean aphid colonies, plants with flea beetle damage, plants with beet leafminer eggs, plants damaged by the pygmy mangold beetle and plants damaged by thrips (panels from left to right). Coefficient estimates that do not overlap with the dashed line represent statistically significant effects ($p < 0.05$). Coefficient estimates above the dashed line indicate positive relationships; coefficient estimates below the dashed line negative relationships. For the categorical predictor 'country', a coefficient above the dashed line indicates higher values in Denmark, an estimate below the dashed line higher values in Sweden. Continuous fixed effects were scaled to magnitudes of their standard deviation (z scaling); thus coefficients can be interpreted as changes in the response on the log scale per 1 standard deviation of the fixed effect (for standard deviations, see Table S4). The coefficients were obtained from the truncated part of the zero-inflated models. (*) indicates $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. For statistics, see Table S6.

scales and damage caused by the pygmy mangold beetle at the 1000 m scale, with damage decreasing by 14.2 %, 24.3 % and 18.7 % per ten % increase in cropland cover, respectively (Figs. 4, 5B & C, Supporting Information, Table S6). Edge density was positively related with damage caused by flea beetles at the 2000 m scale with damage increasing by 11.0 % per 10,000 m edge length (Fig. 4 & 5D, Supporting Information, Table S6). Edge density was, however, also negatively related to black bean aphid occurrence at the 1000 m and 2000 m scales, with a decrease by 45.2 % and 11.9 % per 10,000 m edge length, respectively (Fig. 4 & 5E, Supporting Information, Table S6). The crop diversity in the preceding year increased beet leafminer occurrence by 27.4 % per 0.1 units of crop diversity at the 2000 m scale (Fig. 4 & 5F, Supporting Information, Table S6).

4. Discussion

Analysing a monitoring dataset of five insect pests in sugar beet collected in 134 commercially grown fields over five years in two countries, we found pest occurrence and damage to be generally low, with damage thresholds for at least one of the pests being exceeded in 20 % of the fields. Flea beetle damage and beet leafminer occurrence was more common in Sweden while damage caused by thrips was more

common in Denmark. These differences could possibly be related to differences in cropping systems with more alternative hosts such as oilseed rape for flea beetles (Boetzel et al., 2025) in Sweden, and climate, with more suitable weather conditions for thrips in Denmark (Davidson and Andrewartha, 1948). Pest occurrence and damage across all pests varied, however, strongly across individual fields. Since measurements were conducted only in a small part of each field, within-field variability in pest occurrence and crop damage remains unknown. Despite sporadic outbreaks in the monitoring plots of individual fields, pests and crop damage were often absent, resulting in a limited ability to evaluate landscape-scale drivers. Nevertheless, we found some landscape-level effects that can be integrated in sugar beet pest management.

In contrast to our first hypothesis, the inter-annual change of host crop cover was overall not a strong predictor for pest occurrence and damage in sugar beet. We only found a positive relation between an inter-annual increase in sugar beet area and the damage caused flea beetles on sugar beet plants at the smallest spatial scale of 500 m but not at the other two spatial scales. As inter-annual change of host crop cover was much more pronounced at the smallest spatial scale than on the larger spatial scales (Table S4), increases rather indicate an inter-annual concentration of host crop fields close to the studied fields. This could in turn have increased flea beetle damage in the monitoring plots due to

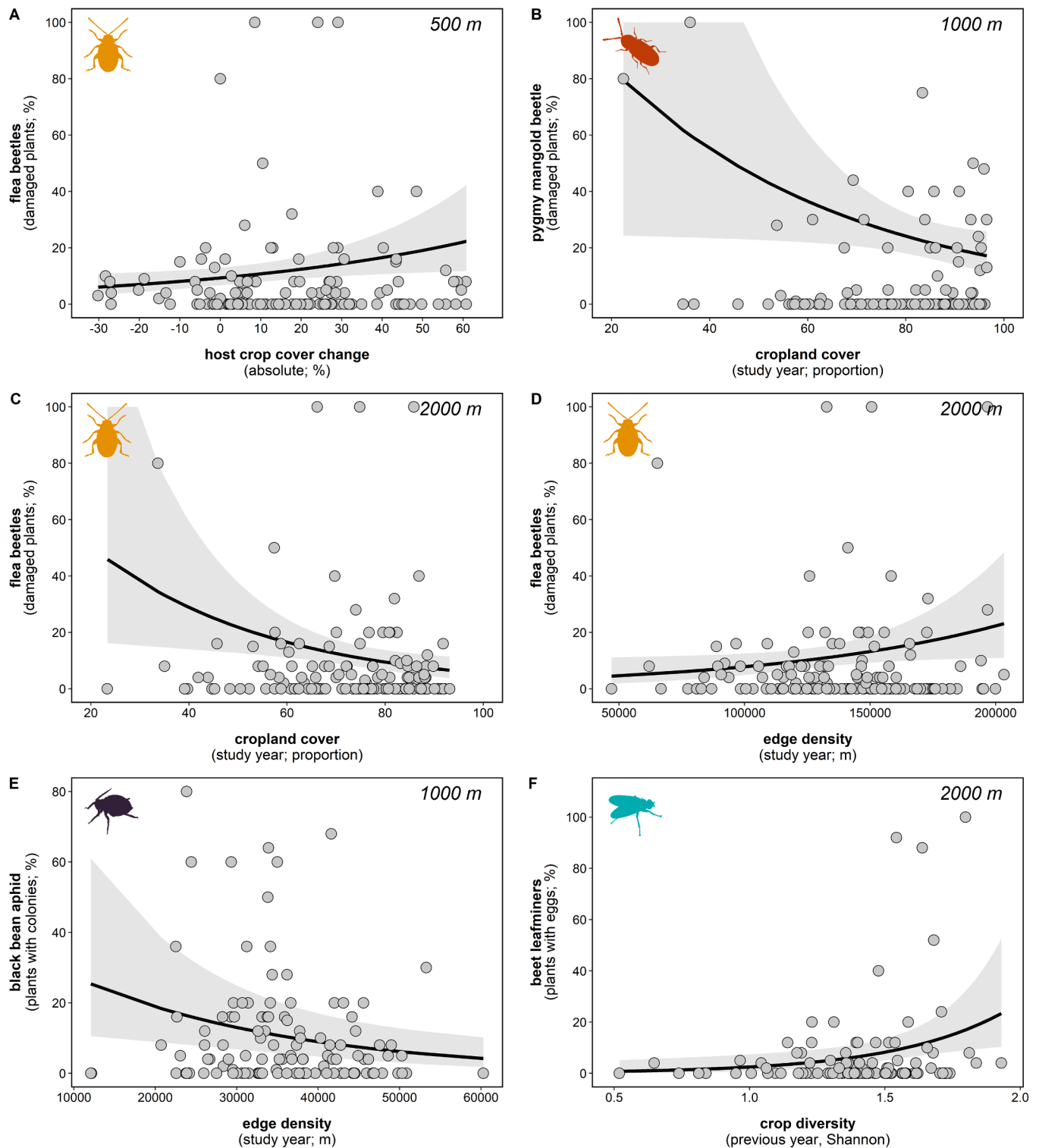


Fig. 5. Selected statistically significant ($p < 0.05$) landscape effects with the largest effect sizes on sugar beet insect pest occurrence and damage responses. All results are shown in Fig. 3. Solid lines are marginal model predictions for the radius stated in italics, grey areas are 95 % confidence intervals, and points are the raw data. From top left to bottom right: The percentage of plants damaged by flea beetles in relation to the absolute change in host crop cover from the previous year to the year of assessment (A), the percentage of plants damaged by the pygmy mangold beetle (B) and the percentage of plants damaged by flea beetles in relation to cropland cover (C), the percentage of plants damaged by flea beetles (D) the percentage of plants with colonies of the black bean aphid in relation to edge density (E), and percentage of plants with eggs of beet leafminers in relation to Shannon crop diversity in the previous year (F). Panels are ordered by the order of hypotheses and the order of Fig. 4. Responses were predicted for the truncated part of the zero-inflated models. For statistics, see Table S6.

the aggregation behaviour of flea beetles (Li et al., 2024). The absence of effects of inter-annual change in host crop cover was especially surprising in two of the more specialised sugar beet pests for which strong effects would be expected, beet leafminers and the pygmy mangold beetle. An inter-annual decrease in host crop cover has previously been shown to concentrate specialised pests of winter oilseed rape on the remaining fields (Schneider et al., 2015; Scheiner and Martin, 2020; Fricke et al., 2023). Compared to earlier work on pest densities, we do not find concentration effects, which could be due to just, apart from aphids, measuring crop damage, which might not only be related to pest abundance but also plant density and growth rate of the crop. In contrast to some previous studies, we used absolute changes in host crop cover instead of relative changes. The same absolute changes can translate to drastically different relative changes in host crop cover, with landscapes having low host crop cover yielding larger relative changes that can be influential for results. As pest individuals reproduce on absolute crop area, we chose to relate absolute changes in host crop cover to measures of pest occurrence or damage. To determine how to best relate changes in host crop cover to changes in pest occurrence or damages, assessments of pest occurrence on multiple crop fields across several years in the same landscapes would be needed. A similar, absolute change-based analysis of specialised Brassica pests found mixed effects of host crop cover change, with the strongest effects similarly at the 500 m scale (Scheiner and Martin, 2020). In general, sugar beet fields were rather uniformly distributed across years and the landscape in our study area (Fig. 1). This temporal stability is likely a result of relatively stable contracts with the sugar producer, leading to limited changes in the host crop cover between years in the landscapes, especially on the 1000 and 2000 m scales (Fig. 1 & Table S4).

According to our second hypothesis we expected a higher cropland cover to indirectly increase pest problems via increased landscape-wide management-intensity, lowering natural pest regulation (Meehan et al., 2011; Rusch et al., 2016). While a higher cropland cover indeed increased the probability of black bean aphid occurrence and thrips damage, we observed the opposite for the magnitude of crop damage caused by the two univoltine sugar beet pests, flea beetles and the pygmy mangold beetle. Disturbances such as insecticide applications likely have stronger negative effects on univoltine pests with limited reproduction capabilities like flea beetles and the pygmy mangold beetle than on multivoltine insect crop pests. As we did not have access to data on landscape-wide management intensity or insecticide use, we could not verify a possible relation between these factors and cropland cover in our study region. In addition, we could not directly test possible simultaneous effects of the availability of refugial habitats for pests that are negatively related to cropland cover. The most important non-crop habitat in the study region, permanent grassland, was almost entirely absent from the studied landscapes. Our results indicate that for flea beetles that need non-crop habitats for overwintering to complete their life cycle, the lack of refugial habitats might reduce crop damage (Boetzel et al., 2025). The pygmy mangold beetle, in contrast, predominantly overwinters directly in the soil of the attacked sugar beet fields (Cochrane and Thornhill, 1987) and a relation to non-crop refugial habitat seems unlikely. We thus believe that cropland cover primarily acted as a predictor for landscape-wide management intensity and insecticide use that in turn negatively affected the pygmy mangold beetle in our study.

According to our third hypothesis, we expected an indirect negative effect of increased edge density on pest occurrence and damage mediated by the beneficial effect of field edges on natural pest control. Field edges foster richness and density of natural enemies (Martin et al., 2016, 2019; Boetzel et al., 2024) and stabilise natural enemy populations across the crop rotation (Boetzel et al., 2020). Edge density was found to promote aphid suppression in soybean (Almdal and Costamagna, 2023), to lower densities of *Phyllotreta* flea beetles in spring oilseed rape (Boetzel et al., 2023) and cereal leaf beetles in wheat (González et al., 2022). In contrast, we found varying effects of edge density on pest occurrence

and crop damage in sugar beet: While the proportion of plants with black bean aphid colonies was negatively related to edge density as expected, the crop damage caused by flea beetles was positively related to edge density. Flea beetles, at least in part, overwinter in crop field edges and grassy margin structures along edges, and emerge from these early in the season (Boetzel et al., 2025). Aphids, in contrast, overwinter in woody vegetation and colonise the field later in the year, and thus might be more affected by natural enemies originating from field edges (Östman et al., 2001, 2003; Boetzel et al., 2024). Our results emphasise that non-crop habitats and field edges can have ambivalent effects for different pests (Karp et al., 2018). For certain pests, field edges can act as refuges as they are comparably undisturbed islands in a highly volatile cropping landscape. Pest densities can be elevated along field edges (Ingrao et al., 2017) and crop damage caused by pests can increase with edge density (Martin et al., 2016). Pests that can complete their life cycle within crop fields have been found to not be affected at all by edge density (Martin et al., 2019). Recommendations for increased edge density (e.g. Tscharntke et al. 2021) should thus be nuanced. For a sugar beet pest management that aiming at regulating multiple pests simultaneously, increasing edge density is not a promising measure as benefits for aphid regulation might be outweighed by drawbacks in mitigation of flea beetle damage. Edge density as a metric is a combination of effects of the field edge per se, the field margin, i.e. the non-crop area that can either be present or absent outside the field along the edge, and the average field sizes in a landscape. Field margin composition and management might further also matter. Unveiling which of these local or landscape-scale field edge properties affect different pests and their natural enemies will be necessary to inform pest management.

Landscape-level crop diversity in the preceding year has been positively related to the richness of natural enemies (Raderschall et al., 2022) but also to pest densities, likely due to the provision of alternate host crops facilitating the persistence of the pests in the landscape (Boetzel et al., 2023). The fourth hypothesis of a positive relation between landscape-level crop diversity in the preceding year and pest occurrence and damage was only confirmed for beet leafminer occurrence at the 2000 m scale. Apart from beet cover in the previous year that was negatively correlated with beet leafminer occurrence (Pearson: $r = -0.22$; $p < 0.018$), this result seems to have been driven especially by the presence of potato and other vegetables. In landscapes where potato or other vegetables had been present (38 and 63 out of 112 landscapes), a higher average share of the beet plants had mines of beet leafminers (10.0 % vs. 3.9 % for potato and 7.8 % vs. 3.6 % for other vegetables). The occurrence of the beet leafminer was positively correlated with the landcover of potato (Pearson: $r = 0.35$; $p = 0.033$) and other vegetables (Pearson: $r = 0.36$; $p = 0.004$) in the preceding year. While beet leafminers mainly reproduce on wild and cultivated members of the *Amaranthaceae* family, e.g. sugar beet, spinach or several species of the genus *Atriplex*, they do occasionally reproduce on various *Solanaceae* and have been reported attacking potatoes. This suggests that potato and other vegetables act as alternative host for at least one of the species of beet leafminers in our region and requires confirmation, e.g., by systematic trapping across candidate crops. The absence of negative effects on pest occurrence and damage emphasises that increasing crop diversity might not always be beneficial for pest control. Alternative host crops should be identified, and their spatiotemporal distribution should be minded in pest management strategies, rather than crop diversity per se.

Our results indicate a limited influence of landscape-scale drivers on pests in unsprayed plots of sugar beet fields with a pyrethroid seed treatment. No single landscape-scale simultaneously affected damage by all pests. For growers, our results can nevertheless be useful for determining some risk factors for pests in their sugar beet crops. This knowledge can be further developed into a predictive tool that would enable growers to receive information on field-specific risk based on landscape factors and increase monitoring and management for high-risk pests. Based on our results, low cropland cover decreases the

probability of presence of black bean aphids and thrips damage but increases the risk for severe damage by pygmy mangold beetle and flea beetles. High crop diversity in the preceding year (or potentially rather potato crops), increases the risk for infestation by beet leafminers. Strong inter-annual concentrations in beet area at a small scale should be avoided as they can lead to a concentration of flea beetles. A low edge density reduces flea beetle injury but increases aphid densities. To some extent the landscape aspects examined here can also be manipulated by sugar beet growers to reduce pressure from certain pests should they become chronically problematic, although this would often require collective action of communities of land managers at the landscape scale (Lundin et al., 2021). Especially for thrips that most often caused relevant damage beyond the pest control threshold, however, no landscape-level predictors for the magnitude of crop damage were found, possibly due to their polyphagous nature. For some pests like beet leafminers and the pygmy mangold beetle, the generally low damage levels might, however, have camouflaged potential landscape-level drivers. If a pest is predominantly absent, factors that modulate pest densities will likely not be detected.

In summary, we found that insect pests generally caused limited damage to sugar beet in Denmark and Sweden in a five-year period following the ban of neonicotinoid seed treatments. They nevertheless had occasional outbreaks above thresholds that would cause significant economic damage in individual fields if not treated chemically with foliar applications of insecticides. To produce sugar beets with dwindling opportunities for chemical insect control, the cause of such occasional economical damage needs to be better understood, and countermeasures developed. We demonstrated here that landscape scale drivers affect pest occurrence and damage patterns, but incidental factors such as weather, conservation biological control (Jachowicz et al., 2024), field management and crop rotation including the use of cover crops (Heimbach and Garbe, 1996) and intercropping with service crops (Favrot et al., 2024), sugar beet fertiliser and weed management (Purvis and Curry, 1984), as well as alternative and environmentally sustainable pesticide options (e.g., Jactel et al. 2019) can also modulate pest occurrence and damage and deserve further attention. In addition, insect-transmitted sugar beet diseases could cause economically relevant yield loss even at low pest densities (Hauer et al., 2017) and should be included in future assessments. Further, we only examined the net effect of bottom-up and top-down landscape scale drivers on insect pest densities and crop damage, and it would be useful to differentiate between them in future studies, e.g., by including measurements of natural enemies and biological control. Integrating landscape-scale drivers with local field management would be needed for the development of economically and environmentally sustainable insect pest regulation in sugar beet.

CRedit authorship contribution statement

Ola Lundin: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Anne Lisbet Hansen:** Writing – review & editing, Supervision, Resources, Methodology, Investigation. **Nika Jachowicz:** Writing – review & editing, Resources, Methodology, Investigation, Data curation. **Boetzel Fabian Alexander:** Writing – review & editing, Writing – original draft, Visualization, Validation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Acknowledgements

We are grateful to consultants at Nordic Sugar and the Swedish Board of Agriculture for collecting the monitoring data and to the landowners

for their participation and access to their fields. National research and development funds provided to OL and FAB by the Swedish Board of Agriculture supported the project.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109999.

Data availability

Data are publicly available from the Swedish National Data Service (Svensk nationell datatjänst): <https://doi.org/10.5878/r2ak-sf73>

References

- Almdal, C.D., Costamagna, A.C., 2023. Crop diversity and edge density benefit pest suppression through bottom-up and top-down processes, respectively. *Agric. Ecosyst. Environ.* 349, 108447. <https://doi.org/10.1016/j.agee.2023.108447>.
- Boetzel, F.A., Schuele, M., Krauss, J., Steffan-Dewenter, I., 2020. Pest control potential of adjacent agri-environment schemes varies with crop type and is shaped by landscape context and within-field position. *J. Appl. Ecol.* 57, 1482–1493. <https://doi.org/10.1111/1365-2664.13653>.
- Boetzel, F.A., Bommarco, R., Aguilera, G., Lundin, O., 2023. Spatiotemporal isolation of oilseed rape fields reduces insect pest pressure and crop damage. *J. Appl. Ecol.* 60, 1388–1398. <https://doi.org/10.1111/1365-2664.14424>.
- Boetzel, F.A., Sponsler, D., Albrecht, M., Batáry, P., Birkhofer, K., Knapp, M., Krauss, J., Maas, B., Martin, E.A., Sirami, C., Sutter, L., Bertrand, C., Baillod, A.B., Bota, G., Bretagnolle, V., Brotons, L., Frank, T., Fusser, M., Giral, D., González, E., Hof, A.R., Luka, H., Marrec, R., Nash, M.A., Ng, K., Plantegenest, M., Poulin, B., Siriwardena, G. M., Tschamtk, T., Tschumi, M., Vialatte, A., Van Vooren, L., Zubair-Anjum, M., Entling, M.H., Steffan-Dewenter, I., Schirmel, J., 2024. Distance functions of carabids in crop fields depend on functional traits, crop type and adjacent habitat: a synthesis. *Proc. R. Soc. B Biol. Sci.* 291, 20232383. <https://doi.org/10.1098/rspb.2023.2383>.
- Boetzel, F.A., Malsher, G., Bommarco, R., Lundin, O., 2025. Flea beetles in spring oilseed rape differ in phenology and habitat choices for reproduction and overwintering—implications for pest management. *Agric. For. Entomol.* 27, 241–251. <https://doi.org/10.1111/afe.12659>.
- Brooks, M.E., Kristensen, K., van Benthem, K.J., Magnusson, A., Berg, C.W., Nielsen, A., Skaug, H.J., Mächler, M., Bolker, B.M., 2017. Modeling zero-inflated count data with glmmTMB. *bioRxiv*, 132753. <https://doi.org/10.1101/132753>.
- Cochrane, J., Thornhill, W.A., 1987. Variation in annual and regional damage to sugar beet by pygmy beetle (*Atomaria linearis*). *Ann. Appl. Biol.* 110, 231–238. <https://doi.org/10.1111/j.1744-7348.1987.tb03253.x>.
- Davidson, J., Andrewartha, H.G., 1948. The influence of rainfall, evaporation and atmospheric temperature on fluctuations in the size of a natural population of thrips imagnis (Thysanoptera). *J. Anim. Ecol.* 17, 200–222. <https://doi.org/10.2307/1485>.
- Deguine, J.-P., Aubertot, J.-N., Flor, R.J., Lescouret, F., Wyckhuys, K.A.G., Ratnadass, A., 2021. Integrated pest management: good intentions, hard realities. *A review. Agron. Sustain. Dev.* 41, 38. <https://doi.org/10.1007/s13593-021-00689-w>.
- Esri Inc., 2023. ArcGIS Pro Esri Inc., Redlands, CA, USA.
- European Court of Justice, 2023. 1st Chamber, Judgment of 19.01.2023, Pesticide Action Network Europe ASBL and Others v. État belge, Case C-162/21, ECLI:EU:C:2023:30.
- FAO, 2024a. Raw cane or beet sugar production in 2021. UN Food and Agriculture Organization Corporate Statistical Database (FAOSTAT).
- FAO, 2024b. Sugar beet production in 2021. UN Food and Agriculture Organization Corporate Statistical Database (FAOSTAT).
- Favrot, A., Maupas, F., Royer, C., Raaijmakers, E., Dufrane, C., Wauters, A., Makowski, D., 2024. Efficacy of neonicotinoid and non-neonicotinoid treatments on virus yellows and sugar beet yields. *Crop Prot.* 180, 106658. <https://doi.org/10.1016/j.cropro.2024.106658>.
- Fox, J., Weisberg, S., 2019. *An R Companion to Applied Regression*. Sage, Thousand Oaks CA.
- Frank, E.G., 2024. The economic impacts of ecosystem disruptions: costs from substituting biological pest control. *Science* 385, eadg0344. <https://doi.org/10.1126/science.adg0344>.
- Fricke, U., Redlich, S., Zhang, J., Benjamin, C.S., Englmeier, J., Ganuza, C., Haensel, M., Riebl, R., Rojas-Botero, S., Tobisch, C., Uhler, J., Uphus, L., Steffan-Dewenter, I., 2023. Earlier flowering of winter oilseed rape compensates for higher pest pressure in warmer climates. *J. Appl. Ecol.* 60, 365–375. <https://doi.org/10.1111/1365-2664.14335>.
- González, E., Bianchi, F.J.J.A., Eckert, P.W., Pfaff, V., Weiler, S., Entling, M.H., 2022. Ecological requirements drive the variable responses of wheat pests and natural enemies to the landscape context. *J. Appl. Ecol.* 59, 444–456. <https://doi.org/10.1111/1365-2664.14062>.
- Hanse, B., Schneider, J.H.M., Termorshuizen, A.J., Varrelmann, M., 2011. Pests and diseases contribute to sugar beet yield difference between top and averagely managed farms. *Crop Prot.* 30, 671–678. <https://doi.org/10.1016/j.cropro.2011.02.018>.

- Hansen, A.L., 2023. Bekæmpelse af tidligt forekommende skadedyr, trips. NBR Fagl. Beret. 2023 75–78.
- Hartig, F., 2022. DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models.
- Hauer, M., Hansen, A.L., Manderyck, B., Olsson, Å., Raaijmakers, E., Hanse, B., Stockfisch, N., Märkländer, B., 2017. Neonicotinoids in sugar beet cultivation in central and Northern Europe: efficacy and environmental impact of neonicotinoid seed treatments and alternative measures. *Crop Prot.* 93, 132–142. <https://doi.org/10.1016/j.cropro.2016.11.034>.
- Heimbach, U., Garbe, V., 1996. Effects of reduced tillage systems in sugar beet on predatory and pest arthropods. *Acta Jutlandica* 71, 195–208.
- Ingrao, A.J., Schmidt, J., Jubenville, J., Grode, A., Komondy, L., VanderZee, D., Szendrei, Z., 2017. Biocontrol on the edge: field margin habitats in asparagus fields influence natural enemy-pest interactions. *Agric. Ecosyst. Environ.* 243, 47–54. <https://doi.org/10.1016/j.agee.2017.04.011>.
- Jachowicz, N., Kramer Jacobsen, S., Sigsgaard, L., 2024. The Worst Pest Makes the Best Prey: Higher Proportion of *Myzus persicae* than *Aphis fabae* in the Gut Content of Generalist and Specialist Predators Compared to Field Densities. <https://doi.org/10.2139/ssrn.4968320>. SSRN preprint.
- Jactel, H., Verheggen, F., Thiéry, D., Escobar-Gutiérrez, A.J., Gachet, E., Desneux, N., 2019. Alternatives to neonicotinoids. *Environ. Int.* 129, 423–429. <https://doi.org/10.1016/j.envint.2019.04.045>.
- James, G., Witten, D., Hastie, T., Tibshirani, R., 2013. *An Introduction to Statistical Learning with Applications in R*. Springer, New York NY.
- Jordbruksverket, 2024. Kartor och Geografiska informationssystem - Årsraser skiftesdata. Jordbruksverket.
- Karp, D.S., Chaplin-Kramer, R., Meehan, T.D., Martin, E.A., DeClerck, F., Grab, H., Gratton, C., Hunt, L., Larsen, A.E., Martínez-Salinas, A., O'Rourke, M.E., Rusch, A., Poveda, K., Jonsson, M., Rosenheim, J.A., Schellhorn, N.A., Tschamtké, T., Wratten, S.D., Zhang, W., Iverson, A.L., Adler, L.S., Albrecht, M., Alignier, A., Angelella, G.M., Zubair Anjum, M., Avelino, J., Batáry, P., Baveco, J.M., Bianchi, F.J. J.A., Birkhofer, K., Bohnenblust, E.W., Bommarco, R., Brewer, M.J., Caballero-López, B., Carrière, Y., Carvalho, L.G., Cayuela, L., Centrella, M., Četković, A., Henri, D.C., Chabert, A., Costamagna, A.C., De la Mora, A., de Kraker, J., Desneux, N., Diehl, E., Diekötter, T., Dormann, C.F., Eckberg, J.O., Entling, M.H., Fiedler, D., Franck, P., Frank van Veen, F.J., Frank, T., Gagic, V., Garratt, M.P.D., Getachew, A., Gonthier, D.J., Goodell, P.B., Graziosi, I., Groves, R.L., Gurr, G.M., Hajian-Forooshani, Z., Heimpel, G.E., Herrmann, J.D., Huse, A.S., Inclán, D.J., Ingrao, A.J., Iv, P., Jacot, K., Johnson, G.A., Jones, L., Kaiser, M., Kaser, J.M., Keasar, T., Kim, T.N., Kishinevsky, M., Landis, D.A., Lavandero, B., Lavigne, C., Le Ralec, A., Lemessa, D., Letourneau, D.K., Liere, H., Lu, Y., Lubin, Y., Luttermoser, T., Maas, B., Mace, K., Madeira, F., Mader, V., Cortesero, A.M., Marini, L., Martinez, E., Martinson, H.M., Menozzi, P., Mitchell, M.G.E., Miyashita, T., Molina, G.A.R., Molina-Montenegro, M.A., O'Neal, M.E., Opatovsky, I., Ortiz-Martinez, S., Nash, M., Östman, Ö., Ouin, A., Pak, D., Paredes, D., Parsa, S., Parry, H., Perez-Alvarez, R., Perovici, D.J., Peterson, J.A., Petit, S., Philpott, S.M., Plantegenest, M., Plečáček, M., Pluess, T., Pons, X., Potts, S.G., Pywell, R.F., Ragsdale, D.W., Rand, T.A., Raymond, L., Ricci, B., Sargent, C., Sarthou, J.-P., Saulais, J., Schäckermann, J., Schmidt, N.P., Schneider, G., Schüepp, C., Sivakoff, F.S., Smith, H.G., Stack Whitney, K., Stutz, S., Szendrei, Z., Takada, M.B., Taki, H., Tamburini, G., Thomson, L.J., Tricault, Y., Tsafack, N., Tschumi, M., Valentin-Morison, M., Van Trinh, M., van der Werf, W., Vierling, K.T., Werling, B.P., Wickens, J.B., Wickens, V. J., Woodcock, B.A., Wyckhuys, K., Xiao, H., Yasuda, M., Yoshioka, A., Zou, Y., 2018. Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. In: PNAS, 115, pp. E7863–E7870. <https://doi.org/10.1073/pnas.1800042115>.
- Landbruksstyrelsen, 2024. Internet Markkort (IMK). Ministeriet for Fødevarer, Landbrug og Fiskeri, København.
- Lange, W.H., 1987. Insect pests of sugar beet. *Annu. Rev. Entomol.* 32, 341–360. <https://doi.org/10.1146/annurev.en.32.010187.02013>.
- Larsson, H., 1991. Jordlevande skadedyr i sockerbeter. Faktatblad om Växtskydd. SLU Publikationstjänst, Uppsala.
- Lemic, D., Schumann, M., Tilcher, R., Czarnecki, O., Mikac, M.K., Vučemićević-Jurić, D., Viric Gasparic, H., 2024. Enhancing pest management in sugar beet cultivation: impact of variety selection and insecticide seed treatments on sugar beet flea beetles and weevils. *Plant Prot. Sci.* 60, 278–287. <https://doi.org/10.17221/8/2024-Pps>.
- Li, Z., Costamagna, A.C., Beran, F., You, M., 2024. Biology, ecology, and management of flea beetles in brassica crops. *Annu. Rev. Entomol.* 69, 199–217. <https://doi.org/10.1146/annurev-ento-033023-015753>.
- Lüdecke, D., Ben-Shachar, M., Patil, I., Waggoner, P., Makowski, D., 2021. Performance: an r package for assessment, comparison and testing of statistical models. *J. Open Source Softw.* 6, 1–8. <https://doi.org/10.21105/joss.03139>.
- Lundin, O., Rundlöf, M., Jonsson, M., Bommarco, R., Williams, N.M., 2021. Integrated pest and pollinator management – expanding the concept. *Front. Ecol. Environ.* 19, 283–291. <https://doi.org/10.1002/fee.2325>.
- Martin, E.A., Seo, B., Park, C.-R., Reineking, B., Steffan-Dewenter, I., 2016. Scale-dependent effects of landscape composition and configuration on natural enemy diversity, crop herbivory, and yields. *Ecol. Appl.* 26, 448–462. <https://doi.org/10.1890/15-0856>.
- Martin, E.A., Dainese, M., Clough, Y., Báldi, A., Bommarco, R., Gagic, V., Garratt, M.P.D., Holzschuh, A., Kleijn, D., Kovács-Hostyánszki, A., Marini, L., Potts, S.G., Smith, H.G., Al Hassan, D., Albrecht, M., Andersson, G.K.S., Asís, J.D., Avron, S., Balzan, M.V., Baños-Picón, L., Bartomeus, I., Batáry, P., Burel, F., Caballero-López, B., Concepción, E.D., Coudrain, V., Dänhardt, J., Diaz, M., Diekötter, T., Dormann, C.F., Duflot, R., Entling, M.H., Farwig, N., Fischer, C., Frank, T., Garibaldi, L.A., Hermann, J., Herzog, F., Inclán, D., Jacot, K., Jauker, F., Jeanneret, P., Kaiser, M., Krauss, J., Le Féon, V., Marshall, J., Moonen, A.-C., Moreno, G., Riedinger, V., Rundlöf, M., Rusch, A., Scheper, J., Schneider, G., Schüepp, C., Stutz, S., Sutter, L., Tamburini, G., Thies, C., Tormos, J., Tschamtké, T., Tschumi, M., Uzman, D., Wagner, C., Zubair-Anjum, M., Steffan-Dewenter, I., 2019. The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe. *Ecol. Lett.* 22, 1083–1094. <https://doi.org/10.1111/ele.13265>.
- Meehan, T.D., Werling, B.P., Landis, D.A., Gratton, C., 2011. Agricultural landscape simplification and insecticide use in the midwestern United States. *Proc. Natl. Acad. Sci.* 108, 11500–11505. <https://doi.org/10.1073/pnas.1100751108>.
- Meier, U., Bachmann, L., Buhtz, E., Hack, H., Klose, R., Märkländer, B., Weber, E., 1993. *Phänologische Entwicklungsstadien der Beta-Rüben (Beta vulgaris L. spp.)*. Codierung und Beschreib. nach der erweiterten BBCHSkala Mit. Abbild. Nachr. Des. Dtsch. Pflanzenschutz. 45, 37–41.
- Menard, S., 2002. *Applied Logistic Regression Analysis*. Sage, Thousand Oaks CA.
- Morrissey, M.B., Ruxton, G.D., 2018. Multiple regression is not multiple regressions: the meaning of multiple regression and the non-problem of collinearity. *Philos. Theory Pract. Biol.* 10, 1–24. <https://doi.org/10.3998/ptpbio.16039257.0010.003>.
- Oerke, E.C., 2006. Crop losses to pests. *J. Agric. Sci.* 144, 31–43. <https://doi.org/10.1017/S0021859605005708>.
- Östman, Ö., Ekblom, B., Bengtsson, J., 2001. Landscape heterogeneity and farming practice influence biological control. *Basic Appl. Ecol.* 2, 365–371. <https://doi.org/10.1078/1439-1791-00072>.
- Östman, Ö., Ekblom, B., Bengtsson, J., 2003. Yield increase attributable to aphid predation by ground-living polyphagous natural enemies in spring barley in Sweden. *Ecol. Econ.* 45, 149–158. [https://doi.org/10.1016/S0921-8009\(03\)00007-7](https://doi.org/10.1016/S0921-8009(03)00007-7).
- Perez-Alvarez, R., Nault, B.A., Poveda, K., 2018. Contrasting effects of landscape composition on crop yield mediated by specialist herbivores. *Ecol. Appl.* 28, 842–853. <https://doi.org/10.1002/eap.1695>.
- Purvis, G., Curry, J.P., 1984. The influence of weeds and farmyard manure on the activity of carabidae and other ground-dwelling arthropods in a sugar beet crop. *J. Appl. Ecol.* 21, 271–283. <https://doi.org/10.2307/2403053>.
- R Development Core Team, 2024. *R: a Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.
- Raderschall, C.A., Lundin, O., Aguilera, G., Lindström, S.A.M., Bommarco, R., 2022. Legacy of landscape crop diversity enhances carabid beetle species richness and promotes granivores. *Agric. Ecosyst. Environ.* 340, 108191. <https://doi.org/10.1016/j.agee.2022.108191>.
- Rundlöf, M., Andersson, G.K.S., Bommarco, R., Fries, I., Hederström, V., Herbertsson, L., Jonsson, O., Klatt, B.K., Pedersen, T.R., Yourstone, J., Smith, H.G., 2015. Seed coating with a neonicotinoid insecticide negatively affects wild bees. *Nature* 521, 77–80. <https://doi.org/10.1038/nature14420>.
- Rusch, A., Chaplin-Kramer, R., Gardiner, M.M., Hawro, V., Holland, J., Landis, D., Thies, C., Tschamtké, T., Weisser, W.W., Vinqvist, C., Woltz, M., Bommarco, R., 2016. Agricultural landscape simplification reduces natural pest control: a quantitative synthesis. *Agric. Ecosyst. Environ.* 221, 198–204. <https://doi.org/10.1016/j.agee.2016.01.039>.
- Sánchez-Bayo, F., 2014. The trouble with neonicotinoids. *Science* 346, 806–807. <https://doi.org/10.1126/science.1259159>.
- Savary, S., Willcoquet, L., Pethybridge, S.J., Esker, P., McRoberts, N., Nelson, A., 2019. The global burden of pathogens and pests on major food crops. *Nat. Ecol. Evol.* 3, 430–439. <https://doi.org/10.1038/s41559-018-0793-y>.
- Scheiner, C., Martin, E.A., 2020. Spatiotemporal changes in landscape crop composition differently affect density and seasonal variability of pests, parasitoids and biological pest control in cabbage. *Agric. Ecosyst. Environ.* 301, 107051. <https://doi.org/10.1016/j.agee.2020.107051>.
- Schneider, G., Krauss, J., Riedinger, V., Holzschuh, A., Steffan-Dewenter, I., 2015. Biological pest control and yields depend on spatial and temporal crop cover dynamics. *J. Appl. Ecol.* 52, 1283–1292. <https://doi.org/10.1111/1365-2664.12471>.
- Tschamtké, T., Grass, I., Wanger, T.C., Westphal, C., Batáry, P., 2021. Beyond organic farming – harnessing biodiversity-friendly landscapes. *Trends Ecol. Evol.* 36, 919–930. <https://doi.org/10.1016/j.tree.2021.06.010>.
- Verheggen, F., Barrès, B., Bonafos, R., Desneux, N., Escobar-Gutiérrez, A.J., Gachet, E., Jérôme, L., Siegwart, M., Thiéry, D., Jactel, H., 2022. Producing sugar beets without neonicotinoids: an evaluation of alternatives for the management of viruses-transmitting aphids. *Entomol. Gen.* 42, 491–498. <https://doi.org/10.1127/entomologia/2022/1511>.
- Zuckerberg, B., Cohen, J.M., Nunes, L.A., Bernath-Plaisted, J., Clare, J.D.J., Gilbert, N.A., Kozidis, S.S., Mares Nelson, S.B., Shipley, A.A., Thompson, K.L., Desrochers, A., 2020. A review of overlapping landscapes: pseudoreplication or a red herring in landscape ecology? *Curr. Landsc. Ecol. Rep.* 5, 140–148. <https://doi.org/10.1007/s40823-020-00059-4>.