

Effects of regional crop rotations on autumn insect pests in winter oilseed rape

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Abstract

Background: Chemical control of insect pests in oilseed rape (OSR) is becoming increasingly difficult due to the development of resistance and restrictive insecticide approvals in Europe. At the same time, there is a lack of preventive and alternative control measures. Crop rotation mostly fails to control insects due to their mobility; however, changing regional cropping densities can dilute or concentrate pest pressure. In this study, we investigated whether the local occurrence of *Psylliodes chrysocephala* and *Delia radicum*, serious insect pests in winter OSR, is influenced by distance from the previous year's OSR fields and how changes in OSR rape cropping density at a regional scale (up to 10 km radius) affect pest pressure.

Results: Abundance of *P. chrysocephala* in yellow water traps decreased with increasing distance to previous year's OSR. Estimated catches in the first 3 weeks of migration were about 68–76% lower at 10 km distance compared to 1 km in autumn 2019 and 2020. However, in both seasons *P. chrysocephala* was able to disperse over distances of 10 km. Probability of root damage by *D. radicum* was affected by changes of OSR cropping area at a spatial scale of 2.5 km radius; it increased if acreage of OSR decreased. Furthermore, aphid infestation was lower when OSR was distant in the previous year.

Conclusion: This study could enable field-specific risk assessment and prediction of pest pressure. To decide about the effectiveness of cropping breaks at a regional level as a preventive crop protection measure, more knowledge on other pest species and antagonists is needed.

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Keywords: *Psylliodes chrysocephala*; *Delia radicum*; integrated pest management; spatio-temporal analysis; dispersal capacities; aphids

1 INTRODUCTION

Oilseed rape (*Brassica napus* L.) (OSR) is an important arable crop in many European countries.¹ Worldwide it was the second most important arable oilseed crop in 2019 with Australia, Canada, China, India and Europe being the largest producers (FAO, 2022 <https://www.fao.org/faostat/en/#data/QCL>). One of the major challenges in OSR cultivation is the control of insect pests as demonstrated by Zheng et al. (2020),² who estimated average annual yield losses of about 15% in Europe due to herbivorous insects. The control of insect pests currently mainly relies on synthetic insecticides. However, the development of insecticide resistance^{3–6} and an increasingly restrictive approval of pesticides in the European Union are a threat to OSR production in Europe.

In autumn, the main insect pests of OSR in northern Europe are the cabbage stem flea beetle (*Psylliodes chrysocephala* L.) and the cabbage root fly (*Delia radicum* L.).^{7–9} Additionally, aphids, mainly the Green peach aphid (*Myzus persicae* Sulzer), can colonize the crop in autumn and transmit the turnip yellows virus (TuYV).⁸ Many European regions have suffered from massive pest pressure by *P. chrysocephala* in recent years, which has resulted in a decline of OSR cultivation area.^{10,11} There is also a lack of preventive and efficient non-chemical

control methods for insect pests in OSR as recently reviewed for *P. chrysocephala* by Ortega-Ramos et al. (2022).¹² Preventive measures such as breeding resistance against insect pests are still in the early stage of development for OSR, with the exception of virus-tolerant varieties.¹³ Other research approaches as part of integrated pest management strategies being currently pursued include the enhancement of conservation biological control^{14,15} and the application of cultural methods such as the adjustment of sowing date, reduced soil tillage or companion planting.^{10,12,16–19} Cultural methods aim to reduce the damage potential of pest populations e.g. by influencing the temporal coincidence between pest and host, interfering with host plant location by pests, or enhancing the crop's ability to

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compensate for damage. For instance, ongoing research reveals some positive results of companion planting of OSR with other plant species on the infestation with *P. chrysocephala*.^{12,16} However, the success of these alternative control methods is highly dependent on environmental conditions i.e. weather or pest densities and can vary between years and regions.^{20,21} For this reason, the effectiveness of such methods is difficult to predict and there is a need for control options that potentially reduce the overall pest populations.

Crop rotation, i.e. the assignment of crops to specific fields over time,²² can interrupt pest reproduction cycles and thereby reduce pest pressure. In case of soil-borne pathogens, crop rotation on a given field is considered an important preventive measure² and is widely practiced in agriculture. Crop rotation is also successful against insect pests that are specialized and have limited mobility.^{23,24} Many OSR insect pests are specialists, meaning that they can reproduce only on a narrow range of host plants. According to the landscape-moderated concentration and dilution hypothesis²⁵ it is expected that changes in the availability of habitat resources interact with the population development of specialists at a landscape scale. Further, it is assumed that higher trophic levels of specialists such as predators and parasitoids are more sensitive to changes compared to those of lower trophic levels and that populations can be affected at different spatial scales.²⁵ Recent studies have demonstrated effects of changes in OSR cultivation on herbivore, parasitoid and pollinator communities in OSR,^{17,26–32} however, these focus mainly on spring pests. Oilseed rape is by far the most important host plant for *P. chrysocephala*⁹ and also important for *D. radicum* in areas without cabbage production. Both species can generally reproduce on several *Brassica* species, but OSR is a superior host plant in terms of both quality and quantity.^{33,34} The aphid *M. persicae*, which has a broad host range, can also successfully reproduce on OSR and benefits from its large cropping area.

Currently, there is still a lack of knowledge about the influence of landscape configuration on insect dispersal capabilities. Even though difficult to conduct, existing studies suggest that important OSR pest species may have a dispersal capacity of several kilometers. For example, Stechmann and Schütte (1976)³⁵ marked adult pollen beetles (*Brassicogethes aeneus* F.), which flew more than 10 km within two days after their emergence in summer. Dlabola and Taimr (1965)³⁶ marked pollen beetles in spring, some of which were recaptured more than 4 km from their release site after eight days. For the cabbage seedpod weevil (*Ceutorhynchus obstrictus* M.) a dispersal rate of about 55 km per year from established populations was estimated in western Canada.³⁷ For *D. radicum* and *P. chrysocephala* dispersal capacities of 2–3 km are reported.^{38,39} The ability of many insect pests to migrate over great distances currently limits the effectiveness of crop rotation as a tool for their control. In their review on global challenges of OSR production, Zheng et al. (2022)² therefore proposed that a waiver of OSR cultivation at a regional scale could interrupt pest population dynamics, resulting in reduced pest pressure in the following year. This needs to be studied in the field, especially because the knowledge on the dispersal capacities and migration patterns of OSR pests is limited.

The possibility that insect pests are influenced by crop rotations at a regional scale was investigated by Schütte (1979)⁴⁰ in a one year-trial. In that study the pest pressure in two adjacent regions (each about 800 ha) with and without OSR cultivation in the previous year was compared. Effects of reduced pest

pressure were found for brassica pod midge (*Dasineura brassicae* W.), whereas no effects were detected for cabbage seedpod weevil and pollen beetles. Other studies, for example on cabbage stem flea beetle⁴¹ and stem weevils,⁴² suggested that pest infestation in a given crop is influenced by the distance from the previous year's OSR crops.

In addition to the distance and amount of host plant area, the amount of semi-natural habitats (SNH) within the landscape may also affect pest densities on a specific field, i.e. these areas are used by insect pests for aestivation or overwintering.⁹ The cross-habitat spillover hypothesis²⁵ suggests, that there is an interaction between habitats and an exchange of resources and energy, i.e. species from adjacent habitats regularly migrate into arable fields.⁴³ Studies revealed positive effects of SNH such as calcareous grasslands or flower strips on the abundance of pollinators and parasitoids in OSR.^{26,43–45} Therefore, a relevant impact of SNH on both the pests and its natural antagonists can be expected; however, research is needed to clarify at what spatial scales effects can be found.

The objective of this study is to assess the influence of the spatio-temporal configuration of OSR crops and natural habitats on the pressure exerted by three autumn pests, namely *P. chrysocephala*, *D. radicum* and aphids. We present results of a 2-year pest monitoring study conducted in a region in north-east Germany with a strong gradient between almost no OSR cultivation in the center and frequent OSR cultivation in the periphery. We assumed that i) the pest pressure of autumn insect pests on a monitoring site decreases with increasing distance to the previous year's OSR fields, (ii) the changes in OSR acreage around the monitoring site result in a concentration or dilution of pest abundance and (iii) the absolute area of semi-natural habitats near the monitoring site decreases pest abundance. Following this approach, we offer new knowledge on the dispersal capacity of autumn active insect pests of OSR. The results could be used to improve integrated pest management strategies and reduce the reliance on insecticides for insect pest control.

2 MATERIALS AND METHODS

2.1 Monitoring area

The assessments were conducted in the growing seasons 2019/20 and 2020/21 in an area of approximately 3000 km² in north-east Germany (Supporting Information: Figs S1 and S2). The region was chosen because the establishment of OSR almost failed in the central area of the region in the season 2018/19 due to drought in autumn 2018. When the cultivation of OSR was continued in 2019/20, this provided an opportunity to monitor locations with varying proportions and distances to previous year's OSR in the surrounding landscape. The river Elbe and the large forest of Gartow structure the region. West of the forest, the landscape is more complex and agricultural fields are relatively small. In the wetlands along the river Elbe, a higher proportion of grassland is present. North of the Elbe and east of the forest, fields are larger and the landscape is simplified. There was no cultivation of spring OSR in the monitoring area. In both seasons, monitoring was conducted in conventionally managed OSR fields only. Similarly to 2018, soils in autumn 2019 were very dry. For this reason, there were only a few newly sown OSR fields available in the center of the monitoring area. Therefore, all available OSR fields for which access was possible and that had the agreement of farmers

to participate in the study were used as monitoring sites, while in the peripheral areas with higher OSR density, monitoring sites were selected at random. In the second season, sowing conditions in autumn were more optimal and there were many more OSR fields available in the center of the monitoring area. The fields in the second year were selected as evenly as possible across the monitoring area. In the 2019/20 season, 22 fields were sampled, and 30 fields in 2020/21. All assessments during each season were made in defined plots of about 30 × 30 m (further referred to as monitoring sites) that were confined about 30 m from the field margins. In most cases, these monitoring sites were grown without insecticide use. Farmers provided data on the management of each field, e.g. the use of insecticidal seed treatments or spraying of insecticides (Supporting Information: Table S1).

2.2 Field assessments

2.2.1 Adult *Psylliodes chrysocephala* in yellow water traps

Yellow water traps (YWT) (type Moerike Ø = 22 cm) were placed in sample sites whenever possible immediately after sowing of the crop filled with water and detergent. In the first season, YWTs were installed between 12th–19th September 2019. In this year, one or two traps per field were used, totaling 35 traps on 22 fields. When two traps per field were used (large fields or those with an elongated shape) they were on opposite sides of the field with a minimum distance of 400 m from each other. Traps were emptied approximately weekly. The catches were conserved in 70% ethanol and adult *P. chrysocephala* were counted in the laboratory. On 11th November 2019, all YWTs were emptied for the last time. In the second season, 30 YWTs were placed on 30 single fields between the 28th August and 3rd September. They were emptied approximately weekly until 11th November 2020.

2.2.2 Adult *Psylliodes chrysocephala* feeding damage and aphid infestation

OSR seedlings and young plants in the monitoring sites were assessed for feeding damage by *P. chrysocephala* approximately weekly over 5 weeks in autumn 2019 and 2020 (plant growth stages BBCH 10–18⁴⁶). On each monitoring site, five rows of 2 m length were randomly chosen and feeding damage per row was estimated.⁴⁷ In 2019, only approximate classes of damage were estimated (zero, low, medium, high damage), whereas in 2020 feeding damage was assessed in defined classes 0–4 (Supporting Information: Fig. S3). Since assessments differed between years, we only differentiated between presence and absence of feeding damage in analysis. During the assessments in autumn 2020, 10 plants were examined to determine the proportion of plants infested by aphids.

2.2.3 Larvae of *Psylliodes chrysocephala* and feeding damage by *Delia radicum* in plant samples

OSR plant samples were taken twice in both years (year 1: 11th November 2019 and 16th January 2020; year 2: 11th November 2020 and 6th February 2021). Ten plants per monitoring site were randomly collected and brought to the laboratory. The roots of the collected plants were washed and the feeding damage by *D. radicum* was assessed as the percentage of brownish and scarred root surface according to *EPPO (2021)*.⁴⁸ The root neck diameter was then measured and the plants were dissected to count the larvae of *P. chrysocephala*. On 15th October 2020, 10 additional plants per monitoring site were sampled and

assessed for root damage of *D. radicum* in order to gain information about early infestation.

2.3 Landscape analysis

All flowering OSR fields of the previous year and the sampling year within 10 km radius around each monitoring site were mapped using SENTINEL II satellite data, (accessed via <https://browser.code-de.org/>). Satellite data from 30th April 2019 to 12th May 2019, 21st April 2020 to 09th May 2020 and 09th May 2021 to 31st May 2021 were used for the seasons 2018/19, 2019/20 and 2020/21, respectively. Fields were mapped using the software quantum geographic information system (QGIS) (version 3.14.16-Pi), which was also used for processing of the data. The surrounding habitat types were retrieved from the ATKIS database (ATKIS-Objektartenkatalog, Version 7.1.rc.1 Basis-DLM of the 31.07.2018) and were processed in QGIS. We defined the following five landscape indicators that were calculated at different spatial scales up to 10 km (Table 1). The spatial scales were determined prior to analysis of the data based on the published dispersal capacities of OSR insect pests^{35,36} and existing studies on spatial landscape analysis.^{27,30,43} Concerning the effect of the previous year's OSR, we tested two indicators. First, the distance (DIST) from the monitoring site to the nearest previous year's OSR fields were analyzed, to test the effect of distance on the recolonization of the monitored crop i.e. current OSR (cOSR), which refers to our first hypothesis. To account for the size of individual fields, we tested not only the distance to the nearest crop (DIST 1 ha), but also the nearest distance to a defined acreage of previous year's OSR (DIST 10, 50, 100 ha). Second, the acreages of previous year's OSR (pOSR) in defined distances around the monitoring site were examined to enable impacts of the change of OSR acreage between years to be assessed, which refers to our second hypothesis.

2.4 Statistical analysis

All analyses were performed using R (version 4.1.2)⁴⁹ in the user interface R-Studio. Separate generalized linear mixed effect models (GLMM) were fitted using the package *glmmTMB*.⁵⁰

Dependent variables were the counts of *P. chrysocephala* adults in YWTs, feeding damage on OSR seedlings (yes, no), number of larvae per plant, the infestation of OSR roots by *D. radicum*, and the proportion of OSR plants infested by aphids. In all models, landscape indicators (Table 1) were included as fixed explanatory variables. Further explanatory variables are described below. Given that the sampling dates differed between the 2 years, each year was analyzed separately.

The counts of *P. chrysocephala* in YWT were analyzed assuming negative binomial distribution of the response. Besides the landscape indicators, the date of assessment was included as explanatory variable. Because emptying of YWTs was not always regular, the number of days of active catch were included as an offset in the models. Feeding damage of OSR seedlings was analyzed assuming a binomial distribution with distance to the nearest OSR field in the previous year (DIST 1 ha) and date of assessment as fixed explanatory variables. The counts of *P. chrysocephala* larvae per plant were also analyzed with negative binomial distribution and the date of assessment, insecticide spray applications at the monitoring site and the root neck diameter of the assessed plants as additional explanatory variables. Due to the drought in autumn 2019, plant size was very uneven within monitoring sites and between farms (Supporting Information: Fig. S4). For this

Table 1. Overview of different landscape indicators, which were derived at different spatial scales to analyze effects on the pest incidence on current oilseed rape (OSR) monitoring sites. Fields with flowering OSR were mapped using satellite data. Abbreviations, indicator definitions and the data sources are given

Indicator	Spatial scales	Abbreviation	Explanation	Data source
previous year's OSR (pOSR) (acreage in ha)	1 km	pOSR 1	pOSR in a radius (spatial scales of 1–10 km) around the monitoring site	QGIS field calculator
	2.5 km	pOSR 2.5		
	5 km	pOSR 5		
	7.5 km	pOSR 7.5		
	10 km	pOSR 10		
current OSR (cOSR) (acreage in ha) in the year of monitoring	1 km	cOSR 1	cOSR in a radius (spatial scales of 1–7.5 km) around the monitoring site	QGIS field calculator
	2.5 km	cOSR 2.5		
	5 km	cOSR 5		
semi-natural habitats (SNH) (acreage in ha)	0.5 km	SNH 0.5	Forests, woodland, heath, moor, swamp or wild land in a radius (spatial scales of 0.5–2.5 km) around the monitoring site	ATKIS data, vegetation layers 'veg02' and 'veg03'
	1 km	SNH 1		
	2.5 km	SNH 2.5		
pOSR/cOSR-ratio	1 km	rel 1	Acreage pOSR divided by acreage cOSR (pOSR/cOSR) at different spatial scales	
	2.5 km	rel 2.5		
	5 km	rel 5		
	7.5 km	rel 7.5		
distance (DIST) to previous year's OSR fields (in km)	1 ha	DIST 1 ha	Distance of monitoring site to the border of the nearest OSR field of the previous year	QGIS, measured by hand
	10 ha	DIST 10 ha	Distance to the center of the nearest OSR fields of the previous year around the monitoring site covering at least an acreage of 10, 50, and 100 ha. For this purpose, the area of the nearest fields was summed up to at least 10, 50, and 100 ha. The distance from the monitoring site to the center of the field exceeding the threshold was used.	QGIS, measured by hand
	50 ha	DIST 50 ha		
	100 ha	DIST 100 ha		

reason, only presence of larvae (yes/no) was analyzed using binomial models. Damage by *D. radicum* was rather low (<15% damaged root area), therefore, only the presence of root damage (yes/no) was analyzed using binomial models. The date of assessment, insecticidal seed treatment and the root neck diameter of the sampled OSR plants served as additional explanatory variables. Aphid infestation in autumn 2020 (proportion of infested plants) was analyzed with a beta-binomial model (because of overdispersion), including date of assessment and insecticidal seed treatment as explanatory variables.

For the evaluation of the five landscape indicators, models were set up with the individual landscape indicators measured at different spatial scales (Table 1) and ranked using the second order Akaike Information Criterion (AIC_c).⁵¹ For each indicator, the spatial scale resulting in the lowest AIC_c value was included in the global model (Supporting Information: Tables S2 and S3). The landscape indicators were z-transformed before analysis to improve the convergence of models.

Collinearity between the chosen landscape indicators was checked via variance inflation factor (VIF), which was <3 with the exception of *P. chrysocephala* larvae data in 2019 and the aphid infestation data in autumn 2020. In both cases, the landscape indicator 'current OSR (cOSR)' was excluded from analysis to circumvent collinearity issues.

Monitoring sites were repeatedly sampled and hence included as random terms in global models and when several

plants per site were sampled, sampling date was nested in monitoring site to account for pseudo-replicates per site. Several candidate models were fitted, containing all possible combinations of the predictor variables of the global model, and were compared using the function *dredge* of the package *MuMin*.⁵² All candidate models within delta AIC_c < 2 were compared to the global model and the 'Nullmodell' (with fitted intercept only) via AIC_c, AIC_c weights and R² using the package *performance*.⁵³ (Supporting Information: Tables S2 and S3). To assess variable importance, we calculated the sum of Akaike weights (Σw_i) for predictor variables across candidate models within delta AIC_c < 2 compared to the best-fitting model (Supporting Information: Table S4; in addition, Table S6 shows the analysis of deviance tables, type II Wald χ² tests, of the best-fitting models).

The residuals of models were checked with the package *DHARMA*.⁵⁴ Moran's I test was performed to check for spatial autocorrelation in residuals (Supporting Information: Table S5), which was found in the data of *P. chrysocephala* counts in YWTs in autumn 2019. For this reason, a random term for YWTs in the same fields and closely neighbored fields was further included in the model. As a result, the number of independent locations in the data set decreased from 22 to 14.

For the presentation of results, predicted means and 95% confidence intervals of the models with the lowest AIC_c were

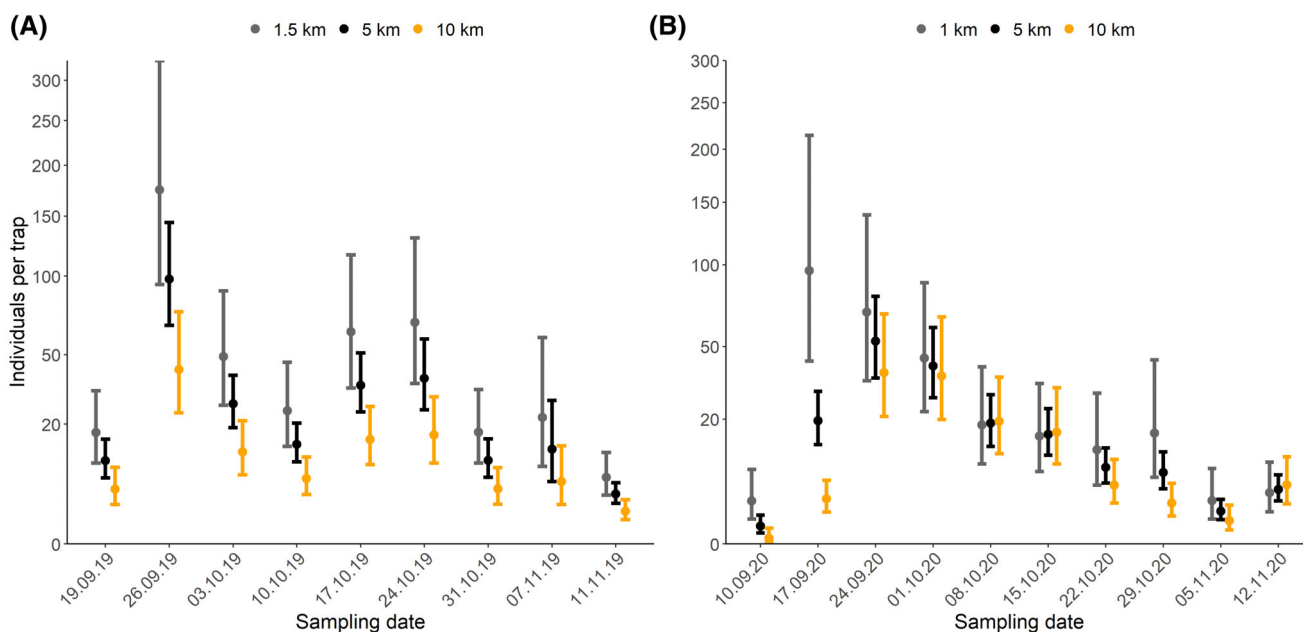


Figure 1. Estimated numbers of *Psylliodes chrysocephala* trapped in yellow water traps (YWT) in oilseed rape (OSR) crops positioned at different distances (1 and 1.5, 5, 10 km) from the nearest OSR in the previous year (A) in 2019 and (B) in 2020. Points show predicted means with 95% confidence intervals, obtained from the models *PCHR_19a* ($n = 14$) and *PCHR_20a* ($n = 30$) (models in detail in Supporting Information: Table S3).

calculated using the packages *emmeans*⁵⁵ and *effects*.⁵⁶ In addition, we present full and conditional coefficients and confidence intervals, which were averaged across candidate models within $\Delta AIC_c < 2$ ⁵² (Supporting Information: Fig. S5). If categorical variables showed significance, post-hoc analysis was performed using a Tukey test at an alpha level of 0.05. To facilitate interpretation, results are presented for predictor variables at the original scale (i.e. unstandardized) and count data are presented at square root transformed y-axes (Figs 1 and 4).

3 RESULTS

3.1 *Psylliodes chrysocephala*

3.1.1 Adult abundance

In the first season, the migration of *P. chrysocephala* into the current crops had already started when the first YWTs were set up in the fields. In total, an average of 221 (\pm SD 178; min. 38; max. 658 beetles) beetles per YWT was caught. In autumn 2020, YWT were set out immediately after sowing. In this season, there was again a heavy infestation of *P. chrysocephala* and an average

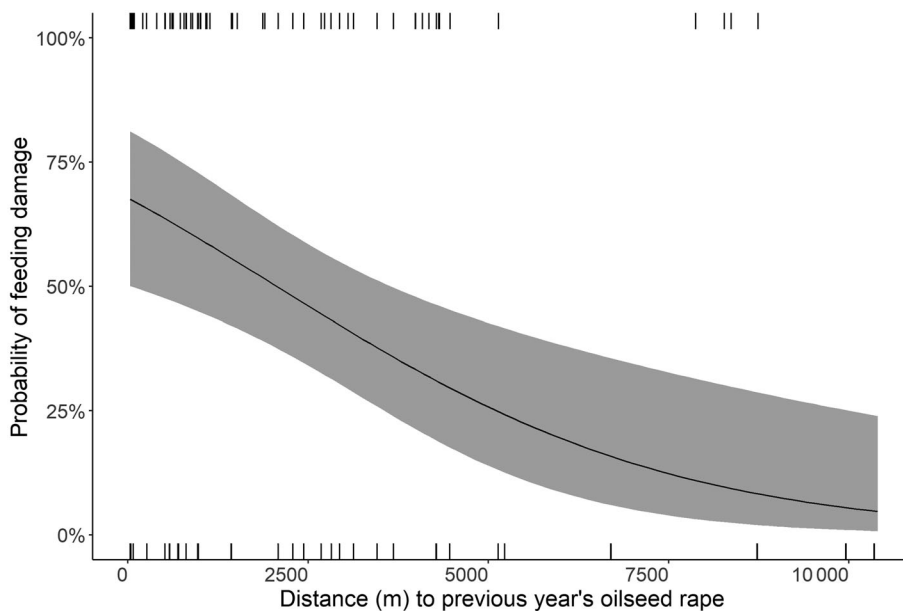


Figure 2. Probability of feeding damage to oilseed rape (OSR) plants by *Psylliodes chrysocephala* in relation to the nearest previous year's OSR in autumn 2020. Line shows predicted means with 95% confidence intervals (shaded area), obtained from the model *moFr20*. (Supporting Information: Table S3). Vertical dashes indicate the observations (yes; no) on the scale of the x-axes.

cumulative number of 179 (\pm SD 128; min. 33; max. 524 beetles) beetles per YWT was caught. In both years, migration started within the first 10 days of September. There were three best-fitting models within $\Delta AIC_c < 2$ in 2019 and two models in 2020, explaining the migration of *P. chrysocephala* into the fields (Supporting Information; Table S3). All models included the sampling date ($\sum w_i = 1$) and the distance to previous year's OSR acreage ($\sum w_i = 1$). In both years, the nearest distance to a minimum amount of OSR acreage in the previous year was more important than the distance to the nearest hectare (2019: DIST 100 ha; 2020: DIST 50 ha; see Supporting Information: Table S2). Only in autumn 2020, did the interaction between sampling date and distance improve the model's fit ($\sum w_i = 1$). To interpret the continuous variable distance to previous year's OSR, we calculated the numbers of *P. chrysocephala* adults per YWTs for 1 (1.5) km, 5 and 10 km over the sampling dates (Fig. 1). The estimated number of beetles in YWTs after 3 weeks of migration was about 68–76% lower with an increase in distance from 1 (1.5) km to 10 km to the previous year's OSR. Additionally, in 2020, the first

immigration of *P. chrysocephala* started approximately one week later in fields at 10 km distance compared to one km distance to previous year's OSR (Fig. 1B).

Additional explanatory variables included in the best-fitting models were pOSR 7.5 (increase, $\sum w_i = 1$) and SNH 0.5 (decrease, $\sum w_i = 0.38$) in 2019 and cOSR 2.5 (increase, $\sum w_i = 1$) and pOSR 10 (increase, $\sum w_i = 0.29$) in 2020 (Supporting Information Table S4).

3.1.2 Feeding damage

In autumn 2019, feeding damage was recorded on all plants sampled from the study crops. At the first assessment (29.09.2019), the damage threshold of 10% leaf damage (=damage class 4) was exceeded at 14 monitoring sites (see Supporting Information: Fig. S3), none of which were further than 4400 m from the previous year's OSR. Feeding damage in autumn 2020 was rather low; only two monitoring sites exceeded the damage threshold (distance to previous year's OSR: 45 m and 2440 m). The probability

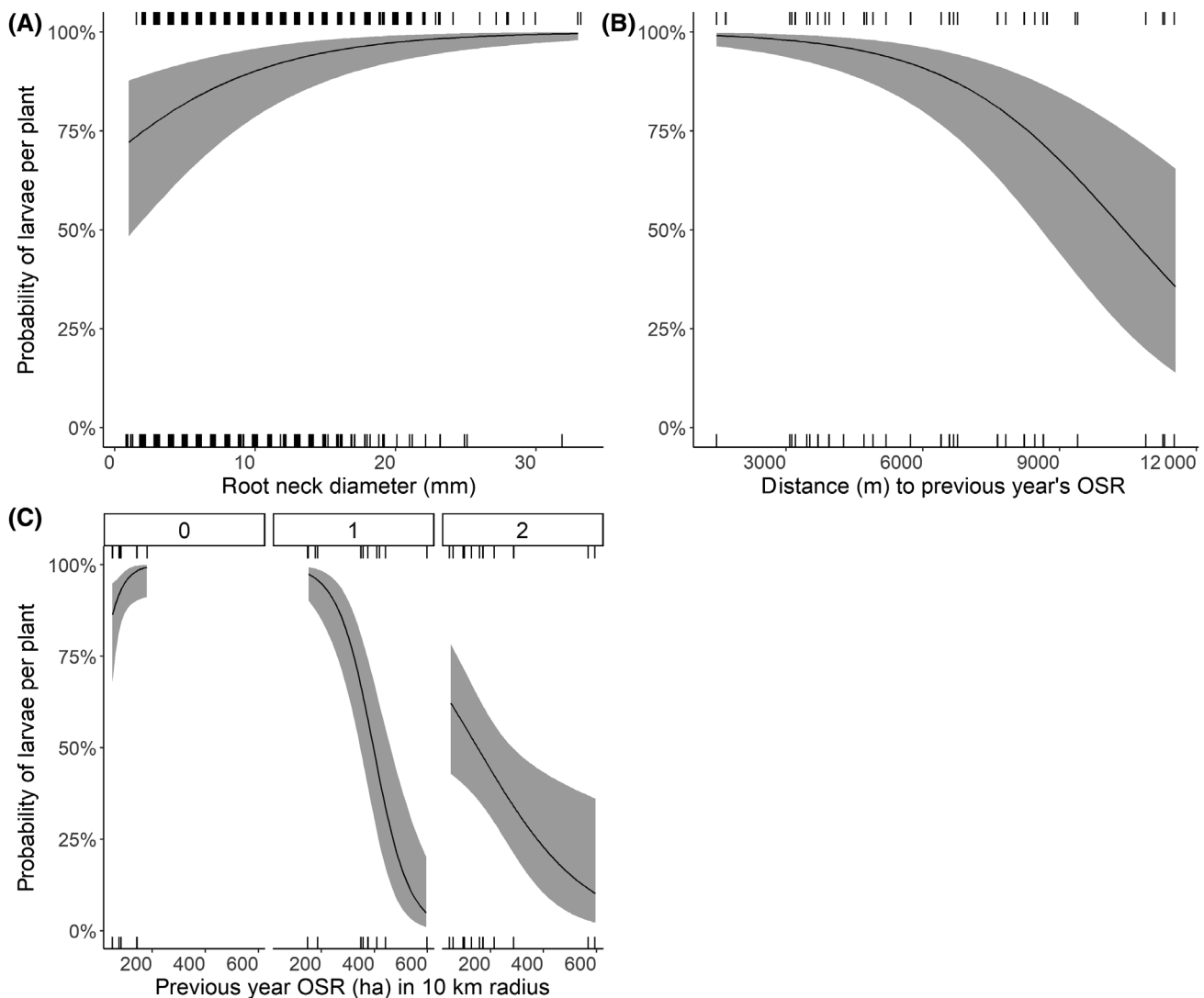


Figure 3. Probability of *Psylliodes chrysocephala* larval infestation in oilseed rape (OSR) plants in relation to (A) OSR plant root neck diameter, (B) minimum distance to an acreage of 100 ha OSR in the previous year (DIST 100 ha) and (C) the interaction of insecticide applications (0;1; two or more applications) and previous year's oilseed rape (OSR) acreage at 10 km radius in 2019/20. Lines show predicted means with 95% confidence intervals (shaded areas) obtained from the model *PCHR_L_19a* (Supporting Information: Table S3). Vertical dashes indicate the observations (yes; no) on the scales of the x-axes.

of feeding damage decreased with increasing distance to OSR of the previous year (Fig. 2).

3.1.3 *Psylliodes chrysocephala* larvae per plant

Over the two dates of assessment, the average larval densities per monitoring site increased from 3.19 (SD = 5.80; min. 0; max. 15.90) to 7.14 (SD = 10.39; min. 0.1; max. 41.70) larvae per plant in 2019. In 2020, larval densities were higher and slightly increased from 10.41 (SD = 17.52; min. 0.8; max. 61.5) in November 2020 to 11.21 (SD = 15.78; min. 0.6; max. 53.6) larvae per plant in February 2021.

According to the best-fitting models (Supporting Information: Table S3), the probability of larval presence in plants in the first season 2019, increased with increasing root neck diameter ($\sum w_i = 1$) (Fig. 3A) and decreased with distance to the previous year's OSR ($\sum w_i = 1$) (Fig. 3B). Additionally, the model included the interaction of insecticide use and the previous year's OSR acreage at a 10 km radius ($\sum w_i = 1$); with decreasing probability of larvae at high insecticide levels and higher OSR acreages (Fig. 3C). There were potentially nine best-fitting models within delta $AIC_c < 2$ explaining the abundance of larvae per plant in winter 2020. Because the assessments were done in commercial farmers fields and pest infestation was very high, 18 of the 30 monitoring sites were treated with pyrethroid insecticides. These applications significantly reduced larval densities ($\sum w_i = 1$) (Fig. 4B) and probably masked effects of investigated landscape indicators. As a second explanatory variable, the root neck diameter was included in all best-fitting models ($\sum w_i = 1$). Bigger plants were infested with higher numbers of larvae (Fig. 4A). The model with the lowest AIC_c value additionally included the amount of previous year's OSR at the spatial scale of 1 km

($\sum w_i = 0.52$) (Fig. 4C). However, the R -squared (40.7%) increased marginally by only 1.7% compared to the model that included only insecticide use and root neck diameter.

3.2 *Delia radicum*

Damage by cabbage root fly, *D. radicum*, was at low levels in both seasons, with an average infestation of 42% (SD = 49) and 46% (SD = 50) plants with damaged roots in 2019/20 and 2020/21, respectively. The average severity of damaged root area was 13.15% (SD = 22.55) in 2019 and 9.67% (SD = 15.69) in 2020. Increasing root neck diameter ($\sum w_i = 1$) significantly increased the probability of root damage and was included in all best-fitting models within delta $AIC_c < 2$ in both years (Fig. 5 C/F; Supporting Information: Table S3). The four best-fitting models in autumn 2019, additionally included date of assessment ($\sum w_i = 1$), insecticidal seed treatment ($\sum w_i = 1$) (Fig. 5B) and the amount of previous years OSR at a spatial scale of 2.5 km ($\sum w_i = 1$). The probability of root damage by *D. radicum* increased with increasing OSR acreage in the previous year at a 2.5 km radius around the sampling site (Fig. 5A). Furthermore, the probability of root damage decreased with increasing area of current OSR cropped within a 2.5 km radius in autumn 2020 ($\sum w_i = 1$) (Fig. 5D, Supporting Information: Table S3). Also, the change in OSR cultivation area (pOSRcOSR-ratio) at a spatial scale of 2.5 km radius was included in the models in 2020 ($\sum w_i = 1$); a decrease in OSR acreage resulted in a higher probability of infestation by *D. radicum* (Fig. 5E).

3.3 Aphids

Aphid infestation of plants was evaluated only in the second year of the study. The average infestation rate ranged between 33%

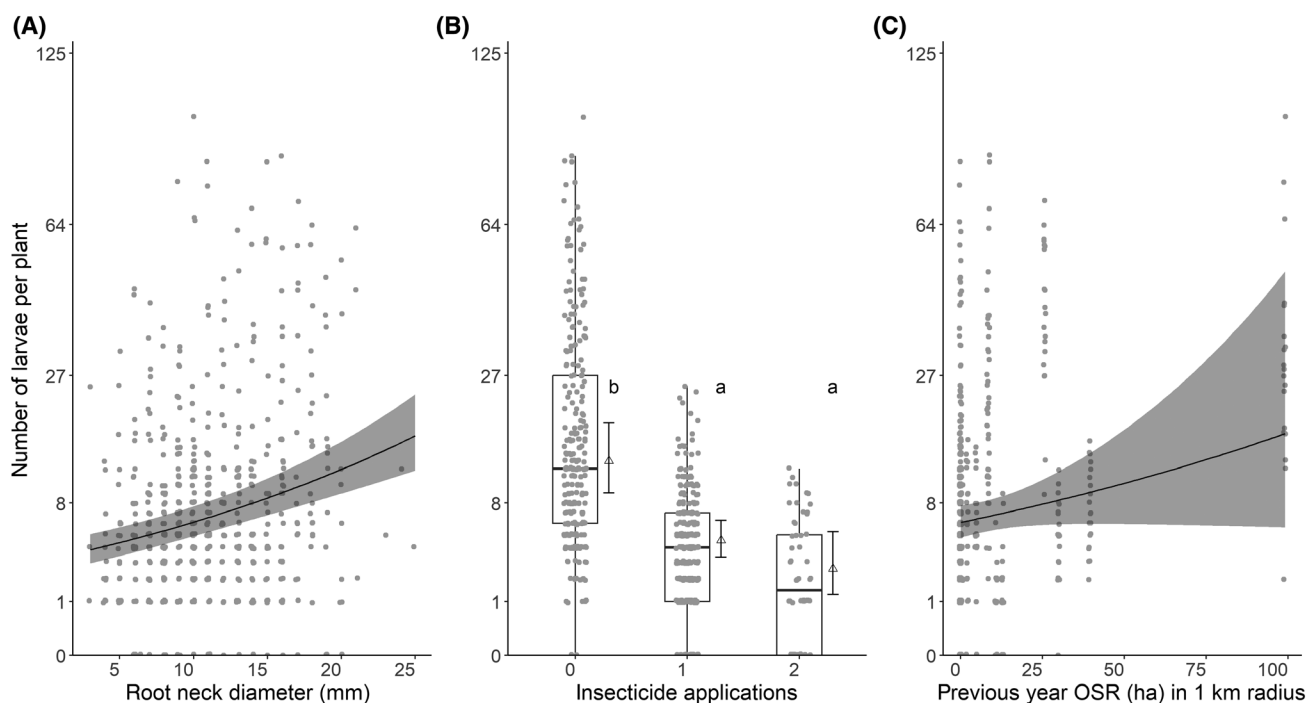


Figure 4. Effects of (A) oilseed rape (OSR) root neck diameter, (B) insecticide applications and (C) previous year's OSR acreage at 1 km radius on the number of *Psylliodes chrysocephala* larvae per OSR plant in 2020/21. Observations are displayed as grey points. Lines show predicted means with 95% confidence intervals (shaded areas) obtained from the model *PCHR_L_20a*. (Supporting Information: Table S3). Effects of insecticide applications (B) are shown as boxplots with median and error bars indicating the 10th and 90th percentile. Calculated means (triangles) and \pm 95% CI are obtained from the model *PCHR_L_20a*. Different letters indicate significant differences between treatments ($P < 0.05$).

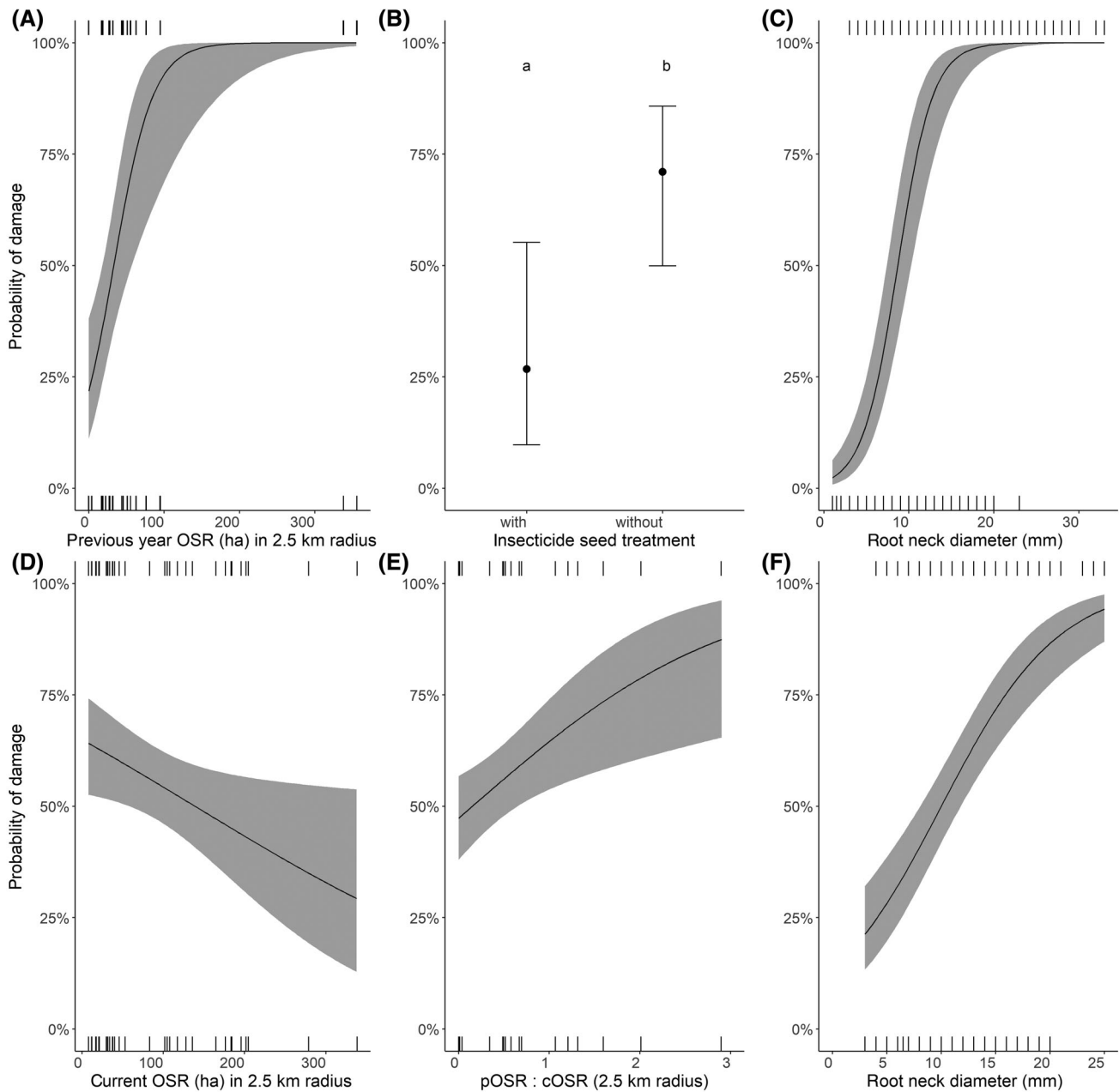


Figure 5. Probability of root damage of oilseed rape (OSR) roots by *Delia radicum* in relation to (A) acreage of previous year's OSR at 2.5 km radius, (B) the use of insecticide seed treatment (cyantraniliprole) and (C) root neck diameter in autumn 2019/20 and relation to (D) acreage of current oilseed rape (cOSR) at 2.5 km radius, (E) the change in oilseed rape cultivation at 2.5 km radius and (F) root neck diameter in autumn 2020/21. Lines show predicted means with 95% confidence intervals (shaded areas), obtained from the models *DRAD_19a* and *DRAD_20a* (Supporting Information: Table SI3). Vertical dashes indicate the observations (yes; no) on the scales of the x-axes. Different letters (B) indicate significant differences between treatments ($P < 0.05$).

(± 27) and 54% (± 30) of plants monitored for the different assessment dates. Multimodel inference revealed that date of assessment and distance (DIST 50 ha) from the nearest OSR crop in the previous year were the strongest explanatory variables. Aphid abundance decreased with increasing distances to OSR of the previous year (Fig. 6).

4 DISCUSSION

This study shows that pest abundance of the univoltine species *P. chrysocephala* declines with increasing distance to host crop area of the previous year. For *D. radicum*, a multivoltine species,

the changes of OSR cropping area at a spatial scale of 2.5 km affected pest abundance and damage. Furthermore, aphid infestation was lower when OSR was distant in the previous year. Our results indicate that the management of crop rotations at the regional level within landscapes has the potential for reducing insect pest pressure.

4.1 Distance to previous year's OSR fields

Just as crops change on a field as part of crop rotations, insect pests must likewise find their host plants anew every year. Distance to previous year's crops and changes in cropping area is known to affect pest pressure in the following year for different

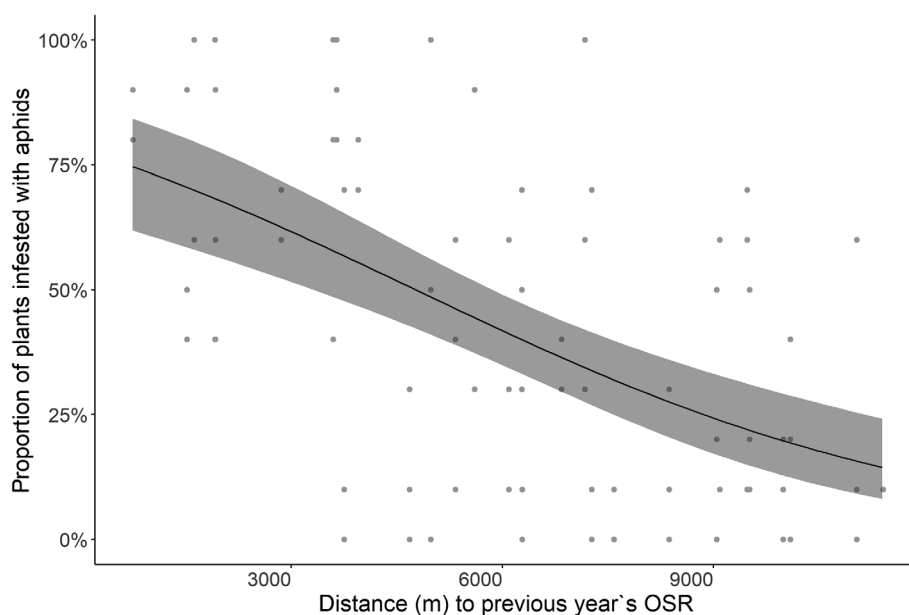


Figure 6. Proportion (%) of oilseed rape (OSR) plants infested by aphids (%) and nearest distance to acreage of 50 ha previous year's OSR (DIST 50 ha). Observations are displayed as grey points. Line shows predicted means with 95% confidence intervals (shaded area), obtained from the model *Aphid20*.

insect pests.^{23,29,57} Most coleopteran pests of OSR leave the crop after the emergence of the new generation in early summer and search for places to aestivate or hibernate.⁹ From there, they migrate to the current OSR fields. If the previous year's OSR field is taken as the starting point, because this is where the highest proliferation of pests has taken place, we hypothesized that the pest abundance at a monitoring site in the following season decreases with increasing distance. The rationale being that a given number of organisms is spread over a larger area with increasing dispersal distance.⁵⁸ For *P. chrysocephala*, our observations support this hypothesis as we found lower beetle numbers in yellow water traps with increasing distance to previous OSR crops in both seasons. If OSR of the previous year is considered as a source of insect pests, it is likely that not only the distance to a field, but also the size of the field affects the dispersal to a new crop.⁵⁸ Therefore, we tested not only the distance between the monitoring site and the nearest hectare of the previous year's crops (DIST 1 ha), but additionally included the distance to different OSR acreages in the previous year (DIST 10, 50 and 100 ha). The best-fitting models included the explanatory variables DIST 50 ha and DIST 100 ha, which confirms the importance of field size in describing its effects as a source of *P. chrysocephala*.

Moreover, this spatial effect was accompanied by a temporal effect in the second season. *Psylliodes chrysocephala* immigration into fields at distances of 10 km from previous crops started about one week later compared to fields only 1 km away from OSR of the previous year. Accordingly, our data indicate that the probability of feeding damage occurring on emerging plants decreased with increasing distance from the previous year's OSR in autumn 2020. However, in autumn 2019, all monitored field sites showed damage, and two fields were even ploughed up by farmers and re-sown with another crop due to drought and high pest pressure. In the best-case scenario, delayed immigration and thus a later beginning of *P. chrysocephala* maturation feeding can help to reduce the need for early insecticide measures because the OSR plants may be sufficiently developed to compensate for feeding damage.

Our findings suggest that *P. chrysocephala* is capable of dispersing over distances further than 10 km within a few days. Long distance flights and a prolonged migration period consumes additional energy.⁵⁹ This could have negative impacts on female oogenesis and fecundity and may be the reason for the effect of distance on the probability of *P. chrysocephala* larvae infestation in 2019/20. However, only weak effects of previous year's OSR on the number of larvae in plants in 2020/21 were found. A reason for this may be that the beetles initially have a period of feeding and sexual maturation after immigrating into the OSR fields⁶⁰ and may compensate energy losses. Only then oviposition starts, which is a temperature-dependent process and can extend into the following spring.⁶¹ Warm temperatures in autumn and mild winters prolong the potential oviposition period. Consequently, a larger distance up to 10 km from the previous year's OSR seems to be suitable to delay and reduce the initial immigration of *P. chrysocephala*, but is unlikely to prevent larval damage in years with high pest densities.

The occurrence of aphids in OSR was only assessed in autumn 2020. Aphid species present in the field were *Myzus persicae* and *Brevicoryne brassicae*, however, not all aphids were accurately identified to species level. The incidence of aphids decreased with increasing distance to previous years OSR fields. This supports Cocu et al. (2005)⁶² who found a positive correlation between the abundance of *M. persicae* and the acreage of OSR at regional scales of 50–75 km radius. *Brevicoryne brassicae* is mainly found on plants of Brassicaceae, whereas *M. persicae* has a broad range of host plants including potato, sugar beet and common weeds.⁶³ For this reason, our study is limited, and further work should take into account other spatial parameters such as the proportion of arable land or the acreage of other important host crops to gain more detailed information about aphid migration pathways.

4.2 Changes in host plant cultivation area

In theory, changes in the area of host plant cultivation should result in dilution or concentration of specialized herbivore pest species,²⁵ which was our second hypothesis. In our study,

probability of damage by *D. radicum* was not related to the distance from the previous year's OSR crops. However, it was affected by the ratio of previous to current OSR acreage, i.e. it increased with higher OSR acreage in the previous year and decreased with increased OSR acreage in the studied season. The observed effects were strongest at a spatial scale of 2.5 km radius, which corresponds well to known dispersal capacities of the fly.³⁹ Whether these findings can be also applied to areas with further relevant host plants i.e. cabbage crops,⁶⁴ needs to be investigated. Increasing plant damage with reduced OSR acreage at the landscape level was also found for pollen beetles and brassica pod midge at spatial scales of 2 km.²⁹ No such relationship was observed in our study for *P. chrysocephala*, even though the previous year's OSR acreage in a 7.5–10 km radius and current OSR acreage in a 2.5 km radius were as explanatory variables in the best-fitting models (see Supporting Information: Table S3). In contrast to our findings, Valantin-Morison et al. (2007)¹⁷ reported that with increasing proportions of OSR in a 500 m radius there was an increase of damage by *D. radicum* and a decrease for proportion of plants with *P. chrysocephala* larvae. They investigated organic OSR crops and argued that higher proportions of OSR in the region could reduce pest pressure by *P. chrysocephala* due to higher insecticide pressure on neighboring conventionally managed farms. Larsen et al (2021)⁶⁵ found that if field and farm size increased, the propensity of farmers to spray crops increased, but the amount of pesticide applied to treated fields decreased in 9000 fields studied in the United States. Greater professionalization and thus more targeted insecticide use could also explain the lower probability of infestation by *P. chrysocephala* larvae that we found with increasing acreage of previous year's OSR at a 10 km radius in the first study year (Fig. 3C).

4.3 Surrounding habitats

Positive effects of semi-natural habitats on ecosystem services such as pollination or natural pest control have been revealed by previous studies.^{26,43,66,67} *Delia radicum* uses *Brassicaceae* species as host plants, but feeds polyphagously on various flowers, which provide nutritional resources. Josso et al. (2013)⁶⁸ found that semi-natural habitats supported *D. radicum* as well as its main natural enemies at distances of up to 500 m. Also *P. chrysocephala* uses SNHs for aestivation.⁹ However, different types of landscape elements could support pest pressure or act as natural barriers. We found no impact of surrounding habitats on pest pressure in our data. A more precise differentiation of surrounding habitats may have been needed. In addition, there are alternative promising statistical approaches to measure biological responses in spatial analyses.^{69,70} For example, it is a shortcoming of traditional threshold-based methods that spatial scales of landscape indicators are set more or less arbitrarily and regarded as discrete. Instead, landscape indicators can be weighted by functions that decrease with distance, which makes biologically more sense if mobile organisms are investigated.^{69,70} We investigated the importance of previous year's crops on the colonization of current crops at distances up to 10 km, which is a fairly coarse scale. Effects of SNHs may be rather local and the approaches described could be tested.

4.4 Cultural and agronomic effects

Larval numbers of *P. chrysocephala* in our study were strongly influenced by plant size (root neck diameter). This makes sense because larger plants provide space and food for more larvae,

although the agronomic damage does not necessarily increase.¹² The increase in *D. radicum* infestation was also greater with increased root neck diameter of the OSR plant, which supports previous studies^{17,71} and indicates a preference of *D. radicum* females for larger plants.

Regarding the effects of insecticide use, we found that in the season 2020/21 a single pyrethroid application led to a 70% reduction of larval numbers per plant on average, regardless of the treatment date, implying that the resistance confirmed under laboratory conditions^{4,72} does not yet seem to have strong effects in the field in the area sampled. For control of *D. radicum*, a seed treatment (a.i. cyantraniliprole) is currently available in Germany, and we found significantly lower root damage on treated fields than untreated fields in the first season.

4.5 Conclusions

This work offers valuable insights on the spatial and temporal effects of regional crop rotations on the migration and damage of autumn insect pests in OSR. The broad application of regional crop rotations would be difficult in practice because of the current agricultural structure with individual and independent farmers. Moreover, the farmers in the center of a region with no OSR in the previous year would benefit most. Nevertheless, the insights gained could be used for field-specific risk assessments and prediction of pest pressures. For example, suitable sites for organic rapeseed cultivation could be selected. Likewise, in many areas there are natural buffers, such as large forest areas or grassland areas, which may influence the expected pest pressure. Aspects on other pest species also need to be added to this research in future. It is also likely that higher trophic levels such as antagonists may be more strongly affected than pest species, which needs more investigation.

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CONFLICT OF 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.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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