

# Spatiotemporal distancing of crops reduces pest pressure while maintaining conservation biocontrol in oilseed rape

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## Abstract

**BACKGROUND:** Agricultural landscapes provide resources for arthropod pests as well as their natural enemies. To develop integrated pest management (IPM) practices, it is important to understand how spatiotemporal location influences crop colonization and damage severity. We performed a 3-year (2016–2018) field experiment in winter oilseed rape (OSR, *Brassica napus*) fields in Estonia, where half of the fields were within 500 m of the location of the previous year's winter OSR field and half were outside this zone. We investigated how distance from the previous year's OSR crop influences the infestation and parasitism rates of two of its most important pests: the pollen beetle (*Brassicogethes aeneus*) and the cabbage seed weevil (*Ceutorhynchus obstrictus*).

**RESULTS:** When the distance from the previous year's OSR crop was >500 m, we recorded significantly reduced pest pressure by both *B. aeneus* and *C. obstrictus* in the study fields. Biocontrol of both pests, provided by parasitic wasps, was high in each study year and commonly not affected by distance. Mean parasitism rates of *B. aeneus* were >31%, occasionally reaching >70%; for *C. obstrictus*, mean parasitism was >46%, reaching up to 79%, thereby providing effective biocontrol for both pest species.

**CONCLUSION:** Spatiotemporal separation of OSR fields can reduce pest pressure without resulting in reduced parasitism of OSR pests. This supports a spatiotemporal field separation concept as an effective and sustainable technique for IPM in OSR.

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**Keywords:** agricultural land management; biological control; cabbage seed weevil; integrated pest management; pollen beetle; rapeseed

## 1 INTRODUCTION

Agriculture is one of the most important economic sectors globally, with cultivated crops occupying around 11% of the Earth's land area.<sup>1</sup> Global increase in food demand led to substantial intensification of agricultural practices and associated loss of natural and seminatural habitats in agricultural landscapes, becoming an important driver of global biodiversity loss.<sup>2,3</sup> Agricultural intensification has also led to dependence on agrochemicals, as well as to the simplification of landscapes.<sup>4</sup> However, simplified landscapes with large monocultures do not sustain ecosystem service providers, resulting in reduced natural pest control, pollination, and nutrient cycling, each being vital for sustainable crop production.<sup>5–8</sup> Monocultures are even more widespread for crops grown for industrial use, such as oilseed rape (OSR, *Brassica napus* L.). OSR is a widely cultivated cruciferous crop, with numerous insect pests that can cause damage during different growth stages.<sup>9</sup> Two of the main pests of OSR in Europe are the pollen beetle *Brassicogethes aeneus* Fabricius (syn. *Meligethes aeneus* Fabricius), which causes damage when adult beetles feed on the developing flower

buds, and the cabbage seed weevil *Ceutorhynchus obstrictus* Marsham (syn. *Ceutorhynchus assimilis* Paykull), whose larvae consume developing seeds within seed pods.<sup>10</sup>

The oil obtained from OSR seeds can be used for human consumption, but its global production has increased mainly due to its use to produce biofuel.<sup>11,12</sup> OSR is attacked by multiple insect

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pests that are managed by intensive use of insecticides (mainly pyrethroids), which has also triggered the widespread pyrethroid resistance in *B. aeneus*.<sup>13–17</sup> For *C. obstrictus*, pyrethroid resistance was reported in Poland and Germany.<sup>16,18,19</sup> As problems of resistance increase and research continues to document pyrethroids as unsafe for the environment,<sup>20,21</sup> farmers started to use alternative insecticides (e.g. neonicotinoids). Although no neonicotinoid resistance in *C. obstrictus* has yet been reported, the first indications of reduced susceptibility to thiacloprid appeared in *B. aeneus* populations.<sup>22,23</sup> Additionally, multiple studies have highlighted the negative effects of neonicotinoids on beneficial insects,<sup>24–29</sup> leading to an EU-wide ban on their outdoor use.<sup>30</sup> There is now a pressing need to find alternative methods of OSR pest management, raising renewed interest in nonchemical methods.

Crop rotation, a foundation of integrated pest management (IPM), can also be effective in preventing damage caused by pests overwintering in fields or field edges.<sup>31</sup> Crop rotation confers the direct benefit of reduced insecticide use,<sup>32</sup> and a temporal rotation, together with maintaining spatial separation between fields of a given crop, can maximize this benefit.<sup>33</sup> To be effective, rotational growing requires knowledge on the dispersal abilities of the relevant pests and beneficial insects, but our knowledge of this area is surprisingly limited. For the Colorado potato beetle (*Leptinotarsa decemlineata* Say), a distance of >400 m from the previous year's crop reduces infestation during the subsequent spring.<sup>33</sup> To limit the spread of the western tarnished plant bug (*Lygus hesperus* Knight) between cotton fields, a minimum distance of 1500 m from the source field is recommended.<sup>34</sup> Although no similar data on spatiotemporal field distancing for OSR pests exist, *B. aeneus* has a 1.2-km average dispersal range,<sup>35</sup> with a majority of marked beetles within 500–1000 m of the release point.<sup>36</sup>

While crop rotation and spatiotemporal distancing can reduce pest colonization, generalist natural enemies like ground beetles, rove beetles and spiders contribute to lower pest abundance in fields.<sup>37</sup> Specialist parasitoid wasps are effective natural enemies, and the parasitism rate for OSR pests can reach 90%.<sup>38,39</sup> However, natural enemies are not always able to keep up with the dispersal of their hosts. In some cases, parasitoid wasps arrive late to the fields and the control effect is delayed.<sup>40</sup> This results in pest density increase and ongoing damage to the crop, therefore large distances between OSR fields in consecutive years may create dispersal barriers, thus diminishing biocontrol services.<sup>41</sup>

Here we examined the effects on pest density and parasitism of spatiotemporal separation between OSR fields in a 3-year study. We aimed to determine what role distance plays in reducing infestations of two primary OSR pests and the consequences for biocontrol services provided by their specialist hymenopteran parasitoids. As there is no reliable evidence about the dispersal ability of these parasitoid wasps, a model distance of 500 m was chosen based on a previous German study on interannual changes in OSR field area and its effect on parasitism rate.<sup>41–43</sup> We examined (i) whether the abundance of both *B. aeneus* and *C. obstrictus* and the proportion of pods damaged by *C. obstrictus* were influenced by distance from the nearest previous year's OSR field and (ii) whether the parasitism rates of *B. aeneus* and *C. obstrictus* were influenced by distance from the nearest previous year's OSR fields.

## 2 MATERIALS AND METHODS

### 2.1 Study area and experimental design

The study was carried out in conventional winter OSR fields in Tartu County, Estonia, 2016–2018. The total study region (covering

all study fields in a given year, plus an additional buffer radius of 500 m from the outermost study fields) varied between 10 567 ha in 2017 to 28 195 ha in 2018 (Table S1). The landscape in the study region was predominantly agricultural land (50–61% during the 3 years), followed by forest (26–32%), wetlands and rivers (9%), residential areas (15%), and peat bogs (18%). Agricultural land in the study region also contained other OSR fields, with total area, including all study fields, varying between 388 ha in 2018 and 1604 ha in 2016 (Table S1). Each year, 12 OSR fields were selected: six were located <500 m from the previous year's nearest OSR field and the other six were >500 m from the previous year's nearest OSR field (Table S2). To understand whether the proportion of OSR grown in the two field groups (<500 and >500 m) was similar, we measured the amount of OSR grown within a 500 m radius from sampling points in each focal field and statistically compared the group means. We concluded that the amount of OSR growing around the focal fields was similar between the two treatment groups (<500 and >500 m) in all study years (Table S3). All fields were bordered by narrow grassy strips. In 2018, data on *C. obstrictus* in one <500 m field were excluded due to significant damage caused by the cabbage stem weevil (*Ceutorhynchus pallidactylus* Marsham). Crops were managed conventionally, with insecticides used during the green bud stage (following the decimal code by Lancashire *et al.*<sup>44</sup>; BBCH 50–51), or right after flowering (BBCH > 61; Tables S4–S6). ArcGIS 10.6<sup>45</sup> was used to analyse landscape coverage and to measure distances between study fields.

### 2.2 Insect sampling

#### 2.2.1 *B. aeneus* and its key parasitoids

To estimate the abundance of overwintered adult *B. aeneus* in OSR fields, the plant tapping method was used,<sup>46,47</sup> which is also the main method used by farmers to assess the threshold level. The main raceme of the selected plants was tapped three times over a tray to dislodge the beetles from the buds and flowers,<sup>47</sup> and all *B. aeneus* that fell onto the tray were counted. In each field, 10 plants were randomly selected at each of five sampling points, 25 m apart, along a linear transect running parallel from the field edge, 12 m from the crop edge. The field edge sampled always faced the nearest previous year's OSR field. Sampling started at the beginning of the green bud stage (BBCH 50) and ended when the main raceme started to flower (BBCH 61–63). Five sampling occasions were performed in 2016, two in 2017 (in 2017, OSR plants developed fast from the bud to the flowering stage, preventing further sampling), and four in 2018. Weather data for the plant tapping experiment were obtained from the Estonian Weather Service database.<sup>48</sup> The mean temperature in all years varied between 12.4 and 16.3 °C. Precipitation was between 0.01 and 2.13 mm (for details see Fig. S1).

Flight activity and immigration of *B. aeneus* and their key parasitoids were monitored using yellow water traps. Each water trap consisted of a 500-mL plastic bowl painted UV-bright yellow (Sparvar Leuchtfarbe, Spray Color, Merzenich, Germany), installed at canopy height, and adjusted at each sampling occasion in accordance with crop growth. Each water trap was filled with ~300 mL water and a drop of unscented dishwashing liquid to break the surface tension. Five water traps per field, 60 in total, were installed during the OSR yellow bud stage (BBCH 57–59) 12 m from the edge of the field; all sampling points were 25 m from the adjacent sampling point(s). Traps were emptied twice a week until the end of OSR flowering (BBCH 70) by sieving the collected arthropods through a fine mesh and placing the sample into plastic bags. Samples were stored at –20 °C until identification.

To estimate the parasitism rate, second-instar larvae dropping from plants to pupate in the soil were collected using funnel traps. Traps were 31-cm diameter funnels with plastic vials fixed to their bottom which were half-filled with water to prevent falling larvae escaping. Funnel traps were installed close to plant stems (vials were dug into the ground to stabilize the funnel). There were five funnel traps per field, i.e. a total of 60 funnel traps per study year. Traps were placed close to the yellow water traps. Traps were emptied weekly from full flowering (BBCH 65) until the beginning of the pod stage (BBCH 71–72); this covered the whole *B. aeneus* larval dropping period. The contents of the funnel traps were sieved through a fine mesh and placed into labelled plastic bags. Samples were sorted in the laboratory immediately after collection and only *B. aeneus* larvae (identification key by Osborne<sup>49</sup>) were subsequently stored in distilled water in Eppendorf tubes at  $-20^{\circ}\text{C}$ . All *B. aeneus* larvae were counted and dissected under a stereo microscope (Olympus, Tokyo, Japan), using green food colour dye as a contrast medium to detect parasitoid eggs and larvae. Over the entire study, 3707 *B. aeneus* larvae were dissected (805 in 2016, 870 in 2017, and 2032 in 2018). All parasitoid eggs and larvae were counted and, when possible, identified to species or genus (identification key by Osborne<sup>50</sup>).

### 2.2.2 *C. obstrictus* and its key parasitoids

*C. obstrictus* flight activity and immigration were monitored using yellow water traps (described in Section 2.2.1). To assess the parasitism rate of *C. obstrictus* and the crop damage caused by this pest, seed pod samples were collected at the beginning of the seed-ripening stage (BBCH 76–84). Examining seed pods allowed us to assess crop damage and parasitism rate at the same time. In each field, seed pods were collected from five sampling points, 25 m apart, along a linear transect running parallel from the field edge, 12 m from the crop edge. The field edge sampled always faced the nearest previous year's OSR field. At each sampling point, 20 seed pods per plant (10 from the main raceme and 10 from side branches) were collected from 10 randomly chosen plants. In total, 1000 seed pods per study field were collected. The sample of 20 seed pods, collected from each plant, were placed in separate plastic bags. In the laboratory, seed pods were placed in cardboard emergence boxes,<sup>39</sup> each box containing 20 seed pods collected from the same plant. Boxes were kept at room temperature for 1 month, after which the boxes were opened and emerged parasitoid adults and *C. obstrictus* larvae were counted. All pods were carefully examined and dissected to find *C. obstrictus* or parasitoid remains and their exit holes. Based on the number of exit holes, the damage rate of pods caused by *C. obstrictus* was calculated. The parasitism rate was calculated for each sample using the formula provided by Kovács *et al.*<sup>51</sup>:

$$\% \text{parasitism of } C. \text{ obstrictus} = \frac{\sum_1^n \text{parasitoids}}{\sum_{\text{larvae}} \text{healthy} + \sum_{\text{larvae}} \text{dead} + \sum_{\text{larvae}} \text{parasitized} + \sum_{\text{parasitoid}} \text{alone} + \sum \text{holes}} \times 100$$

Parasitoid adults were stored in 70% ethanol at  $-20^{\circ}\text{C}$  and identified using a stereo microscope according to identification keys.<sup>52–56</sup>

## 2.3 Statistical analysis

Statistical analyses were performed in R v1.2.1335<sup>57</sup> using the R packages 'lme4',<sup>58</sup> 'car',<sup>59</sup> 'emmeans'<sup>60</sup> and 'MASS'.<sup>61</sup> For all analyses, generalized linear mixed-effects models (GLMMs) with Wald statistic Type III empirical standard error were used, including the sampling point as the random factor. The location of the field ( $<500$  or  $>500$  m) was used as the independent variable. The model with the best fit was chosen based on Akaike information criteria values. Gaussian distribution was used for *B. aeneus* funnel trap data as well as for *C. obstrictus* parasitism data. Negative binomial distribution was used to analyse plant tapping data, the abundance of *B. aeneus*, key parasitoids of *C. obstrictus* and *B. aeneus*, and seed pod damage caused by *C. obstrictus*. Pairwise comparison was performed via least-squares means with Tukey adjustment. Student's *t*-test was used to analyse differences between OSR proportions in the two landscape groups ( $>500$  and  $<500$  m).

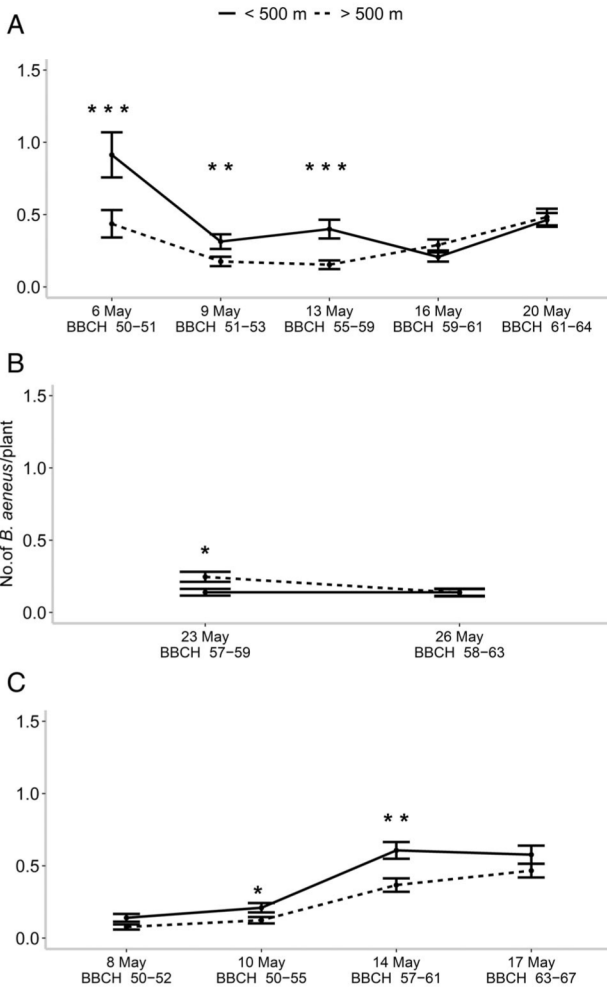
## 3 RESULTS

### 3.1 *B. aeneus* abundance

In general, adult *B. aeneus* abundance was low. Plant tapping indicated a 3-year average of 0.29 *B. aeneus* adults per plant. Despite this low abundance, significantly more *B. aeneus* adults were found in  $<500$  m fields than in  $>500$  m fields in both 2016 (season mean of  $<500$  m fields = 0.46 *B. aeneus* adults per plant; season mean of  $>500$  m fields = 0.31 *B. aeneus* adults per plant;  $\chi^2 = 15.12$ ,  $df = 1$ ,  $P < 0.001$ ) and 2018 (season mean of  $<500$  m fields = 0.38 *B. aeneus* adults per plant; season mean of  $>500$  m = 0.26 *B. aeneus* adults per plant;  $\chi^2 = 16.23$ ,  $df = 1$ ,  $P < 0.001$ ). In 2016, at the beginning of the green bud stage (BBCH 50–51), *B. aeneus* adult abundance in  $<500$  m fields was significantly greater than in  $>500$  m fields ( $\chi^2 = 9.67$ ,  $df = 1$ ,  $P = 0.002$ ; Fig. 1(A)) and remained so during the second (BBCH 51–53) ( $\chi^2 = 4.95$ ,  $df = 1$ ,  $P = 0.02$ ) and the third sampling occasions (BBCH 55–59) ( $\chi^2 = 11.27$ ,  $df = 1$ ,  $P < 0.001$ ) (Fig. 1(A)).

In 2017, the abundance of *B. aeneus* adults was extremely low, and no significant differences were detected between the  $<500$  and  $>500$  m fields (season means of 0.14 and 0.19 *B. aeneus* adults per plant, respectively;  $\chi^2 = 3.45$ ,  $df = 1$ ,  $P = 0.06$ ). In 2017, due to particularly warm weather conditions, OSR plants developed very quickly from bud to flowering growth stage, allowing only two plant tapping surveys to be performed, making the *B. aeneus* data in 2017 unsuitable for comparison with the other years. Nonetheless, on the first sampling occasion, *B. aeneus* adult abundance in  $>500$  m fields was significantly higher than in  $<500$  m fields ( $\chi^2 = 6.36$ ,  $df = 1$ ,  $P = 0.01$ ; Fig. 1(B)). No difference was observed on the second sampling date ( $\chi^2 = 0.01$ ,  $df = 1$ ,  $P = 0.93$ ).

In 2018, in the bud stage (BBCH 50–61), the abundance of *B. aeneus* adults in  $<500$  m fields was significantly higher in the second (BBCH 50–55) and third (BBCH 57–61) sampling occasions



**Figure 1.** Mean ( $\pm$ SE) number of adult *Brassicogethes aeneus* per oilseed rape plant (OSR) in OSR fields closer than 500 m from the previous year's nearest oilseed rape field (<500 m) and OSR fields further than 500 m from the previous year's nearest oilseed rape field (>500 m) during and following the most damage susceptible stage of OSR growth stage BBCH 50–61 in a 3-year study: 2016 (A), 2017 (B) and 2018 (C). Asterisks (\*) indicate significant differences (\* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$ ) between the <500 and >500 m fields.

( $\chi^2 = 4.87$ ,  $df = 1$ ,  $P = 0.03$  and  $\chi^2 = 9.96$ ,  $df = 1$ ,  $P < 0.001$ , respectively; Fig. 1(C)), but no significant difference in abundance between the two groups was recorded in the first and fourth sampling occasions ( $\chi^2 = 3.75$ ,  $df = 1$ ,  $P = 0.06$  and  $\chi^2 = 1.99$ ,  $df = 1$ ,  $P = 0.16$ , respectively).

### 3.2 Flight activity of *B. aeneus* and its key parasitoids

The number of *B. aeneus* adults and the key larval parasitoids of *B. aeneus* that were caught in yellow water traps from inflorescence emergence until the pod ripening stage (BBCH 50–81) showed overlapping flight activity (Fig. 2(A)–(F)). Both in 2016 and 2017 the abundance of *B. aeneus* adults did not differ between <500 and >500 m fields (2016, season mean of 2.77 and 2.22 *B. aeneus* adults per trap, respectively;  $\chi^2 = 3.20$ ,  $df = 1$ ,  $P = 0.07$ ; 2017, season means of 9.5 and 9.48 adult *B. aeneus* per trap, respectively;  $\chi^2 = 0.001$ ,  $df = 1$ ,  $P = 0.98$ ). The main parasitoid species caught in yellow water traps were *Phradis interstitialis* Thomson, *Phradis morionellus* Holmgren, and *Tersilochus heteroceris* Thomson (Table S7). As expected, the number of *B. aeneus* parasitoids

collected was relatively low compared to that of their host (Fig. 2(D)–(F)). No significant difference was detected in 2016 between <500 and >500 m fields (season means 0.49 and 0.41, respectively;  $\chi^2 = 1.22$ ,  $df = 1$ ,  $P = 0.27$ ), whereas in 2017 there were more parasitoids in <500 than >500 m fields (season means 0.48 and 0.21 parasitoids per trap, respectively;  $\chi^2 = 12.49$ ,  $df = 1$ ,  $P < 0.001$ ). There were significantly more *B. aeneus* adults and parasitoids in <500 than in >500 m fields in 2018 (season means 11.23 and 7.95 *B. aeneus* adults per trap, respectively;  $\chi^2 = 9.89$ ,  $df = 1$ ,  $P = 0.001$ ; 2018 season means 0.11 and 0.05 parasitoids per trap, respectively;  $\chi^2 = 4.84$ ,  $df = 1$ ,  $P = 0.02$ ).

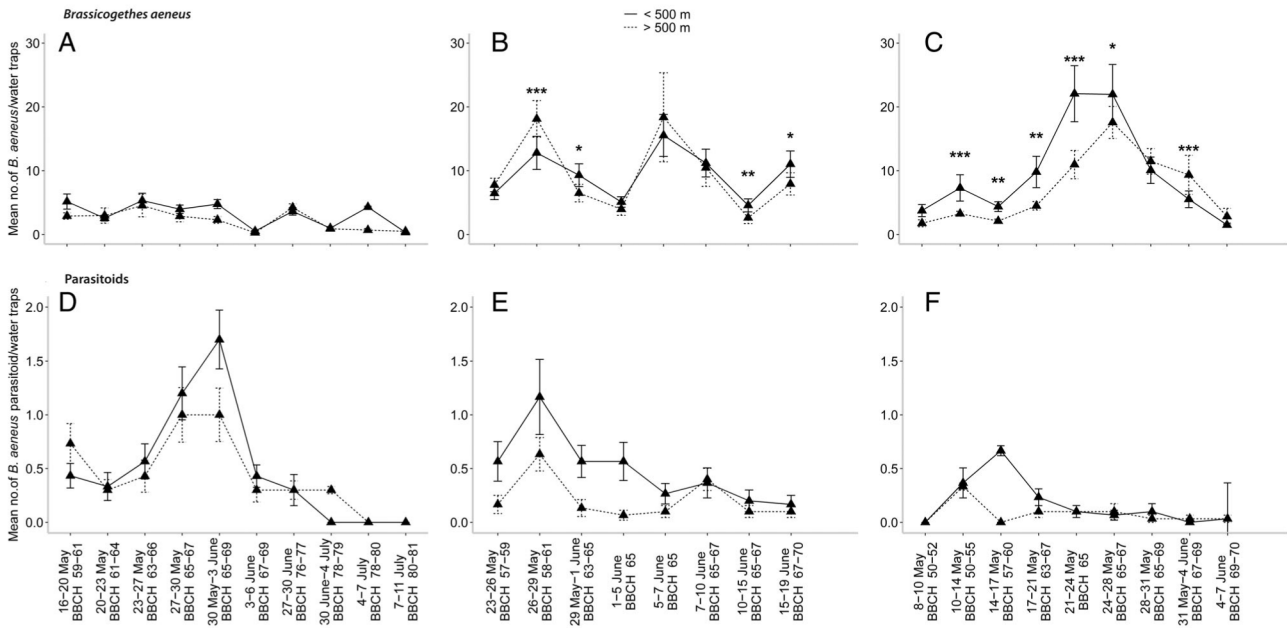
### 3.3 *C. obstructus* flight activity and damage

Overall, the number of *C. obstructus* adults caught by yellow water traps was low in all study years (Fig. 3). Both in 2016 and 2018, there were significantly more *C. obstructus* adults in <500 than >500 m fields (2016, means of 0.42 and 0.22 *C. obstructus* adults per trap,  $\chi^2 = 7.04$ ,  $df = 1$ ,  $P = 0.008$ ; Fig. 3(A); 2018, mean; of 2.14 and 0.69 *C. obstructus* adults per trap,  $\chi^2 = 19.28$ ,  $df = 1$ ,  $P < 0.0001$ , respectively; Fig. 3(C)). In 2017, there were no significant differences in the numbers of *C. obstructus* adults caught in yellow water traps between <500 and >500 m fields (means 1.58 and 2.35 *C. obstructus* adults per trap, respectively;  $\chi^2 = 2.36$ ,  $df = 1$ ,  $P = 0.12$ ; Fig. 3(B)). Yellow water trap data indicated that both *B. aeneus* (Fig. 2(A),(B)) and *C. obstructus* occurred in the fields at the same time, *C. obstructus* were captured in the first sampling assessment, at the early bud growth stage (BBCH  $\geq 50$ , when the main inflorescence is visible but still closed; Fig. S2). The proportion of damaged pods caused by *C. obstructus* varied between years ( $\chi^2 = 29.16$ ,  $df = 2$ ,  $P < 0.001$ ; Fig. 4). In 2016, the mean pod damage rate was not affected by the closeness of the previous year's nearest OSR field (10.85% pod damage in <500 m fields; 10.97% pod damage in >500 m fields;  $\chi^2 = 0.02$ ,  $df = 1$ ,  $P = 0.87$ ; Fig. 4(A)). In 2017 and 2018, a larger distance from the previous year's nearest OSR field significantly decreased seed pod damage (2017, <500 m fields, 3.28% pod damage; >500 m fields, 0.88% pod damage;  $\chi^2 = 37.49$ ,  $df = 1$ ,  $P < 0.001$ ; Fig. 4(B); 2018, <500 m fields, 20.58% pod damage; >500 m fields, 14.18% pod damage;  $\chi^2 = 27.57$ ,  $df = 1$ ,  $P < 0.001$ ; Fig. 4(C)).

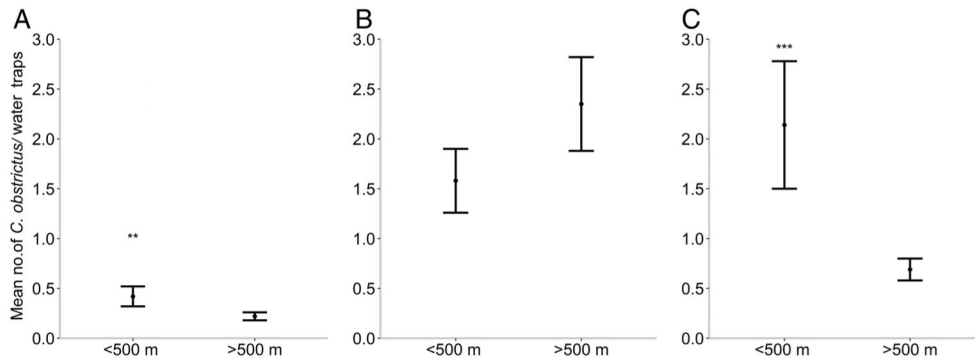
### 3.4 Effect of spatial distance on parasitism rates

The mean parasitism rates of *B. aeneus* varied from 31% in 2018 to 74% in 2016, and were significantly different between years ( $\chi^2 = 81.59$ ,  $df = 2$ ,  $P < 0.001$ ; Fig. 5(A)–(C)). In both 2016 and 2018, the mean parasitism rate of *B. aeneus* was similar between the >500 and <500 m fields (2016:  $\chi^2 = 0.88$ ,  $df = 1$ ,  $P = 0.35$ ; 2018:  $\chi^2 = 1.31$ ,  $df = 1$ ,  $P = 0.25$ ). Only in 2017 was the mean parasitism rate of *B. aeneus* significantly lower in >500 m fields (35.9%) compared to <500 m fields (49.5%;  $\chi^2 = 5.40$ ,  $df = 1$ ,  $P = 0.02$ ; Fig. 5(B)). The main parasitoid species identified from larval dissections was *T. heteroceris* (Table S8).

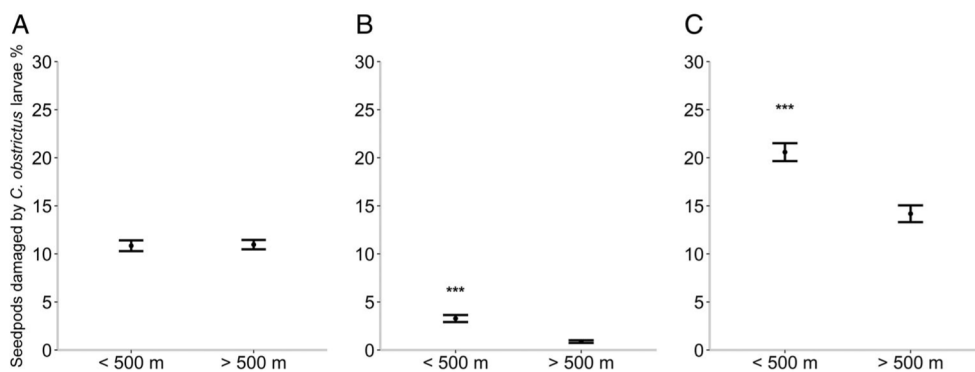
Similar to the parasitism of *B. aeneus*, the parasitism rate of *C. obstructus* varied between years ( $\chi^2 = 28.49$ ,  $df = 2$ ,  $P < 0.001$ ; Fig. 5(D)–(F)) and was notably high in all years, reaching 78.8% in 2016 (Fig. 5(D)). There were no significant differences between >500 and <500 m fields (2016,  $\chi^2 = 2.22$ ,  $df = 1$ ,  $P = 0.14$ ; 2017,  $\chi^2 = 0.12$ ,  $df = 1$ ,  $P = 0.73$ ; 2018,  $\chi^2 = 1.29$ ,  $df = 1$ ,  $P = 0.26$ ). The most common parasitoid species of *C. obstructus* reared from pods were *Trichomalus perfectus* Walker, *Stenomalina gracilis* Walker and *Mesopolobus morys* Walker. The most dominant species in all study years was *T. perfectus*, while the abundance of both *S. gracilis* and *M. morys* varied between years (Table S9).



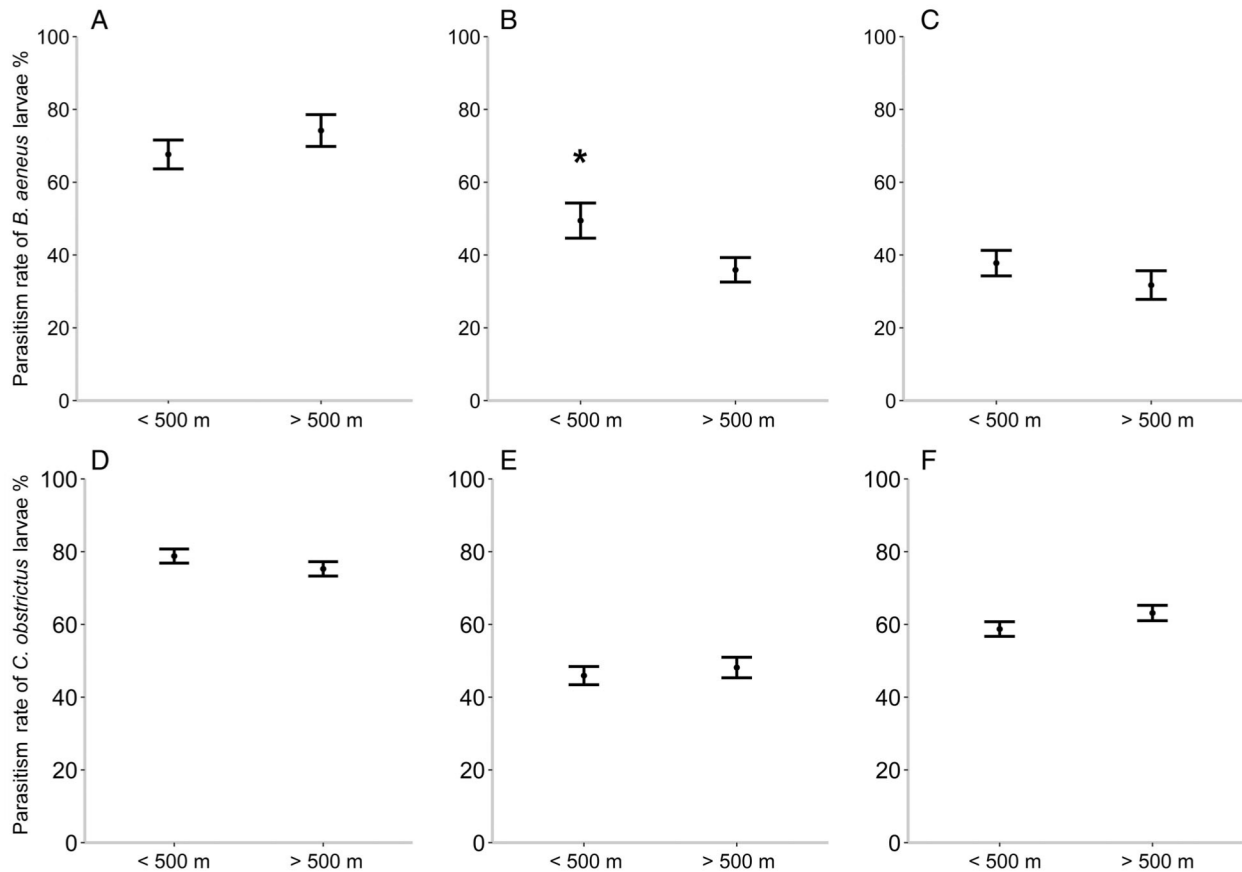
**Figure 2.** Mean ( $\pm$ SE) number of adult *Brassicogethes aeneus* (A–C) and its key parasitoids (D–F) caught by yellow water traps in oilseed rape crops closer than 500 m from previous year’s nearest oilseed rape crop (<500 m) and in oilseed rape crops further than 500 m from the previous year’s nearest oilseed rape crop (>500 m) on different sampling dates and crop growth stages (BBCH 50–81) in 2016 (A, D), 2017 (B, E) and 2018 (C, F). Asterisks (\*) indicate significant differences (\* $P$  < 0.05, \*\* $P$  < 0.01, \*\*\* $P$  < 0.001) between <500 and >500 m fields.



**Figure 3.** Mean ( $\pm$ SE) number of adult *Ceutorhynchus obstrictus* caught by yellow water traps in oilseed rape crops closer than 500 m from previous year’s nearest oilseed rape crop (<500 m) and in oilseed rape crops further than 500 m from the previous year’s nearest oilseed rape crop (>500 m) in 2016 (A), 2017 (B) and 2018 (C). Asterisks indicate significant differences (\*\* $P$  < 0.01, \*\*\* $P$  < 0.001) between <500 and >500 m fields.



**Figure 4.** Mean percentage ( $\pm$ SE) of seedpod damage caused by *Ceutorhynchus obstrictus* in oilseed (OSR) rape fields closer than 500 m from previous year’s nearest oilseed rape crop (<500 m) and in oilseed rape crops further than 500 m from the previous year’s nearest oilseed rape crop (>500 m) in 2016 (A), 2017 (B) and 2018 (C). Asterisks indicate significant differences (\*\*\* $P$  < 0.001) between <500 and >500 m fields.



**Figure 5.** Mean ( $\pm$ SE) parasitism rate of *Brassicogethes aeneus* larvae (A–C) and *Ceutorhynchus obstructus* (D–F) in oilseed rape fields closer than 500 m from the previous year's nearest oilseed rape field (<500 m) and in fields further than 500 m from the previous year's nearest oilseed rape field (>500 m) in 2016 (A, D), 2017 (B, E) and 2018 (C, F). Asterisks indicate significant differences ( $*P < 0.05$ ) between <500 and >500 m fields.

## 4 DISCUSSION

In this study, we examined the effects of spatiotemporal separation between OSR fields on pest abundance and parasitism rate. The study demonstrated a significant negative effect of spatiotemporal distancing of OSR on pest abundance at a landscape scale, for both *B. aeneus* and *C. obstructus*, with significantly higher *B. aeneus* adult abundance in <500 m than in >500 m fields. The number of overwintered *B. aeneus* adults at the green bud stage were also influenced by mean daily temperature (Fig. S1). Temperatures below 12 °C are not optimal for *B. aeneus*'s migratory activities<sup>62–66</sup> and as the temperature increased and OSR plants started to flower, the abundance of *B. aeneus* increased and distance from the previous year's nearest OSR field no longer influenced pest abundance. Volatile organic compounds emitted by plants during flowering are host-seeking cues for *B. aeneus* searching for oviposition sites.<sup>67–70</sup> Interplay between the rising air temperature and plant volatile cues may facilitate long-distance *B. aeneus* dispersal. However, our results indicate that 500 m represents a sufficient distance to reduce intercrop infestation of *B. aeneus* during the most susceptible OSR growth stage (BBCH 50–59). When *B. aeneus* adults emerge from their overwintering habitats (e.g. field edges, hedgerows, forest edges, meadows, grasslands,<sup>10,71–73</sup> but also from previous OSR fields<sup>74</sup>), they seek food plants in the proximity of their emergence sites.<sup>66</sup> The availability of overwintering habitats in the study area, as well as their distance from OSR fields, can influence the beetles'

migration to the host crop,<sup>74</sup> but the current study did not focus on overwintering habitats and their influence on pest abundance; this should be investigated in future studies.

In 2017 and 2018, the pod damage rate caused by *C. obstructus* was significantly greater in <500 m than in >500 m fields. This was also supported by water trap data, where in 2016 and 2018, more adults of *C. obstructus* were caught in traps from fields that were <500 m than >500 m from the previous year's nearest OSR field. *C. obstructus* adults prefer to overwinter at field edges,<sup>62,75,76</sup> and sowing an OSR crop near the previous year's crop may facilitate the pest's immigration. Our results support the effectiveness of spatiotemporal isolation to reduce the subsequent year's infestation by *C. obstructus*. In 2018, the first adults of *C. obstructus* were caught in the water traps during the early green bud stage (BBCH 50–52), with the highest number caught during bud development (BBCH 50–55; Fig. S2), indicating that they arrived at the inflorescence emergence stage. Williams<sup>10</sup> previously stated that adults of both sexes migrate to OSR crops during the flowering stage. Our study in Estonia shows that *C. obstructus* adults migrated to OSR much earlier than previously reported and that the highest abundance was recorded before the flowering stage. Insecticide treatment targeted against *B. aeneus* was carried out only in two fields in 2016 (one <500 m and one >500 m field), but the majority of study fields were treated against *C. obstructus* between full flowering (BBCH 65) and pod development (BBCH 70–71; Tables S4–S6). As insecticides were

applied to both treatments (<500 and >500 m) relatively equally, we presume a similar impact on both <500 and >500 m fields. Our study was carried out in conventionally managed fields to study the spatiotemporal effect on pest and parasitoid abundances, and we did not ask farmers to change their common field management practice. Future studies should be carried out where insecticide treatment is a part of the experimental design to assess the impact of insecticide use concurrently with spatiotemporal distancing between OSR fields.

The primary parasitoids of *B. aeneus* are larval endoparasitoids that complete their metamorphosis below the soil surface of OSR fields, next to the remains of their hosts, and overwinter at the same location in the following crop.<sup>38</sup> Adult parasitoids emerge from the soil in spring and migrate to new OSR crops to parasitise *B. aeneus* larvae or eggs.<sup>68,77</sup> We observed a significantly higher parasitism rate of *B. aeneus* in <500 m than in >500 m fields in 2017. The parasitoids of *C. obstrictus* are ectoparasitoids, and adults emerge from OSR seed pods, subsequently overwintering as adults in sheltered areas.<sup>78,79</sup> The parasitism rate of *C. obstrictus* was very high across all years in all fields, regardless of the distance to the previous year's OSR. These results suggest that the parasitoids of *C. obstrictus* have more efficient host-seeking abilities or are stronger fliers than parasitoids of *B. aeneus*. However, adults of *C. obstrictus* and *B. aeneus* are attracted to various cruciferous plants, therefore their parasitoids can also parasitise their host developing on other cruciferous plant species.<sup>51,80–83</sup>

Consequently, parasitoids could have reached the OSR field from other habitats containing cruciferous plants (e.g. natural or seminatural habitats) and not necessarily from the previous year's OSR crop. This may be an additional reason why pest abundance, as well as seed pod damage rate, were lower in >500 m fields. Furthermore, parasitoids of *C. obstrictus* can parasitise other *Ceutorhynchus* species,<sup>53,84</sup> so it is also possible that the key parasitoids of *C. obstrictus* have emerged from alternative hosts. To establish whether the presence of the key parasitoids of both *C. obstrictus* and *B. aeneus* parasitoids in the studied fields is a consequence of their general presence in the landscape, or because of their superior dispersal capacity, further studies are needed on possible alternative hosts, parasitoid dispersal power, and the spatiotemporal distancing effect. Distance from seminatural habitats and other OSR fields, and the proportion of each in the landscape, can have an effect on parasitoid community composition.<sup>42,85,86</sup> Practices for enhancing populations of different parasitoid species may include reducing disturbances in agricultural fields,<sup>87</sup> and providing suitable feeding and overwintering sites in the surrounding natural and seminatural habitats, where numerous natural enemies occur.<sup>88,89</sup>

An increasing proportion of monocultural land and the decline in agro-biodiversity<sup>90–95</sup> may lead to increased crop damage in many agroecosystems. Agricultural landscape management needs to combine multiple ecologically sustainable techniques to maintain biocontrol services while simultaneously minimizing crop damage. Habitat heterogeneity in agricultural landscapes can benefit biocontrol.<sup>7,8,42,96</sup> Spatiotemporal crop distancing should be based on pest phenology, life history, and dispersal abilities, and when needed spatiotemporal crop distancing should be modified accordingly.

Based on our findings, the damage caused by *B. aeneus* and *C. obstrictus* could potentially be reduced by appropriate spatial distancing between the previous and the subsequent year's OSR fields. The efficacy of this management practice may increase if practised over a landscape scale, which would support the view

that landowners and agricultural practitioners need to cooperate.<sup>96</sup> Furthermore, maintaining a sufficient spatiotemporal aspect to crop production on a landscape scale could potentially reduce pest pressure without affecting biocontrol service provision, thereby reducing the need for applying insecticides.

## 5 CONCLUSION

Managing agricultural pests is becoming more challenging because conventional agricultural management practices are not ecologically sustainable. This study was conducted to determine whether between-year spatial distancing between OSR crops could potentially reduce pest pressure by two of its main pests, *B. aeneus* and *C. obstrictus*, and whether this influences the biocontrol services provided by their specialist parasitoids. Our results demonstrate the ability to maintain biocontrol service provision when implementing spatial distancing between crop locations in consecutive years, and this can help to achieve sustainable crop production. We suggest that similar spatiotemporal distancing of crops, especially when implemented on a landscape scale, can work at the core of an IPM framework and can be applied to a broad variety of crop–pest systems. This practice would require planning and cooperation between landowners and agricultural practitioners, and could result in reducing the need for agrochemical inputs.

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## CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

## AUTHOR CONTRIBUTIONS

EV, GK, and RK designed the study. SS, GK, RK, JW, and EV participated in the fieldwork and data collection. SS, GK, EV, and JW identified the pest species and parasitoid wasps. SS wrote the original draft of the manuscript and analysed the data. SS and GL visualized the data. RK analysed the landscape data. All authors contributed to the writing and revision, and approved the manuscript. Authorship is by the first-and-last principle.

## 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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