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# Reduced soil tillage and insecticide use in pollen beetle management on oilseed rape in Finland

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Brassica oilseeds are important protein crops for Nordic agriculture. Oilseed production is challenged by multiple insect pests, most importantly the pollen beetle (*Brassicogethes aeneus*). Concerns about pyrethroid resistance and potential harm to beneficial insects demands seeking for alternatives to synthetic insecticides. Conservation biological control through supporting natural enemies is a promising option for pollen beetle management. Here, four soil tillage strategies were applied with and without insecticide (pyrethroid tau-fluvalinate) to oilseed rape (*Brassica napus* L.) grown over three years in South-Western Finland to investigate the effect of different management strategies on the number of pollen beetle and its key natural enemies, oilseed rape yield and economic profitability. The use of tau-fluvalinate was not detrimental for parasitic wasp activity, but there was variability in their response to tau-fluvalinate treatment by cultivation strategy and year. However, tau-fluvalinate combined with repeated heavy soil management increased the number of pollen beetles, indicating disrupted dynamics between pollen beetles and their natural enemies. Importantly, economic profitability was sustained without insecticide inputs when soil cultivation was minimized.

*Key words*: biological control, *Brassica napus* L., *Brassicogethes aeneus*, parasitic wasps, profitability, soil cultivation

## Introduction

Brassica oilseeds are high-value protein crops with a good market demand for food, animal feed and industrial uses. In Finland, domestic demand currently outweighs oilseed production. Oilseeds are also well suited as break crops diversifying northern, cereal dominated crop rotations (Peltonen-Sainio and Jauhiainen 2019). Oilseed rape (*Brassica napus* L.) (OSR) is the dominant oilseed grown in Europe and Scandinavia (Eurostat 2024) but, due to climatic constraints, spring turnip rape (*Brassica rapa* subsp. *oleifera*) is the predominant oilseed cultivated in Finland (Luke Statistic Database 2025).

The areas cultivated with both turnip rape and OSR have declined steadily through the last 10–20 years in Finland (Luke Statistic Database 2025). Oilseed cultivation is challenged by multiple problematic insect pests, most importantly the pollen beetle (*Brassicogethes aeneus* Fab. syn. *Meligethes aeneus* Fab.) (Coleoptera: Nitidulidae) (Alford et al. 2003, Menzler-Hokkanen et al. 2006, Williams 2010). Pollen beetle is particularly damaging on spring-sown oilseed crops, which are the dominating form cultivated in Finland (Alford et al. 2003, Luke Statistic Database 2025). The most susceptible stage for pollen beetle damage is the green bud stage (Williams and Free 1978), although some compensation for yield loss by increased number of branches and higher seed weight can take place (Tulisalo and Wuori 1986).

Pollen beetle is univoltine, and the adult pollen beetles overwinter in the soil, litter, field margins and forest edges, and start to migrate into oilseed crop fields when the temperature rises to around +15 °C (Alford et al. 2003, Ferguson et al. 2015, Mauchline et al. 2018). The adults damage the oilseed crops by feeding on the pollen from flowers and buds, and after mating, females lay their eggs in the buds of *Brassicaceae* plants (Williams and Free 1978). Hatched 1$^{st}$ instar larvae feed inside the buds, and 2$^{nd}$ instar larvae continue feeding on pollen in open flowers, moving always to the newly opened flowers (Williams and Free 1978). The larvae drop into soil for pupation and emerging adults can be detected feeding on pollen before overwintering in field surroundings.

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Pollen beetles are frequently controlled with insecticides, mainly pyrethroids. This has led to a high selection pressure in the pest population and a widespread occurrence of pyrethroid-resistant pollen beetle populations in Europe (Slater et al. 2011, Stará and Kocourek 2018, Kann et al. 2021). Due to the diminished efficacy of chemical control and concerns over potential risks to the environment and beneficial arthropods like pollinators and natural enemies (Potts et al. 2016, Kaila et al. 2023, Nicholson et al. 2024), biological control has been proposed as a promising option to control pest insect populations (Begg et al. 2017, Hokkanen and Menzler-Hokkanen 2024).

Hymenopteran parasitoids, i.e. parasitic wasps, are among the most important natural enemies of pollen beetle (Ulber et al. 2010). There are at least nine parasitic wasp species known to parasitize eggs or larvae of pollen beetle in Europe (Veromann et al. 2006a). In Finland, the ichneumonid parasitoid *Phradis morionellus* Holmgr. and the braconid parasitoid *Diospilus capito* Nees have been reported to occur across the country where rapeseed is cultivated (Hokkanen et al. 1988). The average parasitism rate of pollen beetle larvae in Northern Europe is generally recorded to be between 8–50 %, but can be up to 74–100 %, with variation by year and by site (Hokkanen 2008, Ulber et al. 2010, Veromann et al. 2013, Kaasik et al. 2014, Vilumets et al. 2023, Sulg et al. 2024).

Being well synchronized with the life cycle of pollen beetle, *P. morionellus* is regarded as the most important parasitoid species, and *D. capito* as common but less important (Hokkanen 2000, 2006, 2008). The univoltine koinobiont parasitoid *P. morionellus* overwinters in the soil, emerging from the previous year's rapeseed field in the mid-summer (Hokkanen and Menzler-Hokkanen 2024). *D. capito* is multivoltine and generally appears on oilseed crops later in the growing season (Veromann et al. 2006a). *D. capito* is believed to have two annual generations although there is little knowledge on its life cycle in Finland (Hokkanen et al. 1988). Pollen beetle parasitism in OSR can extend from the green bud stage until the end of flowering, which emphasizes efforts to minimize insecticide use during this time period. Furthermore, at least *P. morionellus* overwinters in soil of OSR fields, and in previous studies, reduced tillage after OSR (fallow or direct drilling) has increased the overwintering survival of pollen beetle parasitoids compared to ploughing or disc harrowing (Nilsson 1985).

Biological control of pollen beetle can potentially be promoted by altering the extent and timing of soil tillage and pesticide use (Hokkanen et al. 1988, Hokkanen 2008, Nilsson et al. 2015, Skellern and Cook 2018). At farm level, adopting integrated pest management (IPM) involves producers modifying their plant protection practices towards minimized use of chemical pesticides, which leads to shifts in costs and returns. Economic evaluation is crucial for making meaningful recommendations and demonstrating the value of alternative management practices (Norton et al. 2005).

The aim of this study was to find effective and economically feasible strategies for pollen beetle management on oilseed rape in Finland. A three-year field study was conducted to address whether reduced tillage and omitting insecticide use impacted the dynamics of pollen beetles and their key natural enemies *P. morionellus* and *D. capito*, or OSR yield. The economic profitability of pollen beetle management strategies was also evaluated.

## Material and methods

A total of eight trial fields were established in South-Western Finland (Fig. 1) in 2020 and managed by different soil cultivation strategies (Table 1) for four years. The trial fields were clay soils, except for trial field 2, which was fine sand. In each field and year, spring OSR cultivar Drago (NBZ Lembke) was sown with a cultivation area ranging from 0.7 to 1.1 ha. New OSR area with the same cultivation strategy was always sown in the subsequent spring with a maximum distance of 100 m to the previous year's OSR area, whereas spring cereal (oat or barley) was always sown in the exact location of the previous year's OSR. Trial fields with different cultivation strategies were located with a minimum distance of 800 m to each other and to farmer's OSR fields, to minimize the direct mixing of the insect populations.

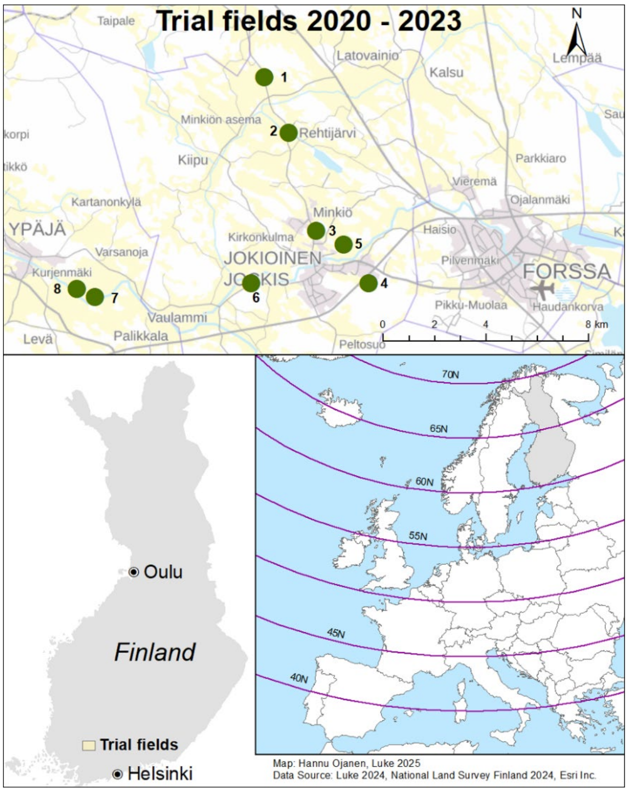


Fig. 1. Locations of the trial fields in 2020–2023

## Cultivation strategies

Four different soil cultivation strategies were applied in the eight trial fields. Autumn tillage for the trial fields 1–4 was carried out in October each year. The trial fields 1 and 2 ("autumn ploughing") were ploughed with a Kverneland 3×14" (plough body No. 8) at the working depth of 25 cm. The trial fields 3 and 4 ("autumn cultivation") were cultivated with a Potila tine cultivator. In the trial fields 5 and 6 ("harrowing"), the disc harrow Amazone Catros and the seed bed cultivators Potila Magnum Plus or Multiva Mega were used. Although the trial fields 7 and 8 ("direct drilling") were planned to have only direct drilling in the spring, a very light disc harrowing with Amazone Catros was carried out each year to open the heavy soil in these fields. Of these, autumn ploughing was considered as the most intensive tillage method, with the intensity of soil management reducing gradually from autumn cultivation and harrowing to direct drilling (Table 1). OSR and spring cereals were sown in May each year, following the common practices and weather conditions, with Väderstad Rapid.

Table 1. Different management strategies applied on the eight trial fields. The autumn cultivation describes practices done after the harvest of oilseed rape (OSR), whereas the spring cultivation stands for the practices carried out in the subsequent spring, before sowing the spring cereal (oat or barley) following last year's OSR. The exact coordinates for the trial fields are represented for 2021, as the OSR in subsequent year always located not further than 100 metres from the last year's location.

| Trial field | Locations of trial fields (WGS84) | Short description of tillage methods | Autumn cultivation | Spring cultivation | Chemical control on oil seed rape |
|---|---|---|---|---|---|
| 1 | 60,871 23,443 | "Autumn ploughing" | Autumn ploughing | Seedbed tillage | Tau-fluvalinate |
| 2 | 60,854 23,460 | "Autumn ploughing" | Autumn ploughing | Seedbed tillage | No insecticide |
| 3 | 60,820 23,483 | "Autumn cultivation" | Cultivating | Seedbed tillage | Tau-fluvalinate |
| 4 | 60,801 23,526 | "Autumn cultivation" | Cultivating | Seedbed tillage | No insecticide |
| 5 | 60,814 23,505 | "Harrowing" | No autumn tillage | Disc harrow and seedbed tillage | Tau-fluvalinate |
| 6 | 60,799 23,439 | "Harrowing" | No autumn tillage | Disc harrow and seedbed tillage | No insecticide |
| 7 | 60,791 23,328 | "Direct drilling" | No autumn tillage | Direct drilling | No insecticide |
| 8 | 60,794 23,314 | "Direct drilling" | No autumn tillage | Direct drilling | Tau-fluvalinate |

## Chemical control

For the four trial fields (1, 3, 5 and 8) where chemical control of pollen beetles was carried out in OSR, sprayings were made once each year with tau-fluvalinate (240 g $l^{-1}$) (product name Mavrik®, Adama Northern Europe B.V., AK Leusden, Netherlands) at the dose rate of 0.2 l $ha^{-1}$ at BBCH 57–59. Spraying dates were 2 to 9 July in 2021, 4 to 8 July in 2022, and 11 July in 2023, according to the growth stage of each OSR trial field. No other chemical control was applied for either OSR or the cereals sown after OSR. Sprayings were made with a tractor mounted field sprayer (Kasi 12 equipped with Hypro Flat Fan 110° nozzles F110-03).

## Prevalence of pollen beetle, *P*. *morionellus* and *D*. *capito*

The numbers of pollen beetles and the parasitoids *P. morionellus* and *D. capito* were assessed from each trial field in 2021, 2022 and 2023 using five observation spots established on each of the trial fields after the emergence of OSR. One of the observation spots was in the center of the field and the four other spots were equally dispersed over the field with a minimum of 14 meters from field edges. Pollen beetles were counted twice per week from BBCH 50 (inflorescence emergence) to BBCH 69 (end of flowering). Beetles were collected into a cup by shaking 10 randomly chosen plants per each observation spot, counted in the field and released back to OSR plants after counting.

To assess the abundance of *P. morionellus* and *D. capito*, yellow sticky traps (10 cm × 25 cm) (Biotus Oy, Forssa, Finland) were set on three of the five observation spots. The traps were collected and changed into new ones twice per week, simultaneously with pollen beetle counting. The numbers of *P. morionellus* and *D. capito* were counted from the collected traps under a Leica M 80 microscope. Braconid parasitic wasps were distinguished from ichneumonid wasps by the absence of forewing vein 2m-cu (present in the Ichneumonidae) and species identification followed the diagnostic characteristics described by Ferguson et al. (2010).

## OSR yield

From each trial field, OSR was harvested from five representative 2 m × 10 m areas near the observation spots with Sampo 8000 plot combiner, equipped with Trials Equipment yield assisting system (Trials Equipment UK Ltd., Braintree, Essex, UK) for measuring the fresh weight and seed moisture at harvesting.

## Meteorological conditions

The weather data were acquired from the Finnish Meteorological Institute weather station located in Jokioinen (Supplementary Table in Appendix). In 2021, May and August were very rainy, while June and July were exceptionally warm and dry, leading to shortened flowering period of OSR. In 2022, the growing season started rather early, but the weather remained cool until the end of May. The conditions were optimal for sowings and OSR germination. June 2022 was warm with low precipitation, whereas in July the mean temperature and the precipitation sum were close to long-time averages. These conditions were favorable for the growth and flowering of OSR. In 2023, the growing season started early in April, but spring was cold, and the weather turned warm only in mid-June. Precipitation was low until the start of July and due to the long-lasting drought in spring, the germination and growth of OSR were uneven.

## Statistical analysis

OSR growth on each of the observation spots was assessed each autumn just before harvesting. Based on these observations, some of the yield samples were discarded from the statistical analyses as the OSR plants in these spots deviated from the other parts of the trial field due to inferior growth, or lodging caused by deer or other external factors. Every year from each of the trial field a minimum of four yield samples were included in the analyses.

The data on the number of pollen beetles (averages over measurements at BBCH 50–67), *P. morionellus* and *D. capito*, as well as the OSR yield, was analyzed using linear models including tillage method, chemical control, year and all their interactions as fixed effects. The model used assumes that observations are independent, which is by definition not so in this case as the 3–5 observations with the same treatment are collected from the same trial field, i.e. they are pseudoreplications from the same trial field. However, the correlations between the observation points were separately modelled using spatial covariance structures, and it was found that the correlations were negligible. Thus, the data was analyzed as if the observations were independent, using the chosen linear models.

The model assumptions were examined through graphical inspection of various residual plots. The data on the number of pollen beetles, *P. morionellus* and *D. capito* was skewed and therefore square root transformation was used. The presented estimated means and confidence intervals for these transformed variables have been transformed back to the original scale. The statistical analyses were conducted using the MIXED procedure of SAS 9.4 (SAS Institute Inc., Cary, NC).

### Profitability of oilseed production

The profitability of oilseed production under different management strategies was measured per hectare by calculating the contribution margins, in accordance with recognized methods. Contribution margin analysis is suitable when the review period is short, i.e. the production capacity is the same for the whole period as in this study.

The formula used for the calculation is:

*Contribution margin = Revenue – Variable costs*

Revenues consist of

$$P \times Q + s$$

where $P$ = the three-year average selling price of the product (€), $Q$ = yield per hectare (in tons) and $s$ = agricultural subsidies per hectare (€). The subsidies did not differ among the strategies. The variable costs consist of all costs for production inputs, including contracted work. In this study, all mechanical work was assumed to be contracted services in order to improve the comparability between the different strategies. The costs for fertilizer, seed and liming were the same for all trial fields.

Due to the poor crop stand in 2021, harvesting OSR would not have been an economically viable option in practical farming. Hence, the yields from 2021 were excluded from the profitability analyses.

## Results

### Effect of cultivation strategy and chemical control on pollen beetles

The economic action threshold for pollen beetle control in Finland (10–20 beetles in 10 plants) during the flower bud stage was met in all years in all OSR trial fields (Natural Resources Institute Finland, 2026). The number of pollen beetles varied among different trial fields and years, with the emergence peaks following the abundance of flowering OSR plants (Fig. 2a). Overall, pollen beetles were most numerous in trial fields not treated with tau-fluvalinate.

In 2021, tau-fluvalinate treatment reduced the number of pollen beetles with all the cultivation strategies except “direct drilling” (for “autumn ploughing” $t_{96}$ = 4.25; $p$ < 0.001, for “autumn cultivation” $t_{96}$ = 7.48; $p$ < 0.001 and for “harrowing” $t_{96}$ = 2.73; $p$ < 0.01) (Fig. 3a). In 2022, the number of pollen beetles was low overall, and the controlling effect of tau-fluvalinate treatment was significant only with “harrowing” ($t_{96}$ = 2.94; $p$ = 0.004). In 2023, tau-fluvalinate treatment reduced the number of pollen beetles with “harrowing” ($t_{96}$ = 4.00; $p$ < 0.001), but with “autumn ploughing” ($t_{96}$ = -2.28; $p$ = 0.03) and “autumn cultivation” ($t_{96}$ = -6.17; $p$ < 0.001), the number of pollen beetles was higher in tau-fluvalinate treated fields. With “direct drilling”, tau-fluvalinate treatment had no statistically significant effect on the number of pollen beetles in any of the trial years.

Over the three studied years, the insecticide treatment reduced the number of pollen beetles with “autumn ploughing” and “harrowing” ($t_{96}$ = 2.09; $p$ = 0.04 and $t_{96}$ = 5.58; $p$ < 0.001, respectively). The number of pollen beetles was highest with “autumn ploughing” strategy with no insecticide treatment.

### Effect of cultivation strategy and chemical control on parasitoids *P. morionellus* and *D. capito*

The emergence peak of *P. morionellus* in the trial fields mostly occurred in the end of June – start of July, and generally its numbers coincided well with the peak abundance of pollen beetle (Fig. 2b).

In 2021, tau-fluvalinate treatment reduced the number of *P. morionellus* in "autumn ploughing" ($t_{48}$ = 8.33; $p < 0.001$) and "autumn cultivation" ($t_{48}$ = 9.88; $p < 0.001$) trial fields (Fig. 3b). In contrast, with "direct drilling" the tau-fluvalinate-treated field had higher abundance of *P. morionellus* ($t_{48}$ = -3.60; $p < 0.001$). In 2022, similarly with pollen beetle, the number of *P. morionellus* was low in all the trial fields (Fig. 3b) and the differences between tau-fluvalinate-treated and untreated fields were significant only with "direct drilling", where the number of *P. morionellus* was higher in the untreated field ($t_{48}$ = 2.77; $p < 0.01$). In 2023, *P. morionellus* was more abundant in the untreated fields with "autumn ploughing" ($t_{48}$ = 2.27; $p$ = 0.03) and "harrowing" ($t_{48}$ = 4.60; $p < 0.001$)). With "autumn cultivation", the pattern was opposite ($t_{48}$ = -6.57; $p < 0.001$), and with "direct drilling", tau-fluvalinate treatment had no effect. Over all the three years, the insecticide treatment reduced the number of *P. morionellus* in all other trial fields except for "direct drilling" ($t_{48}$ = 5.89; $p < 0.001$, $t_{48}$ = 2.43; $p$ = 0.02 and $t_{48}$ = 3.34; $p < 0.01$ for "autumn ploughing", "autumn cultivation" and "harrowing", respectively).

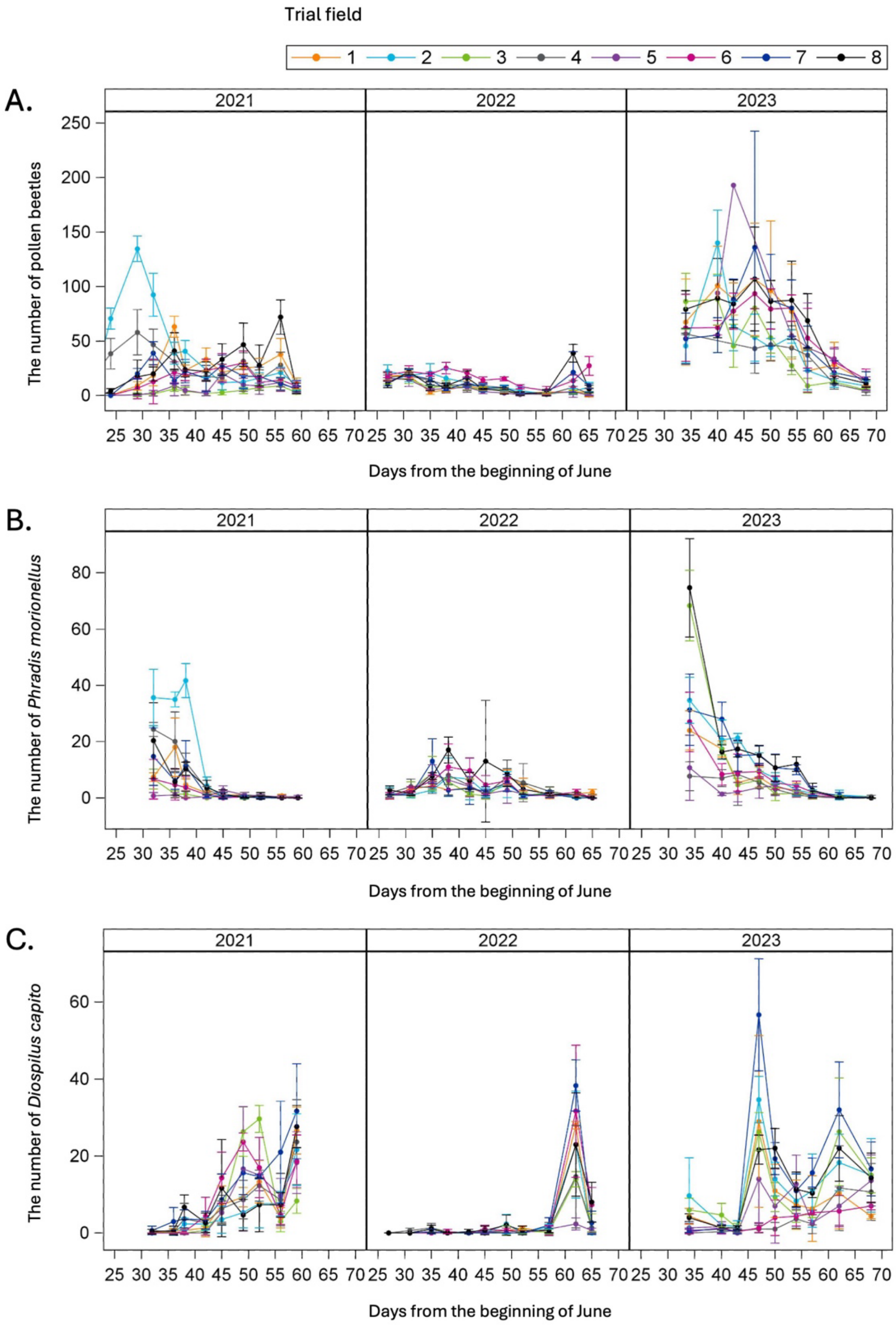


Fig. 2. The numbers of A.) pollen beetles, B.) *Phradis morionellus* and C.) *Diospilus capito* in the eight trial fields in 2021, 2022 and 2023. The observations were made from all fields at BBCH 50–67. The y-axis represents the number of insects at each observation timepoint, and the x-axis represents the days from the beginning of June. Each line (coloured) represents one trial field, numbered as in Table 1.

Of the two parasitoid species detected, *D. capito* was the most abundant, appearing later in season compared to *P. morionellus*, with the number of adults starting to rise from the end of July. *D. capito* occurred most prevalently in the later sown trial fields, where OSR also flowered later (Fig. 2c).

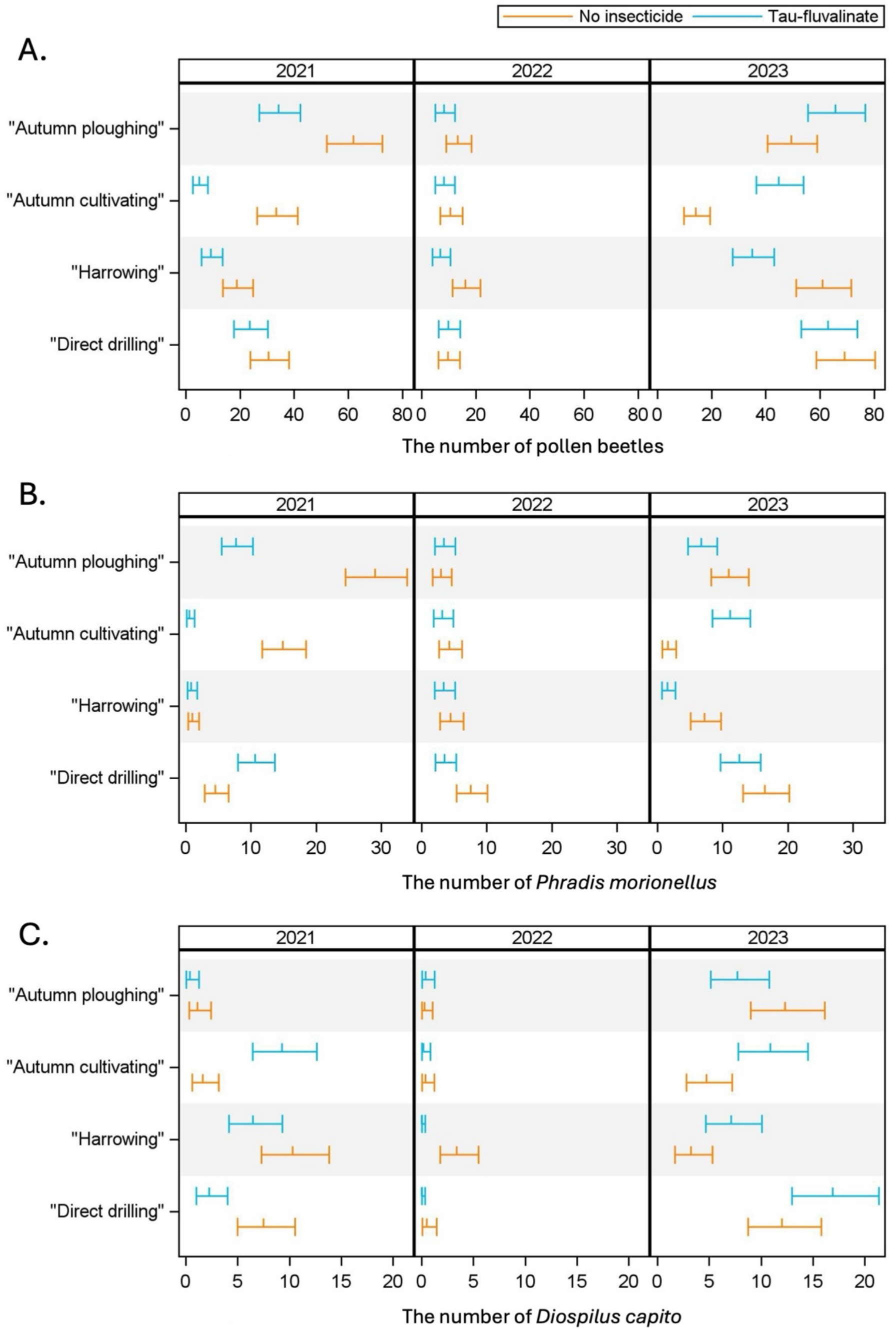


Fig. 3. The effect of cultivation strategy and insecticide treatment on the number of A.) pollen beetles, B.) *Phradis morionellus* and C.) *Diospilus capito* in 2021, 2022 and 2023. The different cultivation strategies are listed on the y-axis and the x-axis represents the fitted mean values for insect abundance. The numbers of pollen beetles were calculated per ten oilseed rape plants, and the numbers of P. morionellus and *D. capito* were calculated per sticky trap.

In 2021, the number of *D. capito* was the lowest in both "autumn ploughing" trial fields (Fig. 3c). The difference between tau-fluvalinate-treated and untreated field was significant with "autumn cultivation" ($t_{48}$ = -4.85; $p$ < 0.001) and "direct drilling" ($t_{48}$ = 3.40; $p$ = 0.001). However, the number of *D. capito* was higher in tau-fluvalinate-treated field with "autumn cultivation", and with "direct drilling", in untreated field. In 2022, the number of *D. capito* was overall low. It was abundant only in the untreated field with "harrowing", the difference to tau-fluvalinate-treated field being significant ($t_{48}$ = 4.73; $p$ < 0.001). In 2023, the numbers of *D. capito* were the highest, but intriguingly, *D. capito* was more abundant in the tau-fluvalinate-treated fields with all the cultivation strategies except "autumn ploughing" ($t_{48}$ = 2.01; $p$ = 0.05). The difference in *D. capito* number between tau-fluvalinate-treated and untreated OSR was only marginally significant in "direct drilling" ($t_{48}$ = -1.78; $p$ = 0.08). Over the three studied years, the number of *D. capito* was higher with "harrowing" and marginally significantly higher with "direct drilling" in the untreated compared to the tau-fluvalinate-treated field ($t_{48}$ = 2.41; $p$ = 0.02 and $t_{48}$ = 1.89; $p$ = 0.07, respectively). With "autumn cultivation", the number of *D. capito* was higher in the tau-fluvalinate-treated field ($t_{48}$ = -4.30; $p$ < 0.001).

## Effect of management strategy on the OSR yield

In 2021, OSR yield was higher in the untreated "autumn ploughing" and "harrowing" trial fields compared to their tau-fluvalinate-treated counter-pairs. With "autumn cultivation" and "direct drilling", the yield difference was not statistically significant between tau-fluvalinate-treated and untreated OSR (Fig. 4). In 2022, tau-fluvalinate treatment gave higher yields in all management strategies except the "direct drilling" (for "autumn ploughing" $t_{92}$ = -8.94; $p$ < 0.001, for "autumn cultivation" $t_{92}$ = -5.26; $p$ < 0.001 and for "harrowing" $t_{92}$ = -5.22; $p$ < 0.001). With "direct drilling" the difference was non-significant. In 2023, the OSR yield was higher in tau-fluvalinate-treated fields with "ploughing" ($t_{92}$ = -4.46; $p$ < 0.001) and "cultivation" ($t_{92}$ = -2.46; $p$ = 0.02), and with "direct drilling" the OSR yield was higher in untreated field ($t_{92}$ = 3.25; $p$ < 0.01).

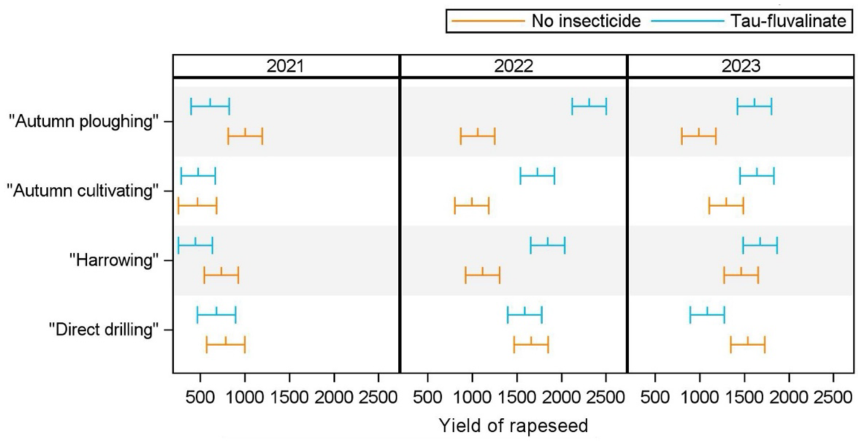


Fig. 4. Oilseed rape yields (kg ha$^{-1}$) in the different trial fields in 2021, 2022 and 2023

## Profitability of oilseed production

The profitability of oilseed production varied widely among management strategies (Table 2). In 2022, the contribution margin ranged from 314 € ha$^{-1}$ ("autumn cultivation", untreated) to 913 € ha$^{-1}$ ("autumn ploughing" with tau-fluvalinate). In 2023, the contribution margin ranged from 291 € ha$^{-1}$ ("autumn ploughing", untreated) to 713 € ha$^{-1}$ ("direct drilling", untreated). The high variation was mainly a consequence of the differences in yield levels in combination with a high selling price of the oil seed rape (536 € tn$^{-1}$). The costs for the mechanical work were highest for the most machine-intensive strategy i.e. "autumn ploughing" combined with tau-fluvalinate treatment (364 € ha$^{-1}$). This can be compared to the least machine-intensive strategy ("direct drilling", untreated) which had a cost of 196€ ha$^{-1}$ for mechanical work.

Table 2. The profitability of oilseed production for the different trial fields in 2022–2023, measured per hectare as the contribution margin

| Trial Field | Tillage method | Chemical control of pollen beetle | Contribution margin 2022 (€) | Contribution margin 2023 (€) |
|---|---|---|---|---|
| 1 | "Autumn ploughing" | Tau-fluvalinate | 913 | 567 |
| 2 | "Autumn ploughing" | No insecticide | 326 | 291 |
| 3 | "Autumn cultivation" | Tau-fluvalinate | 646 | 601 |
| 4 | "Autumn cultivation" | No insecticide | 314 | 464 |
| 5 | "Harrowing" | Tau-fluvalinate | 755 | 670 |
| 6 | "Harrowing" | No insecticide | 425 | 598 |
| 7 | "Direct drilling" | No insecticide | 773 | 713 |
| 8 | "Direct drilling" | Tau-fluvalinate | 706 | 455 |

The cost for the chemical control with tau-fluvalinate of pollen beetles was 30.9 € $ha^{-1}$ in 2022 and 31.9 € $ha^{-1}$ in 2023. When considering the selling price of the OSR (536 € $tn^{-1}$), this would require a yield increase of 58 kg $ha^{-1}$ and 60 kg $ha^{-1}$ respectively, to cover the excess costs. These requirements were fulfilled in all strategies that included chemical control, except for “direct drilling”, where tau-fluvalinate treatment did not increase the yield at any of the trial years.

# Discussion

Although the numbers of pollen beetles and the natural enemies *P. morionellus* and *D. capito* varied greatly among the three study years, as well as did the OSR yield, a pattern of reduced number of pollen beetles was observed with minimizing the soil cultivation. With the lightest tillage method, no statistically significant difference in the number of pollen beetles was observed between tau-fluvalinate-treated and untreated trial fields. Most importantly, “direct drilling” with no tau-fluvalinate treatment yielded one of the highest contribution margins.

Pollen beetles were abundant in all study years, exceeding the action threshold (Natural Resources Institute Finland 2026) for control in all OSR trial fields. The controlling effect of tau-fluvalinate on pollen beetles varied across management strategies. In 2021, tau-fluvalinate treatment decreased the number of pollen beetles under all soil cultivation strategies except “direct drilling”, but in 2023, the number of pollen beetles was actually higher in tau-fluvalinate-treated “autumn ploughing” and “autumn cultivation” fields compared to their untreated counterparts. The repeated heavy soil management combined with tau-fluvalinate treatment may have negatively affected the beneficial insects, allowing the number of pollen beetles to increase. However, the mean number of pollen beetles was fitted over the whole growing season, and counting was not made directly after spraying. Furthermore, when the pest pressure is high in the surrounding environment, the effect of tau-fluvalinate may not be prominent for a very long period.

While tau-fluvalinate treatment did not significantly affect the number of pollen beetles in any of the studied years with “direct drilling”, its effect on the parasitoid wasps varied among years with no clear pattern. This result indicates that minimized soil cultivation may benefit also other natural enemies of pollen beetle in addition to parasitic wasps, consecutively providing better control of pollen beetles regardless of insecticide treatment. This assumption is supported also by the observation that in the “autumn ploughing” fields, the abundance of pollen beetles was high both in 2021 and 2023, apart from tau-fluvalinate treatment. Autumn tillage potentially harms key natural enemies such as generalist predators including ground beetles, rove beetles and spiders, also preying on pollen beetle larvae (Nilsson et al. 2015). In an Estonian study comparing spring oilseed rape plots with a standard (ploughing and pesticides) and minimised (direct drilling and no pesticides) cropping system, less pollen beetle damage, fewer pollen beetles and more carabid beetles were detected in the minimised plot (Veromann et al. 2006b).

As expected, the ichneumonid parasitoid *P. morionellus* and braconid parasitoid *D. capito* were found in all three years. Both species belong to the most common parasitoid wasps detected to parasitize the pollen beetle in Europe together with *Phradis interstitialis* (Thomson) and *Tersilochus heterocerus* Thomson (Veromann et al. 2006a, Ulber et al. 2010). Complementary activity periods and niche separation have been reported for these parasitoids (Veromann et al. 2006b, Berger et al. 2015), which was also found in our study with the peak activity of *P. morionellus* occurring before *D. capito* (coinciding more with the peak of new generation of pollen beetle). This is important also in terms of reducing interspecific competition and multiparasitism (Billqvist and Ekbom 2001). A characteristic density-dependent response between host and parasitoid was also found in our study in year 2022, with low numbers of both pollen beetle and especially *P. morionellus* detected.

Generally, *P. morionellus* was found most abundant in the fields with the highest incidences of pollen beetles. This species is specialized in parasitizing pollen beetle and overwinters as an adult within pupal cocoon in the previous year’s oilseed fields (Ulber et al. 2010). Reduced soil tillage can benefit survival of this parasitoid in OSR fields (Nilsson 1985). Here, OSR was always sown in close proximity of the previous year’s OSR as both pollen beetle abundance and parasitism rate have previously been lower with a reduction in the proportion of oilseed cultivation within a 1-km range (Schneider et al. 2015).

The abundance of *D. capito* also followed the occurrence of pollen beetles in the field relatively well. Interestingly, in 2022, with low abundance of pollen beetle, *D. capito* peak appeared later than in 2021 and 2023, indicating a potential temporally adjusted host-parasitoid response. Minimized tillage seemed to favour *D. capito* indicating that as *P. morionellus*, also *D. capito* might overwinter in OSR fields more commonly than expected. Difference in weed cover and weed species diversity with differential tillage strategies may also impact parasitoids through influencing availability of sugar-rich resources such as floral nectar (Serée et al. 2023). Interestingly, in 2023, *D. capito* was more abundant in trial fields that were treated with tau-fluvalinate, with all cultivation strategies except "autumn ploughing". Overall, tau-fluvalinate treatment seemed to affect *P. morionellus* more negatively, which could be due to the observed later appearance of *D. capito* adults in OSR fields. *D. capito* adults may appear in the fields after insecticide spraying, whereas *P. morionellus* may encounter heavier insecticide exposure due to earlier emergence. When insecticides are applied right before the start of OSR flowering, the negative effect on beneficial insects is greater compared to insecticide treatment earlier in the bud stage (Hokkanen et al. 1988). Earlier, Jansen and San Martin (2014) reported a decline in adult parasitic hymenopteran population assessed by sweep netting after treatment with tau-fluvalinate, thiacloprid, phosmet or chlorpyriphos-ethyl, while only thiacloprid and chlorpyriphos-ethyl led to a reduced ratio of parasitoids to pollen beetle hosts in the end of growing season, indicating higher harm by those on natural control. In a study by (Brandes et al. 2018), no effect on pollen beetle larval parasitism by *Phradis* spp. was detected by either tau-fluvalinate, thiacloprid or lambda-cyhalotrin insecticide treatment. In Hanson et al. (2015), insecticide use reduced the number of emerging parasitoid females in Sweden while there was no difference between reduced versus conventional soil tillage.

The weather conditions varied significantly among the studied years, influencing the growth and yield of OSR as well as the abundance of the insect species. The second observation year (2022) offered the most favourable growing conditions for OSR, as reflected in the higher yields compared to the first (2021) and third (2023) year. In contrast, in 2022 the abundance of all studied insects was generally very low in all trial fields. In 2021, the sowings were belated due to excess soil moisture, and after this, long periods of drought during the summer lowered OSR yields in all trial fields. In 2023, due to the cool spring, the germination and emergence of OSR was slow and the growth was quite uneven. The annual variation in weather conditions and weather extremes such as drought episodes highlight the importance of multi-year studies.

The landscape including variation in seminatural, forested and arable areas also affects the overwintering, survival and migration of different insect species including pollen beetles and their natural enemies (Dainese et al. 2017). Here, the field sites were selected to be as uniform as possible regarding the local landscape factors, with none of the trial field sites highly differing from others in terms of access to e.g. pest overwintering habitat. It is however important to highlight that each combination of cultivation strategy and insecticide treatment was applied only in one field at the time. Hence, we had no true replicates per year, although when tested statistically, the pseudo replicates were not correlated with each other and were thus handled as true replicates in the statistical analysis. The data across years have more statistical power. The study design was selected to mimic practical farming conditions with larger plot size, and different treatments were not applied in the same field to prevent the movement of insects between different treatments. This trades-off with statistical robustness.

Based on the economic profitability of different strategies, to achieve a high contribution margin, the farmer has two options: high input approach (extensive soil cultivation combined with insecticide treatment) and low input approach (minimized soil cultivation without insecticide treatment), promoting biological control). Farmers could also support natural biological control by establishing separate "sacrifice" field areas to attract pollen beetles and maintain populations of natural enemies. Importantly, consistent results with natural control strategies require long-term implementation of these practices over multiple years (Hokkanen 2008, Fricke et al. 2025).

## Conclusions

Reduced tillage combined with the omission of insecticides was found to be an economically viable strategy for OSR cultivation in the Finnish agricultural context. The use of tau-fluvalinate was not detrimental to the parasitic wasps *P. morionellus* and *D. capito* over the growing season, but their response to insecticide treatment varied by cultivation strategy and year. However, intensive repeated soil management coupled with tau-fluvalinate use was associated with higher number of pollen beetles, suggesting disrupted interactions between pollen beetles and their key natural enemies. Importantly, economic profitability was sustained even without insecticide inputs when soil cultivation was reduced the most (direct drilling). Long-term studies and consistent management strategies are essential to develop sustainable, pesticide-free pollen beetle control in northern agriculture.

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# Appendix

Supplementary Table. Monthly weather data (May–September) at trial sites in Jokioinen area during the study years 2021–2023. Source: Finnish Meteorological Institute.

| Year | Monthly precipitation (mm) | Monthly average precipitation (mm) 1991–2020 | Monthly average temperature (°C) | Monthly average temperature (°C) 1991–2020 | Effective temperature sum (°C) | Effective temperature sum (°C) 1991–2020 |
|---|---|---|---|---|---|---|
| May 2021 | 98.4 | 38 | 9.8 | 10 | 157 | 189 |
| June 2021 | 34.9 | 68 | 18.6 | 14.3 | 565 | 468 |
| July 2021 | 25.7 | 74 | 20 | 17 | 1029 | 839 |
| August 2021 | 164.7 | 72 | 14.7 | 15.5 | 1329 | 1163 |
| September 2021 | 30.6 | 54 | 8.9 | 10.6 | 1445 | 1331 |
| | | | | | | |
| May 2022 | 29.4 | 38 | 9.3 | 10 | 147 | 189 |
| June 2022 | 40.6 | 68 | 16.5 | 14.3 | 491 | 468 |
| July 2022 | 65 | 74 | 16.8 | 17 | 858 | 839 |
| August 2022 | 36.1 | 72 | 17.7 | 15.5 | 1253 | 1163 |
| September 2022 | 39.4 | 54 | 8.5 | 10.6 | 1357 | 1331 |
| | | | | | | |
| May 2023 | 25.3 | 38 | 10.2 | 10 | 207 | 189 |
| June 2023 | 18.7 | 68 | 15.8 | 14.3 | 531 | 468 |
| July 2023 | 135.2 | 74 | 16.1 | 17 | 874 | 839 |
| August 2023 | 149.8 | 72 | 16.4 | 15.5 | 1227 | 1163 |
| September 2023 | 42 | 54 | 14.3 | 10.6 | 1505 | 1331 |