Temporal and spatial dynamics of pesticide use in three field vegetable crops with respect to sowing date and degree days

Kati Räsänen (kati.rasanen@luke.fi)  
Natural Resources Institute Finland

Janne Kaseva  
Natural Resources Institute Finland

Marja Aaltonen  
Natural Resources Institute Finland

Irene Vänninen  
Natural Resources Institute Finland

Research Article

Keywords: Carrot, swede, fresh pea, insect pests, plant protection product (PPP) use, chemical control

Posted Date: July 6th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3136462/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License
Abstract

We analyzed the timing of pesticide treatments for eventual analysis of temporal environmental risks associated with pesticide use in field vegetable crops. We also investigated the extent to which timing of treatments reflected predicted flight times of pests to gain an understanding of whether farmers followed the model predictions in their decision-making as part of Integrated Pest Management (IPM). The data cover chemical plant protection in field vegetable farms in southwestern Finland in 2009–2019.

The timing of treatments, made with different pesticides in the weeks following sowing, corresponded with the known phenology of different pests of the three crops. The same was true for the carrot fly, the pea moth and the 2nd generation of the cabbage root fly when phenological models using historical data were used to predict the timing of treatments. Carrot psyllids, root flies and pea moths were the most targeted insects in carrot, swede and peas, respectively. Spray frequencies against carrot psyllid increased over time for carrot. The use of insecticides was least for fresh pea.

We conclude that farmers acted in accordance with the principles of IPM when practising chemical control. For those species that lacked phenological predictive models in the study years, the degree days for the observed timing of treatments can be used as a starting point if such models are developed in the future. Our results can be used as a long-term baseline in future surveys on the changes in pesticide use and their risks regarding the studied crops.

Key message

- We studied chemical plant protection actions of over 100 farmers of vegetables over 10 years
- The timing of treatments corresponded with the known phenology of pests of the tree crops
- The timings coincided also with predictions of phenological models using historical weather data
- Growers were concluded to have used pesticides according to the principles of IPM
- Temporal dynamics of pesticide use can be fed into models to analyze their environmental risks

Introduction

The European Union (EU) aims to decrease chemical risks to humans and the environment via different strategies in the Green Deal, including Farm to Fork and the biodiversity strategy. Moreover, the environmental and health risks associated with pesticides should be reduced via Integrated Pest Management (IPM) in crop production (EC 2009).

In a previous publication (Räsänen et al. 2022), we showed that for four important field vegetable crops, chemical plant protection has been dominant over the past 20 years (and even before), although development of resistance to pesticides and removal of the most hazardous plant protection products (PPP) from the market recently began to affect this dominant position. In addition, according to the
directive on sustainable use of pesticides (EC 2009), sustainable biological, physical and other non-chemical methods must be preferred to chemical methods if they provide satisfactory pest control. The Farm to Fork strategy (EC 2020) aims at halving pesticide use and risks in the EU by 2030. Following these developments, and because the progress of IPM must be measured (EC 2009), it is important to be able to gauge the change that is expected to take place in the use of plant protection methods and the magnitude of the resulting environmental risks in the coming years. Based on the timing of the PPP treatments reported by farmers, it may be possible to estimate whether management was carried out on the basis of a real need or routinely based on the calendar or the phenology of a crop; the latter would go against the principles of IPM. The correspondence between the treatment time and the need for management can be studied by comparing the control time points with both empirical information on pest phenologies (Swetnam et al. 1999) and the treatment time recommendations given by pest phenological prediction models, when historical site-specific weather data are used in modelling.

As a part of IPM, the principles concerning the timing of chemical treatments with PPPs can be used to identify the need for crop protection in carrot (Daucus carota), swede (Brassica napus) and fresh pea (Pisum sativum), the three model crops of the current study. In Finland, key pests that might need to be managed using chemical pesticides in these crops can have substantial effects on yields. The key pests are: in carrot, the carrot psyllid (Trioza apicalis), the carrot fly (Psila rosae), and Lygus spp. bugs; in swede, cabbage flies (Delia spp.), flea beetles (Phyllotreta spp.) and the diamondback moth (Plutella xylostella); and in fresh pea, the pea moth (Cydia nigricana), the pea aphid (Acyrthosiphon pisum) and the pea weevil (Sitona spp.). These pests have different phenologies, biological characteristics, and behaviors, many details of which are still not documented.

In the 1990s, phenological prediction models for peak flight times were developed for the carrot fly (Markkula et al. 1998; Tiilikala et al. 1998, Table 1) and for the cabbage root fly (Tiilikala et al. 1998) for Finnish conditions. For the pea moth, a phenological model for its emergence is available for German conditions (Saucke et al. 2020, Table 1). In Finland, the occurrence of pea moths is determined with the help of pheromone traps, and the estimated time of treatment of newly hatched larvae is then calculated based on the development time of the eggs using a formula (e.g. Macaulay et al. 1985, Table 1). The Finnish prediction models are publicly available, and they have been used over the years to alert farmers to the approaching flight times of the carrot and cabbage flies and the pea moth so they can prepare control treatments if thresholds are exceeded (Luke 2023a and 2023c).

In a previous paper (Räsänen et al. 2022), we studied the volumes of pesticide used and treatment frequencies for herbicide, fungicide and insecticide applications in the crops grown in southwest Finland over 17 years. In the current paper, our aim is to analyze the timing and key pests controlled by pesticide applications during the growing season for three crops in southwest Finland. Furthermore, we compare the timing of the pesticide treatments for the crops as reported by farmers with the timing predicted by degree day (DD) models available for the carrot fly in carrot, the cabbage root fly in swede, and the pea moth in fresh pea. Such analysis can determine how well the reported timings of treatments correspond with model predictions. If the models predict pest emergence and flight peaks correctly, we could then
determine the extent to which farmers follow the model predictions for their decision-making as part of IPM.

Based on the availability of sufficient data in the treatment database that we had access to, the following research questions (A-C) were formulated:

1. What were the temporal profiles of PPP treatments for different pest groups (weeds, diseases, insects) in carrots, swede and fresh pea in 2009–2019?
2. Which insect pest species were predominantly targeted in the studied crops in 2009–2019 and did treatment frequencies change over the years?
3. For selected insect pest species, what was the distribution of DD sums of treatment times of the pest species in each crop, and how well did realized treatment times correspond with available model predictions for pest emergence or flight times based on DDs?

**Material and methods**

**The database**

The data cover chemical plant protection activities on contract farms of the Finnish food processing company Apetit Ruoka Ltd. in southwestern Finland in 2009–2019. The contract farmers record their plant protection activities in the intranet of the company for the contract crops they grow. During the study we discussed with Apetit Ruoka Ltd. experts to learn more about practical issues on the farms. According to the Apetit Ruoka Ltd. experts, they provide instructions and guidance for farmers on IPM for different crops. The instructions include a requirement to assess the need for control before treating the crops with PPPs.

The database covers over 100 farms and was described in more detail in Räsänen et al. (2022). The results are based on farmers' reports of the target pests for pesticide applications on the studied crops. We do not have information on whether the target pests were identified by a third party, such as advisors. The data on pesticide treatments in the database included unique crop field identifiers, field area, year, crop identifiers, sowing date, and PPP information for each pesticide application: commercial product name(s), application rate/ha, date of pesticide application, and target pest (species or genus level, depending on pest) for each pesticide application. It must be noted that the database includes data only for field parcels where there was chemical PPP treatment.

**Crops included in the study**

Carrot (family *Apiaceae*) is the most widely grown root vegetable in Finland, occupying an area of about 1650 ha (Luke 2023b). Most domestically produced carrots are sold fresh. The carrots included in this study were produced for frozen convenience food. In Finland, carrot is usually sown at the beginning of May and harvested in September–October. In our data (8114 pesticide sprayings in 2009–2019), 9% of carrot fields were sown in April, 90% in May, and 1% in June.
Swede (family *Brassicaceae*) is well suited to the humid climate of northern Europe. In Finland, it is cultivated on about 400 ha (Luke 2023b), and in this study this crop was for human consumption. Swede is usually sown in the latter half of May and harvested at the end of August to early October in Finland. In our data (1166 pesticide sprayings), 2% of swede fields were sown in April, 70% in May, and 28% in June.

Pea (family *Fabaceae*) is grown on over 10,000 hectares in Finland (Luke 2023b) for feed and food production. Its cultivation as fresh garden pea, which the data represent in this study, has increased during the past decade, and since 2017 is grown on over 4,000 ha. Fresh pea is sown from the beginning of May to the end of June and harvested at the end of July to late August–early September. In our data (5133 pesticide sprayings), 0.4% of fields were sown in April, 70% in May, and 29% in June. Apetit Ruoka Ltd. guides pea farmers as to when to sow and pea sowing is consequently staggered. The growing period for fresh peas is only 60–80 days in comparison with approximately 100 days for hard peas. The cool and light intensive Nordic growing season, from May to early August, well suits fresh pea cultivation for freezing and it has become a high-quality export product in the study area because of local cultivation knowledge and a well-planned production chain.

**Indicators**

To answer research question A, the pesticide application frequency per active ingredient (ai) per field was calculated for the weeks from sowing to herbicide, fungicide and insecticide application. If the number of PPPs was more than one per field visit (tank mixes or products containing more than one active ingredient), the number of pesticide sprayings was considered to be the total number of active ingredients used. We did not specify the pest species when answering research question A because we only wanted to determine the mean temporal dynamics of total pesticide group application frequencies, which serves as a proxy for the temporal distribution of pesticide loads in the studied fields.

To answer research question B, the pesticide application frequencies per target key pest were calculated from the database as an average for each year (2009–2019). There were three key pests in each crop as described. For swede, the dropdown menu of the database offered only cabbage flies as a target without specifying the species (*radicum* or *oralis*, that both occur in Finland, Havukkala et al. 1984), because it is difficult for farmers to differentiate the two species from the yellow sticky traps used for monitoring. Another issue to consider when using the database was how the target pests were presented to growers in the dropdown menu. The menu included options with a single pest species as well as options that included several pest species that could occur simultaneously and are controlled either with the same PPP or a tank mix. The latter options were not included in this analysis because it could not be verified whether all pest species in the multiple species options occurred simultaneously. Thus, total insecticide applications per crop for research question A (where target species were not defined) were higher than for research question B, where only insecticide applications reported against single pest species were included. The insecticide application frequency per key pest and year serves as a proxy for inferring potential changes in the prevalence of the most important target pest species over time.
To answer research question C, the pesticide application frequency per active ingredient (ai) per field was calculated for different weeks from sowing for each target pest (see previous section) and crop from the database. To compare treatment timing with model predictions, the degree days that accumulated in each year by the treatment days were calculated using 5°C as the base temperature and compared with DD model predictions. The corresponding historical weather data were obtained from the Finnish Meteorological Institute via Luke (Venäläinen et al. 2005). The DDs for each treatment and respective model predictions for treatment timing for the carrot fly, the cabbage flies and the pea moth (Table 1) were calculated at municipality level because field-level data were not available.

### Table 1
Degree days (DD) based thresholds for timing of control of carrot fly in carrot (Markkula et al. 1998; Tiilikkala et al. 1998) and cabbage root fly in swede (Tiilikkala et al. 1998) for Finnish conditions, and the pea moth in fresh pea (Saucke et al. 2020) for German conditions

<table>
<thead>
<tr>
<th>Carrot fly (P. rosae) (DD, T_{sum} above + 5°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>260 DD</td>
</tr>
<tr>
<td>360 DD (T)</td>
</tr>
<tr>
<td>560 DD</td>
</tr>
<tr>
<td>800 DD</td>
</tr>
<tr>
<td>860 DD (T)</td>
</tr>
<tr>
<td>960 DD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cabbage root fly (D. radicum) (DD, T_{sum} above + 5°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 DD</td>
</tr>
<tr>
<td>150 DD (T)</td>
</tr>
<tr>
<td>250 DD</td>
</tr>
<tr>
<td>600 DD</td>
</tr>
<tr>
<td>750 DD (T)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pea moth* (C. nigricana) (DD, T_{sum} above + 8,135°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>104**</td>
</tr>
<tr>
<td>485**</td>
</tr>
<tr>
<td>568** (T)</td>
</tr>
<tr>
<td>693**</td>
</tr>
</tbody>
</table>

T = threshold value when insecticide application is recommended to be made.
*In Finland, pheromone traps are advised to be taken to the pea fields at 450 DDs \((T_{\text{sum}} \text{ above } + 5^\circ \text{C})\), Luke 2023c). Another threshold used in Finland is 80 DDs \((T_{\text{sum}} \text{ above } +10^\circ \text{C})\) from the biofix (e.g. Macaulay et al. 1985), i.e. the threshold of more than 7 males in both of the two pheromone traps per pea field in two consecutive checking days that are 2–3 days apart. The 80 DDs threshold (7–12 days from the biofix) is used to determine the time of first chemical treatments against L1-larvae.

** All values are means obtained under German field conditions. Note: the base temperature of 8,135\(^\circ\)C in (Saucke et al. 2020) refers to the DDs at which the moths start to emerge from soil in the spring.

**Statistical analysis**

Statistical analyses were performed using the GLM procedure of the SAS Enterprise Guide version 7.15 (SAS Institute Inc., USA). Trends in spray frequencies over the weeks (Figs. 1 and 3) and years (Fig. 2) between fields across crops were examined using linear models (ANOVA and regression). The effect of time was used as a classification variable to examine trends over the whole period. Normality of the residuals was checked through figures, and in the case of skewed distributions, a logarithmic transformation was used for a response variable. Tukey’s method was used for pairwise comparisons of means between timepoints (Westfall et al. 2011), with a significance level of \(\alpha = 0.05\).

**Results and discussion**

**The temporal profiles of PPP treatments used against different pest groups in three crops**

Fungicide, herbicide and insecticide applications for carrot, swede and fresh pea fields in different weeks after sowing for 2009–2019 are shown in Fig. 1a, b, c.

For carrot, on average, fungicides, herbicides and insecticides were applied 1.2, 1.6 and 1.2 times per field per week, respectively. Fungicides were applied during the later weeks of the growth period. The occurrence of plant diseases is affected by factors including temperature and humidity, which usually increase during the growing season. The use of fungicides on carrots (in weeks 10–21 after sowing, 624 fungicide sprayings in 607 fields) coincides with the end of the growing season and approaching harvest to prevent disease-induced weakening of the plant stems. The carrot stems must be healthy to withstand mechanical lifting in the fall. Herbicides were usually sprayed 2–7 weeks after sowing (84% of all herbicide applications, 4633 sprayings in 2511 fields) to prevent weeds from shading the small carrot seedlings, which are not good competitors for light due to their small leaf area. Early weed control is important in vegetables because the seeds are sown in well-spaced rows and the crops grow slowly. In addition, herbicides approved for vegetables are usually effective against weeds only at the young seedling stage or sometimes pre-germination. Full green crop coverage in carrot is not achieved before mid-July. Insecticides were applied on carrots mostly 4–10 weeks after sowing (90% of all insecticide applications, 3077 sprayings in 2614 fields).
For swede, on average, fungicides, herbicides and insecticides were applied 1.0, 1.1 and 1.1 times per field per week, respectively. Few fungicides were applied to swede, mostly mid-growing season, 11–12 weeks after sowing (71% of all fungicide applications, 17 sprayings in 17 fields). Chemical control of diseases in swede is seldom necessary because diseases are mainly controlled through crop rotation and cultivar selection. Herbicides were used before sowing (34% of all herbicide applications, 298 sprayings in 224 fields) or one week after sowing at the seedling stage (53%). According to the instructions for weed control in vegetables, herbicides are often sprayed after tillage but before sowing or immediately after sowing (Tukes 2023). Insecticide applications (854 sprayings in 741 fields) were started during the first week after sowing and continued over the whole growing season until week 17 after sowing.

For fresh pea, on average, fungicides, herbicides and insecticides were applied 1.0, 2.9 and 1.0 times per field per week, respectively. Very few fungicides were applied on fresh pea, and all applications (7 sprayings in 7 fields) were done 6–9 weeks after sowing. Crop rotation is obligatory for fresh pea on the contract farms of Apetit Ruoka Ltd. which, in addition to the short crop cycle, reduces the need to control diseases chemically. Most herbicides were sprayed at the seedling stage, 3–4 weeks after sowing (86% of all herbicide applications, 4268 sprayings in 1567 fields). Weeds in pea plots in the crop rotation scheme are controlled also in the fall preceding the crop of the following spring, but these applications were not included in our study. Most insecticides on fresh pea were applied in the mid-summer 8–9 weeks after sowing (75% of all insecticide applications, 931 sprayings in 902 fields).

To summarize, the timing of PPP treatments with fungicides, herbicides and insecticides in the weeks following sowing corresponded with the known phenology of different weeds, diseases and insect pests on different crops (Luke 2023c). The use of chemical PPPs causes local chemical pressure on the environment. Generally, however, the use of pesticides in crop production in Finland is only 1% or less than used in central and southern European countries (EC 2021).

**Predominantly treated insect pest species in three crops**

The frequencies of insecticide treatments in 2009–2019 for the three crops against different key pests are shown in Fig. 2a, b, c.

The use of insecticides was more frequent in carrot and swede crops compared with fresh pea. Carrot psyllid is the worst pest of carrot in northern Europe, including Finland (e.g., Markkula et al. 1976; Nissinen et al. 2012), and parts of central Europe (reviewed in Láska 2011). This was also confirmed by Apetit Ruoka Ltd. concerning the farms in our database. Carrot psyllid was the most targeted insect in carrot (95% of all insecticide applications against the three key pests, 2275 sprayings in 1893 fields). The treatment frequencies against this pest increased over time ($\beta = 0.228, p < 0.001$), mainly due to recent increased frequencies. Treatments against this pest were made 3.9 times per field and year, on average, and in 2019 as many as 6.8 times, which differed significantly from treatment frequencies for 2009–2017 ($p < 0.001$). Confidence intervals were similar and small in all years, indicating that treatment frequencies against carrot psyllids were similar among fields of different farms. We previously reported
(Räsänen et al. 2022) that insecticide application frequencies for carrot generally increased between 2013 and 2019 ($\beta = 0.21$, $p < 0.001$), which was supported by the estimations of Apetit Ruoka Ltd. experts. According to their experience, treatment frequencies against carrot psyllids increased over the years in the company’s contract carrot fields. The current analysis supports this, and the increasing trend indicates that the reason is increased use of insecticides against carrot psyllids. There are reports of increasing populations of carrot psyllid from the 1990s (Tiilikkala et al. 1996) and 2010s (Haapalainen et al. 2018). Nissinen et al. (2012) showed that the carrot psyllid can seriously damage carrot yields. With the current pesticide regime in Finland, the carrot psyllid in carrots (Nissinen et al. 2020) and the cabbage and turnip root flies in swedes (Nissinen and Jauhiainen 2016) are most effectively controlled using insect nets, not pesticides. Many contract farmers of Apetit Ruoka Ltd. started to use insect nets in carrot crops since 2020 because chemicals are no longer effective against carrot psyllids due to suspected development of insecticide resistance. Data from 2020 are not included in our study but should be taken into consideration in the future to see if the use of insect nets results in decreasing overall numbers of chemical treatments against the carrot psyllid.

Regarding the carrot fly, an average of 1.7 pesticide applications per year were made against the pest, but with a decreasing trend over the years ($\beta = -0.128$, $p < 0.05$, 88 sprayings in 77 fields). Interestingly, no treatments against carrot fly were reported for 2018 and 2019 among the single-pest options of the database. According to Apetit Ruoka Ltd., the most important pest of carrot is carrot psyllid. When carrot psyllid is sprayed carrot fly is also affected if present but may not be necessarily be documented separately as a target pest in the database. Such situations can occur, particularly in June, when the first generation of carrot fly occurs with carrot psyllid. In July/August when the second carrot fly generation emerges, there is usually no need to control carrot psyllid – solely carrot fly is reported as a target pest. Our decision to use only singly reported target pests as data may give too optimistic a picture of the need to control carrot fly. Because it is controlled using the same substances as carrot psyllid, the need to control carrot fly may seem minor, particularly concerning the first generation.

Lygus bugs in carrot were sprayed about once a summer. Insecticide application frequencies against this pest decreased over time ($\beta = -0.016$, 44 sprayings in 44 fields), but the trend was not statistically significant. Treatment frequencies in 2012 were significantly higher than in other years ($p < 0.001$). Confidence intervals were small, indicating similar control needs against lygus bugs among farms where they occurred.

In swede, most insecticide applications were against root infesting flies (*Delia* spp.) (55% of all key insecticide applications in swedes, 354 sprayings in 334 fields). There was an average of 3.14 treatments per field per year. The decrease in treatment frequencies over time ($\beta = -0.091$) was not statistically significant. Confidence intervals were large in all years, suggesting that the control pressure exerted by *Delia* spp. varied considerably among fields. According to Apetit Ruoka Ltd., in recent years, insect nets have been used to control cabbage and turnip root flies. Insect nets are currently perceived as the most viable solution to prevent damage by both carrot psyllids and cabbage root flies (Nissinen et al. 2020).
In swede, flea beetles were the second most controlled pest after cabbage flies in terms of treatment frequencies (35% of all insecticide applications against three key pest species in swede, 226 sprayings in 192 fields). Flea beetles were sprayed on average 2.1 times per year. The insecticide application frequency decreased over time ($\beta=-0.142, p<0.001$). In 2011, significantly more treatments were made against flea beetles in comparison with other years, except 2012. Insecticides were used against the diamondback moth on average 1.8 times per year, and the trend of treatment frequencies increased significantly over time ($\beta = 0.130, p<0.01, 68$ sprayings in 59 fields). We showed in our previous paper (Räsänen et al. 2022) that the overall trend for insecticide treatment frequencies in swede decreased from 2003 to 2019 ($\beta=-0.09, p<0.01$). In accordance with the information given by the representatives of Apetit Ruoka Ltd., we assumed that the decreasing trend was at least partly because some farmers used insect nets since 2012 to protect swede fields. However, the decreasing trend from 2009 onwards in the current study was significant only for treatments against flea beetles. The most likely reason for the different results concerning the temporal trends is that we investigated two different time periods: 2003–2019 in our previous paper (Räsänen et al. 2022) and 2009–2019 in this study.

For fresh pea, fewer insecticide treatments were reported than for swede and carrot. The frequency of insecticide treatments on fresh pea was stable over time, with no statistically significant trends. As shown also in Räsänen et al. (2022), fresh peas are associated with very low and stable use of PPPs, which can be explained by the short growth period and a long crop rotation (5–6 years) that effectively keeps pest populations low. Such management may have helped keep the pea moth under control despite the assumption that pea moth infestation would increase as pea cropping expanded (Huusela-Veistola and Jauhiainen 2006). Most of the insecticide applications were for pea moths (91% of all applications against key insect pests on fresh pea, 637 sprayings in 632 fields). The pea moth, the pea weevil and the pea aphid were sprayed once per year. Treatment frequencies against insect pests in pea were quite similar for different farms, as seen from the narrow confidence intervals for the pea moth and the pea weevil (42 sprayings in 42 fields), and no confidence intervals for pea aphid (21 sprayings in 21 fields). Even though the volume of used chemicals is small, the treatments are essential to improve management of insect pests on peas. The risk of pea moth damage was higher for organic farming and plant protection more difficult than for conventional cultivation using chemical control (Huusela-Veistola and Jauhiainen 2006).

To summarize, the use of insecticides was more frequent on carrots and swedes compared with fresh peas. Carrot psyllid was the most targeted insect pest of carrot. For swede, most insecticide applications against root flies (Delia spp.). The frequency of insecticide treatments on fresh pea was stable over time and most of the insecticide applications were against the pea moth. There were changes in the control of key pests over time depending on the pest species and crop: e.g., spraying frequencies against carrot psyllid increased over time.

**Distribution of DD sums of treatment timings for insect pests in carrot, swede and fresh pea**
For carrot, the peak insecticide application against carrot psyllid was in weeks 6–9 after sowing (71% of all insecticide applications against carrot psyllids, 2275 sprayings in 1893 fields, Fig. 3a), which fits quite well with the known phenology of this pest in carrot: the carrot psyllid, against which the need for chemical control is assessed with yellow sticky traps, starts flying usually in mid-June, sometimes even during the first week of June (Luke 2023c). Our study agrees with this information: carrot psyllid was mostly sprayed in June (65%) and second most in July (33% of all insecticide applications against this pest). The average temperature sum of the insecticide application times in weeks 6–9 after sowing ranged between 393 and 526 DD. Farmers sprayed carrot psyllid about 1.2 times per week and there were no statistical differences between weeks. However, according to the contract farmers of Apetit Ruoka Ltd., there exists wide regional variation in occurrence of carrot psyllids; in some cases, the pest pressure differs between adjacent fields. Nissinen et al. (2021) showed that there can be large variation in the number of carrot psyllids and their feeding damage among years within the same farm and even within the same field. They also highlighted the effects of environmental conditions, especially the amount of precipitation and effective temperature sum, associated with carrot psyllid damage. More research into the effects of this insect pest is needed. There were no phenological prediction models available for the carrot psyllid for 2009–2019. If such models are developed in the future, their ability to predict the DDs of treatment times against this pest using historical data can be tested as was done in our study for cabbage and carrot flies.

Insecticide treatments against the carrot fly were done in weeks 3–16 after sowing, mostly in July (39%) and August (41% of all insecticide applications against the carrot fly, 88 sprayings in 77 fields, Fig. 3a). Carrot fly was sprayed about 1.1 times per week and there were no statistical differences between weeks. Curative chemical control against the carrot fly, which is monitored with yellow sticky traps, is targeted either at adult flies with pyrethroids or at larval stages with dimethoate (Luke, 2023c); registered chemicals against both life stages were available during the study period. The first peaks of spraying against the carrot fly were in week 7 (11% of all insecticide applications against carrot fly), with an average temperature sum of 559 DD. According to the predictive threshold value for carrot fly, which has two generations in the studied area (Luke 2023c; Tiilikkala et al. 1998), the first generation of the pest appears at 360 DD (Markkula et al., 1998; Tiilikkala et al. 1998, Table 1). However, the need for controlling the carrot fly's first generation, as well as documenting treatments against it, could be partly masked by carrot psyllid treatments, as explained in section 3.2. This may be the reason why the first control peak is not obvious from the database. The majority of the treatments were done in weeks 11–13 after sowing (53%), with an average temperature sum at 894 DD, which is very close to the predictive thresholds for the carrot fly's second generation flight peak at 860 DD (Markkula et al. 1998; Tiilikkala et al. 1998, Table 1). We suggest that this second peak in our study describes farmers’ control of the pest’s second generation. Use of historical data for predicting the flight peak of the pest corresponded well with timing of treatments against it, as reported by the farmers in the database.

For carrot, lygus bugs were the earliest pests to be treated. Most treatments were concentrated in week 4 after sowing (57% of all insecticide applications against bugs, 44 sprayings in 44 fields, Fig. 3a), at an average temperature sum of 227 DD. The remaining applications were distributed over weeks 2–3 and 5–
Sprayings were applied in May (50%) and June (50% of all insecticide applications against this pest), as supported by the common knowledge that they arrive in the carrot fields at the end of May (Luke 2023c). Farmers sprayed against lygus bugs once per week, irrespective of which fields were treated.

Cabbage flies are the most damaging pests of swede. In Finland, two Delia spp. are pests of Brassica crops: the cabbage root fly (Delia radicum), with two generations per growth season, and the turnip root fly (Delia floralis) with a single generation (Havukkala et al. 1984). The appropriate time to control (mostly with pyrethroids) adult flies, if threshold values are exceeded, is before egg-laying, while larvae are controlled (mostly with dimethoate) as they emerge from eggs (Luke 2023c). According to our study, 46% (161 sprayings) of treatments against cabbage flies were made with the larvicide dimethoate and 54% (191 sprayings) with other chemicals (mostly pyrethroid adulticides). In principle, treatments against larvae should be made later than those against adults, but there were no differences in this respect between treatment timing with adulticides and larvicides (data not shown).

Regarding root flies that occur on swede, predictive models for timing PPP treatments in Finland have been developed only for the cabbage root fly: the flight peak of its first generation occurs at the temperature sum of 150 DD and that of the second generation at 750 DD (Tiilikala et al. 1998, Table 1). The adults of the first generation of the cabbage root fly hatch at the turn of May and June and their flight and egg-laying are most abundant in early June (Luke 2023c). That there was no clear peak for treatment of the first generation of cabbage root flies in June may be explained by the first fly generation being mostly controlled with seed dressings. By the time the second generation of D. radicum and the turnip root fly appear in July, the effect of the seed dressing has ceased. There is no information about seed dressings in the Apetit Ruoka Ltd. database. The flight of the second generation of D. radicum starts in the middle of July and the peak is usually between July and August, followed by peak egg-laying in August (Tiilikala et al. 1998). The turnip root fly has a longer flying period, from the beginning of July to the end of August (Havukkala et al. 1984). According to our study, cabbage flies were mostly sprayed in July (52%) and August (38% of all insecticide applications against cabbage flies, 354 sprayings in 334 fields, Fig. 3b). Treatments against the flies were done mostly in weeks 6–12 after sowing (75% of all insecticide applications against root flies in swede), when the average temperature sum was 571–945 DD. These DDs match closely to the predicted model values for the flight of the second generation of D. radicum, but they coincide approximately with the known flight phenology of the turnip root fly. Due to overlap and because the two species are not differentiated in the database, we cannot differentiate between the timing of control of the two species. Farmers sprayed Delia spp. about 1.07 times per week and there was a decreasing trend over the study years (β=−0.015, p < 0.001).

Flea beetles in swede were sprayed mostly in weeks 2–4 after sowing (84% of all insecticide applications against flea beetles, 226 sprayings in 92 fields, Fig. 3b), at temperature sums 251–316 DD. The flea beetles were treated about 1.1 times per week, with no statistical differences between weeks. In swede, the diamondback moth was controlled mostly in weeks 4–5 after sowing (48% of all insecticide applications against diamondback moth, 68 sprayings in 59 fields, Fig. 3b), at average temperature sums
Farmers sprayed the moth larvae about 1.1 times per week and there were no statistical differences between weeks.

The pea moth is the most serious pest of pea plants in Finland, but also in other Nordic countries (Borgström et al. 2019), Germany (Saucke et al. 2020), Poland (Kaniuczk 2009), Russia (Berim n.d.) and Belarus (Богуславская 2009). Farmers sprayed the pea moth about once per week and there were no statistical differences between weeks. In fresh pea, the pea moth was sprayed in weeks 2–11 (except week 5) and mostly in weeks 8–10 after sowing (91% of all insecticide applications against the pea moth, 637 sprays in 632 fields, Fig. 3c), at an average temperature sum of 755 DD ($T_{\text{sum}}$ above + 5 $^\circ$C) and 487 DD ($T_{\text{sum}}$ above + 8.135$^\circ$C, as described in Saucke et al., 2020). A German prediction model guideline is to treat the pea moth at 568 DD ($T_{\text{sum}}$ above + 8.135$^\circ$C, which indicates the temperature at which moths start to emerge from soil) against L1 (larval stage 1) (Saucke et al. 2020, Table 1). The timing of treatments in our study did not coincide with the recommendations of the German phenological model. This was true for treatments of pea crops sown in May and those sown in June (data not shown).

The emergence of the pea moth can be affected by many environmental factors. Thöming and Saucke (2011) showed that field, air and soil temperature, but also solar radiation and day length, correlated strongly with pea moth emergence in spring. In our study, pea moth was mostly sprayed in July (81%) and August (16% of all insecticide applications against pea moth) – the two peaks are most likely due to staggered sowing times for peas. The main peak corresponds with the information that in Finland adult moths start emerging in late June, and their flight peak occurs at the beginning of July (Luke, 2023c).

Most treatments were applied at temperature sums higher than 450 DD ($T_{\text{sum}}$ above + 5$^\circ$C). Monitoring the pea moth is recommended to be started at 450 DD, and the biofix DD for treatments is 80 DD ($T_{\text{sum}}$ above + 10$^\circ$C) from the day when the threshold number of moths in pheromone traps is exceeded (see Introduction and Table 1). Control is targeted at newly emerged larvae prior their boring into pea pods; the timing of control is based on the occurrence of flight peak, monitoring of male flies with pheromone traps and DDs or number of days that accumulate after a threshold number of males were observed in the traps. Thus, the window for successful control (with pyrethroids) is relatively narrow and should be based on the local weather conditions (Luke 2023c). Assuming that after placing the traps in the fields at 450 DD, a number of DDs, 100–150 or more, accumulate before the threshold is exceeded, and additional DDs (about 160$^\circ$C when taking + 5$^\circ$C as the base temperature) accumulate from the biofix onwards before the L1 emerge from eggs. Thus, an approximate sum of 700–800 DD is when treatments against L1 should be done. This corresponds with the observed average DDs for treatments. The moth’s response times to environmental conditions, particularly temperature, can differ in the Finnish climate compared with the German, and biological differences between populations cannot be ruled out. Research is needed to construct a prediction model based on emergence times of adult pea moths under Finnish conditions.

Minor pests of fresh peas include the pea weevil and pea aphid, which can periodically require control. Pea weevils must be controlled before the adults start laying eggs (Luke 2023c). Insecticides were applied against pea weevils mostly in weeks 3–4 (64% of all insecticide applications against pea weevils, 42 sprays in 42 fields, Fig. 3c), with average temperature sums ranging from 323 to 264 DD, mainly in
June (69%). The pea aphid is usually controlled similarly to the pea moth (Luke 2023c). In our study, it was treated in weeks 2–10 (not 5) and mostly in weeks 8–10 after sowing (76% of all insecticide applications against pea aphid, 21 sprayings in 21 fields, Fig. 3c), at average temperature sums ranging from 621 to 789 DD. Farmers sprayed both pea weevils and pea aphids once a week with no differences between weeks, meaning that chemical plant protection is similar among fields and farms.

A limitation of our study is that only temperature was used to predict occurrence of pests with the models, and not other environmental factors that also can influence pest phenology (see Thöming and Saucke 2022, on radiation and precipitation effects on the pea moth; Овчаренко and Николаева 2020, on the importance of precipitation for the carrot fly). Another limitation was that we could not use farm- or field-specific weather data when calculating the DDs for treatment times or phenological predictions. Even so, the treatment times reported in the database for different pests corresponded relatively well with model predictions using historical weather data.

**Conclusions**

Although the database does not contain direct information on what farmers based their control decisions on over the years, we concluded that they did not merely routinely carry out treatments according to the calendar or the phenology of the crop. The results showed that the frequency of applications varied depending on the summer, reflecting pest pressure, and that pests were sprayed in different weeks after sowing. We thus conclude that farmers followed the principles of IPM in using chemical plant protection. This conclusion is in accordance with the company's IPM-guidelines, stating that pests must be monitored, and treatment decisions must be based on the results of monitoring.

The predictions obtained with the models corresponded with the treatment times of the second generation of the carrot fly, the second generation of the cabbage root fly (although we cannot distinguish treatments of this species from those used against the turnip root fly), and with the treatment times of pea moths based on the biofix (which was thus concluded to be an appropriate method to predict treatment times for the pea moth in Finland). Furthermore, for several pest species with no prediction models available, the mean and variation of DDs for treatment times were calculated. Such calculations can be used as starting points and reference data if phenological prediction models are to be developed for these pest species in the future. More research is needed for developing country-specific prediction models as suggested by the non-correspondence of German DDs for emergence of pea moths and treatment times in the Finnish pea fields. The two geographical populations are likely to respond differently to weather conditions in the spring.

We produced new information on the temporal occurrence of the largest pesticide loads for the three crops. Now that the times and places for spraying PPPs in the crops are known, the environmental risks of pesticides can be studied in more detail. The results would enable more precise timing for taking residue samples, and based on the new information, allow refinements to be made for risk management
of PPPs. The current results also serve as a starting point when monitoring changes in the use of pesticides on these crops in the future.

**Declarations**

**Acknowledgements**

We thank Apetit Ruoka Ltd. for the excellent data and good cooperation. The company gave confidential rights to the Natural Resources Institute Finland (Luke) to use its data (agreement 2703/12 01 01 06/2019 between Luke and Apetit Ruoka Ltd.) for the current and previous study. We are grateful for the financial support (42660) of Maa- ja Vesitekniikan Tuki ry. for this study. We owe a dept of gratitude to our good colleague Dr. Asko Hannukkala who kindly helped us with the data and supervised the work. This publication is published posthumously for him. We would also like to thank the following researchers at Natural Resources Institute Finland (Luke): Mr. Pentti Ruutunen, Dr. Anne Nissinen, Dr. Erja Huusela-Veistola and Mr. Lauri Jauhiainen for sharing their expertise on the pests and their control and prediction models. We also thank Docent Jonathan Robinson for language revision.

**References**


22. Овчаренко ФВ, Николаева ЗВ (2020) Особенности развития морковной мухи в условиях Тверской области. Вестник Алтайского государственного аграрного университета, 1:31-37.


Figures
Figure 1

**a, b, c** Fungicide, herbicide and insecticide spraying frequency of the total (% on left) and the number of sprayings per field (mean with 95% confidence limits, on right) in different weeks after sowing for carrots (8334 pesticide sprayings in 5732 fields), swede (1169 pesticide sprayings in 982 fields) and fresh pea (5206 pesticide sprayings in 2476 fields) for 2009–2019, as reported by farmers in the database. Week 0 indicates pre-sowing pesticide application.
Figure 2

The number of insecticide applications (mean with 95% confidence limits), as reported by farmers in the database, targeted at key insect pests of carrot (2407 sprayings in 2014 fields), swede (648 sprayings in 585 fields) and fresh pea (700 sprayings in 695 fields) over 2009–2019
Figure 3

**a, b, c** Insecticide spraying frequency of the total (% on the left) and number of sprayings per field (mean with 95% confidence limits, on the right) against the key pests of fresh peas, and DDs (T$_{\text{sum}}$ above +5°C) for the control time in different weeks after sowing carrot (2407 sprayings in 2014 fields), swede (648 sprayings in 585 fields) and fresh pea (700 sprayings in 695 fields) over 2009–2019, as reported by farmers in the database. Week 0 means that pesticide was used before sowing. The highest bars are faded due to overlap with the DD curves.