IPM Decisions

D4.14 - DSS evaluated for economic and environmental benefits: aphids and vegetable pests

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1 Table of Contents

2 Public Summary

We present a model-based approach for assessing the value of decision support systems (DSS) that target insect pests. Compared to spraying insecticide based on a calendar date, DSS could save thousands of euros per hectare.

3 Executive Summary

The cost effectiveness of applying insecticides to insect pests is highly variable between years and locations. In a low pest pressure year, the use of a pesticide may be an unnecessary cost, whereas in a high pest pressure year it may save thousands of euros per hectare if it manages to save an otherwise destroyed crop. Decision support systems offer a means to pragmatically inform when it is likely to be beneficial to apply pesticides.

Ideally the value of a DSS should be established from field trials run across various sites and seasons. Typically, however, this is prohibitively expensive. If the DSS has been field tested, then this is usually only for the area in which the DSS was developed. How then do users know the value of a DSS in areas with different insect pest pressures?

In this deliverable we aimed to quantify the value of DSS targeted at insect pests. To do so we developed models to estimate the effect of a spray at a given time on the damage done to the crop, and then compared the marketable crop yield when insecticides were applied according to a phenology-based rule, or purely based on a calendar date. The models were derived from basic principles and parameterized for two types of root fly and one cutworm using data from the literature. Data collected from pheromone traps allowed us to estimate the potential value of such a DSS in areas where field trials had not been carried out.

For the two root flies and the cutworm considered, the DSS performed considerably better than a calendar-based spray program, although decision support for cabbage root fly saved less than the cost of a single insecticide spray.

The method presented does not currently incorporate the accuracy of either the DSS or of weather variables, and this would be an interesting avenue for future research.

4 Introduction

This deliverable focuses on exploring analytical methods to assess the value of decision support systems (DSS) for the chemical control of insect pests. We focus on DSS that use mathematical models to identify optimal times at which to apply pesticide to a problematic insect pest, thereby improving control of the pest and protecting the yield and/or quality of a crop. The value of such a DSS can be economic, via a reduction in the amount of yield lost, or environmental, should it allow a reduction in the number of pesticide applications without incurring significant yield loss or crop damage.

There are numerous decision support systems that address insect pests. Most use one or more weather variables (predominately air temperature, soil temperature, humidity and/or precipitation) to predict the phenology of an insect pest, as insects develop fastest in optimal weather conditions (Rebaudo and Rabhi, 2018). These DSS aim to predict the proportion of the insect population in different life stages, and so predict when the optimal time to apply pesticides would be. Some DSS (for example Howard and Dixon, 1990) also include a damage threshold and will only recommend spraying if the insect density is predicted to be high enough that it could compromise yield.

Ideally the value of a DSS would be assessed with field trials specifically testing the difference between using a DSS prescribed programme compared with a standard application program. In practice such experiments are rarely carried out and so alternative methods are needed to estimate the value using the limited data that is available.

In this deliverable we focus on DSS addressing pesticide applications to control three groups of pests as set out in the project proposal, namely root flies (specifically carrot fly and cabbage fly), cutworm (which are pests of cruciferous vegetable crops) and aphids (which can cause damage through both direct feeding as well as the transmission of viruses, and we focus on the rose grain aphid and the bird cherry-oat aphid to represent each form of damage).

To estimate the value, we use data gathered in Deliverable 4.4, which gives counts of adult flying insects in pheromone traps (for root flies and cutworm) or suction traps (for aphids). We assume this data gives an indication of the densities in the field. This data is then used to simulate the development of insect populations, with and without a control spray of insecticide applied. By varying the time of control, we can estimate the value of spraying following the phenology of the pest as opposed to by a calendar spray. In addition, we use Monte-Carlo simulations to estimate the expected value over multiple sites and locations, allowing us to quantify uncertainty in the estimated value.

In the following sections we first provide an overview of each of the insect pests, and relevant decision support systems for each. In section 5 we provide a summary of the data provided in Deliverable 4.4. Section 6 outlines the methodology behind the analysis, including a description of the models we use to calculate the effect of an insecticide spray, and how we use Monte-Carlo simulations to explore variability. Section 6 also includes the parameterisation of a theoretical model for each insect. Section 7 presents the distribution of the value of the DSS for each of the insect pests.

4.1 Insect groups evaluated

The project proposal highlighted two insect groups to focus on, root flies and cutworm, and aphids. The following section provides a brief introduction to each.

4.1.1 Root flies and cutworm

Root flies and cutworm are holometabolous, meaning that (unlike aphids) they have a complete life cycle, typically surviving overwinter as pupae, before emerging in the spring as adults, laying eggs, and maturing into larvae. Root flies and cutworm do damage to various root crops including cruciferous vegetable crops. Adults lay eggs near desirable root plants, and some or all the larva life cycle occurs underground feeding on the roots. In above ground crops a reduction in root mass can lead to wilting and mortality, and in root crops damage decreases the mass of plants but blemishes also reduce the quality of the final product.

4.1.1.1 Carrot fly

Carrot root fly, *Psila rosae*, is an insect pest of carrot, but can also invade roots of parsnip, parsley, and celery, resulting in reduced root mass, and a reduction in quality decreasing the marketable yield.

Adults start flying in spring, before migrating into crops and laying eggs. The larvae hatch after approximately one week, and feed on the plant roots. Larvae pupate in the soil. There are usually two generations per year, but a third generation only occasionally occurs.

Seed treatments are available on carrot, but additional pyrethroid sprays are only effective on adults not larvae. The larvae feed below the soil and so can't be targeted, and so foliar sprays to decrease the larval load of the second generation are applied to the adults at the start of the second generation (Finch, 1993).

4.1.1.2 Cabbage root fly

Cabbage root fly, *Delia radicum*, is the main insect pest of brassica crops in north-western Europe (Mesmin *et al.*, 2019) but is a problem throughout Europe, the US, and parts of Asia.

Adults emerge in suitable conditions between April and early June. After a few days, the adults produce eggs that hatch after approximately a week, and the larvae feed on lateral roots and the main tap root before tunnelling up into the main stem, causing wilting in above-ground organs and root mass loss. After 3–4 weeks the larvae pupate in the soil. There can be several overlapping generations throughout the summer before diapause in autumn.

4.1.1.3 Cutworm

Cutworm are moth larvae, predominately of the turnip moth, *Agrotis segetum*. The larvae of these moths feed on several vegetable crops, including carrot, potato, lettuce, and sugar beet.

Adults fly between early June and late July in the UK. Eggs hatch in between 1 and 4 weeks, and caterpillars feed first on the above-ground foliage, before migrating underground. After two months the larvae pupate, occasionally producing a second generation in the autumn.

Insecticides are typically targeted at the caterpillars while above-ground before the larvae mature and move underground.

4.1.2 Aphids

Aphids are a diverse group of insects, causing both direct feeding damage to a range of crops, as well as being vectors of important viruses. For this deliverable we chose two aphids as examples of each damage type. The rose-grain aphid causes yield loss predominately from direct feeding damage, while the bird cherry-oat aphid is one of the main vectors of barley yellow dwarf virus.

4.2 Decision support systems

This section summarizes decision support systems in Europe for the two insect groups in this deliverable.

As mentioned above, the rate at which the insects progress through each stage is determined to a large extent by the temperature of their environment; too hot or too cold, and the rate of insect development slows down. Several of the DSS described below use weather-based phenology models to predict the time at which insects move between different life stages, while others use regression models to establish the same. None of those found suggested reductions in the dose applied, but some DSS suggested when to check traps, only spraying if the number of trapped insects was above a certain threshold.

4.2.1 Root flies and cutworm

4.2.1.1 Cabbage root fly

Collier, Finch & Phelps (1991) developed a DSS that predicted the development of cabbage root fly. The model aims to understand when the second generation of adults start to lay their eggs so that insecticide could be appropriately targeted. The model integrates temperature-dependent development rates for each insect life stage to predict the proportion of the insect population in each life stage. The model predicts the time at which a certain percentile of the population was in a particular life stage to within a week of observed values Phelps et al (1993).

4.2.1.2 Carrot fly

Phelps et al (1993) developed a decision support system for carrot fly. As with cabbage root fly, the model uses air- and soil-temperatures to describe the rate of development of different life stages and predicts the timings at which different percentiles of the population are in different life stages. These predictions are intended to inform better spray timings.

4.2.2 Cutworm

Four DSS were found relating to cutworm in Europe.

The earliest, described in Mikkelsen & Esbjerg (1981), uses a linear regression with combinations of temperature and rainfall to forecast the attack risk in Denmark in a given year. The model was able to account for 64% of the variation in cutworm attack over the many years of data examined, but was intended to give growers no more than an indication of whether cutworm was likely to be a problem or not, rather than a time to apply pesticides.

Almost concurrently a model was produced in the UK, described in Bowden et al., (1983), that predicts the time at which larvae would move from above-ground feeding to below-ground feeding. The model predicts this time point based on temperature-dependent development curves for eggs and above-ground larvae since the first moth is caught in a light trap. It includes precipitation-based mortality projections to indicate the severity of attack. Using these two measures, the model provides warnings that a spray is needed just before the larvae migrate underground and became unreachable by foliar-applied pesticide sprays.

Since these two papers a substantial amount of work has been done to investigate the phenology of cutworm, updating the previous models with improved phenology relationships (e.g. Esbjerg & Sigsgaard (2019)), and incorporating them into software (Nilars and Esbjerg, 1998).

An additional DSS was published in 2020, also using development rates, that aimed to determine the time at which to apply chemical control against cutworm on sugar beet in Poland (Jakubowska *et al.*, 2020). They found that the optimal spray time was just at the beginning of the third larval instar stage, particularly when sugar beet plants were in the 31–35 BBCH stage. However, they found little correlation between moth and caterpillar densities, making treatment decisions based on damage thresholds difficult.

4.2.3 Aphids

There are many DSS that target various aphid species (see Table 17.1 in van Emden & Harrington (2007) for a recent compilation). Most decision support systems for aphids use phenology models in conjunction with trapping networks, predominately to predict when the first aphids may be entering the crop.

4.3 Aim of deliverable

In this deliverable we aim to evaluate the value of DSS for each of the above insect groups. For each insect, the DSS provides information on the timing of insect phenology, allowing sprays to be targeted at a developing target life history stage. We then demonstrated how one might estimate the value of using such a DSS compared to spraying according to the optimum calendar date,

To do so, we developed several life-history models that enable us to calculate the effect of an insecticide application on different insect stages. Additionally, we define relationships between the density of different stages and ultimately the marketable yield of a crop. We then use these two relationships to estimate the marketable yield when applying insecticide using a phenology-based spray time versus a calendar spray time. Using data from Deliverable 4.4 we then estimate the expected value of the DSS across multiple sites and years.

5 Data

Data provided from project partners to Deliverable 4.4 was used to help estimate the value of DSS in this Deliverable. Two sources of data were available.

5.1 Danish pheromone traps

Firstly, data from Denmark show the numbers of adults of cabbage root fly, carrot fly, and cutworm in pheromone traps (Figure 1).

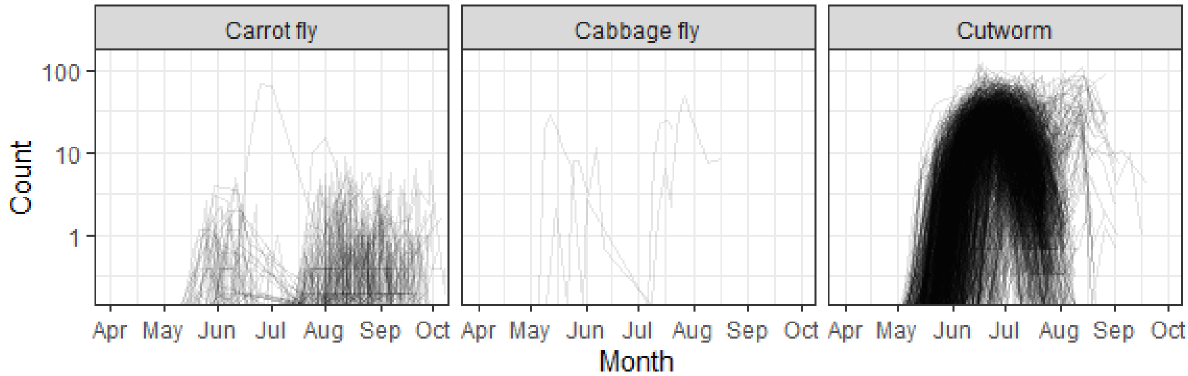

Figure 1. The number of adult carrot fly, cabbage fly, and cutworm (on a log scale) caught in pheromone traps in Denmark.

5.2 UK suction trap network

Suction trap data was provided from the UK suction trap network (Macaulay, Tatchell and Taylor, 1988) spanning from 2010 to 2019 (Figure 2). The UK suction trap network provides weekly numbers of insects sucked into 12.2m suction traps at 12 locations around the United Kingdom. Aphids are then classified and form the basis of several forecasting tools disseminated in the UK.

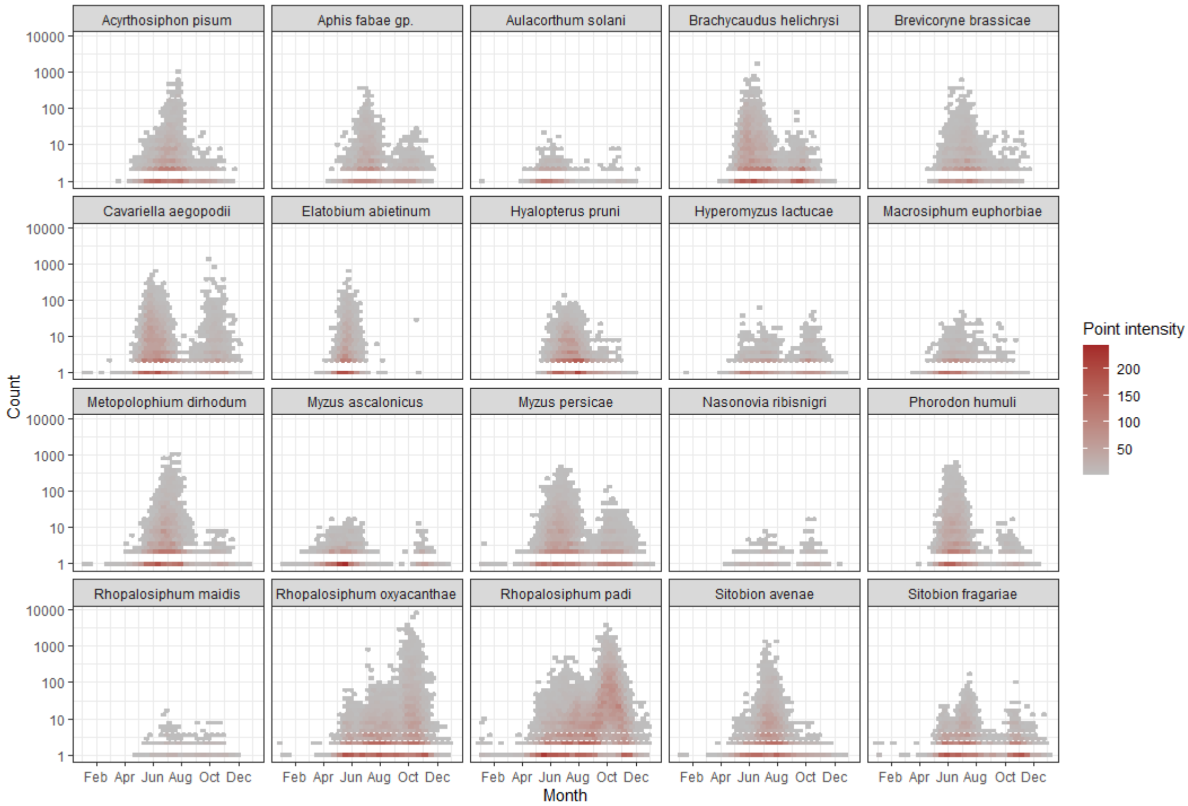

Figure 2. Rothamsted insect suction trap data from 12 sites around the UK between 2010 and 2019. The number of insects trapped on different days are displayed on a log scale. The intensity of each point indicates the number of records at that count level on that date, with grey being very few records, and red indicating a higher intensity of records.

6 Methods

The value of a DSS is the difference between the cost of not following a DSS (C_S) and the cost of following one (C_{DSS}). Across multiple sites and seasons, the expected value (V) is therefore

$$E(V) = E(C_S - C_{DSS})$$

The cost of insecticide application program includes the cost of the insecticide, the cost of applying that insecticide, and the price of any yield or loss in quality due to pest damage. The expected value can be increased by applying less insecticide – reducing the cost of inputs – or decreasing yield loss by applying more insecticide if appropriate, or by optimising the timing of existing insecticide sprays.

The cost of an insect infestation at a single site in a single season is:

$$C = n(I + A) + PL(n, x)$$

where n is the number of sprays, I is the price of the quantity of insecticide applied, A is the cost of applying the insecticide to the crop, P is the price of a unit of yield, and $L(n, x)$ is the amount of yield lost with the spray programme comprising n sprays and insect pressure x.

To estimate the value of DSS in the absence of data from direct field trials, we need to estimate the crop damage caused by following a standard application program vs applying insecticide in accordance with a DSS.

We therefore need to establish two relationships:

1) How applying an insecticide at a given time affects the damage-causing life-stage of the insect pest
2) The degree to which the abundance of the damage-causing life-stage of the insect pest affects the marketable yield of the crop

With these two relationships, an estimate of the price of an insecticide spray, and the price of the crop yield, we can estimate the value of a spray at a specific timing, and therefore of a DSS.

In the following section we describe models that relate an application of an insecticide to some metric of insect density. The metric used depends on the pest and crop in question.

6.1 Models

In this section we describe a model that enables us to relate the timing of an insecticide application with the density of different life stages of root flies and cutworm.

Most DSS described in Section 4.2 aim to predict when the insects are in each stage of their life cycle, so that insecticide applications can be accurately timed. In measuring the effect of a DSS, we therefore need to be able to predict the control achieved when an insecticide is sprayed at different times.

To do so we use a system of delay-differential equations (DDE), with varying rates of insect development, which can describe the time-course of an insect population through its life cycle. Equations 1 describe the rate of change of adults, eggs, larvae, pupae, and the effective dose of insecticide.

$$\begin{aligned} A'(t) &= A_0 f(t) - A_0 f(t-\Delta_A)P(t) - A(t)\, m(D) \\ E'(t) &= \theta A(t) - \theta A(t-\Delta_E) \\ L'(t) &= \theta A(t-\Delta_E) - \theta A(t-\Delta_E-\Delta_L) \\ P'(t) &= \theta A(t-\Delta_E-\Delta_L-\Delta_P) \\ D'(t) &= -\omega D(t) \end{aligned} \qquad Eqns\ 1$$

Adults, $A(t)$, emerge at rate $f(t)$ from an overwintering population with abundance A_0. A time later, specified by the lifespan of the adult life stage, Δ_A, the adults die. During their life adults lay eggs, $E(t)$, at rate θ, which mature into larvae after Δ_E time units. Larvae, $L(t)$, mature into pupae after a further Δ_L time units, and finally pupae, $P(t)$, leave that stage after Δ_P time units.

An application of insecticide is included in the model. We assume a given dose, D_0 of insecticide is added at time t^* which, in this example, affects only the adult life stage of this insect population (some insecticides for cutworms affect the larval stage, and so the equations are slightly different). The variable $m(D)$ specifies the mortality rate of the adults at dose D which, for analytical simplicity we have assumed follows $m(D) = 1 - e^{-\kappa D}$, so that initially the mortality rate increases rapidly, but reaches an asymptote at high doses. This is not a frequently used insecticide dose-mortality curve but is not dissimilar in shape to the log-logit curves used more commonly in other models in the literature and has the advantage of being analytically tractable. As some adults die during their lifespan the rate at which the adults die at the end of their stage time period must be adjusted to account for those that died from insecticide. To do so we must include $P(t)$, the proportion of that stage "born" at time $t - \Delta$ that survive to time t:

$$P(t) = e^{-\left(\frac{A}{\omega}\left(\mathrm{Ei}\left(-D_0 e^{-\omega(t-t^*)}\right) - \mathrm{Ei}\left(-D_0 e^{-\omega(t-t^*-\Delta)}\right)\right) - \Delta\right)} \qquad Eqn\ 2$$

where Ei is the exponential integral.

The model was programmed in R and simulated with the ODE package. An example simulation is shown in Figure 3.

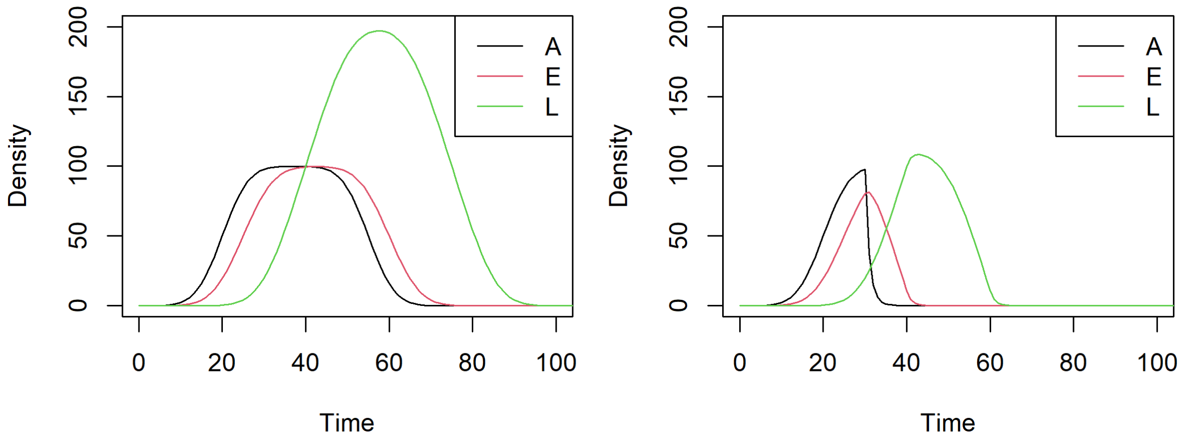

Figure 3. Example simulation of a DDE describing the density of egg (E), larvae (L) and adult (A), phases without (left) and with control (right). Parameters here are: $\theta = 0.1$, $P_0 = 100$, $\omega = 20$, $\sigma = 5$, $\Delta_A = 35$, $\Delta_E = 10$, $\Delta_L = 20$, $D_0 = 1$, $\kappa = 4$, $\omega = 0.2$.

6.2 Monte-Carlo simulation

By combining insect population dynamics with a spray program, each of the models above allow us to estimate $L(n, x)$, the amount of yield lost when n insecticide sprays are applied in a crop with insect pressure x.

To calculate the expected value across multiple sites and seasons, we need to consider the variability in each season, and then calculate the amount of yield lost when applying insecticide following a DSS or following a standard spray program.

To do so we characterised distributions of the rate at which insects increase in time, together with the difference in abundance between different sites and years (see Parameterisation section below); in some years insects develop faster than expected, and in others slower.

We then used Monte-Carlo simulations to simulate the value of a DSS over multiple sites and years. Assuming an accurate DSS, an insecticide spray will be applied as the DSS suggests, whereas a standard spray program will apply an insecticide at the same calendar time each year.

6.3 Parameterisation of case studies

In this section we illustrate our approach by detailing the models used for carrot fly, cabbage root fly and cutworm, together with their parameterisation. Data from suction traps have been shown to have little relation to in field densities. Additionally, the in-field densities are difficult to model since the reasoning for a decline in abundance mid-summer is unexplained. For this reason, we did not try and model aphid abundances. For carrot fly, cabbage root fly and cutworm we only had data on the adult densities in traps, but we needed to model the effect of the insect larval stage on crop yield. Therefore, we parameterised the models from literature. Where literature is lacking, we have made assumptions using relationships from similar insects. This approach can be used for other insect pests.

6.4 Root flies and cutworm

6.4.1.1 Carrot fly on carrot

Foliar insecticide sprays against carrot fly are, by necessity, timed to kill carrot fly adults, since the damage-causing larvae are underground and therefore untargetable. The model used to calculate the density of larvae after an application of insecticide is that described in Equations 1, excluding the pupae. We use this system to model solely the second generation of the life stage.

The length of each life cycle stage depends to a large degree on the weather. For the purposes of this study, however, we assume a constant development rate between each study, and so took longevity at 15 degrees of 10 days, 40 days, 30 days and 35 days for the eggs, larvae, pupae and adults respectively (Collier and Finch, 1996).

The emergence rate of second-generation adults from pupae was modelled according to a normal distribution over time, so that $f(t) = \frac{1}{2\pi} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2}$, where μ is the time of maximum emergence and σ^2 describes the variance in emergence time for a single site. The resulting adult density was simulated using the system of equations (Eqns 1), and was fitted to the data from pheromone traps, for each location in each year, giving estimates of the mean σ and variance, ω, of adult emergence, as well as the initial abundance of adults A_0. Fits were performed by the fitdistrplus package in R. The fits were manually curated, and the mean time of emergence was fitted to a normal distribution, while the standard deviation of emergence and abundance were fit to a beta prime distribution (Figure 4).

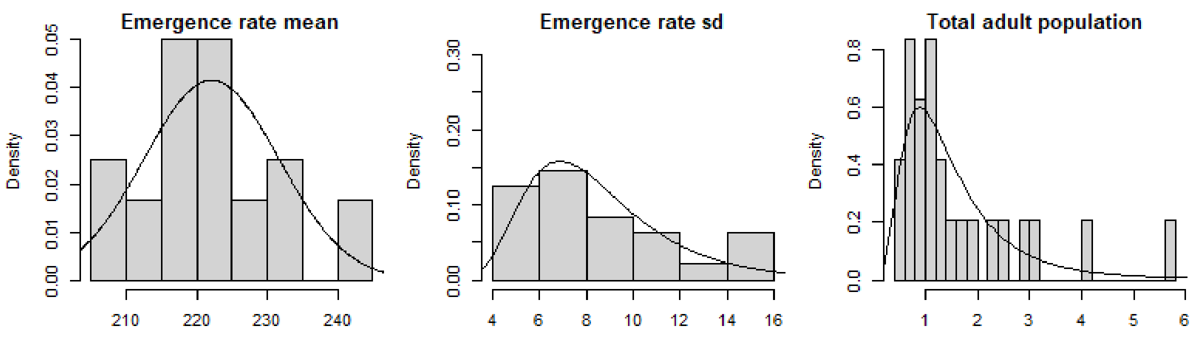

Figure 4. Distribution of fitted emergence parameters (left, the mean in JD, and centre the standard deviation), and the abundance of adults (right). Lines show the fitted distributions.

Using the model above, we estimate the density of carrot fly larvae over time. To link the number of carrot fly larvae to damage, we assume that the number of mines per hundred carrots increases linearly with the area under the larval curve, implying that each day each larva present is directly related to the ultimate number of mines (Wheatley and Freeman, 1982). We then used a linear log-log relationship to relate the number of mines to the percentage of undamaged carrots (Wheatley and Freeman, 1982), and used data from Johansen (1999) to relate the percentage of damaged roots to marketable yield (Figure 5).

Taking the undamaged yields to have a marketable yield of 30 t/ha, we therefore have $Y = Y_0\,(1 - \theta)$, where Y_0 is the amount of untreated yield, and θ is the proportion of damaged roots, $\mathrm{logit}(\theta) = a + b \log \int L\,dt$, with $a = 10$, and $b = -25$.

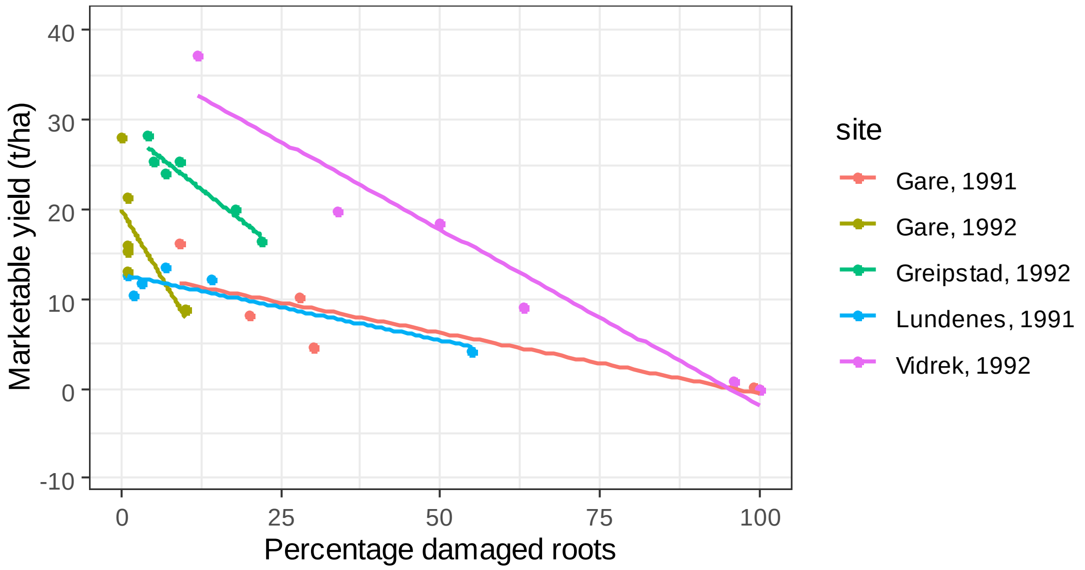

Figure 5. A relationship between the percentage of damaged roots in five distinct site-years.

The efficacy of an insecticide foliar spray was set so that 80% mortality was achieved with a single application.

We assumed a carrot wholesale price of between €350–€500/t (Department for Environment, 2021), and an application cost of €15/ha, and an insecticide cost of €40/ha.

6.4.1.2 *Cabbage root fly on cauliflower*

The larvae of cabbage root fly cause damage by eating the roots of crops, where they are not able to be killed by foliar-applied insecticides. Foliar sprays may be applied to the second generation of adults, before they start to lay eggs, reducing the subsequent density of larvae in the crops. As for carrot fly, we use the system of equations (Eqns 1) without the pupal stage.

As for carrot fly, the longevity of each life cycle stage was taken at 15 degrees, being 6 days, 33 days, 25 days, and 25 days for eggs, larvae, pupae, and adults respectively (Söndgerath and Müller-Pietralla, 1996). An egg production rate of $\theta = 0.1$ was assumed.

There was very little information in the variability in adult densities in the dataset provided, however, Finch (1993) stated that there can be as much as a four week change in the time of oviposition of the second generation, depending on whether it is a warm or cool year. Therefore we assume that in 95% of the simulations, adults emerge within 14 days of the emergence rate mean, so that $\sigma = 7$; the average time point of the emergence rate mean is not important, so we set this as $\mu = 200$. We did not have data on how much the emergence standard deviation varies, and so we set this as a constant value, the average value of the carrot fly data, 10 days. We also had no data on the abundance, and so use the same distribution as for the carrot fly.

We were unable to find data that allowed us to relate the amount of larvae of *Delia radicum* on crops to the marketable yield, but we found data on the amount of damage done on cauliflower (Table 1 of Hellqvist, (1996)), who tested different treatments on the damage done by two *Delia* spp., including *Delia radicum* in field experiments in Sweden. They reported the marketable yield as a function of the root damage index. We could not back transform this directly into percentage damage roots but used this information to inform a yield-damage relationship in which cauliflower can better tolerate small amounts of damage. $Y = Y_0(1 - e^{\kappa\,(\theta-1)})$, with $Y_0 = 22\text{t/ha}$ and $\theta = 5$ (Figure 6).

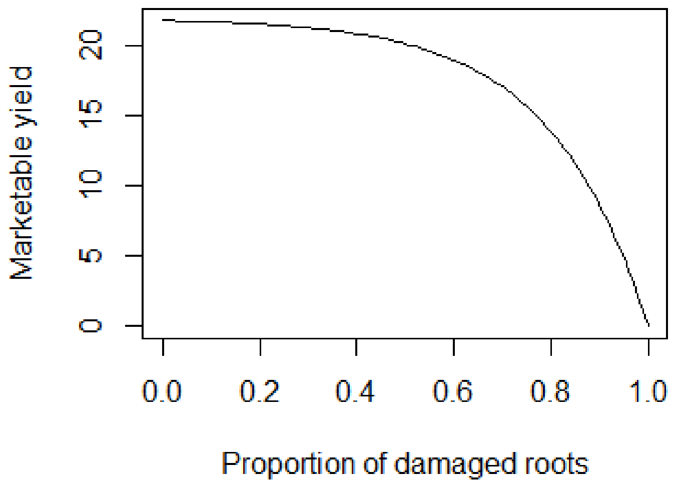

Figure 6. The assumed relationship between proportion of damaged roots and marketable yield (t/ha).In our calculations we assume cauliflower has a wholesale price of between €0.6–€1.2/head (Department for Environment, 2021), with a head typically weighing 0.5 kg, which results in €1600/t. We assume an application cost of €15/ha, and an insecticide cost of €40/ha.

6.4.1.3 Cutworm on carrot

Insecticide sprays against cutworm are typically targeted at the first two *larval* instars, when the caterpillars are above ground feeding on foliage. Once the third instar develops the larvae move belowground and start feeding on the roots of the crops.

The original system of equations (Eqns 1) is therefore modified to include two groups of larvae, those above ground, L_1, and those below ground, L_2. As for cabbage fly and carrot fly, an application of insecticide is applied at a time t^*, which kills the first larval group. The mortality rate, and $P(t)$ are therefore incorporated into the following system of equation:

$$
\begin{aligned}
A'(t) &= A_0 f(t) - A_0 f(t-\Delta_A)P(t) \\
E'(t) &= \theta A(t) - \theta A(t-\Delta_E) \\
L_1'(t) &= \theta A(t-\Delta_E) - \theta A(t-\Delta_E-\Delta_L)P(t) - m(D)L_1 \\
L'_2(t) &= \theta A\left(t-\Delta_E-\Delta_{L_1}\right)P(t) - \theta A\left(t-\Delta_E-\Delta_{L_1}-\Delta_{L_2}\right)P(t) \\
D'(t) &= -\omega D
\end{aligned}
\qquad Eqns\ 3.
$$

Life cycle parameters were extracted from the literature at 15 degrees, with 7 days, 40 days, and 14 days, for the eggs, larvae, and adults respectively (BOWDEN *et al.*, 1983). The egg production rate was assumed to be 0.1 eggs per adult per day.

The distribution of the adult emergence function parameters, and the abundance was calculated from the data provided by Deliverable 4.4 (Figure 7). As for carrot fly, μ the average time of the peak emergence was fit by a normal distribution, while the standard deviation of the emergence function, together with the abundance, were fit by a beta prime distribution.

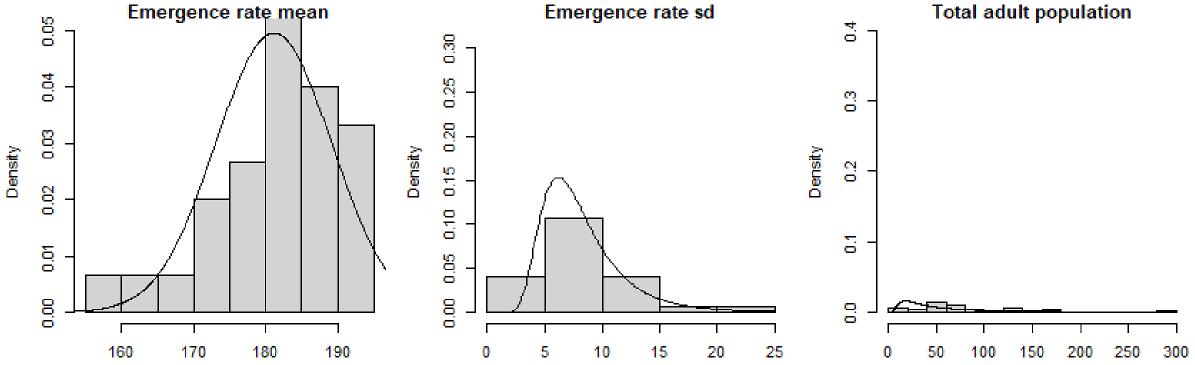

Figure 7. Distribution of the parameters of the cutworm emergence rate mean (left) and standard deviation (standard deviation), as well as the total adult population (right).

The effect of cutworm larvae on the yield of carrots was extracted from Zethner (1980), which contained data on larval density and the percentage marketable yield of carrots (Figure 8). We therefore calculate the marketable yield of carrot using $Y = Y_0 e^{-\alpha L}$, with $Y_0 = 15$, and $\alpha = 0.1$.

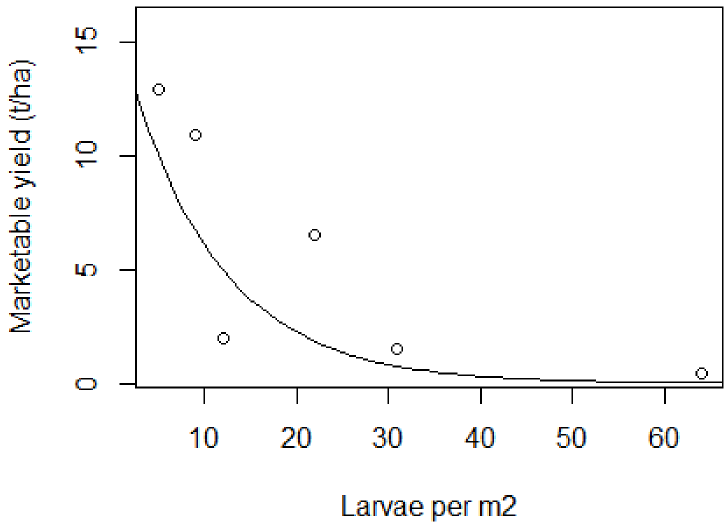

Figure 8. The marketable yield (kg/ha) of carrot is reduced as the density of cutworm larvae increases. Data from Zethner (1980). Line is the fitted curve based on $Y = Y_0 e^{-\alpha L}$.

7 Results

The value of applying insecticide following a DSS compared to a calendar date is shown in Figure 9 for each of the insect/crop combinations we simulated. In the vast majority of simulations, using the DSS resulted in more accurate sprays, and so better pest protection that using a calendar spray. The expected value, $E(V)$ for each species was 1617, 18, and 600 €/ha for carrot fly, cabbage root fly, and cutworm respectively.

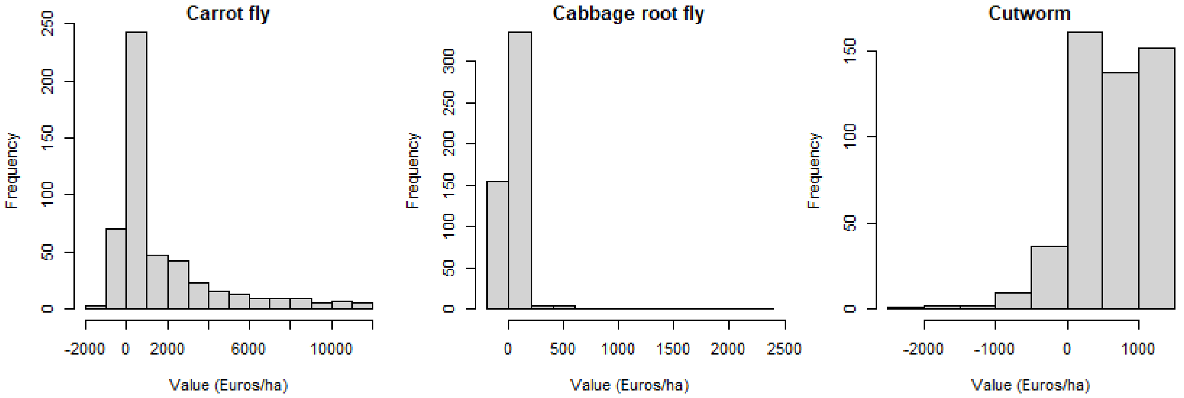

Figure 9. A bar plot showing the distribution of the value of a DSS from 500 simulations for each of the root fly and cutworm species considered. The value was the income when the time of insecticide was applied according to a DSS compared with spraying at a calendar date.

8 Conclusion

Knowledge of the value of decision support systems (DSS) allows growers to select the most appropriate DSS for their situation and also demonstrates the cost-effectiveness of using such tools, potentially increasing their uptake (Gent, De Wolf and Pethybridge, 2011). In this deliverable we have developed a model-based method that uses readily available data from pheromone and suction traps to estimate the value of a DSS aimed at controlling insect pests. While we have not tested a specific DSS in this deliverable, we have demonstrated that data from such sources could be used to evaluate the value of DSS.

We show here that knowledge of insect phenology can enable better control, and quantify the potential value saved for each insect. For root flies and cutworm, the damage-causing larvae are untargetable, and so DSS are especially important.

For aphids, due to the difficulty in modelling within-season densities in the field, we were not able to calculate value, and these DSS would need to be tested in the field.

The method presented has several limitations which should be addressed in future research. Firstly, the method does not account for either the inaccuracy in the DSS, or inaccuracy in weather measurements, both of which would reduce the value of the DSS. Additionally, the susceptibility of the crop to insect damage depends to a great extent on the crop growth stage, which is not incorporated.

9 References

Bowden, J. *et al.* (1983) 'A survey of cutworm attacks in England and Wales, and a descriptive population model for Agrotis segetum (Lepidoptera: Noctuidae)', *Annals of Applied Biology*, 102(1), pp. 29–47. doi: 10.1111/j.1744-7348.1983.tb02663.x

Collier, R. H. and Finch, S. (1996) 'Field and laboratory studies on the effects of temperature on the development of the carrot fly (Psila rosae F.)', *Annals of Applied Biology*, 128(1), pp. 1–11. doi: 10.1111/j.1744-7348.1996.tb07084.x.

Collier, R. H., Finch, S. and Phelps, K. (1991) 'A simulation model for forecasting the timing of attacks of Delia radicum on cruciferous crops', *EPPO Bulletin*, 21(3), pp. 419–424. doi: 10.1111/j.1365-2338.1991.tb01271.x.

Department for Environment, F. & R. A. (2021) *Wholesale fruit and vegetable prices - GOV.UK*. Available at: https://www.gov.uk/government/statistical-data-sets/wholesale-fruit-and-vegetable-prices-weekly-average (Accessed: 22 August 2021).

Van Emden, H. F. and Harrington, R. (2007) *Aphids as crop pests*. Cabi.

Esbjerg, P. and Sigsgaard, L. (2019) 'Temperature dependent growth and mortality of Agrotis segetum', *Insects*, 10(1). doi: 10.3390/insects10010007.

Finch, S. (1993) 'Integrated pest management of the cabbage root fly and the carrot fly', *Crop Protection*, 12(6), pp. 423–430. doi: 10.1016/0261-2194(93)90003-2.

Gent, D. H., De Wolf, E. and Pethybridge, S. J. (2011) 'Perceptions of risk, risk aversion, and barriers to adoption of decision support systems and integrated pest management: An introduction', *Phytopathology*, 101(6), pp. 640–643. doi: 10.1094/PHYTO-04-10-0124.

Hellqvist, S. (1996) 'Mulching with grass-clippings in cauliflower: Effects on yield and brassica root flies (delia spp.)', *International Journal of Pest Management*, 42(1), pp. 39–46. doi: 10.1080/09670879609371967.

Howard, M. T. and Dixon, A. F. G. (1990) 'Forecasting of peak population density of the rose grain aphid Metopolophium dirhodum on wheat', *Annals of Applied Biology*, 117(1), pp. 9–19. doi: 10.1111/j.1744-7348.1990.tb04190.x.

Jakubowska, M. *et al.* (2020) 'Decision Support System to Improve the Effectiveness of Chemical Control Against Cutworms in Sugar Beet', *Sugar Tech*, 22(5), pp. 911–922. doi: 10.1007/s12355-020-00808-z.

Johansen, T. J. (1999) 'Monitoring and control of the carrot fly (Psila rosae fabr.) in northern Norway', *Acta Agriculturae Scandinavica Section B: Soil and Plant Science*, 49(3), pp. 158–166. doi: 10.1080/09064719909362512.

Knight, J. D. and Cammell, M. E. (1994) 'A decision support system for forecasting infestations of the black bean aphid, Aphis fabae Scop., on spring-sown field beans, Vicia faba', *Computers and Electronics in Agriculture*, 10(3), pp. 269–279. doi: 10.1016/0168-1699(94)90046-9.

Macaulay, E. D. M., Tatchell, G. M. and Taylor, L. R. (1988) 'The Rothamsted Insect Survey "12-metre" suction trap', *Bulletin of Entomological Research*, 78(1), pp. 121–128. doi: 10.1017/S0007485300016126.

Mesmin, X. *et al.* (2019) ‘Assessing the relationship between pest density and plant damage: a case study with the belowground herbivore Delia radicum (Diptera: Anthomyiidae) on broccoli’, *Applied Entomology and Zoology*, 54(2), pp. 155–165. doi: 10.1007/s13355-019-00607-3.

Mikkelsen, S. and Esbjerg, P. (1981) ‘The influence of climatic factors on cutworm (Agrotis segetum) attack level, investigated by means of linear regression models’, *Dan. J. Plant Soil Sci.*, 85, pp. 291–301.

Nilars, M. S. and Esbjerg, P. (1998) ‘PC forecasting model for cutworm (Agrotis segetum) in organic farming, based on sex trap catches and data collected with HARDI METPOLE.’, *PC forecasting model for cutworm (Agrotis segetum) in organic farming, based on sex trap catches and data collected with HARDI METPOLE.*, (3), pp. 183–192.

Phelps, K. *et al.* (1993) ‘Monte Carlo simulation method for forecasting the timing of pest insect attacks’, *Crop Protection*, 12(5), pp. 335–342. doi: 10.1016/0261-2194(93)90075-T.

Rebaudo, F. and Rabhi, V. B. (2018) ‘Modeling temperature-dependent development rate and phenology in insects: review of major developments, challenges, and future directions’, *Entomologia Experimentalis et Applicata*, 166(8), pp. 607–617. doi: 10.1111/eea.12693.

Söndgerath, D. and Müller-Pietralla, W. (1996) ‘A model for the development of the cabbage root fly (Delia radicum L.) based on the extended Leslie model’, *Ecological Modelling*, 91(1–3), pp. 67–76. doi: 10.1016/0304-3800(95)00167-0.

Wheatley, G. A. and Freeman, G. H. (1982) ‘A method of using the proportions of undamaged carrots or parsnips to estimate the relative population densities of carrot fly (Psila rosae) larvae, and its practical applications’, *Annals of Applied Biology*, 100(2), pp. 229–244. doi: 10.1111/j.1744-7348.1982.tb01935.x.

Zethner, O. (1980) ‘Control of Agrotis segetum [Lep.: Noctuidae] root crops by granulosis virus’, *Entomophaga*, 25(1), pp. 27–35.