The development of a dynamic simulation model for the biology of the Apple Sawfly *(Hoplocampa testudinea)*, and the implementation as Decision Support System

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Abstract

Apple sawfly is a key pest in organic and low-input apple production systems in Europe. In many organic orchards an annual pesticide application is needed to keep the apple sawfly population at an economic level. With the decreasing availability of insecticides the apple sawfly is an upcoming problem in integrated apple production as well. Most control methods have a narrow window of application. Consultants spend much time on field observations to find the optimal application date for their clients. To substitute this work a dynamic simulation model for the biology of the apple sawfly was developed using published information and results from additional observations made between 2003 and 2015. The model is added to the RIMpro platform to make use of the existing simulation and communication infrastructure, and make it available to all fruit growers and consultants who have their weather stations connected to this platform.

Keywords: Apple sawfly**,** Decision Support System, RIMpro

Introduction

Apple sawfly is a key pest in organic apple production in Europe. After transition from IPM to organic management in most orchards in mid and northern Europe the apple sawfly population increases. After few years 50-80 % crop loss in un-managed situations is not uncommon. Many organic orchards have to be treated against apple sawfly every year to make economic production possible. The apple sawfly is univoltine. The larvae hibernate in the soil. The adult sawflies emerge just before bloom and lay eggs in freshly opened flowers. These eggs hatch after petal fall. The larvae eat galleries in the young fruits and migrate from one to the next fruit in the same cluster, destroying 3-4 fruits per larvae. One month after bloom the full-grown larvae descend to the soil were they prepare for diapause. *Lathrolestes ensator* is common parasitoid of the apple sawfly but the level of parasitation is insufficient to control the apple sawfly population at an economic level. (Zijp, 2002a, 2002b) Several botanical insecticides like nicotine, rotenone and quassia are highly effective to control apple sawfly at the moment of egg hatch. Spinosad is also effective. Quassia is the standard product for selective control of apple swafly in organic fruit production. Azadirachtin might have some effect on larvae migrating from the first to the second fruit. Alternative options to control apple sawfly by the application of insect-parasitic nematodes during egg hatch, or during the decent of the larva to the soil, have not yet been completely explored.

All these control methods have a very narrow window of application. Consultants have to make accurate field observations to help their clients to find the optimal application date, which even might be different for different apple varieties in the same orchard. Skilled consultants are however getting scarce, and it would be helpful if a decision support system could support or substitute these field observations. Details on the development and behaviour of the apple sawfly in relation to weather conditions have been published but until now this information has not been compiled into a practical decision support system that is easy to use and accessible for fruit growers and their advisers. The DSS for

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apple sawfly should accurately indicate the key moments for management and control of the apple sawfly: the moment white sticky traps should be placed in the orchard for monitoring, the start and duration of egg hatch, the period that larvae migrate form the first to the second fruit, and the period that the larvae decent to the soil.

Material and Methods

A dynamic simulation model for the biology of the apple sawfly is developed based on published information and results from additional field observations. The sub stages in the population model follow the successive biological stages: diapause termination, post-diapause development, flight activity, aging of adults, egg deposition, egg development, larval development, and the descent of full-grown larvae to the soil to for diapause.

From 2003 till 2015 organic fruitgrowers in The Netherlands and Belgium installed white sticky traps (Rebell Bianco, Andermatt Biocontroll Switzerland) in their orchards just before the start of bloom. They noted the daily apple sawfly catches, and the start date of flowering (BBCH 60) of their main apple varieties. These observations are used to validate published algorithms for post diapause development, and examine the effect of temperature on the flight activity of the apple sawfly.

In 2007 and 2009 the descent of full-grown larva from affected fruits to the soil was monitored. Shortly before the estimated start of descent approximately 150 affected fruits were picked and placed on chicken wire over a bucket filled with a thin layer of water. The bucked was kept in the shade in the orchard. Each day the number of full grown larva descended in the bucked was noted. To find the larval development time the time of decent was related to the temperature development form start of egg hatch.

The moment the larvae migrate form the first fruit to the second fruit is rather behaviour than a change in biological stage. During consultancy work between 2003 and 2015 occasionally observations were noted on the percentage of the larva that had migrated to the second fruit. In order to estimate the moment of this migration the results of these observations are related to the temperature development form start of egg hatch.

The weather data used to process all observations were taken form ‘on-farm’ weather stations in or near the orchards were the observations were made. (Types: ‘iMetos’ Pessl Instruments-Austria, ‘Davis vantage Pro2’ Davis Instruments-USA, ‘Mety’ Bodata-The Netherlands).

The simulation model is coded in Java EE and JSF2, and uses fractional single- and multidimensional boxcar trains to simulate the dispersion in the sub process. (De Wit, 1974; Rabbinge, 1989) The model is developed for the RIMpro platform to make use of the existing simulation and communication infrastructure. The system runs on a Glassfish application server. The simulation model is driven by local weather data and localized weather forecast to enable a 5 to 7 day prognosis of the development of the apple sawfly population.

Results and Discussion

<u>1- Diapause termination and post diapause development</u>

During diapause the larvae in the soil do not respond to higher temperatures. Mid March diapause is terminated and post diapause development rate is proportional to soil temperature over 4.5 °C. Models based on soil temperature can predict the start of the fight of the apple sawfly with a margin of a few days (Gottwald, 1982; Graf, 1996a, 1996b; Zijp & Blommers, 1997; Tamosiunas, 2013, 2014). However the ‘on-farm’ weather stations widely used for decision support systems are seldom equipped with soil temperature sensors. Zijp & Blommers (1997) developed a model to predict of the start of the flight of the apple sawfly based on air temperature. A temperature sum of 177 DD >4 °C calculated from March 15 proved to be almost as accurate as a model based on soil temperature. This algorithm was verified with the collected field data. From the 2003-2015 trap data the start of flight was determined for each region and year resulting in 42 observation points in 13 years. (Belgium-Flanders, The Netherlands–South, Mid and North). (Figure 1).

The date the first apple sawflies were trapped varied from April 5 (2014), till May 2 (2013) the average temperature sum from March 15 till the day of first catch was 181 DD >4 °C (STD=27, or 4.2 days). This is slightly higher than the 177 DD >4 °C found by Zijp & Blommers, but with a considerably higher standard deviation. In a few cases the start of the flight was predicted much to early. It can't be excluded that in these cases the temperature data used were not representative for the orchard. The results correspond to the observations in Lithuania were the average temperature sum between March 15 and start of flight was found to be 185 DD >4 °C (STD=30) (Tamosiunas, 2013), but differ form observations in Sweden were first apple sawflies were already captured 169 DD >4 °C (STD=20) after March 15 (Sjöberg, 2015). These early observations in Sweden are in contrast to the findings of Graf (1996) who found that the thermal constant increased for apple sawfly populations towards northern Europe.

For the construction of the simulation model not only the first catch, but also the average duration of the post-diapause development is needed. To find the end of the emergence period the average lifespan of a female sawfly, 85.5 DD > 6 °C (Graf, 2001), was counted backwards from the day the last apple sawfly was captured for each of the observation series. In this way the last apple sawfly was calculated to emerge on average 56 DD>4 °C after the first sawfly was trapped. From this follows that the average post diapause development time as calculated form air temperatures is 181 DD + (56 DD/2) = 209 DD >4 °C after March 15. Graf found in his controlled experiments 210 DD>4.5 °C as average post diapause development time. (Graf, 1996b).

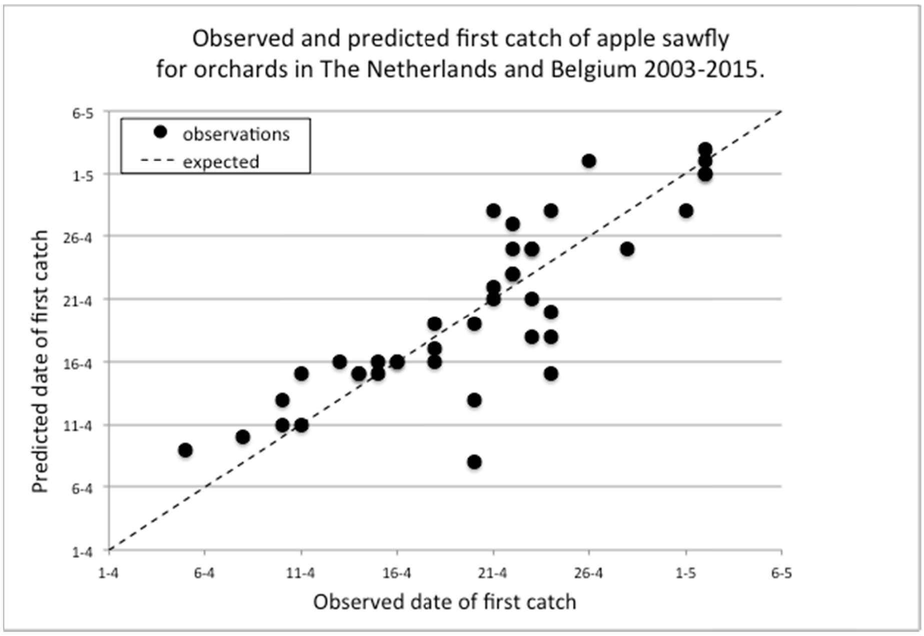

Figure 1: Date of observed first catch of Apple Sawfly, and predicted first catch based on a temperature sum of 181 DD > 4°C air temperature after March 15 (March 14 in leap years) for orchards in The Netherlands and Belgium 2003-2015.

The available information is implemented in the simulation model as follows:

- Post diapause development is started on March 15 (March 14 in leap years).
- Post diapause development rate is proportional to air temperature >4 °C.
- There is no cut-off used for higher temperatures, as soil temperature will profit form higher temperatures.
- The average post diapause development time is 209 DD.
- The relative dispersion in the simulation process is set to 0.1 to produce the first apple sawflies around 181 DD.
- The model predicts and flags the advice to install the white sticky traps for flight monitoring at 160 DD>4 °C.
- The user can set the date the first apple sawfly is trapped as biofix to improve the accuracy of the simulations.

2 - Flight activity and aging of adults

Apple sawflies emerge from the soil at temperatures over 4 °C, but do not fly when the temperature is low. Periods with low temperature stretch the total flight period and delay egg deposition. Catches of plum sawflies (*H.minuta* and *H.flava*) start when maximum day-temperatures reach 8-12 °C, but massive catches only occur over 15 °C. (Wildbolz, 1986).

For one orchard the daily total number of apple sawflies trapped on three white sticky traps was plotted against the maximum temperature that day (as fraction of the total number of sawflies trapped that year). The total catch in this orchard 2010-2015 varied from 355 to 905 apple sawflies per year (Figure 2). The results resemble the observations by Wildbolz for plum sawfly. On days with a maximum temperature below 12 °C never more then 1% of the total number of sawflies was cached. Over 12 °C the maximum daily catches increase proportional to the maximum temperature.

Gottwald (1982) made hourly records and found apple sawflies to fly from 9:00 till 18:00. Male captures were higher in the morning hours but female captures were evenly distributed over the day.

In lab experiments by Graf (2001) using different constant temperatures female lifespans ranged from 24.3 days at 10.5 °C, till 7.0 days at 20.5 °C. Linear regression yielded a lower development threshold of 6°C for the aging process, and average lifespan of 88.5 DD>6 °C. Approximately 90 % of the females reached at least the age of 50 DD>6 °C (Graf, 2001, figure 3).

The available information is implemented in the model as follows:

- There is no flightactivity during the night, during hours of rain, or when the temperature is below 11 °C.
- Over 11 °C air temperature the flight activity of the present females increases proportional to the temperature.
- The average female lifespan is 89 DD>6 °C.
- The relative dispersion in the aging process is set to 0.2 to let the first females die at the age 45 DD>6 °C and the last at approximately 130 DD>6 °C.

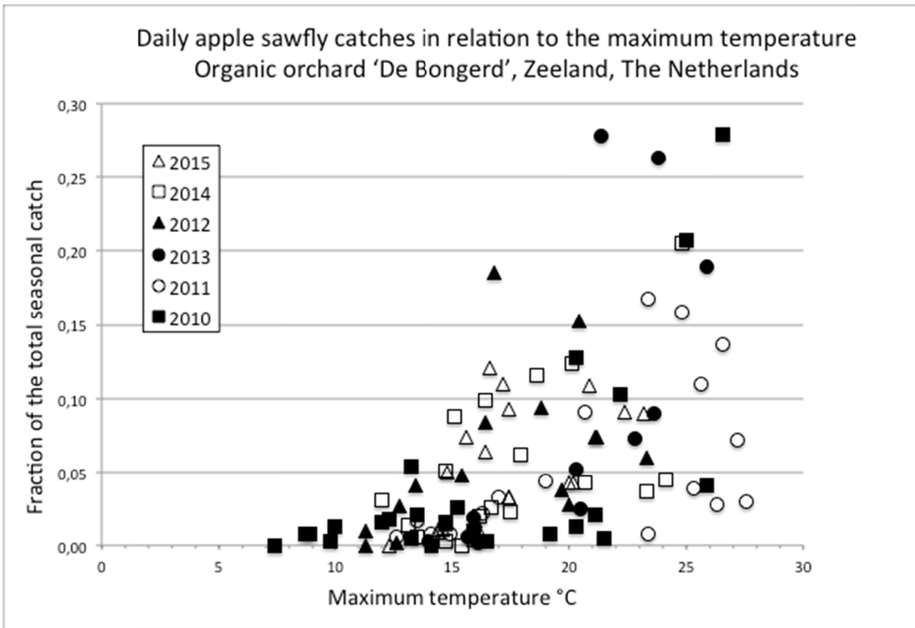

Figure 2: Daily catch of apple sawflies on white sticky traps as fraction of the total yearly catch in relation to the maximum temperature that day. Organic orchard 'De Bongerd', Zeeland, The Netherlands, 2010-2015

3 - Egg deposition

In our 2003-2015 datasets the first apple sawflies were always captured before the first flowers of the main apple varieties opened ('Elstar', 'Jonagold', 'Topaz', 'Santana'). The same was observed in other studies. As a result not the first emerging apple sawflies, but the first opening flowers mark the start of the egg deposition on each apple variety. (Kuenen, 1951; Gottwald, 1982; Tamosiunas, 2014). Apple sawflies concentrate on freshly opened flowers for egg deposition (Chaboussou, 1961). Within an apple variety, the egg deposition starts on the king flowers on the older wood, and later shifts towards the later opening flowers on the one year old twigs. We occasionally found the very first eggs in king flowers on the older wood still in balloon stage, and the very last eggs on the last opening lateral flowers on the one year old wood. On orchard scale the egg deposition starts on the early flowering apple varieties and continues on the later flowering varieties.

Published indications of the total number off eggs deposited per female are highly variable and range from 3 to 116, with averages below 50 (Dickler, 1953; Niezborala, 1980; Graff, 2001). Total effective fecundity seems depending on the weather conditions and lifespan of the individual adults.

The females deposited on average 50 % of their eggs in 40 DD>6 °C, and the egg deposition was more or less finished after 100 DD>6 °C (Graff, 2001). Combining this average fecundity period of 70 DD>6 °C with the data on egg deposition at various constant temperatures provided in Graff (2001) figure 3, a linear relation was found between the number of eggs deposited per day and the average temperature.

The available information is implemented in the model as follows:

- The user has to set the date the first flowers open (BBCH 60) as variety-local biofix.
- There is no pre-oviposition period.
- The average fecundity period is 70 DD>6 °C (RD= 0.2)
- The stock of eggs per female is assumed to be a non-limiting factor.
- When conditions for flight are suitable, egg deposition rate is 0.44 egg/DD per active female.

4 - Egg development

The development time of individual eggs is reported to vary from 7 to 20 days depending on temperature. (e.g. Kuenen, 1951; Niezborala, 1980). Graff (2002) found the lower development threshold for egg development to be 6.9 °C, and the average development time 85 DD>6.9 °C (STD= 4.8). These data have been used effectively for the timing of applications of Quassin in Sweden (Sjöberg, 2015). Falta (2006) used 10 °C as thermal threshold but the starting point for the temperatures accumulation not explained.

The available information is implemented in the model as follows:

- The average embryonal development time is 85 DD>6.9 °C.
- The relative dispersion is set to 0.12 as we assume under field conditions more dispersion than found in the lab experiments.
- The embryonal development is split into 6 steps of equal length according to the morphological development stages as described by Kuenen (1951) to allow validation of the model with field observations.

5 - Larval development and descent of full-grown larvae to the soil.

The time the larvae develop in fruits is 20 to 35 days. (Dickler, 1954; Niezborala, 1980; Gottwald, 1982; Sjöberg, 2015). As no quantitative information on the effect of temperature on the larval development rate is published, the lower development threshold is assumed to be the same as for the embryonal development as this is true for most insects species. From four years of observations published by Gottwald (1982) a temperature sum of 150-250 DD>6.9 °C for the larval development can be estimated.

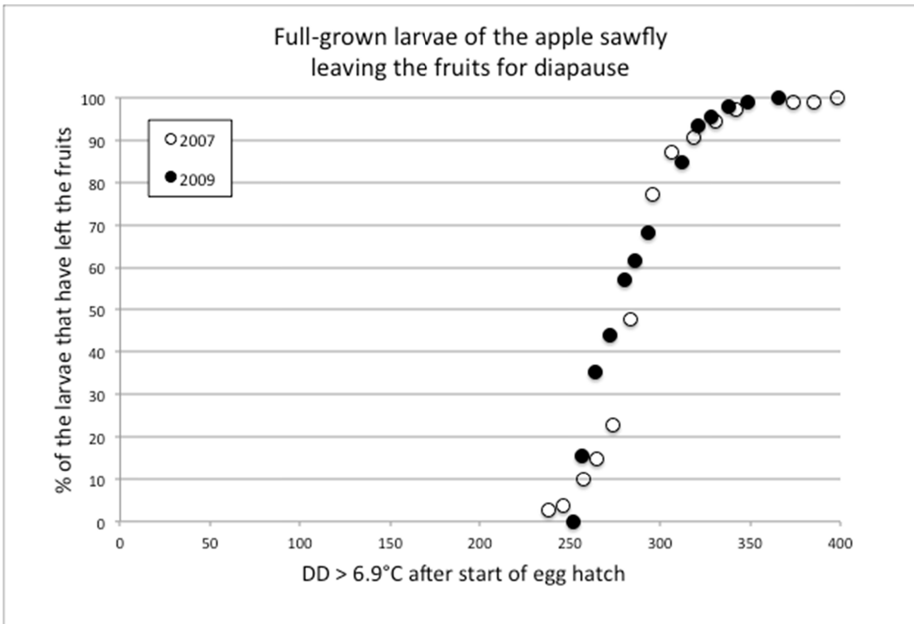

Figure 3: Observed descend of full-grown apple sawfly larvae from a depot of affected apples. Experiments in 2017 and 2009.

Figure 3 shows the results of our experiments in 2007 and 2009. The decent of the full-grown larvae from the fruits is plotted against the accumulated temperature sum in DD>6.9 °C calculated from the start of egg hatch. The results indicate that the decent starts around 240 DD>6.9 °C after start of egg hatch. A field check on June 10 2009 (280 DD>6.9 °C) in the orchard where the sample was taken learned that there were still abundant fruits with larvae. During a next check on June 15 2009 (321 DD>6.9 °C) no more fruits with larvae were found.

6 - Migration of larvae from the initially affected fruitlets to the second fruit

The young larvae make a galley just under the skin of the fruitlet where the egg hatched. After some time they leave this first fruit, and continue their development in a neighbouring fruit in the same cluster. The trigger for this migration is not known. Figure 4 summarizes the field observations on this migration process plotted against the accumulated temperature sum in DD>6.9 °C form the start of egg hatch. The result shows a wide variation, but indicate that the migration to the second fruit starts around 100 DD>6.9 °C after start of egg hatch. Until more accurate information is available on the migration from first to second fruit, the period indicated by the model cannot be more than an estimation.

The available information is implemented in the model as follows:

- The average larval development time in the fruits is 240 DD>6.9 °C.
- The development time is split into 100 DD>6.9 °C until migration to the second fruit and 140 DD>6.9 °C for further development until the larva decent to the soil.
- The relative dispersion for the process is set to 0.12.

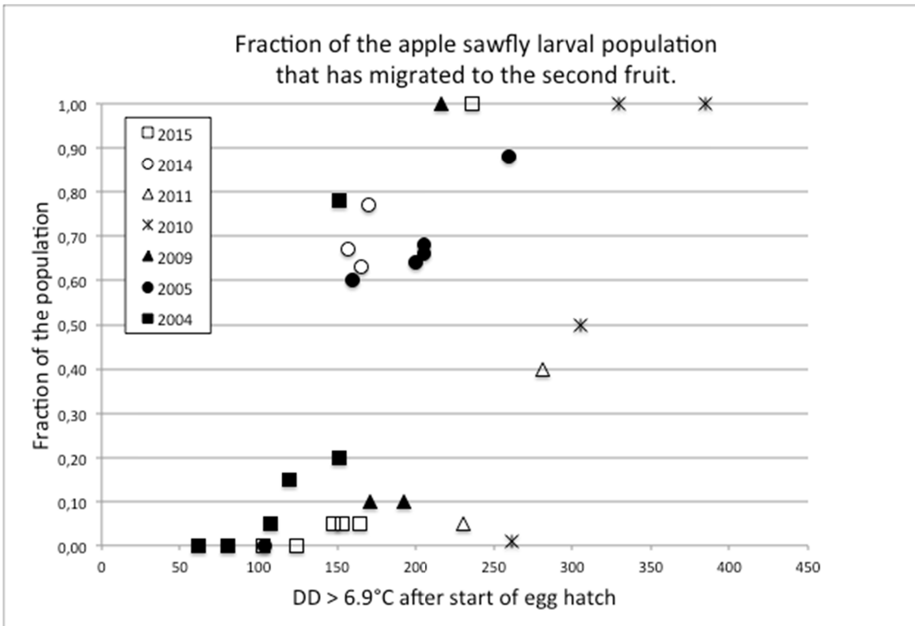

Figure 4: Fraction of the larval population that migrated to the second fruit. Field observations in orchards in The Netherlands and Belgium 2004-2015.

7 - Implementation of the model as decision support system

The model is added to the RIMpro platform to enable online use by fruitgrowers and their advisers. The start of bloom (BBCH 60) is the only parameter that is obligatory to get correct local and variety specific output. All other simulation parameters discussed in this article are set as default values but can be changed by experienced or curious users.

During use in real time, the model forecasts and flags the day that 2 % of the eggs is expected to hatch as the ideal moment for the application of a larvicide.

From the forecasted length of the eggs hatch period the user can decide if the insecticide application has be to split-up or repeated. Figure 5 shows an example of the graphical output of the model.

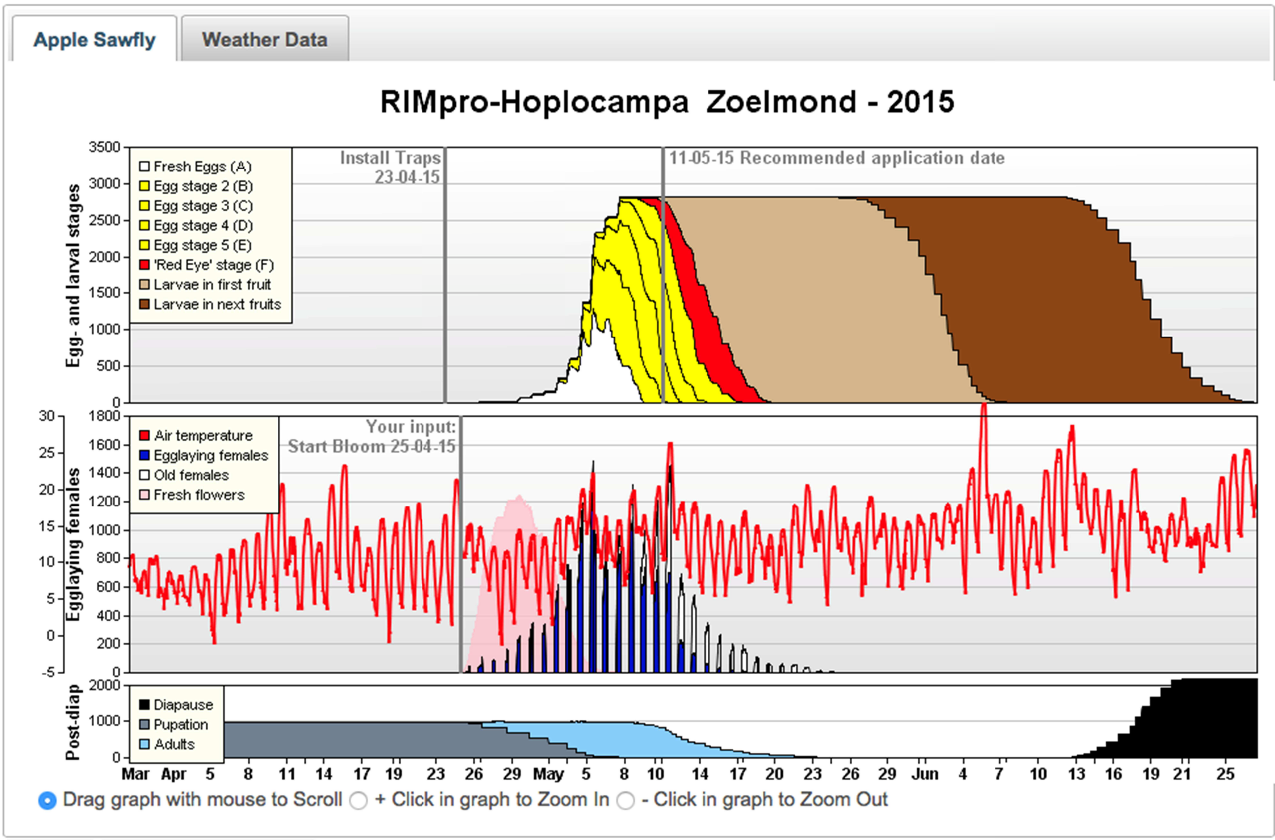

Figure 5: Example of the DSS output. Lower graph: diapause, post diapause development and adult lifespan. Middle graph: temperature, bloom and flight activity. Upper graph: egg deposition, egg- and larval development stages and descend to the soil.

Conclusion

The present knowledge on the biology of the apple sawfly has been made available in a practical decision support system. The system can help to optimize the management of apple sawfly populations in organic and integrated apple production systems. Feedback form users in the coming years will help to further opitmize the model.

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