Phenology modelling of major insect pests in fruit orchards from biological basics to decision support: the forecasting tool SOPRA*

J. Samietz, B. Graf, H. Höhn, L. Schaub and H. U. Höpli

Swiss Federal Department of Economic Affairs DEA, Agroscope Changins-Wädenswil Research Station ACW, Schloss, PO Box 185, CH-8820 Wädenswil (Switzerland); e-mail: joerg.samietz@acw.admin.ch

The forecasting tool SOPRA has been developed with the objective of optimizing timing of monitoring, management and control measures of insect pests in fruit orchards in Switzerland. Applying time-varying distributed delay approaches, phenology-models were developed driven by solar radiation, air temperature and soil temperature on hourly basis. Relationships between temperature and stage-specific development rates for relevant stages of the life cycles were established under controlled laboratory conditions for *Dysaphis plantaginea*, *Hoplocampa testudinea*, *Cydia pomonella*, *Grapholita lobarzewskii*, *Cacopsylla pyri*, *Rhagoletis cerasi*, *Anthonomus pomorum* and *Adoxophyes orana*. The implementation of body temperatures in the models is based on habitat selection and biophysical modelling of habitat conditions. In order to validate modelling, phenology predictions were compared with several years of independent field observations. On the basis of local weather data, the age structure of the pest populations is simulated and crucial events for management activities are announced. Through a web interface, the simulation results are made available to consultants and growers (www.sopra.info) and the latter can be applied as a decision support system for the eight major insect pests of fruit orchards in the alpine valleys and north of the Alps on local and regional scale.

Introduction

Plant protection in modern fruit growing relies on precise timing of monitoring and control of pest populations. Throughout the season particular stages within the life cycle of insects and other pests have to be surveyed by different monitoring procedures in order to establish economic injury levels and to test for the need of control measures (Kogan, 1998). The grower needs precise information about when these stages are present and corresponding techniques have to be applied or monitoring carried out. In sustainable production applying integrated pest management in particular, pests have to be monitored in order to assess the risk and consequently to judge the necessity of intervening with a control measure (Norton & Mumford, 1993; Dent, 1995; Pedigo & Rice, 2005). Modern control measures also rely on precise timing, especially when modes of action aim at very specific developmental stages of the pest (Bloomers, 1994). The required knowledge on the phenology of the pest populations can be established by forecasting systems that at best could be connected with information on the pests and possible management options in decision support systems. Hitherto, temperature sums and, more recently, simulation models have been used in tree fruit growing to predict the phenology of pests and hence to facilitate timing of management and plant protection measures. However, aside from a few exceptions (e.g. Welch *et al.*, 1978; Morgan & Solomon, 1996), the models are often not designed to be used by growers, consultants or extension services. In addition, they are often based on very different approaches and programming languages or require special driving variables, which makes them difficult to use, even by extension services (Rossing *et al.*, 1999; van der Werf *et al.*, 1999). Here we introduce the forecasting tool SOPRA which has been developed to optimize timing of monitoring, management and control measures of major insect pests in Swiss fruit orchards. The system consists of a locally–based user interface with the different species models and a web interface to provide simulation results and decision support to consultants and growers (www.sopra.info).

*Paper presented at the EPPO Conference on 'Computer Aids for Plant Protection' in Wageningen, the Netherlands, 2006-10-17/19.

Phenology models

The flow of entities with variable transit times through a given process, as applicable for insect development, can be easily simulated by time-varying distributed delay models (Manetsch, 1976). This approach makes use of an Erlang density function to generate the frequency distribution of the individual development times, and is parameterized with the thermal constant of the specific developmental stage and its variance. An algorithm originally written by Abkin & Wolf (1976) was adapted to compute the process of ageing within the different developmental stages and to continuously keep track of the age structure of the population. The changes in the age structure of the pest populations are continuously recorded by a balance of input and output from the state variables, i.e. developmental stages. The underlying relationships between temperature and process rates are implemented with linear or nonlinear functions for each stage of the life cycle depending on the nature of the best approximation. All of those relationships for the relevant stages of the life cycles were established thorough individual-based laboratory experiments under controlled conditions with a minimum of four temperature treatments for each species. Developmental rates of the stages are mostly implemented with linear functions; nonlinear functions being used for reproductive rates and survival of adults (e.g. Graf *et al*., 1996; Graf *et al*., 1999; Graf *et al*., 2001a; Schaub *et al*., 2005; Graf *et al*., 2006). Phenology models have been established for Rosy apple aphid (*Dysaphis plantaginea*), Apple sawfly (*Hoplocampa testudinea*), Codling moth (*Cydia pomonella*), Smaller fruit tortrix (*Grapholita lobarzewskii*), Pear psylla (*Cacopsylla pyri*) and Cherry fruit fly (*Rhagoletis cerasi*) and recent experiments have extended the coverage of major pome and stone fruit pests to include Apple blossom weevil (*Anthonomus pomorum*) and Summer fruit tortrix (*Adoxophyes orana*). The implementation of temperatures in the models is based on intensive studies on habitat selection of the developmental stages and biophysical modelling using the three driving variables (solar radiation, air temperature, soil temperature) and structural orchard features. Body temperatures of all implemented developmental stages are approximated by modelling habitat temperatures as close as possible (Table 1). Soil temperature as approximation is used for postdiapause development of *H. testudinea* and *R. cerasi* pupae. Stem surface temperature is implemented for hibernating larvae and pupae of *Cydia pomonella* and *Adoxophyes orana*. Stem surface temperature is simulated from air temperature and solar radiation on the basis of the seasonal azimuth angle of the sun and light extinction of the vegetation (cf. Graf *et al*., 2001b). Inner stem temperature is also simulated from air temperature and solar radiation and implemented for hibernating larvae and pupae of *Grapholita lobarzewskii*. The remaining habitat temperatures are approximated by air temperature (Table 1). For validation, simulated emergence processes from hibernation sites were first compared with emergence data from semifield experiments. In a second step, implemented model predictions were validated with several years of independent field observations for adult activity (e.g. Graf *et al*., 1996; Graf *et al*., 1999; Graf *et al*., 2001a; Schaub *et al*., 2005; Graf *et al*., 2006).

Table 1 Species implemented in the forecasting system SOPRA with modelled stages of the life cycle and temperature driving the models

Species	Implemented stages of the life cycle					Temperature
Rosy apple aphid (*Dysaphis plantaginea*)	Winter eggs	Juveniles	Adults	Juveniles (1. Gen.)		Air
Apple sawfly (*Hoplocampa testudinea*)	Hibernating pupae*	Adults	Eggs	Larvae		Soil* Air
Smaller fruit tortrix (*Grapholita lobarzewskii*)	Hibernating larvae/pupae (M/F)*	Adults (M/F)	Eggs	Larvae	Hibernating larvae (diapause)*	Inner stem* Air
Codling moth (*Cydia pomonella*)	Hibernating larvae/pupae (M/F)*	Adults (M/F)	Eggs 1. Gen.	Larvae (1. Gen.)		Stem surface* Air
	Pupae (1. Gen.)	Adults (1. Gen.)	Eggs (2. Gen.)	Larvae (2. Gen.)	Hibernating larvae (diapause)*	Stem surface* Air
Pear psylla (*Cacopsylla pyri*)	Hibernating adults (M/F)	Eggs 1. Gen.	Larvae (1. Gen.)			Air
	Adults (1. Gen.)	Eggs (2. Gen.)	Larvae (2. Gen.)			Air
Cherry fruit fly (*Rhagoletis cerasi*)	Hibernating pupae (M/F)*	Adults (M/F)	Eggs	Larvae	Hibernating pupae (diapause)*	Soil* Air
Apple blossom weevil (*Anthonomus pomorum*)	Hibernating adults (M/F)*	Active adults (M/F)	Immigrated adults (M/F)	Eggs	Larvae	Soil/Air* Air
Summer fruit tortrix (*Adoxophyes orana*)	Hibernating larvae (M/F)*	Active larvae (M/F)	Pupae (M/F)	Adults (M/F)	Eggs (1. Gen.)	Stem surface* Air
		Larvae (1. Gen.)	Pupae (1. Gen.)	Adults (1. Gen.)	Eggs (2. Gen.)	Air
		Larvae (2. Gen.)	Hibernating larvae (diapause)*			Stem surface* Air

First table lines of each species start with the hibernating stage and following lines represent subsequent generations with the same stages below each other. F – females, M – males.

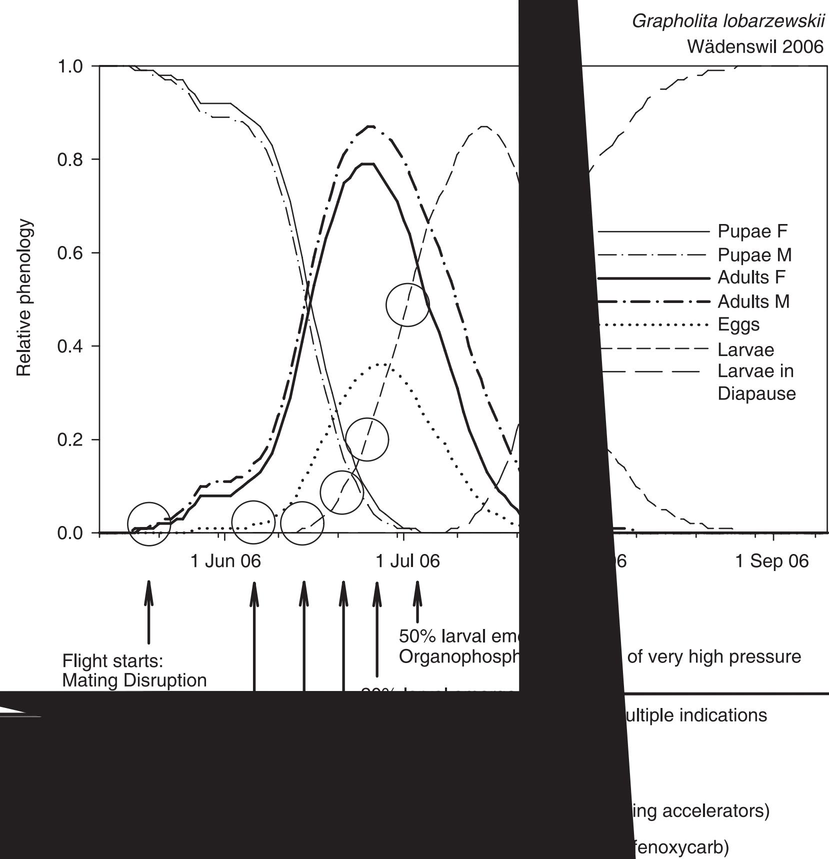

Fig. 1 Simulated relative phenology by example of the Smaller fruit tortrix (*Grapholita lobarzewskii*) with important events in the lifecycle and corresponding suggestions. The decision support system gives more detailed information and, besides timing for optimum monitoring or treatment, also pre or post warning times. F – females, M – males.

Weather data

Local weather data on hourly basis (solar rad[redacted] air temperature at 2 m, soil temperature at −5 c[redacted] from official standard meteorological stations (Met[redacted] and automatically stored daily in the morning in a [redacted] database. Ten-year means on hourly basis serve for proje[redacted] and are merged with the current weather data up to the prese[redacted] day for simulation of phenologies throughout the entire season. Currently 14 weather stations are used to cover all the climatic regions of Switzerland that are important for fruit growing. The stations range from the very early fruit growing regions in the Ticino valley south of the main alpine range (station Magadino, 200 m a.s.l.) to the late fruit growing regions above 600 m in altitude in north-eastern Switzerland (station St. Gallen).

Local simulation tool

The locally based user interface is designed as a common Microsoft Windows® application in order to facilitate the simultaneous use of the different species models, and to standardize the weather data input for all models. The simulation of habitat temperature is integrated into the application with a flexible weather module. Both numerical and graphical outputs are implemented. For further pests a routine is implemented to compute temperature sums for any user-defined temperature threshold.

[redacted]he temperature sum [redacted]ather data input text [redacted]eck boxes allow the [redacted]l and/or graphical [redacted]er data, the relative [redacted]nulated and crucial [redacted]nced on this basis [redacted]t is automatically [redacted]s short recommen-[redacted]er chooses air, soil an[redacted]ecif[redacted] to three different therm[redacted]ng da[redacted]hin the year. The latter als[redacted]of tem[redacted]ture sums from a biofix, e.g. b[redacted]ht in the[redacted]ld.

From the nu[redacted]f single [redacted]ecies models the relative phenologie[redacted]l transferre[redacted] to a database for online presentation an[redacted]upport (se[redacted]below).

Online presentation a[redacted]decision support

Through a web interface, the simulation results are made available to consultants and growers together with extensive information on the pest species and dynamic decision support according to the phenology in German, French, Italian and English (www.sopra.info). The website is entered through the phenology forecasting part to facilitate the shortest possible route from entering the site to viewing an overview of all pests in a certain location. Accordingly the entrance site provides a clickable map of Switzerland with the climatic regions of the 14 representative weather stations (cf. above) drawn in colour shades with relief, rivers, and lakes included.

By clicking a certain point on the map the user is led to a tabled overview of all pests at that location which is centred on the current period. The table with the present alert status can be dynamically scrolled through the entire year or zoomed out for overview. Table cells with species/day combination provide a colour code for monitoring (blue) and control measures (red) that is unified throughout the site. Additionally the code is divided into pre and/or post warning phases of the announced events (light blue and red) and optimum times for certain monitoring and control measures (dark blue and red). For local differences in phenology, e.g. at southern exposed locations, reference links are provided to the earlier and later neighbouring regions.

Clicking on the table cells leads to the core of the decision support system with graphical output of the relative age structure of the pest populations and corresponding verbal interpretation. A chart shows a time line of the proportions of implemented life stages. Fig. 1 is an example of such a visualization of relative age structures for *Grapholita lobarzewskii*. The chart is scrollable throughout the year and has three zoom steps and controls for shifting the current day for which the interpretation is given as decision support. The latter is divided into monitoring and control measures indicated by the colour code mentioned above. The interpretation is referred directly to the age structure of the pest and accordingly announces crucial events for certain management activities (Fig. 1). Preference is given to environmentally friendly and sustainable measures like pheromone mating disruption or insect growth regulators although all other options of control measures are explained as well. The recommendations give reference to a separate part of the web site with illustrated information on the biology and development of the pest species monitoring methods and economic thresholds as well as to the list of suggested plant protection measures with additional information on modes of action, doses, toxicity, restrictions, etc.

In addition to the entrance to the site with the map of climatic regions, we provide a tabulated overview of the current-day alert status for all climatic regions and species. This is especially useful to provide a quick indication of important stages in the life cycle and corresponding events, e.g. for daily visits by consultants. Table cells with the region/species combination lead directly to the graphical output and corresponding verbal interpretation.

Furthermore, for each species an overview table of all climatic regions is available that is sorted by phenology. Those tables are designed especially for consultants that need a more overall impression of the phenology and/or phenology differences between certain regions. The table with colour-coded alert status can be dynamically scrolled through the entire year or zoomed out for an overview. Table cells with the region/day combination also lead directly to the core of the decision support system with graphical output and corresponding verbal interpretation.

Conclusions and outlook

Major obstacles for efficient use of simulation models by extension advisors and consultants are the diversity of model approaches, the missing standards for data input and output, and the lack of a user–friendly interface (Rossing *et al.*, 1999; van der Werf *et al.*, 1999). We solved the main problems with integration of all target species in one flexible and extendable simulation tool that was written as a common Microsoft Windows® application. As a further advantage the local simulation tool of SOPRA can easily be expanded for additional pests since it has an open structure and requires a limited number of simple parameters which can be established by means of standard experiments or – supported by a thorough validation – even from the literature.

The web application allows it to be used both by consultants and growers which was one of the most important aims of our project. Growers reach the information about the pest situation in their area with only one click and the current decision support with just a second click. On the other hand, consultants are provided with overview tables that allow conclusions on a countrywide scale. To keep the system as simple and concise as possible, we did not include a site-specific registration of orchards which can be an advantage in field crops but not necessarily in tree fruit growing.

The spatial resolution of forecasts of course depends on the availability of locally recorded temperature and radiation data. In Switzerland the governmental extension services maintain a growing network of small weather stations for scab, downy mildew and fire blight warnings. Nevertheless, we restrict our data to the official meteorological stations due to their much better accuracy, especially of temperature measurements. Phytopathological forecasts also depend on precipitation data that are more influenced by relief and other local characteristics than the temperature data applied in our system. Although a finer network of stations could lead to a more distinct differentiation of locations, at the present stage the 14 representative climatic regions used in SOPRA seem to provide sufficient information on the Swiss scale.

SOPRA has been successfully applied now for about five years as a reliable tool for recommendations for four apple pests on local and regional scale in Switzerland and also in southern Germany. With the new web application referred to above SOPRA will go online for the six most important tree fruit pests in spring 2007 including *Rhagoletis cerasi* and *Cacopsylla pyri*. The recently validated models for *Anthonomus pomorum* and *Adoxophyes orana* are intended to be online in 2008 and further extensions are planned for the future.

With proper timing of monitoring and pest control measures, decision support by SOPRA increases the efficacy of pest management and reduces side-effects. It suggests environmentally-friendly and safe control measures like mating disruption or insect growth regulators since those measures especially depend on precise timing. SOPRA provides an important contribution to integrated fruit production being a decision-making process in which growers select from a variety of strategies to keep pests below economic damage thresholds, while minimizing environmental impact.

Acknowledgements

Philippe Blaise (ETH Zurich) is acknowledged for his contribution to the first versions of the simulation platform. Roger Hess and Paul Wälti (MSI AG, Buchs) contributed with coding for the web application. Mauro Genini corrected the French and Italian versions of the web application. Anja Lahusen and Thekla Ackermann helped in the laboratory and with field validation experiments. Claudia Daniel and Eric Wyss (FiBL Frick) provided breeding material and were involved with validation of the cherry fly model.

Modélisation de la phénologie des principaux ravageurs des vergers d'arbres fruitiers sur des bases biologiques pour l'aide à la décision: l'outil de prévision SOPRA

L'outil de prévision SOPRA a été développé dans l'objectif d'optimiser les périodes de suivi, de gestion et des mesures de lutte contre les insectes ravageurs des vergers en Suisse. En appliquant des approches « time-varying distributed delay », des modèles phénologiques ont été développés sur la base de la radiation solaire, de la température de l'air et de la température du sol sur un rythme horaire de mesures. Les relations entre la température et les taux spécifiques de développement de chaque stade ont été établies pour les stades de cycles biologiques en conditions contrôlées au laboratoire pour *Dysaphis plantaginea*, *Hoplocampa testudinea*, *Cydia pomonella*, *Grapholita lobarzewskii*, *Cacopsylla pyri*, *Rhagoletis cerasi*, *Anthonomus pomorum* et *Adoxophyes orana*. L'intégration des températures corporelles dans les modèles est basée sur la sélection des habitats et la modélisation biophysique des conditions d'habitat. Afin de valider la modélisation, les prédictions phénologiques ont été comparées à plusieurs années d'observations indépendantes sur le terrain. En fonction des données climatiques locales, la structure d'âge des populations de ravageurs est simulée et les événements cruciaux pour la gestion du ravageur sont annoncés. Via une interface web, les résultats de la simulation sont rendus disponibles pour les consultants et les agriculteurs (www.sopra.info) et peuvent être utilisés comme un système d'aide à la décision pour les huit principaux insectes ravageurs des vergers dans les vallées alpines et le nord des Alpes à l'échelle locale et régionale.

Фенологическое моделирование основных вредных организмов в плодовых садах: от биологических основ до содействия принятию решений. Средство прогнозирования SOPRA

Средство прогнозирования SOPRA было разработано с целью оптимизации времени проведения мониторинга, мер управления и борьбы с вредными организмами в плодовых садах Швейцарии. Благодаря распределенной временной задержке были разработаны фенологические модели, управляемые на почасовой основе параметрами солнечного излучения, температуры воздуха и почвы. Для *Dysaphis plantaginea*, *Hoplocampa testudinea*, *Cydia pomonella*, *Grapholita lobarzewskii*, *Cacopsylla pyri*, *Rhagoletis cerasi*, *Anthonomus pomorum* и *Adoxophyes orana* взаимосвязь между температурой и скоростью развития на разных стадиях жизненного цикла была установлена в лабораторных условиях. Включение в модели температуры тела основано на выборе среды обитания и биофизическом моделировании условий среды. Для валидации моделей в течение нескольких лет фенологические прогнозы сопоставлялись с независимыми полевыми наблюдениями. На основе местных погодных данных было произведено моделирование возрастной структуры популяций вредных организмов, и были объявлены ключевые события для мероприятий по управлению. Через веб-интерфейс результаты такого моделирования передаются консультантам и производителям (www.sopra.info). Затем эти результаты могут применяться в качестве систем, содействующих принятию решений в местном и региональном масштабе, по восьми основным вредным организмам плодовых садов в альпийских долинах, а также к северу от Альп.

References

Abkin MH & Wolf C (1976) *Distributed delay routines. Class Document* no. 8, 1–13. Department Agric. Econom., Michigan State University, East Lansing (US).

Bloomers LHM (1994) Integrated pest management in European apple orchards. *Annual Review of Entomology* **39**, 213–241.

Dent DR (1995) *Integrated Pest Management*. Chapman & Hall, London (GB).

Graf B, Höhn H & Höpli HU (1996) The apple sawfly, *Hoplocampa testudinea*: a temperature driven model for spring emergence of adults. *Entomologia Experimentalis et Applicata* **78**, 301–307.

Graf B, Höhn H & Höpli HU (1999) The smaller fruit tortrix, *Grapholita lobarzewskii*: predicting the phenology of adult emergence. *Entomologia Experimentalis et Applicata* **93**, 299–304.

Graf B, Höhn H & Höpli HU (2001a) The apple sawfly, *Hoplocampa testudinea*: Temperature effects on adult life-span and reproduction. *Entomologia Experimentalis et Applicata* **98**, 377–380.

Graf B, Höhn H & Höpli HU (2001b) Improving the prediction of adult codling moth (*Cydia pomonella* L.) emergence in a natural environment. *IOBC/Wprs Bulletin* **24**, 127–132.

Graf B, Höpli HU, Höhn H & Samietz J (2006) Temperature effects on egg development of the Rosy Apple Aphid and forecasting of egg hatch. *Entomologia Experimentalis et Applicata* **119**, 207–211.

Kogan M (1998) Integrated pest management: Historical Perspectives and Contemporary Developments. *Annual Review of Entomology* **43**, 243–270.

Manetsch TJ (1976) Time-varying distributed delays and their use in aggregative models of large systems. *IEEE Transactions on Systems, Man, and Cybernetics* **6**, 547–553.

Morgan D & Solomon MG (1996) Pest-Man: a forecasting system for orchard pests. *Acta Horticulturae* no. 416, 273–277.

Norton G & Mumford JD (1993) *Decision Tools for Pest Management*. CAB International, Wallingford (GB).

Pedigo LP & Rice ME (2005) *Entomology and Pest Management*. Prentice Hall, Upper Saddle River, New Jersey (US).

Rossing WAH, van der Werf W & Leeuwis C (1999) Quality of modelling in fruit research and orchard management: an introduction to the workshop. *Acta Horticulturae* no. 499, 147–150.

Schaub L, Graf B & Butturini A (2005) Phenological model of pear psylla *Cacopsylla pyri*. *Entomologia Experimentalis et Applicata* **117**, 105–111.

van der Werf W, Leeuwis C & Rossing WAH (1999) Quality of modelling in fruit research and orchard management: issues for discussion. *Acta Horticulturae* no. 499, 151–159.

Welch SM, Croft BA, Brunner JF & Michels MF (1978) PETE: An extension phenology modeling system for management of multi-species pest complex. *Environmental Entomology* **7**, 482–494.