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Web-Based Decision Support for Sustainable Pest Management in Fruit Orchards: Development of the Swiss System SOPRA

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1. Introduction

Plant protection in modern orchard management relies on precise timing of monitoring and control of pest populations. Particular stages within the life cycle of insects and other pests have to be surveyed throughout the season by different monitoring procedures in order to establish economic injury levels and to test for the need of control measures, respectively (Kogan, 1998). Growers need precise information about when these stages are present and corresponding techniques have to be applied or monitoring has to be carried out (Fig. 1). Especially in sustainable production applying integrated pest management (IPM) the pests necessarily have to be monitored in order to assess the risk and consequently to judge the requirement of an intervention with a control measure (Norton & Mumford, 1993; Dent, 1995; Pedigo & Rice, 2005). Precise timing of monitoring measures assures reliability of the results and saves time during the decision finding process (Fig. 1).

In case control is needed, all regarding actions taken need to be scheduled in relation to crop and pest phenology. Modern control measures even rely on more precise timing especially when modes of action aim at very specific developmental stages of the pest (Blommers, 1994). Besides increasing efficacy, the precise timing of plant protection measures reduces their side effects and may substantially reduce the number of treatments and thereby resources and money spent during the process.

The required knowledge on the phenology of the pest populations can be established by forecasting systems that at the best are connected with information on the pests and possible management options to 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 monitoring and plant protection measures.

However, aside from a few exceptions (e.g. Welch, et al. 1978; Morgan & Solomon, 1996), the simulation models to predict the phenology of fruit pests are often not designed to be used by growers, consultants or extension services. Also they are often based on very different approaches and programming languages or require special driving variables, which makes them even difficult to use 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).

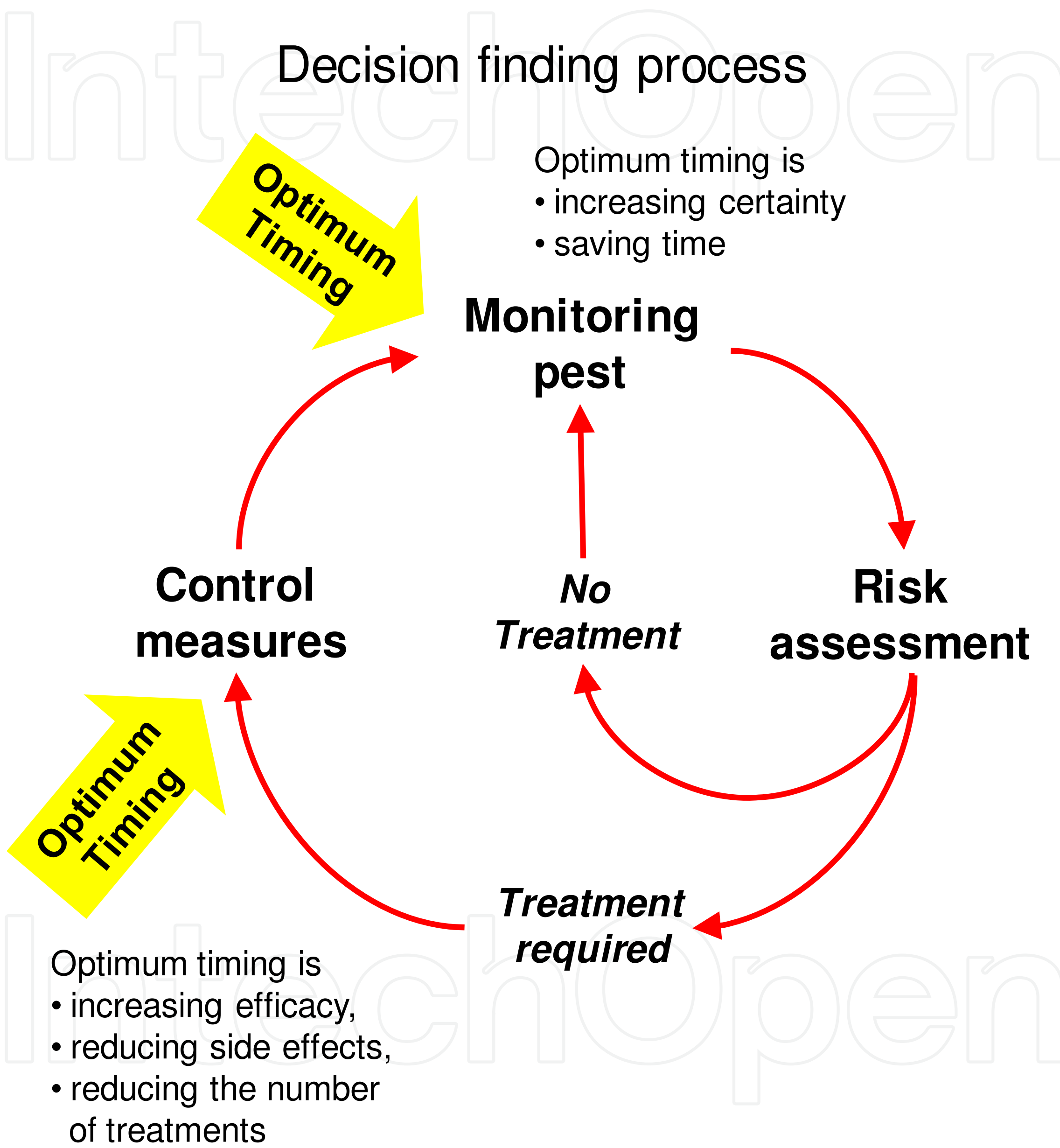

Fig. 1. Importance of precise timing during decision finding process in plant protection

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 the relevant stages of the life cycles were established under controlled laboratory conditions for the most important orchard pests (Fig. 2).

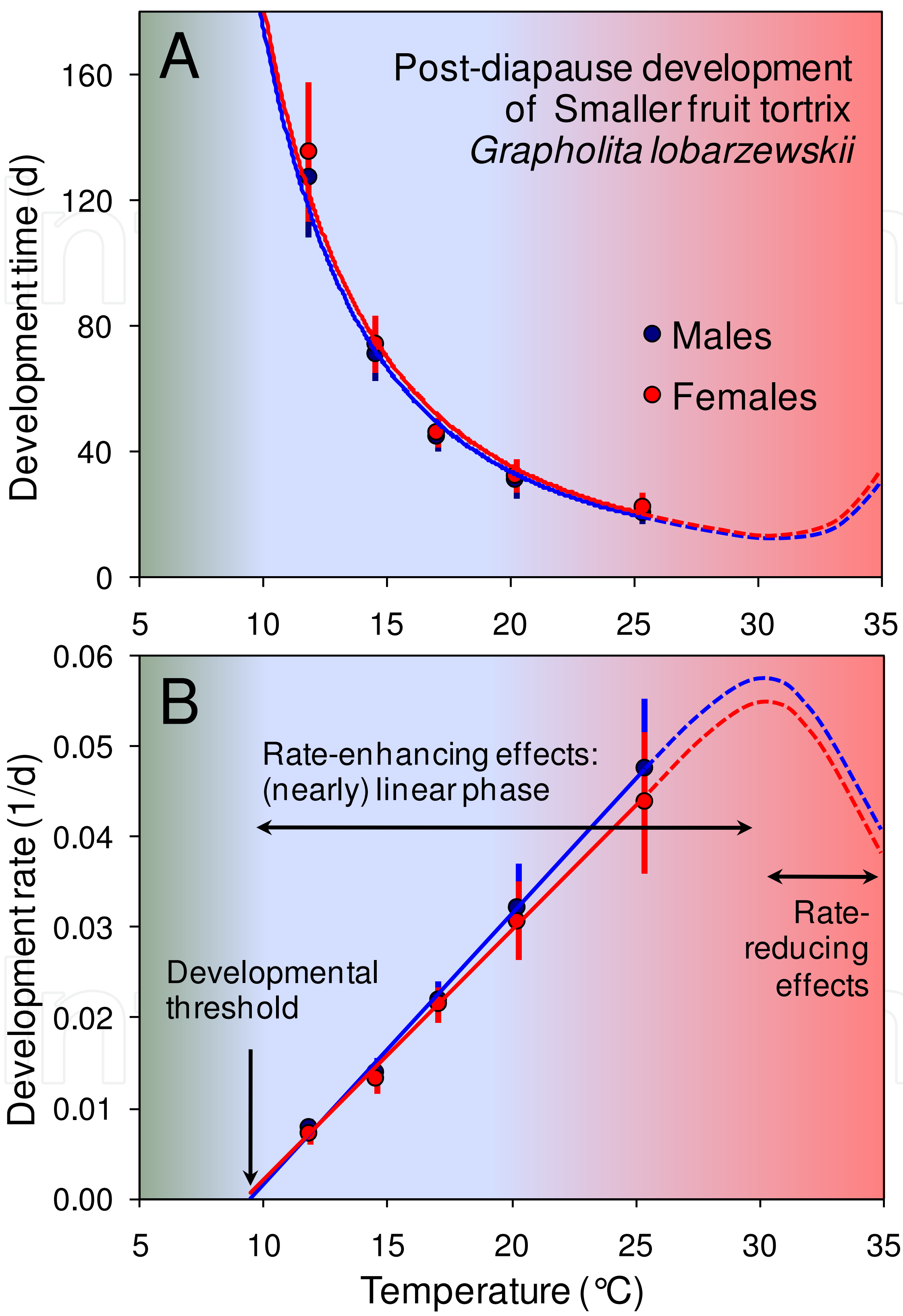

Fig. 2. Effect of temperature on post-diapause development time (A) and development rate (B) of the Smaller fruit tortrix, *Grapholita lobarzewskii* (Data after Graf et al., 1999).

Insect body temperatures in the models of SOPRA are based on studies of habitat selection of relevant developmental stages and according simulations using the driving variables and structural orchard features.
On base of local weather data, age structure of the pest populations is simulated and, based on the simulated phenology, crucial events for management activities are predicted by the SOPRA system.
Through the web-interface, the phenology is directly linked to the decision process of the fruit farmers throughout the season. Thereby SOPRA serves as decision support system for the major insect pests of fruit orchards on local and regional scale and has a wide range of possible applications in the alpine valleys and north of the Alps.

2. Single-species phenology models in SOPRA

2.1 Time-varying distributed delays

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; Severini et al., 1990; Gutierrez, 1996).
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 aging 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. the developmental stages implemented for the single species.
In a poikilothermic development process, the mean transit time in calendar time units and its variance vary dramatically depending on temperature as exemplified here for the Smaller fruit tortrix (Fig. 2 A). Within the rate-enhancing phase of temperature, high temperatures lead to faster development, i.e. higher development rates. Low temperatures slow down biological processes until development nearly stops at the so-called developmental thermal threshold (Fig. 2 B). The relationship of process rate and temperature rises until the so-called optimum temperature is reached and decreases above this optimum due to rate-reducing or destructive effects (cf. Fig. 2), mostly at first as reversible structural damage of the enzyme systems (Somero, 1995; Willmer et al., 2000).
In order to account for these effects of temperature on biological processes, developmental time and variance are not considered as constants in the present modelling approach but as variables that are updated for each simulation step (i.e. for every hour of the season) on the basis of relationships between temperature and process rates (see below). These relationships are kept as simple as possible, which means that linear rate functions are applied wherever they give appropriate approximations (cf. Fig. 2).
Thereby, for a single delay, the ratio between the square of the mean transit time in physiological time units (i.e., the simplifying so-called thermal constant in day-degrees) and its variance specifies the order (k) of the delay and hence the number of first order differential equations required to generate the observed variability. Each of these k first order differential equations represents an age class within the simulated stage and describes the daily changes in this age class as

$$\frac{dQ_i(t)}{dt} = r(t) \times [Q_{i-1}(t) - Q_i(t)] \quad (1)$$

where $Q_i(t)$ stands for the proportion of individuals in age class i at time t. The parameter r(t) is the transition rate from age class i to age class i + 1 and corresponds to the developmental rate that is quantified with the according function describing development as function of temperature. Individuals leaving the last age class are entering the next implemented developmental stage (Fig. 3).

The algorithms implementing the time-varying distributed delay models were originally written in Pascal and later implemented with the program Delphi 6.0 (Borland, Cupertino, CA and Atlanta, GA, USA) in a MS Windows application (cf. below).

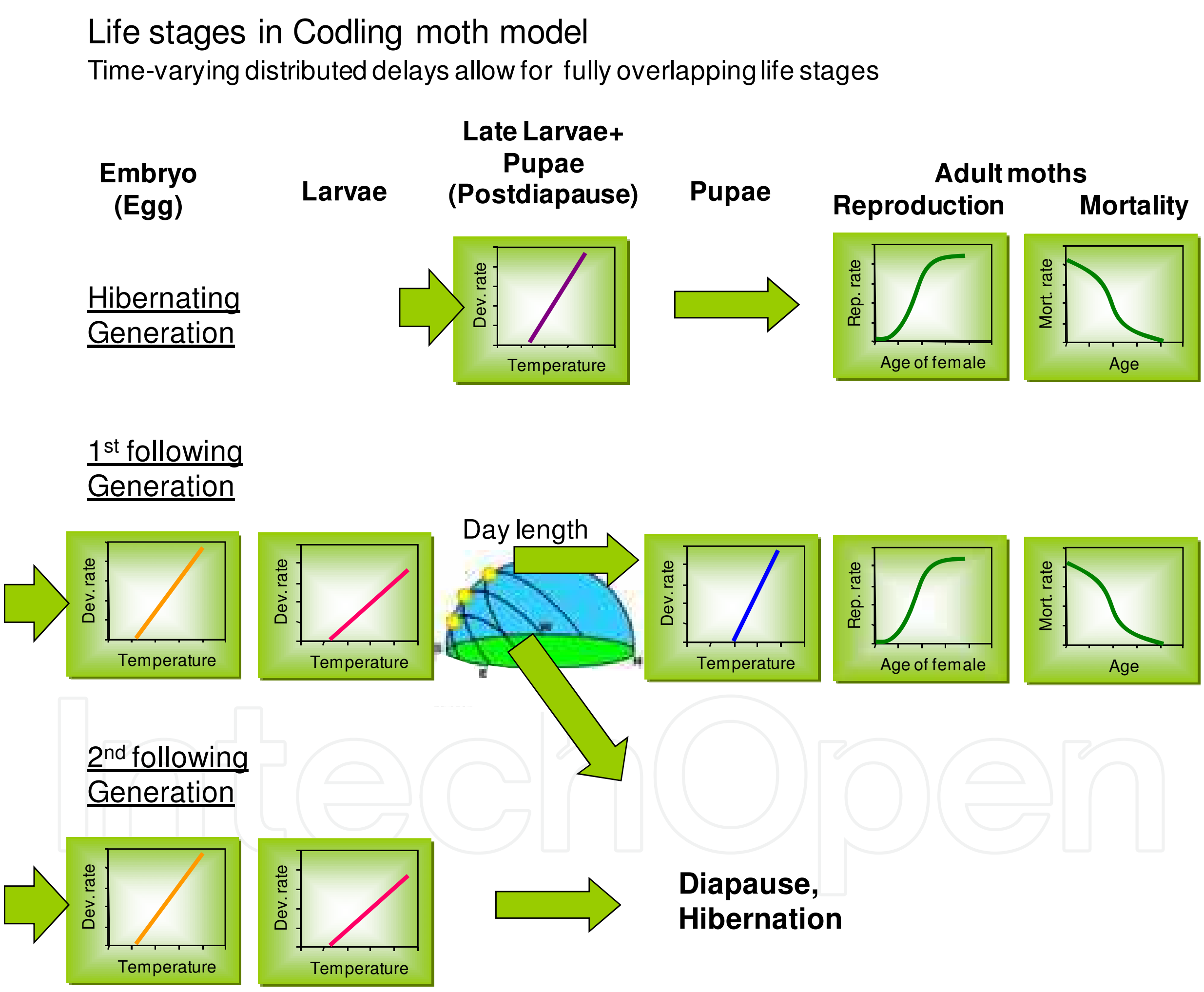

Fig. 3. Life stages implemented in the Codling moth model and schematic relationship between temperature and process rates (development rate, reproduction rate, mortality rate) for the respective stages of the life cycle. Age is always transferred to physiological time above the developmental thermal threshold to account for the temperature effect.

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

Table 1. Species implemented in the forecasting system SOPRA with modelled stages of the life cycle and temperature driving the models. First table line of each species starts with the hibernating stage (Hib.) and following lines represent subsequent generations with the same stages below each other. F - females, M - males.

2.2 Temperature-dependent development

In SOPRA, the relationships between temperature and process rates in the single-species models are implemented with linear or non-linear functions for each stage of the life cycle depending on the nature of the best approximation (Fig. 3). All of those relationships for the relevant stages of the life cycles were established in 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 (cf. Fig. 3). Non-linear functions are 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).

At the present, phenology models in SOPRA are established for Rosy apple aphid (*Dysaphis plantaginea*) Apple sawfly (*Hoplocampa testudinea*), Codling moth (*Cydia pomonella*), Smaller fruit tortrix (*Grapholita lobarzewskii*), Apple blossom weevil (*Anthonomus pomorum*), Summer fruit tortrix (*Adoxophyes orana*), European pear psylla (*Cacopsylla pyri*) and European cherry fruit fly (*Rhagoletis cerasi*). Recent validation of two new models extends the coverage of major pome and stone fruit pests by European red spider mite (*Panonychus ulmi*) and Plum tortrix (*Grapholitha funebrana*).

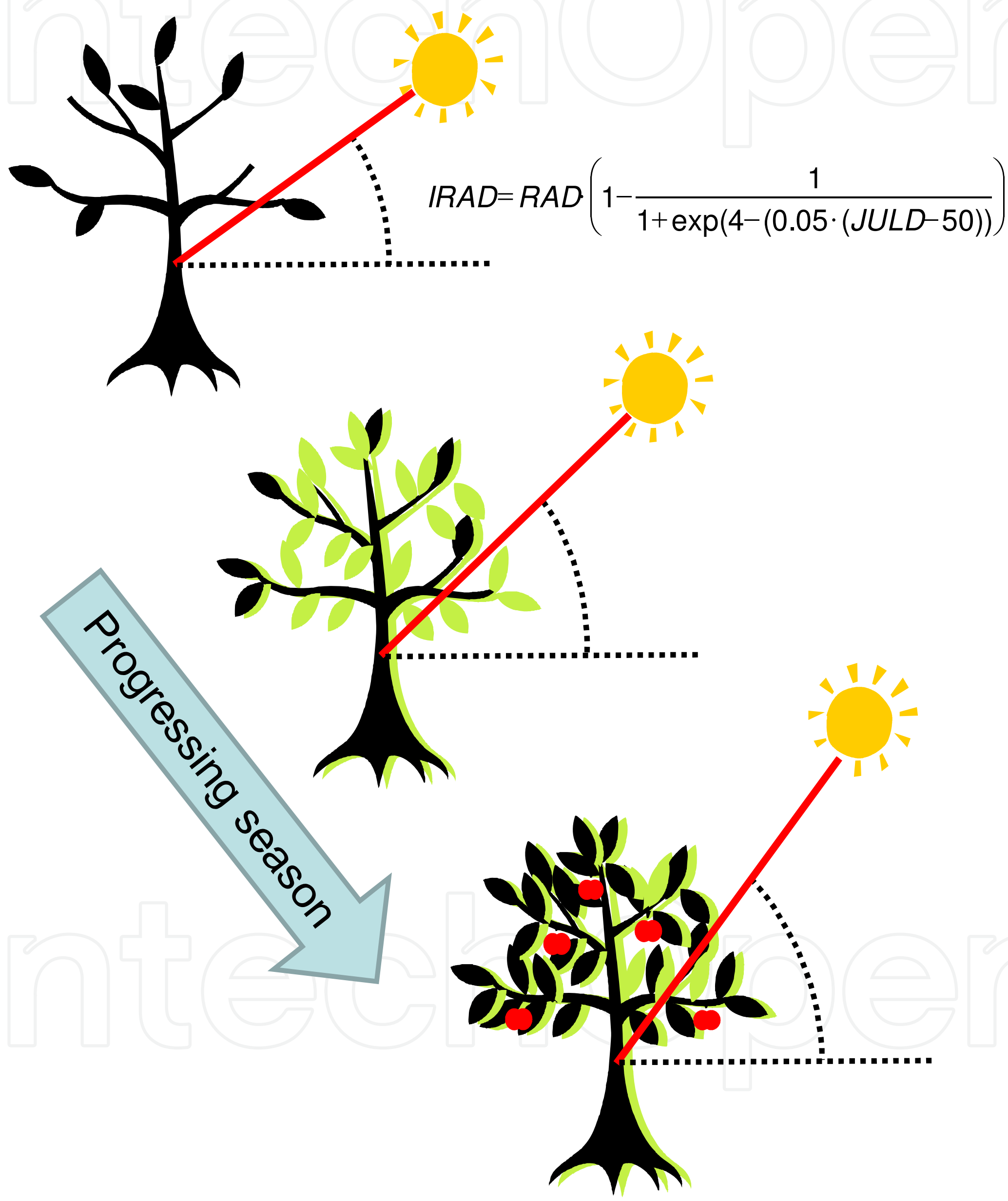

Fig. 4. Simulation of effective solar radiation (IRAD) at the plant stems with progressing season by measured solar radiation (RAD) and day of the year, i.e. Julian day (JULD).

2.3 Habitat selection and simulation of habitat temperatures

The implementation of temperatures in the models is based on intensive studies of 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 is used for post diapause development of Apple sawfly and Cherry fruit fly pupae. Stem surface temperature is implemented for hibernating larvae and pupae of the Codling moth and the Summer tortrix. Stem surface temperature is simulated from air temperature and solar radiation on base of seasonal azimuth angle of the sun and light extinction of the vegetation (Fig. 4; 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 the Smaller fruit tortrix. The remaining habitat temperatures are approximated by air temperature (Table 1).

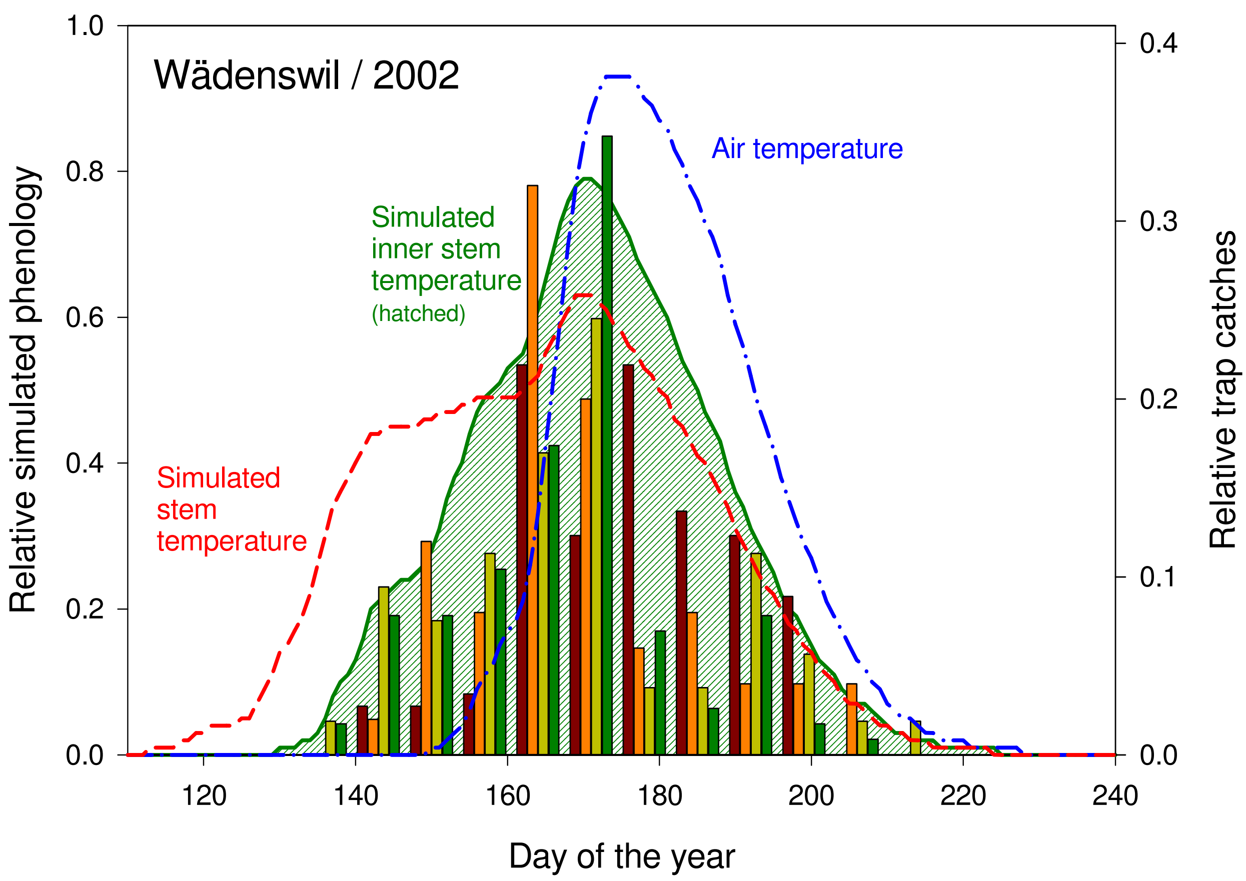

Fig. 5. Exemplified model validation in the Smaller fruit tortrix by simulated male phenology (left axis) with pheromone flight trap data (right axis).

Smaller fruit tortrix exemplifies the high importance of applying the temperature approximated to the habitat as good as possible. When comparing relative trap catches in pheromone traps, simulations of relative phenology with habitat specific inner stem temperature as applied in SOPRA (hatched in Fig. 5) shows a perfect match whereas stem surface and air temperatures lead to high deviations of phenology forecasts (Fig. 5).
For validation, simulated emergence processes from hibernation sites were first compared with emergence data from semi-field experiments. In a second step, implemented model predictions were validated with independent field observations from several years 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).

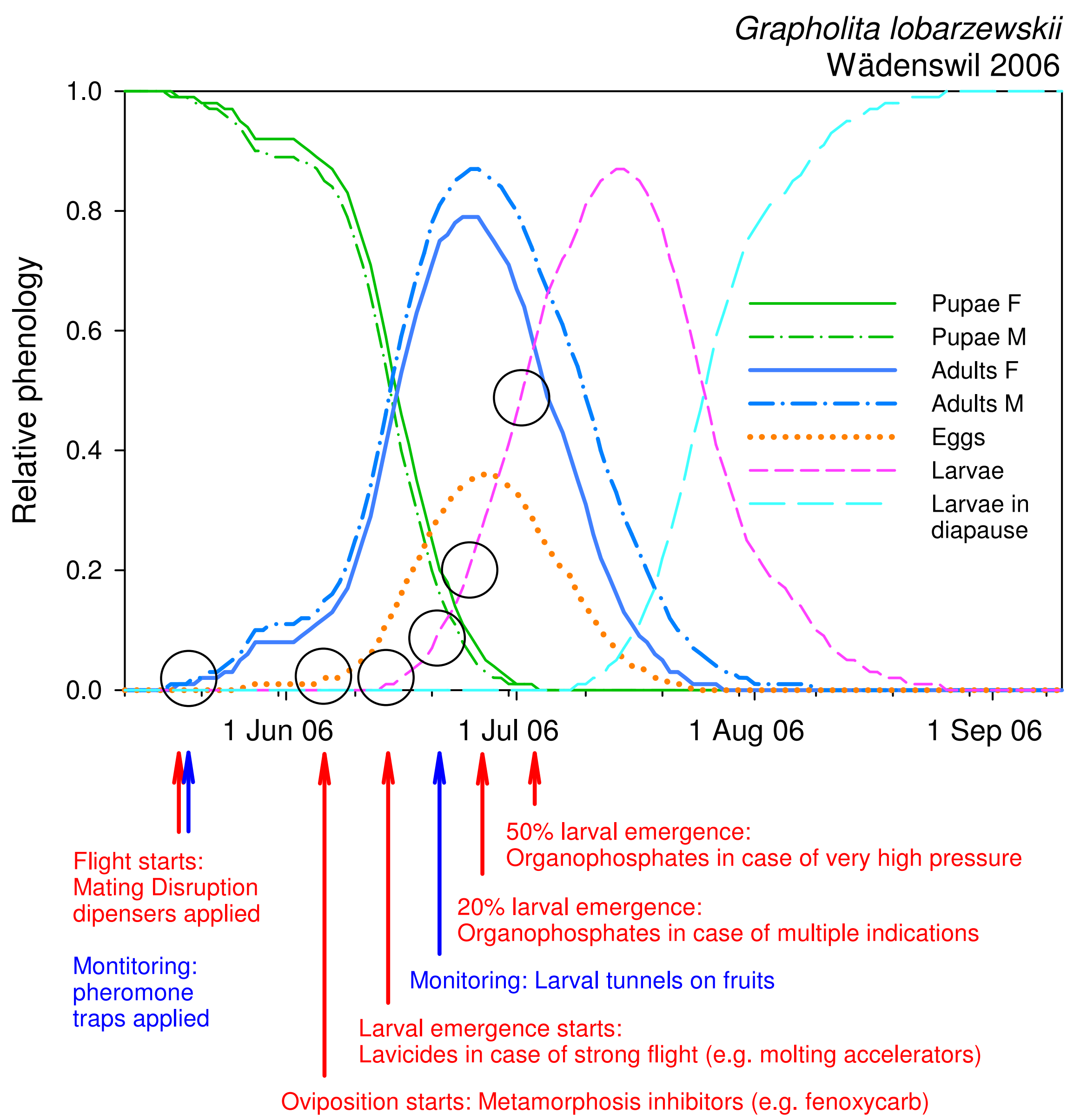

Fig. 6. Simulated relative phenology by example of the Smaller fruit tortrix with important events in the lifecycle and according suggestions. F - females, M - males.

3. Local simulation tool

The locally based user interface is designed as a common MS 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 in 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.

The models for each pest species or the temperature sum routine are accessed with tab controls. Weather data input text files are selected in an "open file" dialog. Check boxes allow to choose the output in numerical and/ or graphical form. On base of the chosen local weather data, relative age structure of fruit pest populations is simulated and crucial events for management activities are predicted on that basis (Fig. 6). For the latter the model output is automatically interpreted in a summary table which delivers short recommendations. The decision support system on the internet platform gives even more detailed information and – besides timing for optimum monitoring or treatment – also pre- or post warning times, respectively (cf. below).
In the temperature sum routine, the user chooses air-, soil and/ or stem temperature and specifies up to three different thermal thresholds and the starting day for calculation within the year. The latter also allows to calculate temperature sums from any biofix, e.g. beginning of adult flight in the field. From the numerical outputs of single species models the relative phenologies are saved and transferred to a data base for online presentation and decision support as explained below.

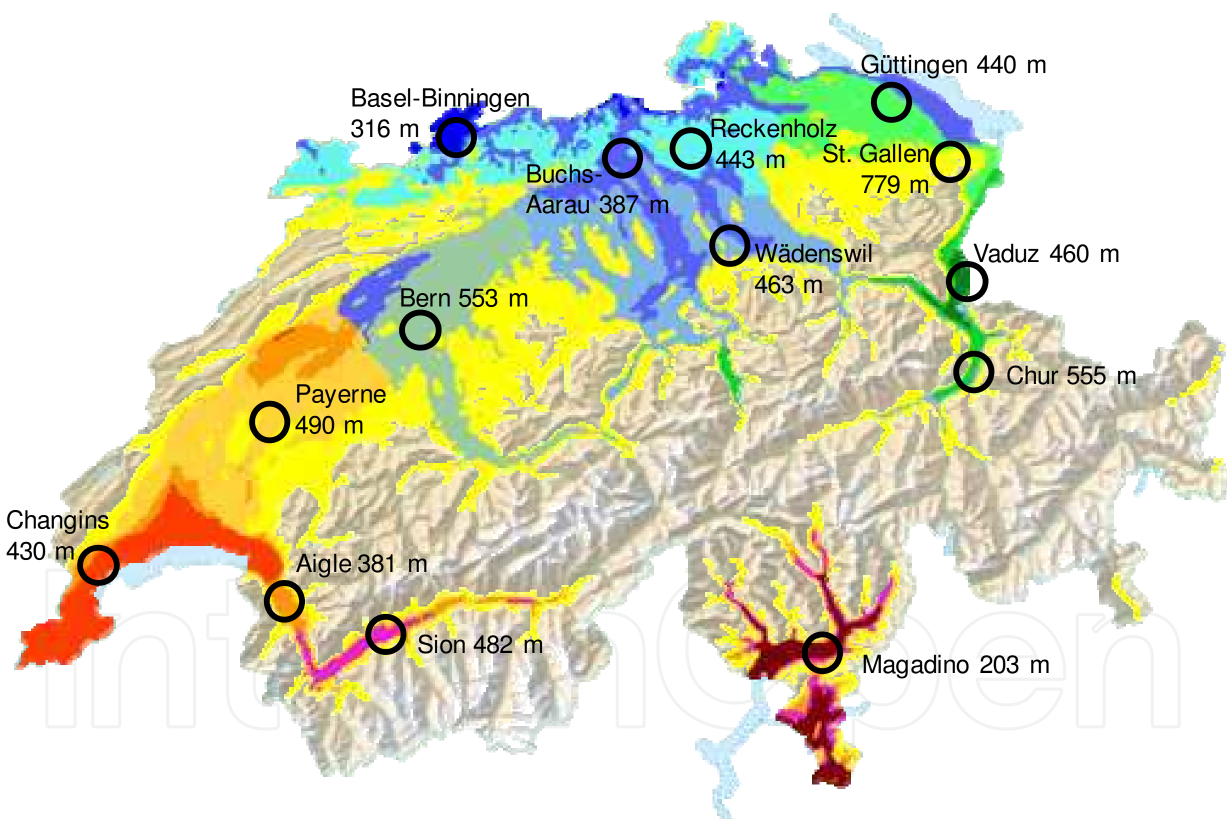

Fig. 7. Weather stations, altitude, and climatic regions that the stations are representing.

4. Weather data for simulating pest phenology

Local weather data on hourly basis (solar radiation flux density, air temperature at 2 m, soil temperature at -5 cm) are retrieved from official standard meteorological stations (MeteoSwiss) and automatically stored daily in the morning in the weather database. Ten-years means on hourly basis serve for projection and are merged with the current weather data until the present day for simulation of phenologies throughout the entire season. Currently 14 weather stations are used to cover all climatic regions of Switzerland that are important for fruit growing (Fig. 7). The stations range from the very early Ticino valley south of the main Alpine range (station Magadino, 203 m a.s.l.), the rather early regions within the Alpine valleys (e.g. station Sion, 482 m a.s.l., station Vaduz, 460 m a.s.l.) to the late fruit growing regions above 600 m altitude in north-eastern Switzerland (station St. Gallen, 779 m a.s.l.).

5. Decision support through web-interface

Through a web-interface, the simulation results are made available to consultants and growers together with extensive information about the pest species and dynamic decision support according to the phenology in German, French and Italian, the three major official languages of Switzerland (www.sopra.info). The website is entered through the phenology forecasting part to facilitate the shortest possible way from entering the site to an overview over all pests of 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 (Fig. 8 A). The table with the present alert status can be dynamically scrolled through the entire year or zoomed out for overview. Table cells with the 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 (Fig. 8 A).

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 according verbal interpretation. A chart shows the proportions of life stages along the time line (Fig. 8 B). Fig. 6 gives an example for such a visualisation of relative age structures for the Smaller fruit tortrix. 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. 8 B). 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 richly illustrated information to the pest species biology and development, to monitoring methods and economic thresholds, anti-resistance strategies as well as to the list of suggested plant protection measures along with additional information on modes of action, doses, toxicity, restrictions etc.

Additionally to the entrance by the map of climatic regions, below we provide a tabulated overview of the current-day alert status for all climatic regions and species (Fig. 9). This is especially useful for quick notion of important stages in the life cycle and according events, e.g. for daily visit by consultants. Table cells with the region/ species combination lead directly to the graphical output and according verbal interpretation.

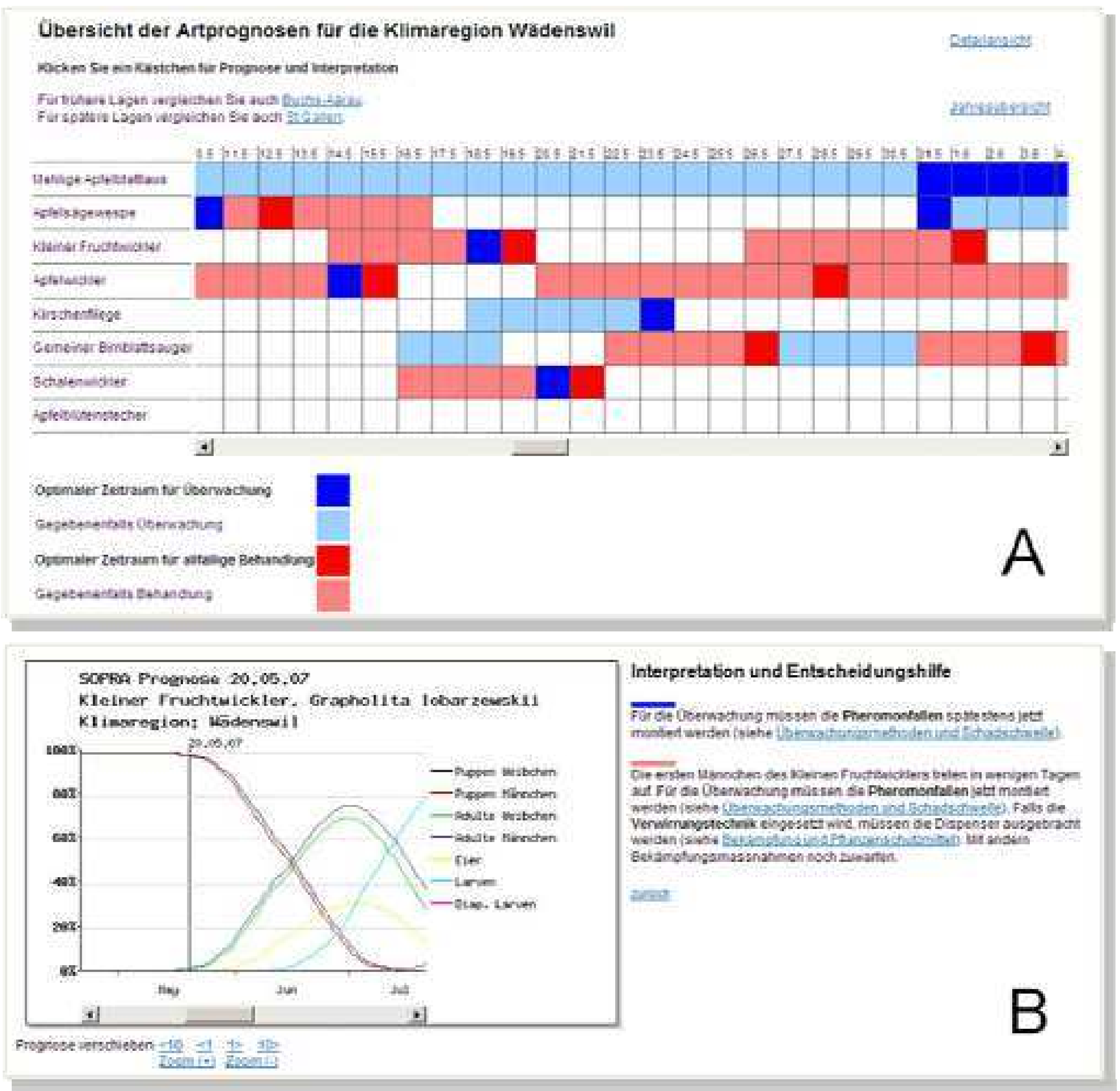

Fig. 8. Screen-shots of the web-based decision support system SOPRA with a tabled overview of all pests at one location (A) and graphical output of the relative age structure of the pest populations (B, left) and according verbal interpretation (B, right) of monitoring options (blue) and plant-protection measures (red).

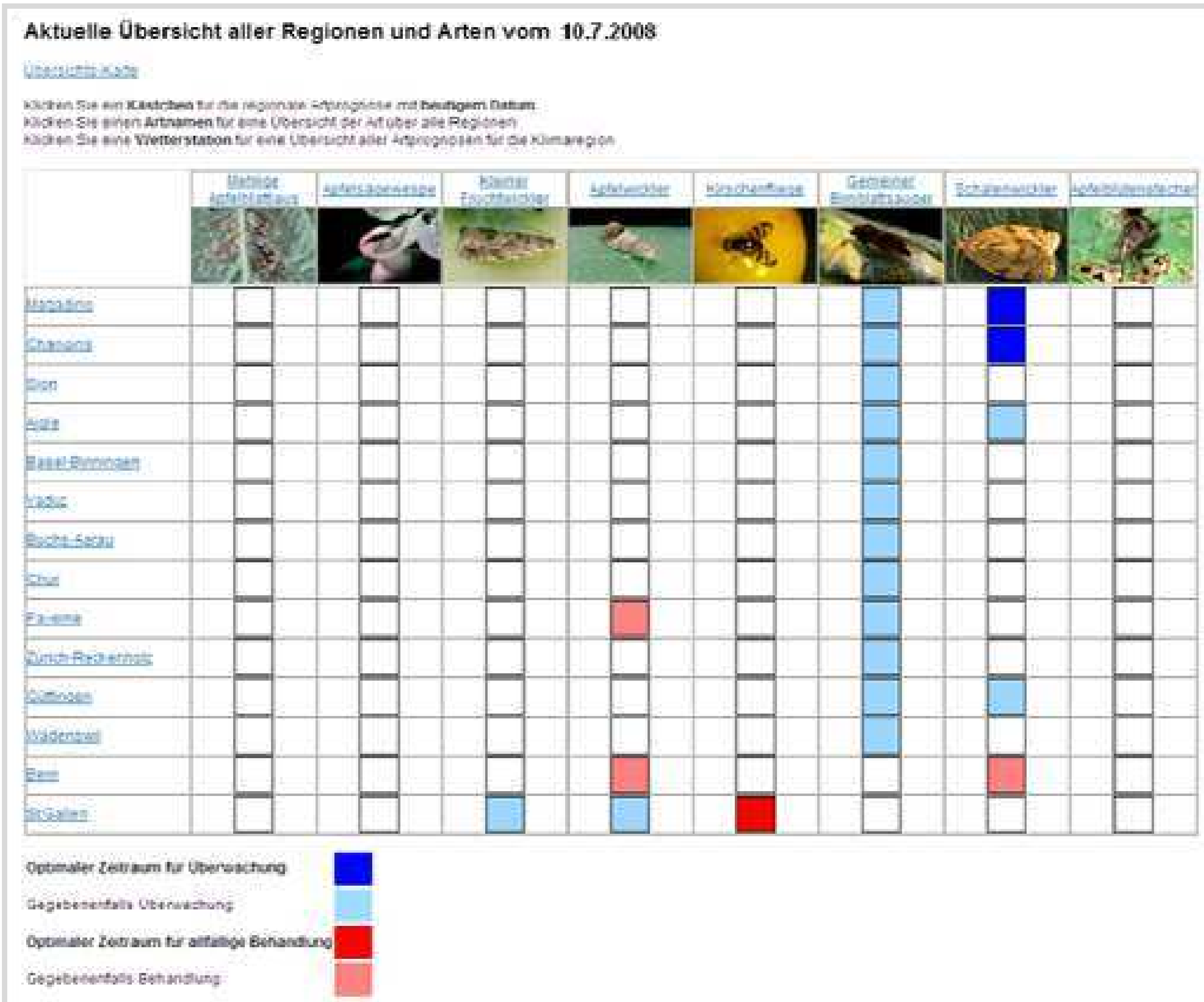

Fig. 9. Current-day alert status for all climatic regions and species in the web-based decision support system SOPRA with colour code for of monitoring options (blue) and plant-protection measures (red). Dark colours stand for optimum times for intervention; light colours pre- and post warning times.

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 its variability between certain regions. Again the table with colour coded alert status can be scrolled through the entire year or zoomed out for overview. Table cells with the region/ day combination also lead directly to the core of the decision support system with graphical output and according verbal interpretation.

6. 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 MS 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 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.

Spatial resolution of forecasts of course depend 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 air temperature measurements (cf. Sacchelli et al., 2008). 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. Nevertheless, interpolation of precise weather data could improve the local application in future.

SOPRA has been successfully applied now for about nine years as a reliable tool for recommendations in apple pests on local and regional scale in Switzerland and also in southern Germany. Since 2007, the system was also implemented for the major pests in cherry and pear, European cherry fruit fly and European pear psylla. In 2008, Apple blossom weevil and Summer fruit tortrix were added. The recently validated models for the European red spider mite and Plum tortrix are intended to be online during 2011 and further extensions are planned for the future.

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

7. Acknowledgments

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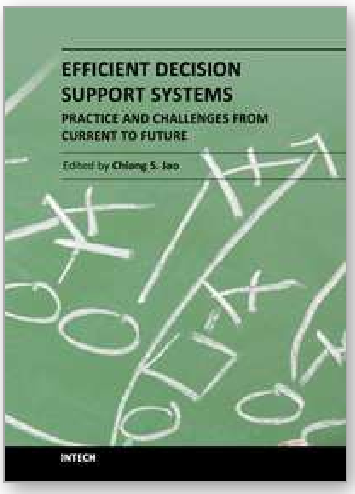

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