WAMS - an adaptive system for knowledge acquisition and decision support: the case of *Scaphoideus titanus*

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Abstract: WAMS (Wireless-sensor-network-based Adaptive Management System) is a pest control tool that makes continuous use of weather and pest monitoring information for the dual purpose of improving the knowledge on pest systems and ameliorating pest management decisions. It operates at the interface between research and pest management, establishes a close-loop between monitoring, management and analysis of systems, and automatically improves the reliability of pest control relevant predictions as soon as additional information becomes available. Population models, based on time-varying distributed delays, are at the core of WAMS. The paper identifies some important WAMS features, evaluates the predictive capabilities and its alert mechanisms as satisfactory, and reports some preliminary experiences that reveal advantages and benefits in the areas of (*i*) knowledge improvement and (*ii*) control rationalization. The preliminary experiences also point to some drawbacks and shortcomings related mainly to (*i*) the need of a continuous engagement of actors (growers, extensionists, applied entomologists) and *(ii)* the importance given to the vector in the case of the case of an economically relevant pathogen-vector-host plant system.

Key words: integrated control, historical temperatures, real-time temperature, pest monitoring, auto-adaptiveness, decision support system, wireless sensor networks

Introduction

In this paper, we present WAMS (Wireless-sensor-network-based Adaptive Management System), which is a pest control tool that is currently developed within a research project called "SMART VINEYARD" funded by the Swiss Federal Commission for Technology and Innovation (Project 11307.1 PFES-ES). This project addresses the challenge of developing and implementing a decision support system that predicts the infestation patterns of *Scaphoideus titanus,* vector of the pathogen that causes the Flavescence dorée (FD) disease of grape vine, and serves for the timing of insecticide applications and the organization of monitoring activities.

Motivation

The main motivation behind this project is the lack of reliable models for explaining and predicting infestation patterns of *S. titanus*, and setting-up a reliable monitoring system. Moreover, the traditional methods currently applied for monitoring *S. titanus* development in the field are very complex and expensive. In particular, activities like measuring and considering temperatures in forecasts, sampling of field populations and managing the observations in the laboratory are time consuming, require considerable human resources and yield appreciable uncertainties (Jermini *et al*., 2013).

With this work, we aim to manage, well in advance, the planning of management operations, i.e. insecticide applications and monitoring activities, in vineyards located in

Southern Switzerland. The complexity of the population system under study and management and of the integrated control system, both associated with a high degree of uncertainty are the rationale for adopting adaptive management (AM) (McFadden *et al*., 2010; Jermini *et al*., 2013).

Goals

The goals of the "SMART VINEYARD" project are multiple. First of all, we aim to combine research and management activities in order to develop an Adaptive Management (AM) system for *S. titanus* populations control (McFadden *et al*., 2010; Jermini *et al*., 2013). According to Comiskey *et al*. (2000), adaptive management is a systematic process for continuously improving management policies and practices by learning from the outcomes of experiences (Jermini *et al*., 2013). Second, we intend to adapt the actions to the current vineyard situation by means of a continuous dialogue between users and the system to be monitored and managed. Third, the software tool has to provide time windows estimations of critical phenological events. In this project, we calibrated the tool in order to validate it in response to the need of Canton Ticino, Southern Switzerland, where vine growers make use of IGR (Insect Growth Regulator) insecticides (Jermini *et al*., 2007). Last, but not least, it is important that the tool is able to auto-adapt with the goal to make, in an automated way, the appropriated corrections of the model, like adapting the values of the model parameters, so to optimize the software algorithm for the next season.

By making use of WAMS, end-users (i.e. vine growers, phytosanitary services, scouts) are given the opportunity to enter into a continuous dialogue with the agro-ecological system, i.e. to operate in a cycle of system monitoring and data processing, and to adapt the actions to the current situation in their vineyards. They have the possibility to follow a protocol and interact by means of a web-based application with the central unit that is charged with the forecasting ecological events and the improvement of the predictive and the explanatory capabilities of WAMS.

Scope of the paper

The uncertainties associated with population parameters (development, mortality, fecundity) and with sampling field populations have been discussed by Rigamonti *et al*. (2011a, 2013). Jermini *et al*. (2013) present the rationale and the characteristics of the AM strategy adopted in this project. The purpose of this paper is to identify some important WAMS features, to evaluate the predictive capabilities of the system and to report the first experiences with the adoption of the WAMS for *S. titanus* control in Southern Switzerland.

Material and methods

WAMS components and functionality

WAMS is composed of:

1. a dedicated Wireless Sensor Network (WSN), distributed in the vineyard for measuring temperatures relevant for pest development;
2. a set of proprietary software implementing:
   - phenology models for predicting infestation patterns of *S. titanus*;
   - the auto-adaptiveness of the system based on machine-learning techniques;
   - a customizable Web Platform for data visualization and analysis.

As shown in Figure 1, the WSN (1) collects temperatures relevant for *S. titanus* development and uses them to drive a software algorithm forecasting the development of

S. titanus (Rigamonti *et al*., 2011a) (2). Once a pest control relevant life stage is reached or a monitoring activity has to be initiated, the system sends an alert message to the end-user (3), who will react according to the message (4). Then, the end-user will communicate his/her feedback to the system, by means of the web-based application (5), so that the system will adapt itself taking into account such an information. Importantly, an explanation of the auto-adaptiveness of the system, based on machine-learning techniques, and a detailed description of the customizable Web Platform for data visualization and analysis goes beyond of the scope of this paper and will be reported elsewhere.

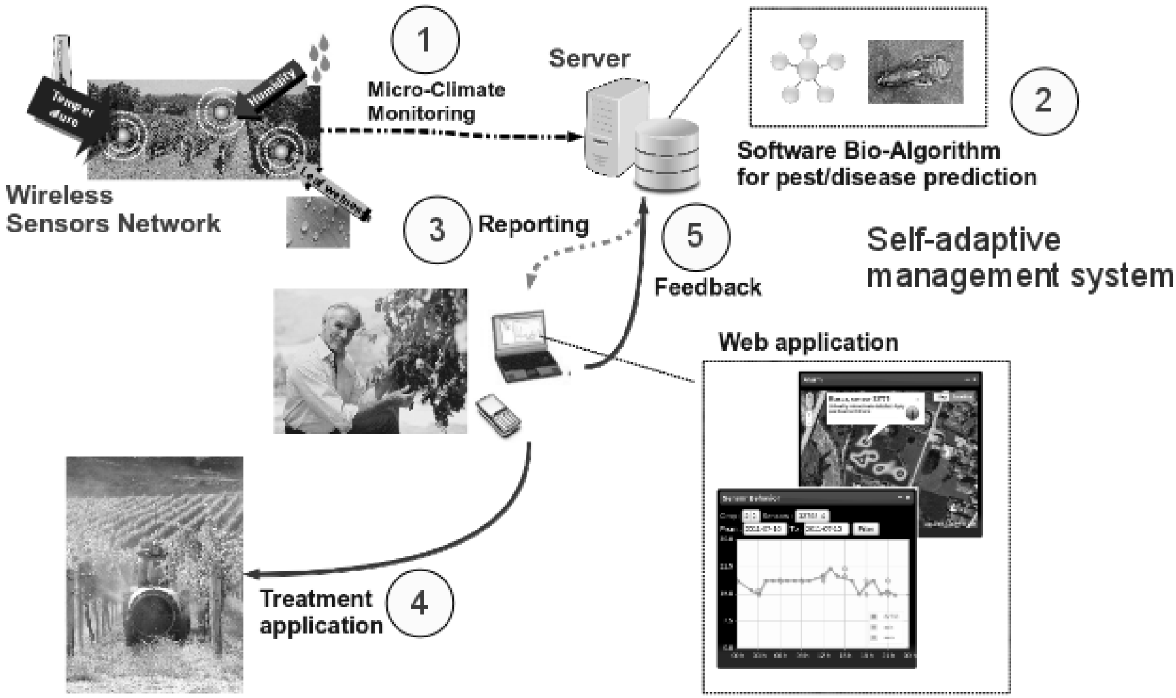

Figure 1. Representation of WAMS adopted to control *Scaphoideus titanus* in Ticino vineyards (Southern Switzerland) within an adaptive management framework.

In- field validation

WAMS has been tested in the Canton of Ticino, Southern Switzerland, where the control of the FD vector, *S. titanus,* is mandatory. During the two-year project, we monitored three vineyards by collecting hourly temperatures by means of wireless sensor networks installed in vineyards located at Biasca, Camorino and Contone (Figure 2). Moreover, we also made use of historical weather data recorded by MeteoSuisse at the weather station in Cadenazzo.

In each of the three vineyards, we deployed at least two sensor nodes (four in Biasca) at the level of trunk shoots (height of 40cm from the ground, Figure 3) and within the canopy (150cm from the ground, Figure 4). We chose two different heights because egg development occurs at 40cm, and the third instar nymphs, relevant for insecticide applications, are detectable at 150cm.

Historical temperature data and real time temperature measurements drove the phenology model and predicted the management of relevant events, i.e. the beginning of egg hatching, the occurrence of third instar nymphs and the emergence of adults. Machine learning techniques are used to change the phenology model parameters in relation to temperatures and monitoring information. After April 15, historical temperatures are continuously substituted by real-time temperatures, with the goal to define time windows estimations for event predictions. 10 days before the predicted egg hatching, predictions are made on the basis of current data until this day and using different sets of historical data thereafter. The earliest and the latest predictions of egg hatching define the time window. Similarly, in the case of L3 occurrence, the time window was defined according to predictions made at the moment of the first L1 observations. Finally, to enable the extension service to organize monitoring activities and the growers to prepare insecticide applications, WAMS generated and sent out alert messages with the predicted dates of the phenological events.

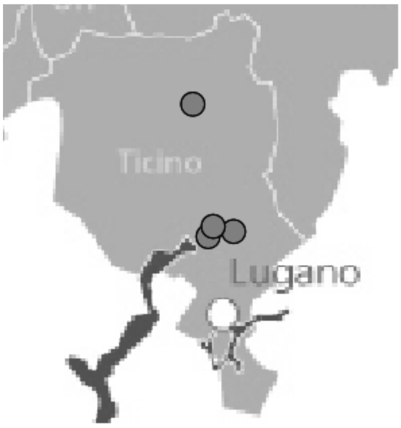

Figure 2. Pilot vineyards locations in Canton Ticino, Southern Switzerland (grey circles).

Figure 3. Recording of real-time temperatures driving the *S. titanus* phenology model. Sensor node at 40cm for recording temperatures relevant for egg development.

The techniques for monitoring the in-field presence of the nymphal instars were:
- First instar nymphs (L1): by means of a visual inspection of canopy leaves (prior to 2011) and trunk shoot leaves (2011).
- Third instar nymphs (L3): by means of a sucking device (D-Vac) and of the beating tray method (at the canopy level).

Figure 4. Recording of real-time temperatures driving the *S. titanus* phenology model. Sensor node at 150cm for recording temperatures relevant for nymph development.

Results and discussion

L1 prediction (egg hatching)

In Table 2, we show four columns for each installation and for the data acquired by using the MeteoSuisse weather station. Next to the column describing the installations, we are presenting the time window estimations. In the column "L1 computed" we show the computed date (for MeteoSuisse installation, only) starting from January 1st, which was the starting computation date of an older version of the model. Under "L1 observed", we indicate when the first L1 were observed in the field by means of the visual control technique. The last column reports the difference in days between the observation of L1 and the beginning of the computed time window. As we can observe, the time window estimation was clearly missed with an error rate between 5 to 11 days. However, the fact that the first alert message was sent out on April 29, allowed the scouts to start their daily inspections in all the fields. In this way it was possible to observe the premature appearance of the first egg hatching in all vineyards, which in our opinion, can be explained by two main aspects:

- the high temperatures at the beginning of April 2011, *i.e.* at the end of the assumed diapause (Rigamonti *et al*., 2013).
- the sampling method was unreliable prior to 2011.

For supporting the first aspect, Table 1 shows that the average temperature, measured during the first 14 days of April, was higher than in previous years, and specifically 7°C higher than in 2010.

Table 1. Mean temperatures at Cadenazzo (Southern Switzerland) during the first 14 days of April 2011 in comparison to previous years (source: MeteoSuisse).

2005	2006	2007	2008	2009	2010	2011
10.8°C	10.6°C	13.5°C	10.3°C	13.3°C	9.4°C	**16.4°C**

With respect to the second aspect, the model was validated with observations on L1 made in the canopy, producing unsatisfactory results. This is explained by the preference of L1 for trunk shoot rather than canopy leaves (Rigamonti *et al.*, 2013). Hence, the here reported validation with the 2011 observations on trunk shoot leaves is seen as progress made in the AM framework. The differences in days are still between 5 to 7 which corresponds to the error (Delta) reported in Table 2.

However, as the scouts were asked to immediately communicate L1 observation dates, WAMS was able to automatically adapt and immediately start the computation of the L3 time window estimation (Table 3).

Table 2. The prediction of first instar (L1) *Scaphoideus titanus* occurrences in Ticino (Southern Switzerland) vineyards using data measured in three pilot vineyards and by the MeteoSuisse weather station.

Installation	L1 Time Window (from April 15th)	L1 computed (from January 1st)	L1 observed (Visual control)	Delta [days]
Biasca	May 12 – 19 (alert sent on May 3)	N/A	May 6	- 6
Camorino	May 11 – 19 (alert sent on May 2)	N/A	May 3	- 8
Contone	May 8 – 18 (alert sent on April 29)	N/A	May 3	- 5
Cadenazzo (MeteoSuisse)	May 14 (computed)	May 6	May 3 (Camorino/Contone)	- 11 / - 3

L3 prediction

In Table 3, we show four columns for each installation and for the data acquired by using the MeteoSuisse weather station. Next to the column describing the installations, we are presenting the time window estimations. In column “L3 computed”, we show the predicted dates. The two “L3 observed” columns indicate when the first L3 were observed in the field by means of the D-vac method and the beating tray technique. The last column reports the difference between the days on that L3 instars were observed and the beginning of the computed time window.

Once L1 was observed and the date reported in the system database by the scouts, WAMS immediately computed the time window for the estimated appearance of L3, which has been observed, at this stage in project execution, by the beating tray and D-vac methods. These methods allow the collection of nymphs and their examination in the laboratory to determine the instars. The absence of L3 observed by means of the beating tray method (Table 3), which was performed at the canopy level, it's not surprising. In fact, early instars have a tendency to colonize the inter-row vegetation (Trivellone *et al*., 2011). The distribution of L3 and their higher mobility in comparison with L1 makes the sampling of L3 difficult. Nevertheless, the time window was quite satisfactory since the error rate was between 0 and 3 days only. This result shows that the warning message, generated by WAMS when L1 life stages appear, is reliable and helpful to plan the beginning of the control by means of IGRs.

Table 3. The prediction of third instar (L3) *Scaphoideus titanus* occurrences in Ticino vineyards (Southern Switzerland) using data measured in the three vineyards and by the MeteoSuisse weather station.

Installation	L3 Time Window estimation	L3 computed	L3 observed (D-vac)	L3 observed (Beating Tray)	Delta [days]
Biasca	May 25 – June 1	May 23	None	None	N/A
Camorino	May 23 – 31	May 22	June 3 (only one L3)	None	+ 3
Contone	May 23 – June 1	May 21	May 25 (only one L3)	None	0
Cadenazzo (MeteoSuisse)	May 23 – 31 (Contone)	May 24 (Contone)	June 3 / May 25 (Camorino/Contone)	N/A	+ 3 / 0 (Cam. / Cont.)

Preliminary experiences

Advantages and benefits are:

- the continuous engagement of end users (growers, extensionists, scouts, applied entomologists);
- the calculation of the time window, to plan insecticide applications, generated on the basis of information on egg hatching;
- the efficient use of existing knowledge and continuous improvement of the system by means of machine learning techniques;
- the possibility of extending the WAMS to other pests in vineyards or other crops and modifying it to deal with population dynamics rather than phenological events. With adaptations in the software algorithms, WAMS could be used in other wine growing areas.
- ameliorating the allocation of the resources used for monitoring activities by using reliable sampling plans (Rigamonti *et al*., 2013);
- improving supervised pest management with respect to the use of pesticides and the number of treatments.
- making use of an evolving tool based on event prediction;
- establishing a continuous interaction between end users and vineyards;
- using efficiently existing knowledge;
- an effective timing of insecticide applications (in Switzerland: Insect Growth Regulators (IGR) based on egg hatching);
- ameliorating resource allocation;
- rationalizing pest management;
- improving the knowledge on both the *S. titanus* population dynamics and the control system.

Drawbacks and shortcomings are:

1. end user training required;
2. continuous engagement of end users needed;
3. low reliability in case of no reference vineyards;
4. importance given to the vector rather than to economically relevant pathogen-vector-host plant system.

In conclusion, a dedicated Wireless Sensor Network (WSN) and phenology models for predicting the infestation patterns of *S. titanus* are important WAMS components. The predictive capabilities and the performance of the WAMS are satisfactory. The WAMS has advantages and benefits in the areas of (*i*) improving knowledge and (*ii*) rationalizing of control. Drawbacks are mainly related to (*i*) the need of end-users engagement (growers, extensionists, applied entomologists) and *(ii)* the importance given to the vector in the case of an economically relevant pathogen-vector-host plant system.

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