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Pest management control of olive fruit fly (*Bactrocera oleae*) based on a location-aware agro-environmental system

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ABSTRACT

This paper investigates the effectiveness of a mobile agro-environmental Location Aware System (LAS) in ground spray applications against olive fruit fly, under real conditions. It aims to the specific needs of pest management control, by means of combining the olive fruit fly population dynamics, the meteorological conditions during the sprayings, the spatiotemporal characteristics of the spraying areas, as well as the environmental sensitive and inhabitant areas located near the spraying areas. From a moderate-scale field experiment conducted for evaluation purposes, the duration of sprays, the amount of spray solution applied and efficacy were statistically analyzed. Results show that the LAS is able to reduce the amount of spraying solution by performing sprays only when and where are really needed. The protection of environmental and inhabitant areas is also achieved, by avoiding off-target sprays. The LAS is able to decrease the duration of the sprayings, minimizing their cost and the possibility of canceling a spray application due to meteorological conditions. The acquisition of the spatiotemporal data during the sprays is able to provide agrotraceability systems with useful information about the olive products. In conclusion, the proposed LAS is shown to be a useful tool for olive farmers, scientists or organizations that can increase the efficacy and decrease the cost of moderate scale pesticide treatments from ground and avoid effects on environmental protected or domestic areas.

1. Introduction

1.1. Discussion of the problem

Olive fruit fly (*Bactrocera oleae* or *Dacus oleae* (Gmelin), Diptera: Tephritidae) is the most serious insect pest of the cultivated olive (*Olea europea* L.) fruits in the world (Economopoulos, 2002) and affects the olive tree cultivation causing serious qualitative and quantitative consequences with economic impacts and monetary losses (Neuenschwander and Michelakis, 1979; Economopoulos et al., 1986). Without treatment and under optimum climate conditions for the development of the olive fruit fly, the insect is able to infest more than 90% of olives in untreated orchards (Athar, 2005; Kapatos and Fletcher, 1984). Olive fruit flies survive best in more humid climates. Also, they infest fruits in olive trees that are grown in dry regions. According to Kapatos and Fletcher (1986) the olive fruit fly survives best in cooler coastal climate, but is also found in hot, dry regions. The optimum temperature for the insect development is between 20 and 30 °C. In practice, the air temperature during the spraying process must be between 12 and 28 °C and the wind speed must be less than 28.8 km/h. High wind speed inhibits the insect flights. Because of this, the olive fruit flies are not fed by the sprayed solution and survive.

The control of *B. oleae* remains almost exclusively based on insecticides, particularly organophosphates (OPs) (Roessler, 1989). Bait sprays with OPs from the ground have the ability to inflict high insect mortality rapidly, and are the most common and effective form of treatment in cases that the insect is very noxious. Dimethoate is an OP used in bait-pesticide sprays in order to control adult olive fruit fly populations. However, it is harmful and irritating to humans, dangerous for the environment, very toxic to bees (*Apis mellifera* L.), harmful to animals, birds and aquatic organisms. Nowadays, bait sprays cover large areas and can be applied by high-pressure sprayers, mounted on tractors. In theory, ground spot sprays are performed once every 2, 3, or even 4 rows of trees. Baits are developed for spray application on a small part of foliage, "spot spraying" (Haniotakis, 2005). However, in practice, a large portion of the tree canopy is sprayed as tractors move between rows of trees. People, wildlife, and the environment are exposed to the spray drift from off-target sprays, leading, to health and environmental effects and property damage. This paper focuses to the prevention of inappropriate sprays,

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to the minimization of the pesticide applied and to the reduction of olive fruit fly population.

The extensive use of insecticides and off-target sprays lead to environmental and public health problems. Inappropriate sprays may occur for many reasons. For example, during the spray applications, the sprayer attendants may not be able to memorize the areas to be sprayed, and/or may not be aware of the areas that must not be sprayed (i.e. domestic or environmentally protected areas, biological cultivations). Air temperature, wind speed and air humidity levels in the spraying area are critical for the continuation of the spraying. During spray applications the values of these critical parameters should not exceed a certain threshold. If a parameter exceeds the optimal threshold in local level, then the adult flies, which are the target of the spray applications, can fly and seek nearby locations. Although the above issues that arise during spray applications are well known to the sprayer attendants, in practice and without the aid of computer and communication technologies, there is limited chance to avoid them. Usually, the sprayings cover large areas. Thus, it is difficult for the tractor attendants to memorize their spraying areas, and as a result over or under spraying may occur. In addition, the spraying attendant cannot determine the spray volume per area and is not aware of the areas which must not be sprayed. As a result, over, under or off-target sprayings can be performed, leading to quality reduction of olive oil and table olives and producing negative consequences to the environment, and to humans.

1.2. Related work

Location aware (LA) systems are nowadays popular in multiple everyday applications (Raper et al., 2007). In agriculture, LA systems have not yet attracted the necessary attention and their use is rare. Instead of LA systems, GIS, ES and DSS have been used in agriculture applications to assist farmers in their work.

Several attempts have been made to develop decision support systems (DSS) and ES for optimizing agriculture operations. DSS and ES systems have been developed for weed control (Macé et al., 2007), irrigation (Srinivasan et al., 1991; Lilburne et al., 1998; Bergez et al., 2004), fertilization (Lewis et al., 2003; Bonfil et al., 2004) and pest management (Ellison et al., 1998; Mahaman et al., 2002; Wharton et al., 2008).

In a similar weed spraying system Zaman et al. (2011) have developed an automated prototype variable rate (VR) sprayer boom for site-specific application of agrochemicals on weeds. This type of VR sprayer does not use prescription maps, but relies on sensors to provide real-time weed detection information which is used to dispense correct agrochemical rates for the weeds. In a similar system, Loghavi and Behzadi Mackvandi (2008) developed a target oriented weed control approach by integration of differential global positioning system (DGPS), GIS, and solenoid-activated spray nozzles in response to signals generated by a displacement sensor. Targeted weed patch herbicide application resulted in 69.5% saving compared to the conventional application (uniform spraying).

In a pest management problem similar to the olive fruit fly problem, Cohen et al. (2008) developed a spatial decision system for monitoring the Mediterranean fruit fly (*Ceratitis capitata* (Wied), Diptera: Tephritidae) on citrus. Their system provides recommendations to the coordinators' decisions in order to reduce the number of unnecessary spray actions and the number of sprayed plots. However, this system does not solve the problems that may arise during the spraying process.

Spraying applications against olive fruit fly depend on meteorological conditions that are rapidly alternated during time; in these cases GIS, ES or DSS are inadequate to provide a solution. The involved personnel should be informed constantly about the meteorological conditions of their area of application. In addition, if spraying of an area has been performed even 1 min ago by another person, the current personnel should be informed and aware. To avoid the aforementioned problems during the spraying control of olive fruit fly, Pontikakos et al. (2010) proposed a mobile agro-environmental Location Aware System (LAS) for ground spray applications against olive fruit fly. The above paper focused mainly to the software and database architecture and included limited experimental results. In this paper, we continue the research of Pontikakos et al. (2010) in order to evaluate the efficacy of the LAS, the pesticide solution application and the spraying process.

1.3. Aim of the project

The main objective of this paper is to investigate under real conditions, the effectiveness of the LAS proposed by Pontikakos et al. (2010), towards environmental and pest management optimization. The general components of the concept of the agro-environmental LAS are described below:

- *Efficacy and low cost*: Efficacy increase and cost reduction of spray applications from ground against olive fruit fly can be achieved by limiting sprays to a minimum requisite. Monitoring regularly the olive fruit fly population as well as the meteorological conditions, the infestation risk per olive cultivation area can be determined. Thus, applying the insecticides accordingly, the infestation risk ensures the optimum sprayings performance, mainly because over or under spraying is avoided.
- *Environmental protection*: During spray applications, the necessary safety precautions should be followed in order to avoid spraying environmentally sensitive areas such as water courses and protected ecosystems.
- *Inhabitant protection*: During spray applications, the necessary safety precautions should be followed in order to avoid applications near domestic areas such as hospitals or playgrounds.
- *Agro-traceability considerations*: Traceability adds value to the overall quality management system by providing the communication linkage for identification, verification and isolation of non-compliance sources to agreed standards and customer expectations. Agro-traceability simply refers to the collection, documentation, maintenance, and application of information related to all processes in the supply chain in a manner that provides guarantee to the consumer on the origin, location and life history of a product. In the case of spraying applications against the olive fruit fly, traceability refers to the ability to identify the specific farms or the olive trees where sprayings were conducted.

The developed framework is based on regulations concerning the agricultural practices, focuses on the integration of these regulations with new technologies and facilitates the collaboration of the users who participate in the spray applications. This framework also adopts today's Integrated Pest Management (IPM) framework, by means of an effective and environmentally sensitive approach that relies on a combination of common-sense practices. IPM programs monitor pests and identify them accurately, so that appropriate control decisions can be made in conjunction with action thresholds. In the case of olive fruit fly, McPhail traps (McPhail, 1937) with various baits are the standard traps for monitoring insect populations (Burrack et al., 2008). This monitoring and identification, removes the possibility of using the wrong pesticide, or a pesticide that is not really needed. The general concept of the developed agro-environmental LAS for ground spray applications against olive fruit fly is illustrated in Fig. 1.

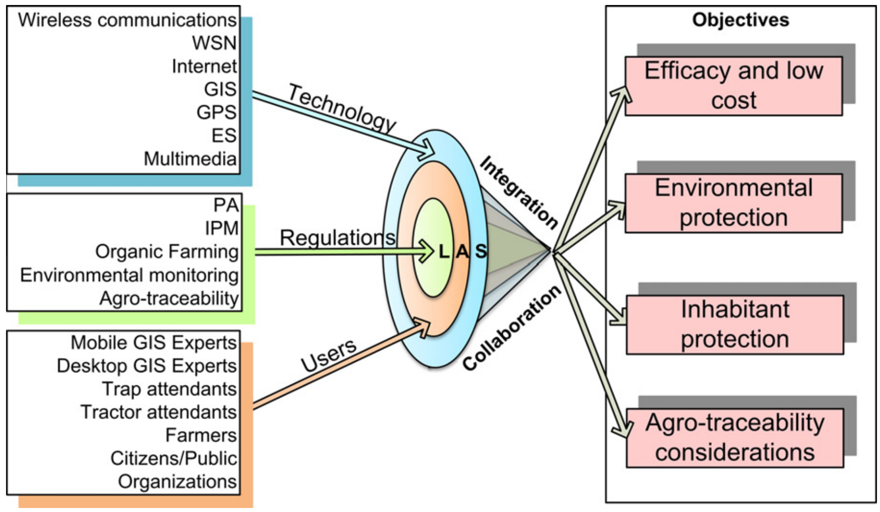

Fig. 1. The general concept of the agro-environmental LAS.

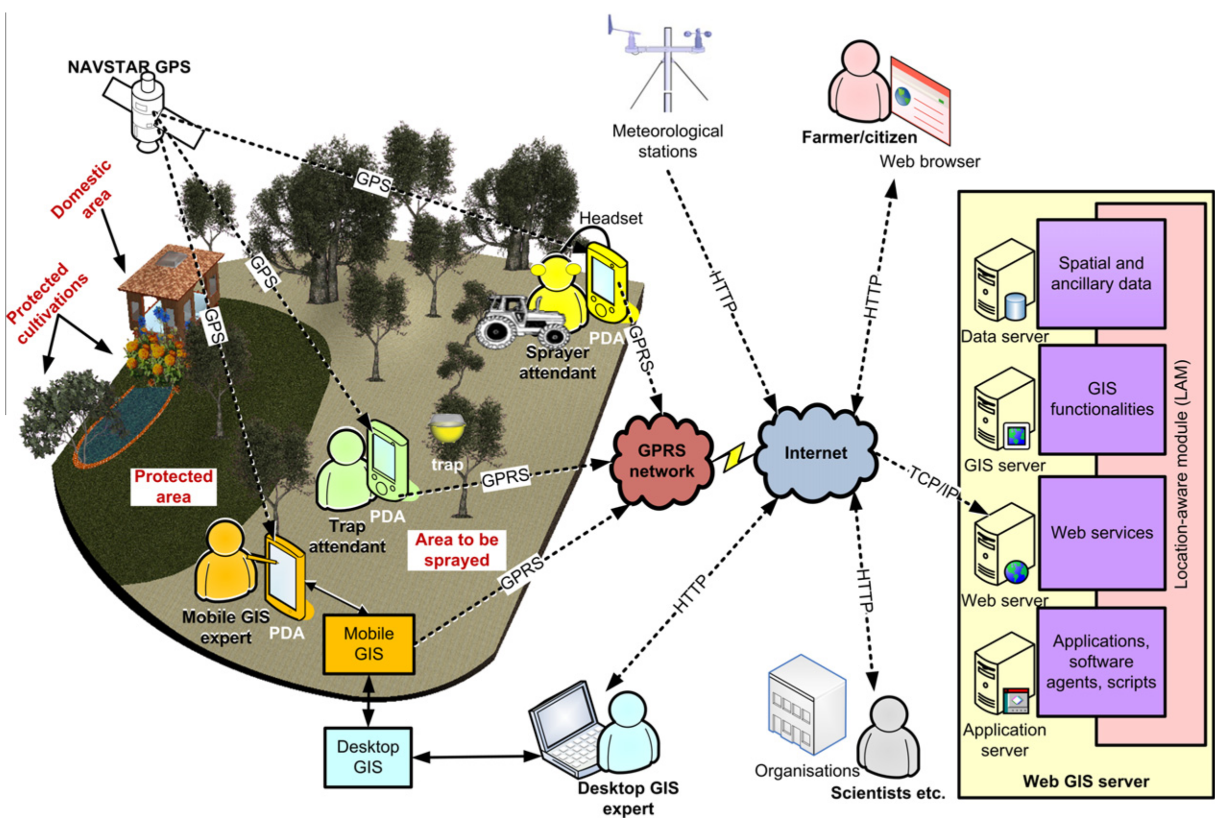

Fig. 2. LAS architecture.

2. Materials and methods

2.1. System architecture

The architecture of the developed agro-environmental LAS is presented in Fig. 2. It adopts the client–server architecture that utilizes web services, and integrates GIS, ES and multimedia technology in order to develop and implement spray management services, suitable for the control of the olive fruit fly. It is able to gather data in a systematic way, making it available for further in-depth analysis, and report the current environmental conditions, as well as foresee and warn about potential problems during the spray process. The GPS can be used by the sprayer attendants to find their position, or by the trap attendants to locate the insect traps.

In a simplified version, the LAS prototype relies on a three-tier architecture composed by the client layer, the application layer, and the database layer. Each level and the required technologies for each layer are described:

- *The client layer*: The client layer enables data-input and analysis functionality in order to provide the ability to input, edit and annotate data locally and/or over the Internet. As the sprayer and trap attendants navigate within the mobile GIS, the position and orientation of the attendants is displayed on a geo-referenced digital map of the area, using Arcpad 7.2 and VBscripts. The mobile GIS is carried out using a PDA with Windows Mobile 5 equipped with a GPS receiver that determines the position of the device. The device also has a GPRS network connection for requesting and transmitting data to and from the application server. Due to the limitations and the relative high cost of the GPRS services, the LAS optimizes the transmission of the available data using local data sets and offline functionalities. This information is transmitted over a mobile phone network.

- *The application layer*: The application layer is where all the processing and distribution of the gathering data takes place. Since all communications between the client layer and the database is made through the application server layer the processing load is balanced, as each tier of the system resides on a separate machine. It is comprised by the following five main components:
  – *Data server*: Provides the appropriate data to the other components of the application layer. All spatial and ancillary data are stored to the data server. Spatial data refers to GIS resources such as maps, geodatabases, satellite images, GIS information layers, tracking paths, etc. Ancillary data refers to meteorological data, weather data, users' profile, tracking events, and user's authorization data. The data server was based on Microsoft SQL server express 2005.
  – *GIS server*: Provides the GIS functionalities and tools for the management of the spatial data. It converts the data, in order to be accessible from the Web to clients with different software and hardware resources and requirements. In our research we utilized the ESRI Web GIS server 9.2.
  – *Web server*: Provides sharing capabilities to the platform from GIS resources across the Internet, shares these resources by first hosting them on the GIS server, and allows client applications to use and interact with these resources. Also, it provides web services; it offers web functionalities to the clients and web-based collaborative applications, using standard technologies and communications protocols. We utilized IIS 5 as a Web server.
  – *Application server*: Provides a number of software agents which have been developed and included in the LAS, so as to invoke automatically the appropriate Web services for managing offline tasks. These applications were implemented using VB.NET 2005 and run on the Windows server 2003 Operating System.
  – *Location Aware Module (LAM)*: Responsible to automate the GIS functionalities, to synchronize the GIS server with the other components, and to support the system with real time capabilities. LAM is also responsible to authorize and authenticate the users and provides them custom functionalities, services and applications. Finally, it provides the tools for gathering data, communicating with the clients and facilitating the collaboration of the participants. This module was implemented using VB.NET 2005 and run on the Windows server 2003 Operating System.
    - *The database layer*: The spatial database layer of LAS is responsible for processing all the queries, both spatial and transactional, in the system. The database of the client and the server is based on SQL data-tables and ESRI shapefiles (.shp).

The communication between the client layer and the database layer is conducted through the application server layer.

2.2. User categories

Generally, six categories of users of the developed LAS can be identified: (a) Mobile GIS experts, (b) Desktop GIS experts, (c) Trap attendants, (d) Sprayer attendants, (e) Organizations and experts on the pest management and (f) farmers, landowners or citizens. In the following, a brief description of their role is given:

- *Mobile GIS experts*: Mobile GIS experts are specialized in GIS and are responsible for collecting and managing spatial and ancillary data. Mobile GIS experts are responsible mainly for collecting field data (farms, boundaries, domestic areas, environmental protected areas, the number of the olive trees of each farm and the position of each tree, the road network). Mobile GIS, together with mobile communications can provide location-aware monitoring data to support fieldwork, facilitating the collection of real-time agro-environmental data.
- *Desktop GIS experts*: The Desktop GIS experts are specialized in GIS design and analysis and are focused on processing and converting appropriate field data, creating the necessary geodatabases, analyzing the available information and managing the GIS. In many cases from the field data the Desktop GIS reproduce new data and GIS information layers. For example, using interpolation an infestation risk layer can be created, showing the insects captured in the traps of a pre-specified area. In other cases, satellite images of an area can be used instead of acquiring data on the field. The satellite images must first be edited using desktop GIS software. The clients could communicate with the server through wireless communication technologies (Wi-Fi, GPRS, 3G, EDGE) and TCP/IP protocols. The users of mobile clients can work in a disconnected mode without losing access to the application and spatial data.
- *Trap attendants*: Trap attendants are trained in identifying and count the olive fruit fly population in the field. In about every 5–6 days they refresh the water solution and count the male and female olive fruit flies of each trap. The measurement of the insect population is then sent to the pest management experts. With the mobile GIS component, which is installed to each trap attendant's pocket PC, the trap attendant downloads from the GIS server the GIS data and uploads the insect population per trap. Depending on the extension of each area, one or more trap attendants can be involved.
- *Tractor attendants*: Tractor attendants perform the spray applications from the ground using tractors equipped with handheld devices able to communicate with the mobile component of the LAS. The LAS consults tractor attendants on how, when and where to spray using maps, screen messages and voice commands. Tractor attendants follow the instruction of the LAS, so as to improve the efficacy of the control applications and avoid off-target sprays.
- *Organizations and experts on the biological cycle and pest management*: Their task is to decide where and when a spray control should be applied. They also monitor the spraying process to ensure compliance with the existing regulations.
- *Farmers, landowners or citizens*: Farmers and landowners provide information about the characteristics of their farm or land (i.e. size, location, and cultivations) to pest managers and GIS experts. Citizens that live nearby the spraying areas or any consumer of olive products can be informed for the spray processes in order to avoid any contact with the insecticide, or the spraying areas.

2.3. Spraying process

The spraying process takes place during the day using tractors. The pesticide solution is applied in a course spray or streamed to a small portion of the tree. There is no need to cover the whole tree, because the adult flies are attracted to the bait, feed on it and die. In practice, depending on the infestation and the meteorological conditions, two to four spray applications per year can be conducted. During ground spray applications the sprayer attendants cannot easily determine the current meteorological conditions, or the distance of protected areas from their current location, or the number of the olive trees per plot, and therefore cannot estimate easily the spray volume per plot that must be sprayed. In addition, the attendants are not aware of the restrictions concerning the spraying and non-spraying areas. The developed LAS integrates an ES module that assists the tractor attendant to take the appropriate decisions during each spraying. The ES module is installed on the tractor attendant's pocket PC integrated with a mobile GIS component. It provides the position of each tractor and takes location-aware decisions about the spraying process. The ES module utilizes the information about the coverage per plot, the olive cultivar susceptibility, the meteorological conditions, and notifies the attendant with an action such as: *Spray with density* 3, or *Spray every third tree*, or *Do not spray*. The detailed description of the decision process of the ES can be found in Pontikakos et al. (2010).

2.4. Study area

A moderate-scale experiment was conducted in order to evaluate the developed LAS. The experiment was carried out between July and October of 2008 in the municipality of Monemvasia in the Lakonia province (South-East Peloponnesus) of Greece. The meteorological data used on the experiment was gathered from the only official meteorological station located closed to the place of the experiment. For this experiment, three regions were selected. The experimental Regions (A, B and C) and the location of the meteorological station are shown in Fig. 3.

Maps of ground elevation are shown in Fig. 4, along with the slopes of the experimental regions that were used to exclude areas difficult to be sprayed using tractors. As it is illustrated, Region A has higher mean elevation compared to Region B, whereas Region B has higher mean elevation compared to Region C, which is located near the sea.

The experimental areas were chosen based on the following criteria:

1. The existence of infestation by the olive fruit fly 1 year before the experiment. The three chosen areas had infestation incidences 1 year before the experiment.
2. The existence of a near-by official meteorological station. The only available meteorological station in the area that could be utilized by the farmers for operations scheduling is illustrated in Fig. 3.
3. The existence of an official government program for the olive fruit-fly infestation management that can dramatically reduce the experimental costs.
4. The existence of different land uses except the olive cultivation, such as biological cultivation and residential areas in the field of the experiment. In this way, the system can demonstrate its capabilities for instructions and directives.
5. The experiment region should be isolated from other regions by natural obstacles such as mountains, hills, or the sea. Region A is isolated from B and C and other regions by hills. North of Region A lies a lowland without olive cultivation present. West of region B lies a land without olive cultivation present, while it is otherwise surrounded by hills. Region C is also surrounded by hill with the sea lying at east.

2.5. Experimental design

To evaluate the LAS, the following notation of treatments was used:

(a) *Treatment T0 – Untreated*: In this case no spray applications were performed. The untreated areas were used as a reference of the insect population dynamics. The population data were used to evaluate the efficacy of the treated areas.
(b) *Treatment T1 – Without LAS and without tracking*: In this treatment neither the LAS consultation, nor the tracking of the sprays were taken into consideration from the tractor attendants. The tractor attendants sprayed using their knowledge and empirical practices. These areas were tested for statistical reasons in order to evaluate the efficacy of the treated areas between the conventional spraying process and the proposed spraying process (with the LAS).

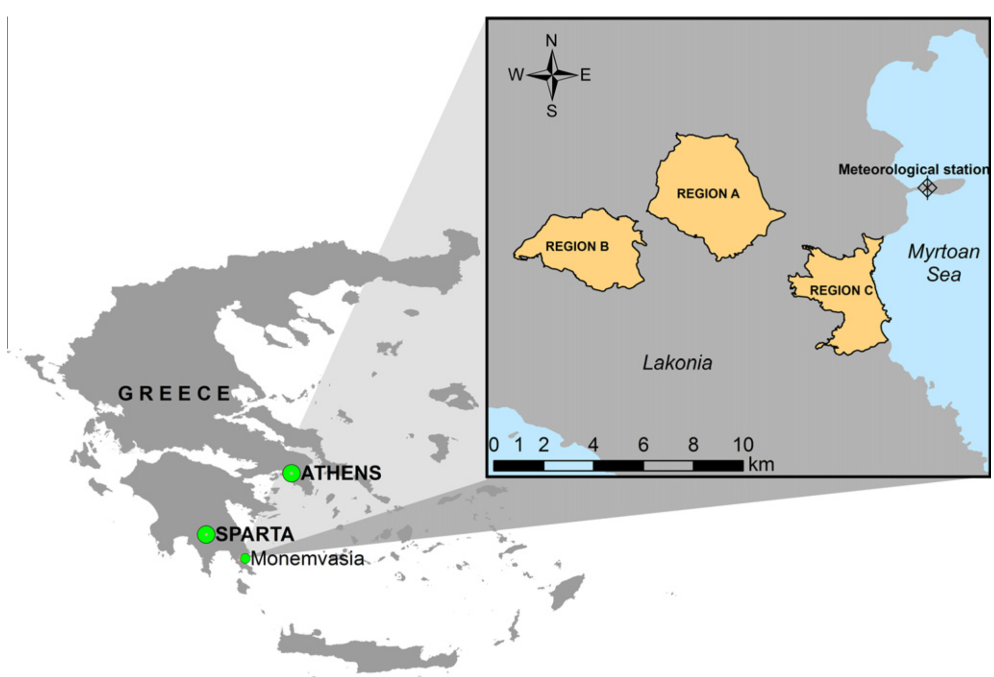

Fig. 3. The experimental regions along with the meteorological station.

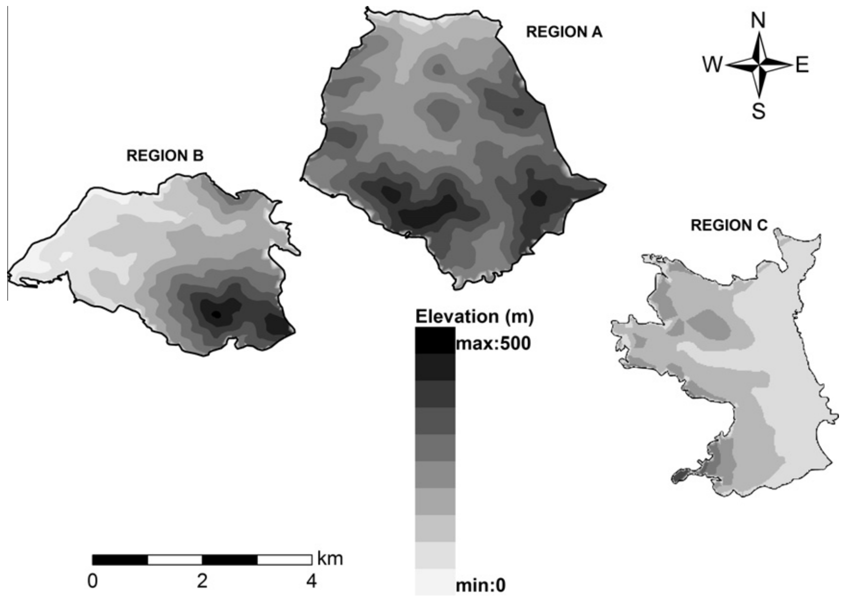

Fig. 4. Ground elevation of the experimental regions.

(c) *Treatment T2 – With Tracking*: In this treatment the tractor's path is recorded by a GPS and the distribution of the sprays is estimated using the LAS. However, the tractor attendants were not advised by the decision support system of the LAS. The tractor attendants sprayed with conventional methods using their knowledge and empirical practices. The tracking information is stored in the database of the LAS and is not visible to the tractor attendants. This information was utilized for comparison reasons between the conventional spraying process and the proposed spraying process (Treatment T3 – with the LAS).

(d) *Treatment T3 – With LAS*: In this treatment the tractor attendants took into consideration the LAS decisions and conducted the sprays, accordingly.

Each of the three Regions A, B and C were further divided in three sub-regions. The spray applications with different types of treatment that were applied in each sub-region or section of a certain region are shown in Fig. 5.

For each Region, one sub-region was used for monitoring the olive fruit fly population (treatment *T*0), another sub-region was used for spray application with treatment *T*1 and the last one for spray applications with treatments *T*2 or *T*3. Note that a spray application uses only a single type of treatment (*T*1, *T*2, or *T*3) and each sub-region, due to its size (number of olive trees) and the limitations of time (spraying process should be completed before air temperature increased), needs three tractors to be sprayed. Because of this, the cases of treatments *T*2 and *T*3 and their corresponding sub-region were further divided in three sections, with each section having about three thousand olive trees sprayed by one tractor. For each section, special characteristics such as cultivation density, cultivation variety, slope and land uses, have been utilized as GIS layers and taken into account by the ES. *T*2 and *T*3 were applied in the same sub-region but in different spray applications and time. Applying *T*2 and *T*3 in the same sub-region but at a different time period, it was possible to compare these treatments under the same spatial characteristics.

The experimental design and the performed type of treatment per spray application are shown in Fig. 6.

It must be taken into account that experiments on bait spray applications from the ground against olive fruit fly, in real conditions are expensive and difficult to perform. During the first spray

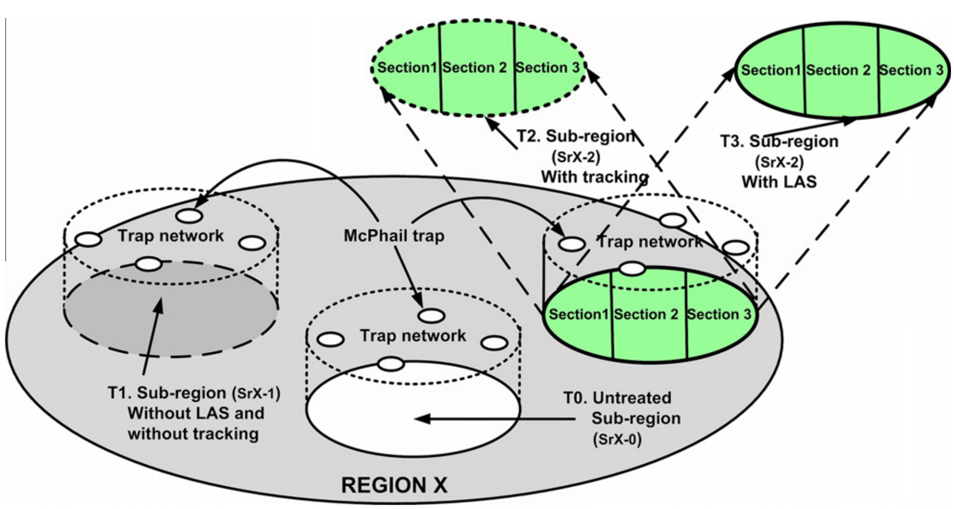

Fig. 5. The experimental treatments.

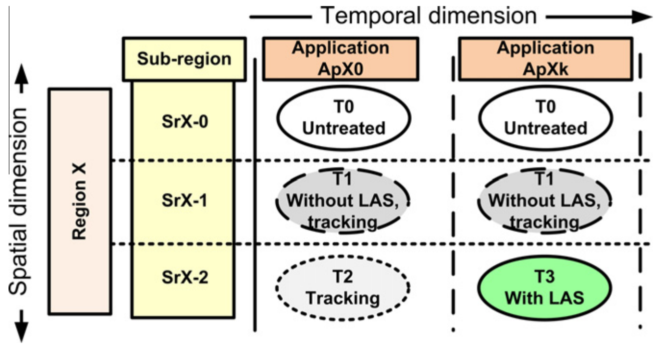

Fig. 6. The experimental design ($k \geqslant 1$: the number of spray applications after the 1st spray application).

application ApX0 that took place in Region X (where X: {A,B,C}), the attendant was not allowed to use the LAS (treatment *T*2). This application was the reference one. In the subsequent spray applications, ApXk (where $k \geqslant 1$) of the sub-region SrX-2 of the Region X, the attendant is able to consult the system in order to spray (treatment *T*3). The total number of spray applications in each region depends on the infestation level and the meteorological conditions prevailed in the region at the time of the experiment, as well as on the number of days before harvest. The applications with the LAS follow the application with tracking; otherwise the decisions recommended by the LAS will be recalled by the tractor attendants in order to be performed in the spray applications with tracking, making the comparison between these treatments unreliable. Note that when the tractor attendants use the LAS they do not have to remember how to spray because the system provides them with recommendation. The insecticide applied for each spray application (except in the untreated areas where no spray occurred) was dimethoate 400 g/l.

2.6. Data

The spatial data is stored locally and can be updated using appropriate commands. It is presented in the information layers and depends on the features of the created services and on the type of the application. A special type of an information layer is the tracking layer, which stores the position of the moving tractors in real-time. Ancillary data are the attributes of the spatial objects (points, polygons, and lines), the users' profile and actions, the system parameters, the sensing data and more. The interactivity of the GIS functionality is achieved by invoking commands (e.g. data updating, system management, browsing, multimedia management), which also use one or more information layers. The layers' data of the current position (where the sprayer attendant sprays) was combined with the current meteorological conditions and the insect infestation risk so that the ES can result to a decision about the spraying process. The GIS information layers that the system supports are the following:

- The *road network layer* showing the areas to be sprayed.
- The *olive tree cultivations layer* showing the plots of each section, namely, the areas covered by olive trees that need to be sprayed and the density of the olive trees in the spray areas.
- The *spray regions layer* showing the boundaries of the spray regions.
- The *tractor area layer* showing the sections designated to be sprayed by each tractor.
- The *environmental protected areas layer* showing the rivers, water courses, biological cultivations etc. that must not be sprayed.
- The *inhabited areas layer* showing the houses, villages, etc., including their buffer-zones that must not be sprayed.
- The *Points of Interest (POI) layer* showing the textual information and multimedia content for specific areas (i.e. protected areas).
- The *tractor's path layer* showing the recorded path by the GPS.
- The *sprayed points' layer* showing the tractor's position and the duration of the sprays.
- The *McPhail trap network layer* showing the olive fruit fly populations.
- The *meteorological data layer* showing the temperature, the relative humidity, and the wind speed.
- The *infestation risk layer* showing the infestation risk of any point of the sprayed area.

The classification of land uses and the experimental regions are illustrated in Fig. 7.

2.7. The McPhail trap network

Usually, the number of individuals caught in a trap cannot be directly translated to population density; however, they provide a good estimate of the insects' dispersion (Dimou et al., 2003). In all treatment cases of the experiment the adult olive fruit fly population was monitored by a network of McPhail traps filled with insect attractants baits of ammonia releasing salts and water. McPhail traps were placed in focal points, such as: gullies, valleys, irrigated spots, and generally in locations where humidity is maintained and temperature is mild. The traps were distributed in each experimental area of each region. Trained personnel (Trap attendants) monitored the traps about once a week, recorded the number of males and females per trap and imported the acquired data into the server using the mobile GIS and Web services. The McPhail trap network used for monitoring the olive fruit fly populations is shown in Fig. 8.

2.8. Statistical analysis

The required statistical analysis was performed using the Statgraphics Centurion XVI Version 15.2.11 statistical package for Windows. It performs two-way analysis of variance (ANOVA) in order to identify the significance in solution applied and the duration of the spray applications, as well as one-way analysis of variance (ANOVA) in order to identify the significance in olive fruit fly

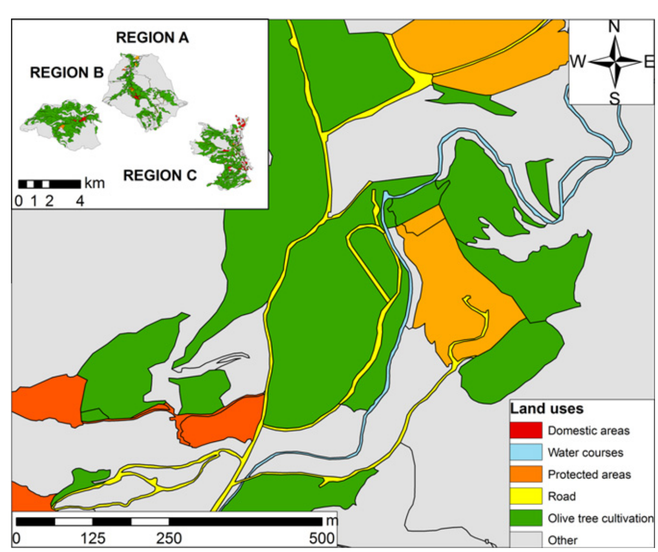

Fig. 7. The land uses of the experimental regions.

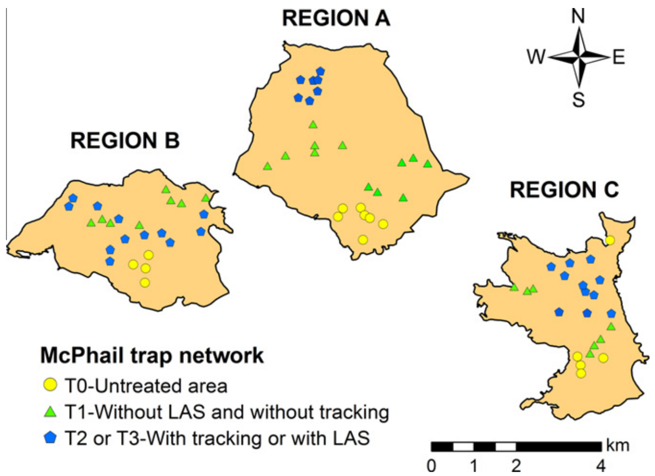

Fig. 8. The McPhail trap network for monitoring the olive fruit fly population.

population reduction of the adult olive fruit flies captured by the McPhail traps. In pesticide trials such as the spray applications against the olive fruit fly, some insects may die from natural causes. In such cases, it is required to work with the corrected population reduction of the insects. Corrected efficacy (%) in this experiment was computed using the Henderson and Tilton (1955) formula, which is a modified version of the Abbott (1925) formula. The formula of the corrected efficacy is given by the following equation.

$$\text{Corrected efficacy }(\%) = \left(1 - \frac{n \text{ in } T0 \text{ before spray} * n \text{ in } T3 \text{ or } T1 + T2 \text{ after spray}}{n \text{ in } T0 \text{ after spray} * n \text{ in } T3 \text{ or } T1 + T2 \text{ before spray}}\right) * 100$$

where n is the adult olive fruit fly population. Note that a P value smaller than 0.05 was considered to be statistically significant. Tukey's tests based on a 95% confidence level were used where significant differences were detected in the ANOVA.

3. Results and discussion

Three spray applications for each sub-region in Region A and two spray applications for each sub-region in Regions B and C were performed. These applications are illustrated in Fig. 9.

The temporal characteristics of the olive fruit fly population in Region A lead to conduct one more spray application at this region compared with Regions B and C. In Regions B and C the insect population decreased in acceptable levels after performing the first spray application and increased at alert level a long time after this application (64 and 77 days for Region B and C, respectively). For the Region A two spray applications were needed, 32 and 65 days after the first one, so as an acceptable infestation level to be achieved. The spray applications conducted for each region during the experiment are shown in Table 1.

As it has been pointed out the main meteorological factors that affect the olive fly population are the air temperature and humidity. Data was collected every 10 min, from a meteorological station located near to the experimental regions, using the LAS. Fig. 10

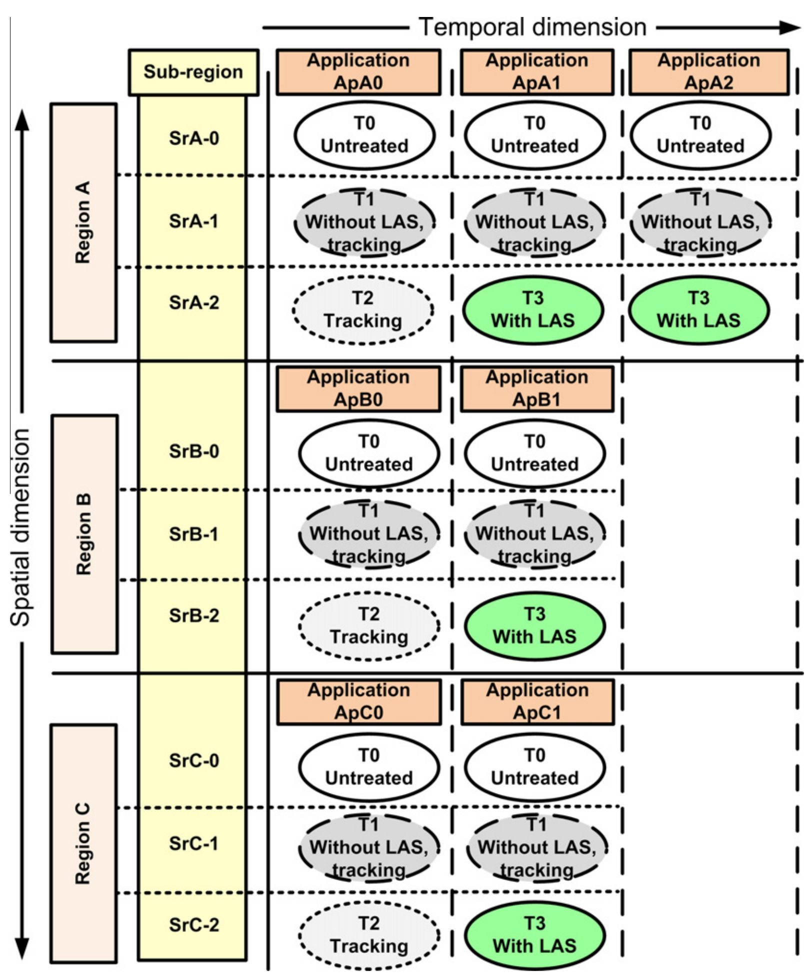

Fig. 9. The spray applications performed to each experimental region.

Table 1
The spraying applications of the experiment.

Spray region	Spray application	Spray application date	Days after the spray application
Region A	ApA0	04-08-2008	0
	ApA1	05-09-2008	ApA0 + 32
	ApA2	28-09-2008	ApA0 + 55
Region B	ApB0	29-07-2008	0
	ApB1	01-10-2008	ApB0 + 64
Region C	ApC0	09-07-2008	0
	ApC1	24-09-2008	ApC0 + 77

shows the mean temperature and the relative humidity values of the study area, obtained in a daily basis during the experiment.

Furthermore, the relative humidity (minimum, mean, maximum) of each spray application is shown in Fig. 11, where the temperature along with the wind speed at the time of each spray application is shown in Fig. 12.

During the reference applications ApA0, ApB0 and ApC0 the tractor attendants were not informed about the meteorological conditions, despite the fact that the LAS was tracking their location and recorded their spray actions. For application ApA0, tractors 1 and 3 terminated their spray applications in about 70 and 50 min respectively, despite the fact that they should have stopped the spraying process due to the prevailed meteorological conditions of the temperature, and/or the wind speed. For the application ApB0, all tractors continued to spray, for about 20 min, while they had to cancel the spray process due the high wind speed. In the same application ApB0 tractor 3 finished the spray application just before the wind air reached the predefined threshold. Moreover, in the same application ApB0, tractor 1, tractor 2 and tractor 3 continued to spray for about 10, 20 and more than 50 min respectively, while they had to cancel the spray process due to the prevailed meteorological conditions. Lastly, all tractors in the reference application ApC0 conducted their sprayings, despite the temperature was not appropriate throughout the duration of the whole spray process.

For the spray applications ApA1, ApA2, ApB1 and ApC1 the tractor attendants utilized the LAS in order to be informed about the meteorological conditions. It is clear that there was no violation on the meteorological conditions during spray applications ApA1, ApB1 and ApC1. However, the spraying process of the application ApC1 was canceled by the LAS, due to inappropriate conditions. For the spray application ApA2 a rise of wind speed at about 7:20 lead the tractor attendants to suspend the spray process for about 10 min.

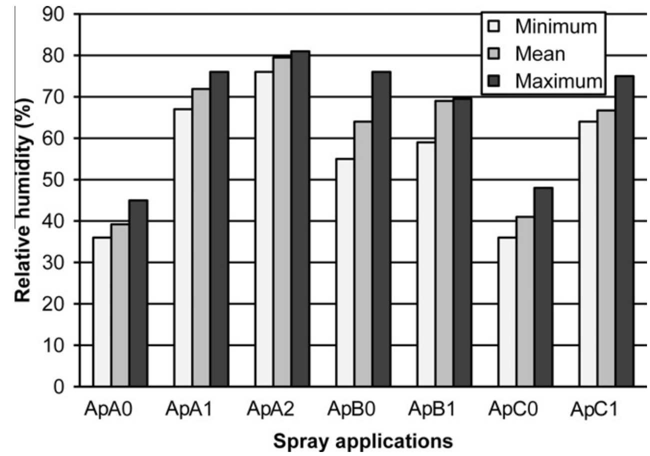

Fig. 11. Relative humidity values (minimum, mean, maximum) during each spray application.

Fig. 13 shows the results of the statistical test in the mean spray duration of each region. The P value is 0.0212 indicating that there is a significant difference between treatments $T3$ ($n = 12$) and $T2$ ($n = 9$) at the 95.0% confidence level.

The mean duration of the spray applications using the LAS ($T3$) was 17.34% less, compared to the With Tracking treatment ($T2$). Lower spray duration, means lesser amount of spray solution and fuel needed for this application, which results in reduction of the spray application's cost. Note that because of the high temperature during summer time in South Greece, consecutive sprays must be performed very early in the mornings, before the temperature rises to unacceptable levels. Thus, if the spray duration is reduced, larger areas per day can be covered. Fig. 14 shows the results of the statistical test in the spray solution applied in each of the three experimental regions.

The P value is less than 0.05, indicating that there is statistically significant difference between $T3$ ($n = 12$) and $T2$ ($n = 9$) treatments at the 95.0% confidence level. The mean spray solution of the spray applications using the LAS ($T3$) was 4.85% less compared to the Tracking ($T2$). The lower spray solution is achieved because off-target spraying or double spraying of the same area was avoided, and the spray solution was applied based on the infestation risk.

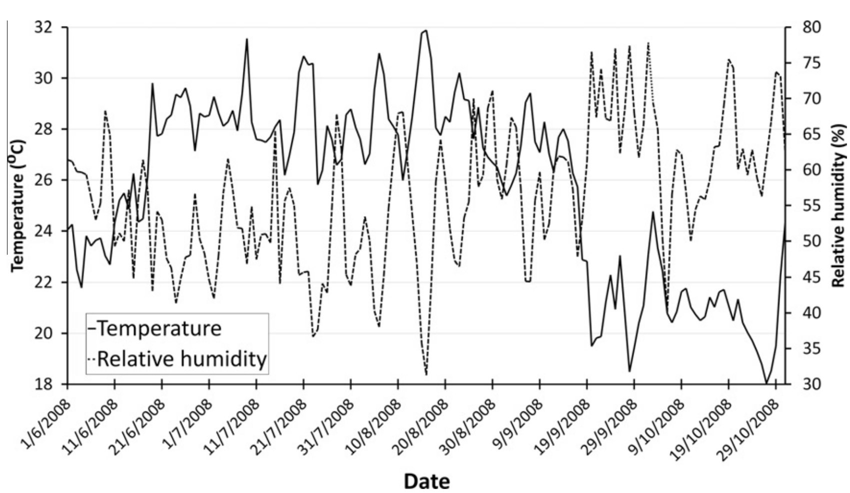

Fig. 10. Mean temperature and relative humidity values during the experimental period.

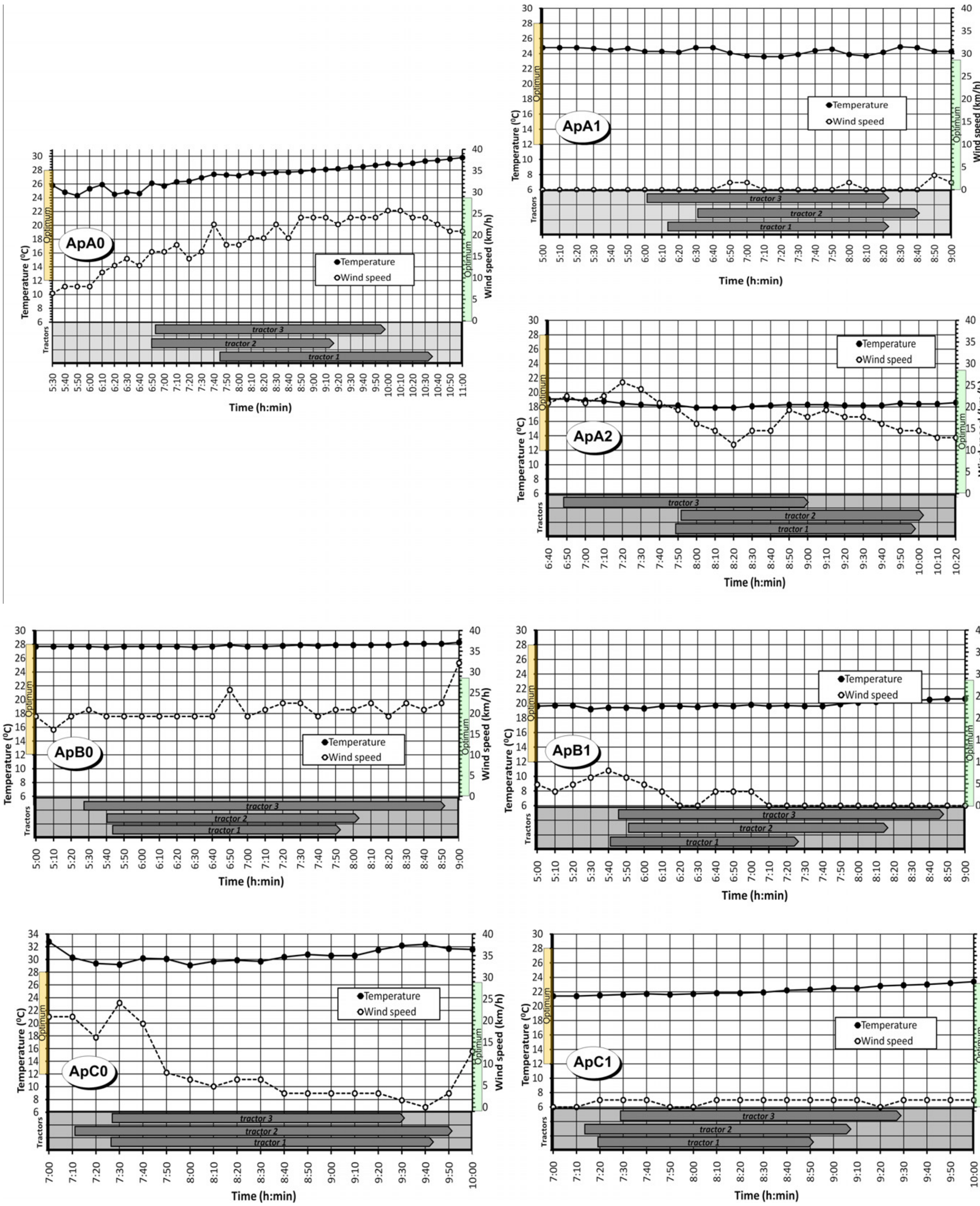

Fig. 12. Temperature and wind speed during each spray application. The arrows show the total duration of spray process of each tractor.

The evaluation of the LAS is based on the olive fruit fly population density expressed by the catches per 6 days in McPhail traps with a pheromone dispenser. These data were compared to the population density of the olive fruit fly and the fruit infestation in the neighboring areas, where bait sprays were applied. The effects on flies' population reduction of the treatments with LAS ($T3$) and without LAS and Tracking ($T1 + T2$) are presented in Table 2. The P value is 0.0238, indicating that there is a significant difference between these treatments at the 95.0% confidence level.

In Table 2 *B. oleae* population values followed by different letter are significantly different ($P < 0.05$).The treatment $T3$ results in a significantly higher efficacy (5.73%) compared to both $T1 + T2$.

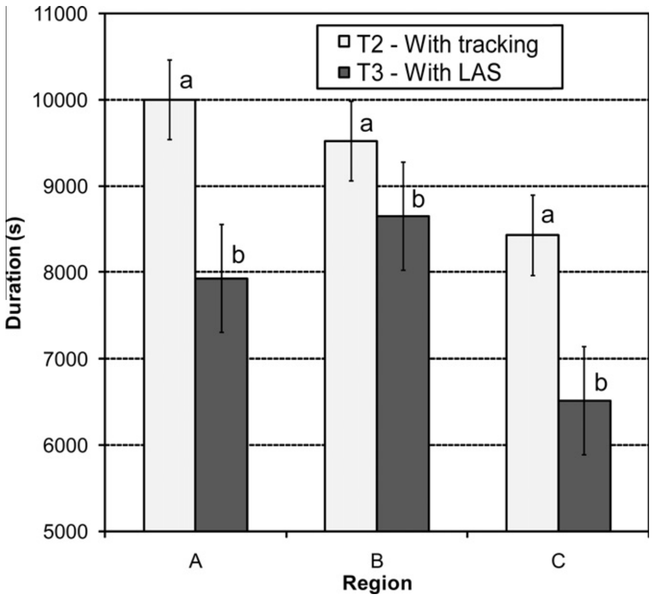

Fig. 13. Duration of spray applications (mean, SE) with LAS (T3) and Tracking (T2). Duration columns with the different letter are significantly different.

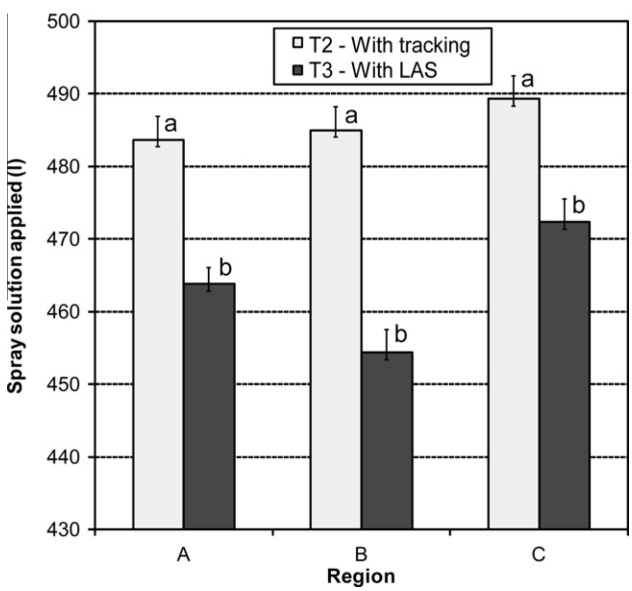

Fig. 14. Spray solution applied (means and SE) in each region with LAS (T3) or Tracking (T2).

Table 2
Mean percent population (mean ± SE) (%) of *B. oleae* and mean corrected efficacy of each treatment.

Treatment	Replicates	Mean population after 6 days (mean ± SE) (%)	Mean corrected efficacy after 6 days (%)
T1 + T2	10	87.50 ± 1.64 a	90.27
T3	4	95.42 ± 2.59 b	96.00

Higher efficacy was achieved because the spray process was based on the infestation risk and the olive fruit fly population characteristics of each region during each spray.

4. Conclusions

B. oleae is a fruit fly that causes serious qualitative and quantitative problems to olive fruits, with economic impacts and losses. The control of olive fruit fly is mostly based on bait spray applications from ground. However, during ground spray applications problems such as off-target sprays and inappropriate sprays might arise, that could affect humans' health, the nearby cultivations and the environment. To face these problems, an innovative, integrated agro-environmental LAS suitable for the ground spray applications of the olive fruit fly was used and evaluated in real conditions.

With the utilization of the LAS, the amount of spray solution was reduced by 4.85%, the duration of the sprays was decreased by 17.34% and the effectiveness of the sprays was increased by 5.73% compared to common spray tactics. In this manner, cost reduction of the spraying application is achieved along with the protection of the environment. Environmental and inhabitant areas protection is also accomplished, by avoiding off-target sprays. The LAS is able to decrease the duration of the sprayings, minimizing their cost and the possibility of canceling a spray application due to meteorological conditions. The acquisition of the spatiotemporal data during the sprayings can provide agro-traceability systems with useful information about the olive products. The LAS can be easily commercialized if parameterization is given to expert administrators or via an easy to use GUI. In conclusion, the LAS can be proven a useful tool to olive farmers, scientists or organizations in order to increase the efficacy and decrease the cost of moderate scale pesticide treatments from ground and avoid effects on environmental protected or domestic areas.

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