PROJECT DELIVERABLE REPORT

Deliverable D6.5: Strategic guidelines for design of locally optimised OFF- & ON-Season IPM, with illustrative implementation scenarios

Project Title:

In-silico boosted, pest prevention and off-season focused IPM against new and emerging fruit flies ('OFF-Season' FF-IPM)

SFS-2018-2

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1. PURPOSE AND SCOPE

The purpose of this deliverable is to formulate strategic guidance to facilitate the scale-up and implementation of the OFF-Season shift in the management of the Mediterranean fruit fly (medfly), *Ceratitis capitata*. More specifically, the guidelines and case-examples presented in this deliverable will be used to promote the concept of the OFF-Season shift in IPM paradigm, train potential end-users, and establish the related *in silico* advisory services to support further development of the concept and its application (outlined in D7.4).

The wider implications and envisaged socio-economic and environmental impacts resulting from technology uptake are discussed in deliverable D6.6, which is being submitted in parallel with this delivery.

2. SUMMARY

The presented guidelines define the basic assumptions and principles underlying the new OFF-Season approach developed within the FF-IPM project, provide basic operational advice for its implementation and extensive reference materials. The guidelines are based on the results of our empirical work carried out on the farms in Greece, Italy and Spain (presented in D6.4) that supported our working hypothesis questioning the classical IPM paradigm when applied to the control of medfly. The on-farm implementation of our *in silico* generated scenarios and the opinions of the farm owners who tried them on their farms positively verified the validity of the postulated OFF-Season shift in medfly control and the substantial benefits arising from its focus on suppressing the early-spring populations that survived winter.

It is worth emphasizing here that the goal of our work on the OFF-Season shift in IPM paradigm was not to discourage or abandon the control of medfly during the main summer-autumn fruiting season, but to develop an improved IPM approach allowing for more confident and effective implementation of pesticide-free biological methods of medfly management in order to partially of fully replace synthetic pesticides.

Therefore, having documented the significant advantages of undertaking control in the OFF-Season, we propose a comprehensive, 'shifted to spring' OFF+ON approach, guided by local fruit phenology rather than medfly monitoring, and implementing its OFF and ON components in proportions adapted to local climatic and terrain conditions.

Knowing from experience and respecting the differences among stakeholder sectors in the degree of interest in the details and biological context of proposed changes to the IPM approach, the guidance is formulated at two distinct levels of complexity and detail and are addressed to different stakeholder sectors. This will facilitate their use according to the needs and interests of the target audiences.

Concise End-Users' Guidelines addressed to IPM practitioners and farmers, formulated in an easy-to-follow bulleted format that summarizes main aspects of the OFF-Season medfly management and provides key advisory points. The users interested in more details are referred to more comprehensive version, below.

Extended Guidelines to The Off-Season Paradigm Shift in Medfly Management addressed to IPM researchers, teachers, IPM trainers, students and advisors. This section explains the relevance of the OFF-Season concept within the latitudinal range of medfly presence in Europe. Importantly, it illustrates variable effects of latitudinal weather differences on medfly behaviour and the relative performance of early versus late medfly control. It also explains the biological basis of the concept and the main processes involved, and the reasons for the low effectiveness of biological methods when used according to the classical IPM paradigm. In addition, it briefly illustrates the influence of rarely considered external factors such as the specificity of fruit markets or the purpose of cultivation (export or local urban markets, intense, organic or amateur production) on the thresholds of tolerable fruit infestation and the perception of the benefits from IPM. The underlying mechanisms and applicability of the developed approaches in different geographic areas are exemplified by illustrative case-scenarios generated *in silico* (presented in Chapter 5 hereby).

3. BACKGROUND AND RELATIONSHIP TO WP6 ACTIVITIES

The presented guidelines build upon earlier accomplishments of the FF-IPM project. Soon after the project start a stakeholder meeting was organised (D6.1) to discuss the local medfly-related problems, and to identify farms in Greece, Italy and Spain for empirical validation of the FF-IPM postulated OFF season shift in IPM paradigm. By necessity, the empirical evaluation was limited to 15 farms, which, however, well represent the diversity and typical structure of European fruit production and also the main latitudinal range of medfly presence in Europe. The experimental farms were located in an area spanning approximately 2,000 km west-east from La Pobla Del Duc in Spain (0.448°W) to Volos in Greece (23.030°E) (Figure 1).

During 2021-2022 the selected farms (6 in Greece, 6 in Italy, and 3 in Spain) were characterised in detail. Extensive data of the thorough characterization allowed the development of virtual representations (Virtual_Farm) of each farm to be used by the PESTonFARM model. In parallel to the farm characterisation, medfly-calibrated decision and service supporting system was developed, composed of the modernised and enhanced PESTonFARM modelling platform and the Virtual-Farm DSS toolbox, that were presented during the previous reporting periods and documented in deliverable D6.2.

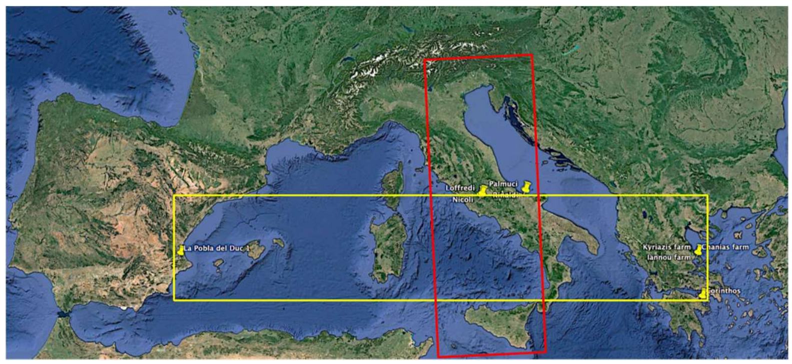


Figure 1. The areas of empirical (yellow) and in silico (red) assessments of the OFF-Season concept.

These accomplishments enabled the development of dedicated portfolios of optional IPM scenarios locally adapted to the specific conditions of each target farm. The developed sets of optional IPM scenarios were presented to farm owners, and in the year 2022, the farmer-selected options were implemented on the farmers' fields in Greece, Italy and Spain. The developed scenarios and preliminary on-farm results were documented in deliverable D6.3 In 2023, the earlier developed IPM scenarios were updated and implemented on the same farms, and the overall results discussed with the farm owners.

Our empirical work carried out on the farms in Greece, Italy and Spain and the results of *in silico* generated IPM scenarios applied by individual farmers provided ample support for our initial hypothesis challenging the guidelines of the classical IPM paradigm, based on medfly monitoring and economic action thresholds. The field results, although naturally variable and somewhat blurred by the fluctuations in starting spring medfly populations, nevertheless confirmed the validity of the postulated OFF-Season shift in medfly management. The results are detailed in the "Developed IPM Technology Project Implementation Report" (D6.4) submitted concurrently with this delivery. Therefore, this document builds on its content without having to repeat it.

The need for a reasonable degree of comparability between the experimental farms meant that their distribution from south to north was relatively narrow (Fig. 1). The latitudinal difference between southernmost Korinthos in Greece (37.887°N) and northernmost Campomarino in Italy (41.931°N) was approximately 340 km, a range that does not fully reflect the climatic diversity of the areas occupied by medflies in Europe. In Italy alone, the medfly's latitudinal range exceeds 1,000 km.

Therefore, to illustrate the broader applicability of the developed OFF-Season concept, beyond the current scope of its empirical evaluation, a series of additional simulations were performed for hypothetical farms located along a 1,000 km transect from Sicily up to Trentino in the subalpine region. (Figure 1). Their results are presented in Chapter 5 of this deliverable.

4. CONCISE END-USERS GUIDELINES

4.1 Principles the classical IPM paradigm

Medfly control should be undertaken:

- ONLY IF the monitoring shows that the trap catches exceed the recommended economic injury level or IPM action thresholds,
- ONLY WHERE there the risk of severe fruit damage is real, imminent and economically damaging.

In most locations in Europe where the Mediterranean fruit fly (medfly, *Ceratitis capitata*) has established populations very early ripening fruit is usually not infested or infested in negligible rates. Therefore, following IPM recommendations in practice means applying control around mid-year and focusing it on vulnerable summer and autumn fruits.

4.2 Specific traits of medfly biology impacting IPM

- *Lack of obligatory diapause:* Like other tropical fruit flies, the medfly has no obligatory (or facultative) diapause. The daily activity of adult females depends only on current weather conditions and in mild climates it may appear sporadically even on warm winter days.
- *Multivoltinism:* Unlike univoltine temperate fruit flies (e.g. *Rhagoletis cerasi*), which emerge in spring as a single group of adult flies that do not increase in numbers throughout the year, medflies (and other tropical fruit flies) are multivoltine and are able to dramatically increase their populations of adult individuals (harmful to the fruit) during the fruiting period.
- *Broad host range:* Unlike oligophagous temperate fruit flies (e.g. *R. cerasi*), tropical fruit flies are polyphagous, and can develop and multiply on a wide range of wild, cultivated and ornamental fruit-bearing hosts.
- *Winter bottleneck:* Medfly has adapted to the Mediterranean climates, and although in most locations it is severely decimated in winter, a limited number of fertile adults or immature individuals can survive even in northern Italy, Croatia or Austria.
- *Long cryptic phase with active reproduction:* The 'winter bottleneck' shapes the annual population patterns into two distinct parts:
    - a 'cryptic' phase lasting about the first half of the year when the medfly is reproductively active but occurs in low densities and is difficult or impossible to detect by ordinary monitoring,
    - a 'prolific' phase that starts in summer, with very rapid (often exponential) population growth that severely threatens the main, summer and autumn fruit crops.

4.3 Shortcomings of classical IPM

- *Hidden' population increase:* To become detected by a typical farmer's monitoring and to exceed the usually recommended IPM thresholds, the overwintering medfly population must first reproduce and substantially increase its population density.
- *Delayed alert:* By the time the IPM threshold is reached, the adult population has already increased several-fold (5-20 times), and also considering the large egg load, larval and pupal populations already present on farm and developing soon, the real increase can be rated as 50-200 times.
- *Pesticides as the most feasible option:* Late alert, after the population of medfly has already substantially increased and entered a phase of rapid, exponential growth, creates a situation when immediately acting pesticides remain the most feasible option that can protect the vulnerable summer and autumn fruits from infestation.

4.4 Factors hampering replacement of pesticides with biological methods.

- *Inherent shortcoming of biology-based medfly management approaches:* There are several control methods available that are practically pesticide-free and "exploit the biology of medfly", such as baiting stations or Attract & Kill (A&K) panels, mass trapping, Sterile Insect Technique, protection of predators, etc. Unlike pesticides, biological methods suffer from inherent shortcoming of gradual mode of action. With sufficient time, they can reach pesticide-comparable suppression of medfly population, but meanwhile, the remaining extant flies can significantly damage crops. When applied at such a late stage, biological methods cannot control a rapidly expanding medfly population.

- *Impact of local landscape:* The results of biological methods depend strongly on farm size, fruit distribution pattern and its phenological structure, and neighbourhood. The combined effect of these factors is difficult to predict but can be simulated and optimised using the FF-IPM developed DSS (see point 2.6, below).
- *Discrepancy between scientist's and farmer's perspectives*: Scientists focus on suppressing the medfly population and typically use trap catches and, rarely, fruit infection to measure it. Invariably, several-fold reductions in trap catches and/or fruit infestations are heralded as proof of success. But experience and our simulations show that such reduction in medfly population does not always translate into reduced fruit infestation. For a farmer, information about a reduced pest prevalence is welcome, but of marginal importance. What really matters is the final net profit, measured by the market value of the fruit minus the cost of control.
- *Sharp decline in market value of fruit with moderate infestation:* In highly competitive fruit markets, the wholesale price drops rapidly to almost zero with even moderate (i.e., qualitative) fruit damage. This infestation threshold varies greatly for different countries, target markets and seasons, but exceeding it makes the fruit harvest unprofitable. Only for amateur growers a small amount of saved fruit can be considered satisfactory.
- *Awareness gap:* Quite commonly farmers appear unaware about the year-round presence and early-spring build-up of medfly on their farms. It is exemplified by the interpretation of early summer trap catches, frequently understood that: "the pest just arrived on my farm' instead of: 'the pest always residing on my farm has already multiplied to the point that it can be detected".
- *IPM cost:* Application of non-pesticide control methods, such as A&K panels, is usually more expensive compared to pesticides. This extra cost is offset, at least partially, by the benefits from the reduced pesticide exposure of the farmer, and obvious benefits to fruit consumers and the environment. However, in most cases, the use of non-pesticide methods can be substantially optimised and adjusted to the local conditions and is the final cost and benefit brought to affordable and acceptable levels (see point 2.6, below).

4.5 The solution – OFF-Season shift in medfly management

Although the developed OFF-Season approach rejects the basic guidelines of the classic IPM paradigm (control the pest only where it causes damage, and only when it exceeds the economic injury thresholds), it enables to achieve the ultimate IPM goal - reducing reliance on synthetic pesticides while achieveing satisfactory control of pests. The OFF-Season shift is not intended to replace traditional (ON-Season) medfly control in the summer, but to complement it, significantly increasing the overall effectiveness of medfly control. It can be summarised in two simple advisory points, fully explained in the Chapter 5 further below:

- **start early before you can even detect your pest,**
- **first focus on the earliest fruit, even if it is usually not damaged to a noticeable extent**

The OFF-Season shift in the classical IPM paradigm allows for comprehensive OFF+ON medfly management, which is not only much more effective compared to the standard IPM approach, but importantly, **enables confident and effective replacement of the pesticides with pesticide-free biological methods, such as A&K panels or mass trapping.**

- *Medfly monitoring:* To start medfly control, do not rely on adult population monitoring, and do not wait until it appears in the traps and exceeds IPM alert threshold. If medfly is established in an area, in most cases its control will be necessary. However, population monitoring can be used as a supportive ‘safety’ measure in late summer and autumn to verify the effects of your IPM and decide if a corrective action is needed.

- *Spring start:* Start control on the earliest ripening fruit crop even if usually it is not infested, apply A&K panels soon (1-2 weeks) after flowering. Afterwards, successively apply A&K panels on subsequent fruits according to their phenology, when the fruit is at the fruitlet stage, at least 2 weeks before its green maturity. Keep the panels on the plots at least 4-6 weeks post-harvest.

Table 1. Comparison of the OFF-Season medfly management approach with the usual farmer’s practice and the classical IPM paradigm

<table>
<tr><th>End-user questions</th><th>Farmer’s practice</th><th>The classical IPM paradigm</th><th>Recommended OFF-Season management*</th></tr>
<tr><td>Where to control?</td><td colspan="2">Where the damage happens (summer & autumn fruit)</td><td>All fruits (even if NOT infested)</td></tr>
<tr><td>When to start?</td><td>Every year, in early summer (June/July)</td><td>ONLY IF medfly catches exceed the economic injury level (IPM threshold)</td><td>▪ Start early spring (soon after flowering)
▪ focus on the earliest fruit even if not infested,</td></tr>
<tr><td>Do I need medfly monitoring for my decision-making?</td><td>NO, timing usually is based on experience, habit and/or calendar</td><td>YES, but the usual result is not much different from the farmer’s practice</td><td>▪ NO, start medfly control in spring long before medfly can be detected,
▪ monitoring can be used in late-summer-autumn to verify the results or decide on a need for corrective treatments</td></tr>
<tr><td>Can I substitute the pesticides with biological method?</td><td colspan="2">NO, in most locations in practice, only immediate-acting pesticides can work at such a late time</td><td>YES, A&K panels or mass trapping can be used effectively</td></tr>
<tr><td>Do I need to optimise the IPM plan to local conditions?</td><td colspan="2" rowspan="2">NO, pesticides can be applied as recommended by the producer</td><td>YES, biological methods are usually more expensive, and local optimisation can substantially reduce the overall cost and increase effects of IPM</td></tr>
<tr><td>Do I need to adjust my IPM plan according to my target fruit market?</td><td>YES, your target market dictates the fruit-infestation thresholds above which harvest is not profitable, which determines the required IPM efficiency, application plan and cost</td></tr>
</table>

- For more detailed information on the specific aspects highlighted in the table above, refer to the relevant sections of the Chapter 5, further below.

4.6 Support for implementation of the OFF- season medfly management

During the FF-IPM, a specialized decision and service supporting platform was developed for computer simulations of the local Pest-Terrain-Weather-IPM system. This platform allows for the rapid *in silico* development of IPM scenario options according to local farm structure, fruit phenology and succession, local site-specific weather conditions, and various hypothetical IPM treatment options. The DSS can support the local optimization of IPM strategies and tactics in accordance with the farmer's preferences, reduce IPM costs and adjust treatment intensity to the fruit-growing goals and requirements of the target fruit market.

For more information about the available support, R&D and advisory services, or training consult FF_IPM or *inSilico*-IPM sites: https://fruitflies-ipm.eu or http://www.insilico-ipm.eu , respectively.

5. EXTENDED GUIDELINES TO THE OFF-SEASON PARADIGM SHIFT IN MEDFLY MANAGEMENT

5.1. The purpose and target audience

The purpose of this chapter is to provide a more advanced and insightful account of the developed 'OFF-Season' concept, addressed to audiences more interested in its mechanisms and biological context, as well as the geographical scope of its applicability. The target audiences include IPM researchers and teachers, stakeholder trainers, IPM and biology students and potentially also environmentalists and policy makers.

5.2. INTRODUCTION

The Mediterranean fruit fly (medfly), *Ceratitis capitata* (Wiedemann), is a highly polyphagous frugivorous pest of Afro-tropical origin (CABI 2023; De Meyer et al. 2002a, b; Gasperi et al. 2002). It has spread far beyond its aboriginal home into the Mediterranean Region and many tropical and sub-tropical regions world-wide (CABI 2023; Szyniszewska and Tatem 2014), becoming a pest of major economic concern (Mitchell 1977; Siebert 1990). Medfly has adapted to the Mediterranean climate, and although in most locations it is severely decimated in winter, a limited number of fertile adults or immature individuals can utilise local shelters and warmer spots and survive even in northern Italy, Croatia or Austria (Egartner et al. 2019, Lemic et al. 2020, Zanoni 2019). The spring medfly population usually has little impact on the earliest fruits, but its rapid population growth in mid-summer can seriously damage the main summer and autumn fruits (Papadopoulos et al. 2001, Israely et al. 1997, Giunti at al. 2023). Like other tephritids, medfly infests ripening fruit shortly before harvest, which is particularly harmful to the fruit, and leaves a narrow "time window" for its control.

The consultations and interviews with stakeholders, carried out during the execution of the FF-IPM project, and the information received from farm owners during the detailed characterisations of the experimental farms (reported in D6.3) have shown that, in most cases, medfly is managed by individual farm owners who largely follow a reactive (therapeutic) approach "control when and where the problem occurs" (Colacci et al. 2022). Following the principles of the classic IPM paradigm, farmers are commonly advised to initiate medfly control when the pest consistently appears in monitoring traps and reaches the economic injury level or the economic threshold (Dekker and Messing 2019; Vincenot and Quilici 1995).

The on-farm experiments (reported in D6.4) conducted during the FF-IPM project confirmed our initial hypothesis challenging the guidelines of the classical IPM paradigm, based on medfly monitoring and economic action thresholds, when applied to the control of medfly, and documented the validity of the postulated OFF-season shift in medfly management. Based on these results, Concise End-User Guidelines were developed, summarising the key aspects of the recommended 'OFF-Season' medfly management.

The extended guidelines presented here build on the results of *in silico* generated scenarios that were evaluated on farmers' fields. The specific scenarios developed for concept testing on individual farms (reported in D6.4) have served their purpose well but are not particularly suitable as means of broader promotion of the developed technology or its training and teaching materials. Therefore, to illustrate the broader relevance of the already on-farm validated IPM concept, beyond the scope of its empirical on-farm testing, a series of case scenarios were generated *in silico* covering the entire 1 000 km latitudinal range of medfly presence in Italy. They elucidate the mechanisms of the developed OFF-Season concept and assess its merits in relation to geographic area and impacts of rarely considered factors influencing its net-effects and farmer perception.

The extended guidelines developed in this way are intended to serve as reference materials for the promotion, teaching and more advanced training of the developed IPM approach.

5.3. METHODS

In silico approach: The estimates of medfly population growth presented here, the evaluation of various IPM options, including the potential advantages of postulated Off-Season medfly control, were performed *in silico* using a "virtual farm" approach - computer simulations of a local Pest-Terrain-Weather-IPM system. This approach allowed for rapid exploration of pest control concepts and IPM options before implementing them on the farm.

The Model: The simulations were performed using the *PESTonFARM* model (Lux 2014, 2018, Lux et al. 2018), enhanced and re-calibrated to the biology of medfly under the FF-IPM project. The model simulates lifetime development (from egg to adult), dispersal and fate of individual medfly females dwelling on the farm according to the local farm topography, site-typical weather patterns, fruit distribution and phenology, and a combination of IPM treatments. It stochastically simulates the daily behaviour of each individual female, oviposition choices and fruit infestation events, its local dispersal and shifts among various fruit species and cultivars, and mortality events caused by natural processes and assumed IPM treatments. Males were not simulated because they do not damage the fruit, but it was assumed that they were present in sufficient numbers on the farm to fertilize all mature females. The model generates an extensive dossier characterising various aspects of the simulated IPM scenario; with a series of charts and diagrams presenting spatial (10 x 10 m resolution) and temporal (daily) densities of medfly females and fruit infestation, and tables with estimates of IPM efficacy (medfly mortalities and fruit infestation at harvest), costs and net benefits of the assumed IPM.

Medfly OFF and ON Seasonality: In line with the typical annual medfly phenological and population dynamics pattern, farmers' perceptions and usual IPM schedules, the medfly's annual cycle has been divided into two distinct parts; (a) winter and spring (hereafter referred to as the OFF season), and (b) summer and autumn (ON season), when IPM against the medfly is usually carried out.

Geographical gradient: To investigate the validity of the OFF-Season medfly management concept, three regions were selected across the almost 1 000 km latitudinal range of medfly presence in Italy, which extends from Sicily in the south to the subalpine zone of Trentino-South Tyrol in the north. Within this transect, in rural areas, the location of three hypothetical farms was selected; near Paterno in the province of Catania (37.48152° N, 14.85874° E); near Cori in the province of Latina (41.63806° N, 12.87835° E) and near Avio in the province of Trentino (45.72492°N, 10.93701°E), respectively (Fig. 2).

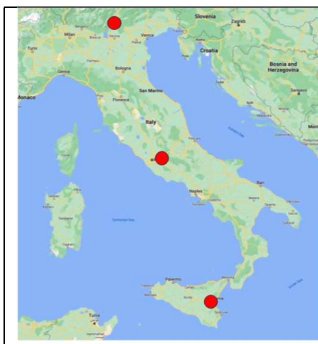


Figure 2 Locations in Italy

Weather data: For each hypothetical farm, local historical weather data sets were obtained from the EU Copernicus ERA5-Land database, covering a period of 22 years (2001-2022) with a spatial and temporal resolution of about 9 x 9 km and 1 hour, respectively. Each set included the following parameters: air temperature, wind speed and direction, precipitation, solar radiation, soil temperature and water content. While air temperature plays a major role, a combination of other parameters such as rainfall intensity, solar radiation, soil temperature and moisture, and wind strength affect insect behaviour and survival, so they were used in the model to drive the simulations.

Site-typical weather: The annual weather cycle was divided into four seasons, defined as follows: winter (December-February), spring (March-May), summer (June-August) and autumn (September-November). Air temperature was used to categorise annual weather patterns, and the deviation of average annual and seasonal temperatures from the corresponding multi-annual (22-year) averages was adopted as a criterion. For each site, the year with the least divergence in annual and seasonal temperatures was identified and used as a "reference year" considered representative of the site. Multi-parameter annual weather data from the relevant reference years, applied at hourly resolution, were used to simulate the IPM scenarios for each location.

Farm structure: A uniform, simplified farm topography was adopted for all simulations. It was assumed that a hypothetical farm, with an area of 9 ha, contains a selection of different fruits grown on a mosaic of 15 plots with an area of 0.6 ha each. The farm spanned a 300 x 300 m square surrounded by a 100 m non-host buffer zone (Fig. 3). All simulations were limited to the farm area and the buffer zone (500 x 500 m). Outside the buffer zone, a similar landscape and pest management were assumed, therefore a balanced population exchange - equal numbers of out- and in-migrating medfly females were assumed between the simulation area and the vicinity. On individual plots of the farm, a standard 8 x 8 m arrangement of trees with an even crown diameter (4 m) was adopted.

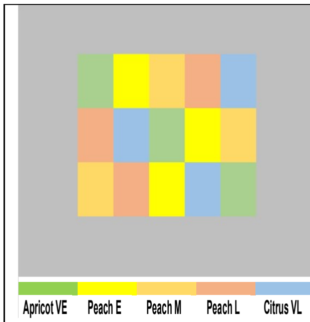


Figure 3. Farm diagram

Fruit availability and seasonality: Two fruit availability scenarios were selected from among the numerous combinations of Mediterranean fruit species and their phenology (1) year-round host availability, typical of mixed apricot/peach and citrus groves in southern regions, with clementines, Navel, Tarocco and bitter oranges, and (2) seasonal (summer-autumn) host availability, typical of mixed orchards in central Italy and more temperate regions, with a variety of apricots and peaches and the addition of some autumn fruits such as apples. For each location, the local fruit availability period was divided into five phenological categories, classified according to fruit maturation and harvest time: very early (VE) e.g., apricot; early (E) such as early peach; middle (M) – peach; late (L) – late peach; and very late (VL) – apple). For each fruit category, the respective values of thermal requirements, the number of Growing-Degree-Days (GDD) necessary for flowering, reaching "green maturity" and "harvest ripeness" were estimated and simulated in the context of location-specific annual weather profiles.

Fruit attractiveness and suitability: Fruit species differ in their attractiveness to egg-laying medfly females and in their suitability for the development of eggs and larvae. The model can take these differences into account, but for the presented simulations a simplifying assumption was made that all fruit categories are equally attractive and suitable.

Medfly 'starting' population: To enable easy comparisons between scenarios and locations, each simulation started on January 1, with the same arbitrary set initial spring population of 900 per farm (100/ha) of randomly distributed medfly females that either survived the winter as adults or hatched from overwintering immature forms.

Medfly activity: Medfly is a diurnal insect, most active around mid-day, optimally at air temperature of 25 ^{0}C. It is active on calm and sunny days when a suitable combination of weather conditions occurs, collectively referred to as the '*weather determined activity window'*. Based on the literature and our observations, the required conditions were estimated as: air temperature ranging from 15 to 35 ^{0}C, sunny conditions (solar radiation above approx. 150 W/m^2). no or weak wind (below approx. 8m/s), no precipitation or very minimal (below approx. 0.5-0.8 mm/h).

Medfly monitoring: It was assumed that on each farm the medfly population was maintained throughout the year using fifteen traps, one in the centre of each plot. It was also assumed that the traps were baited with food bait, e.g. Torula yeast, or a synthetic composition, e.g. three component lure with putrescine, trimethylamine and ammonium acetate (PTA), which mainly attracts female flies. Medfly monitoring was considered a standard farm procedure, the same for all farms and scenarios, and its cost was not included in the cost/benefit estimates of the IPM scenarios tested.

Simulation cycle: All simulations started at the beginning of the year (January 1) and ended on December 31 or next spring to cover the entire fruiting cycle of all fruits on the farm. The latter refers to the citrus fruits in Paterno, which are usually harvested gradually from October-November to February-March. However, the deliverable presents results covering annual cycles (January to December). The simulation results and IPM scenarios are outlined and discussed briefly, while the full documentation of the results generated by the model has been archived on an online repository (ZOHO drive) of the FF-IPM project: https://fruitflies-ipm.eu.

IPM scenarios: For each location, four IPM scenarios of medfly management were simulated:

(A) - NO IPM, unrestricted medfly development used as a reference scenario for IPM comparisons,

(B) - ON season, focused on the fruit usually severely infested by medfly and protected by the farmer,

(C) - OFF season, focused on the earliest fruit that is usually little infested and not protected by the farmer,

(D) - ON+OFF-season, a combination of B & C.

IPM Treatments: In the simulations, instead of the pesticides typically used by farmers, it was assumed that only the "attract and kill" technique was used, consisting of pesticide-coated panels with bait attracting mainly female flies, hereinafter referred to as A&K panels. It was also assumed that the properties of such panels are similar to Magnet™ MED produced by Suterra, which, according to the manufacturer, remains effective for approximately 6 months after field application. A daily bait deterioration rate was assumed at 0.3%, that means about 58% of its initial effectiveness still retained at the 180th day post application. A standard device density of 1/100 m^2 (100/ha) was assumed, and the implementation date was adjusted to the fruit phenology to cover the entire period of fruit susceptibility, from green maturity to harvest, whenever possible with a margin before and after.

IPM alert and action thresholds: Definitions of recommended economic damage thresholds or the threshold for taking IPM action vary by region, season, and fruit type, and range from 1 adult/trap/day (Garcia 2009) to 10–50 adults/trap/week (Cavalloro and Prota 1983). To avoid late IPM alert bias, a stringent operating threshold of 2 females/trap/week was set for all simulations, ensuring that the simulated IPM alert occurred earlier than typically recommended.

IPM cost and farmer's benefit: The simulation of each scenario generated a simplified estimate of its effectiveness from the farmers' perspective - a simple cost-benefit analysis. As a basis for further comparisons, the commercial value of harvested fruit obtained under the simulated scenario of no protection (NO IPM) was assumed. The difference in fruit value for the tested IPM scenario and the base scenario (NO IPM) less the cost of IPM treatments was used as a measure of the effectiveness and profit resulting from the tested scenario.

To compare the simulated scenarios, moderate farm productivity was assumed, the same for all locations: 7 tonnes/ha for apricots, 8, 9 and 10 tonnes/ha for early, mid- and late-season peaches, respectively, and 11 tonnes/ha for citrus or apple. Furthermore, a uniform (same for all fruit) value of fruit in wholesale or local sales ('farm gate') was assumed (€1/kg of uninfected fruit).

Several fruit infection thresholds (from 5 to 30%) were adopted to estimate the value of the crop to consider the different perceptions and expectations of the highly competitive and demanding fruit markets for export, local and farm sales, and amateur fruit growers. In the range from zero infection to the threshold, it was assumed that the value of the fruit is inversely proportional to the actual infection rate and drops to zero if the established infection threshold is exceeded.

To simply illustrate the net gains from each scenario, a moderate threshold of 15% was used, but in addition fruit value estimates were calculated for each scenario for the entire range of thresholds adopted and presented in a separate table.

5.4. RESULTS

5.4.1 Geographical scope and climatic gradient

The selected locations are approximately 500 km apart along ca. 1 000 km south-north axis, representing three climatic scenarios of medfly presence in Europe: hot climate with abundant medfly presence, represented by Paterno in Sicily, warm climate with moderate medfly presence, represented by Cori in Lazio and cool climate of the northern fringe of medfly presence, represented by Avio in Trentino province. The patterns of average monthly temperatures (calculated for 2001-2022) differ between the three locations by an "offset" of approximately 5 °C (Fig. 4). They range from 8.7 to 28.4 °C for Paterno, from 4.5 to 19.8 °C for Cori, and from -0.3 to 22.3 °C for Avio. However, insects living on the farm are exposed to daily and hourly temperature fluctuations, which are frequent and sometimes significant, although often short-term. Therefore, the actual average range of thermal exposure is much wider, as revealed by the average hourly temperatures, and ranges from -0.2 to 40.8 °C for Paterno, -4.3 to 33.7 °C for Cori, -8.8 to 28.0 °C for Avio. In exceptional years in the period 2001–2022, periodic temperature extremes significantly exceeded the above ranges. The analysis of the variability of the average seasonal temperature between individual years allowed the identification of three reference years, typical for each location: 2008 for Paterno; 2009 for Cori; and 2013 for Avio (Table 2). The above reference weather patterns, at hourly resolution, were used to estimate annual, weather-dependent medfly activity windows specific to individual locations. The length of periods of favourable combination of daytime air temperature, solar radiation, precipitation, and wind speed that support medfly activity follows a latitudinal gradient and varies by almost a factor of two between the southernmost and northernmost locations (Table 3).

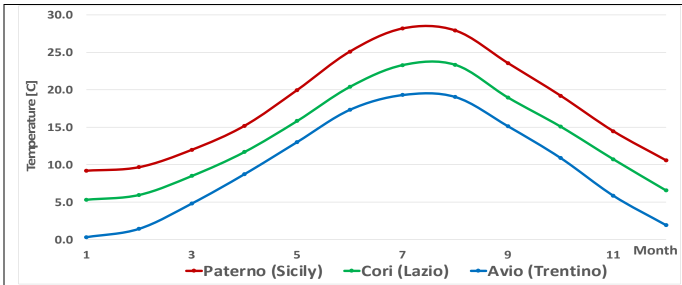


Figure 4. Annual patterns of average monthly temperatures (2001-2022).

Table 2. Deviations of average seasonal temperatures in individual years from long-term averages.

Paterno (Sicily)																						
12M	**0.40**	**-0.26**	**-0.05**	**-0.47**	**-1.00**	**-0.27**	**0.08**	**0.19**	**-0.25**	**-0.41**	**-0.53**	**0.10**	**-0.09**	**0.19**	**-0.04**	**0.58**	**0.19**	**0.33**	**0.09**	**0.09**	**0.53**	**0.61**
Winter M12-2	-0.15	0.01	-0.59	0.33	-1.86	-0.31	0.51	0.16	0.05	0.33	-0.12	-1.34	-0.37	0.82	-0.36	1.31	-0.97	0.60	-0.22	0.68	0.71	0.80
Spring M3-5	1.35	0.27	-0.62	-1.28	-0.38	0.58	0.34	0.41	-0.39	-0.37	-0.82	-0.17	0.60	-0.48	-0.14	1.01	0.72	0.98	-0.79	0.02	0.01	-0.85
Summer M6-8	-0.33	-0.64	1.15	-0.62	-0.95	-0.99	0.30	0.25	0.05	-0.40	-0.74	1.03	-0.74	-0.57	-0.32	-0.47	1.40	-0.66	1.13	-0.56	1.35	1.35
Autumn M9-11	0.73	-0.68	-0.13	-0.30	-0.82	-0.38	-0.83	-0.08	-0.71	-1.20	-0.45	0.90	0.16	1.00	0.67	0.45	-0.39	0.39	0.23	0.24	0.07	1.14
Cold, Aver., Hot	2001	2002	2003	2004	2005	2006	2007	**2008**	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

Cori (Lazio)																						
12M	**-0.08**	**-0.27**	**0.27**	**-0.36**	**-1.04**	**-0.46**	**-0.20**	**-0.23**	**-0.08**	**-0.72**	**-0.31**	**-0.02**	**-0.30**	**0.12**	**0.30**	**0.28**	**0.22**	**0.49**	**0.44**	**0.34**	**0.36**	**1.24**
Winter M12-2	-0.07	0.27	-1.02	0.31	-2.12	-0.60	0.41	0.18	-0.28	-0.81	-0.48	-1.86	-0.62	1.71	0.16	1.24	-0.45	0.48	0.31	1.15	0.71	1.38
Spring M3-5	0.71	0.42	0.26	-1.28	-0.45	-0.27	0.51	-0.21	0.49	-0.59	-0.40	0.15	-0.02	-0.61	0.15	0.35	0.82	0.77	-0.60	0.54	-0.87	0.14
Summer M6-8	-0.41	-1.25	2.07	-0.92	-0.86	-1.00	-0.36	-0.45	-0.05	-0.76	-0.75	0.92	-0.72	-1.55	0.72	-0.39	1.56	-0.09	1.13	-0.27	1.00	2.42
Autumn M9-11	-0.54	-0.52	-0.23	0.46	-0.71	0.03	-1.35	-0.45	-0.48	-0.72	0.38	0.72	0.17	0.94	0.18	-0.08	-1.03	0.80	0.91	-0.06	0.60	1.00
Cold, Aver., Hot	2001	2002	2003	2004	2005	2006	2007	2008	**2009**	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

Avio (Trentino)																						
12M	**-0.33**	**-0.45**	**-0.16**	**-0.82**	**-0.98**	**-0.31**	**0.41**	**-0.32**	**-0.09**	**-1.19**	**0.46**	**-0.42**	**-0.41**	**0.32**	**0.84**	**0.41**	**0.40**	**0.62**	**0.73**	**0.60**	**-0.40**	**1.10**
Winter M12-2	-0.65	-0.32	-1.72	-0.86	-1.87	-0.78	2.00	0.44	-1.07	-1.69	0.57	-2.07	0.13	1.51	1.11	1.54	-0.24	0.01	1.61	1.57	-0.46	1.26
Spring M3-5	0.19	-0.18	0.30	-1.68	-0.31	-1.29	1.66	-0.42	0.86	-0.93	1.27	-0.15	-1.61	0.30	0.74	-0.01	1.30	0.48	-0.38	0.86	-1.41	0.43
Summer M6-8	-0.34	-0.81	2.14	-0.83	-1.01	-0.40	-0.72	-0.54	-0.17	-0.54	-0.77	0.37	-0.25	-1.51	1.29	-0.15	0.99	0.71	1.26	-0.29	0.10	1.48
Autumn M9-11	-0.50	-0.50	-1.36	0.09	-0.73	1.22	-1.31	-0.74	0.01	-1.60	0.75	0.18	0.09	0.96	0.24	0.25	-0.46	1.27	0.45	0.28	0.18	1.24
Cold, Aver., Hot	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	**2013**	2014	2015	2016	2017	2018	2019	2020	2021	2022

Table 3. Annual weather-dependent medfly activity windows during site-typical weather years

Location (year)	**Days/year**	**Hours/year**
Paterno, Sicily (2008)	311	2 351
Cori, Lazio (2009)	214	1 858
Avio, Trentino (2013)	145	1 186

5.4.2. Southern Range of Medfly Presence in Europe - Sicily Case

The Paterno area in Sicily is representative for the southern range of medfly presence in Europe, where winters are very mild, and temperatures rarely approach zero degrees Celsius. On a typical farm, fruits suitable for medfly oviposition and larval development are available almost all year-round, starting from apricot in April, though various cultivars of peaches and nectarines, to citrus (tangerines, clementines, Navel and Tarocco oranges) available in the period from October in autumn until March-April next spring (Figure 5) In a year typical for this site, favourable weather allows for 311 days (2 351 hours) of medfly activity (Table 3), with short episodes on warm winter days and 8-11 hours per day in April-October, but with a noticeable midday reduction in activity on days with excessive temperatures, often exceeding 35 °C in August-September (Figure 5). In such favourable host and weather conditions, the medfly is widespread and abundant, and requires intensive control to prevent fruit devastating outbreaks. Our research has shown that to keep fruit infestation within tolerable limits, usually defined as below 4-5%, farmers resort to frequent, calendar-based pesticide sprays. The earliest apricots and early peach are usually less infested and receive 0-2 sprays. More intense medfly control begins in mid-June with 2-3 pesticide sprays on early peaches, 3-4 on medium peaches, 4-5 on late peaches, and 4-6 sprays on citrus, mostly applied in autumn when the medfly population is at its highest. Citrus fruits are harvested gradually, most of them from mid-December to February, after which only a fraction remains, often neglected and unprotected. With an estimated cost of pesticide treatment ranging from €70 to €120 /hectare, the cost of typical IPM implemented on our hypothetical farm ranges from €1,764 to €4,320/farm/season.

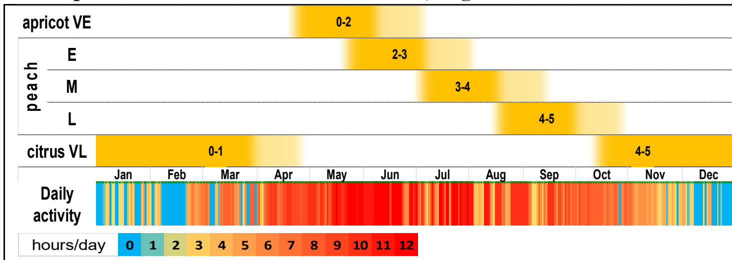


Figure 5. Paterno, Sicily, Italy: Annual patterns of fruit availability with number of pesticide sprays, and days with Medfly activity.

The ON and OFF seasonal IPM implementation schemes, adopted in the simulations presented below, are presented in Table 4. The ON season scenario broadly reflects farmers' usual practice in years with typical seasonal weather and covers early, medium and late cultivars of peach and autumn citrus. The OFF seasonal scenario assumes a very early installation of A&K panels on spring citrus trees and later apricot (Table 4). With an estimated cost of A&K panels €550 /ha (at €100 A&K panels/ha), the cost of IPM implemented on our hypothetical farm equals €1,980 Euro for the OFF season, €3,960 for ON season, and €5,940 for the combination OFF+ON season.

Table 4. Paterno, Sicily, Italy: Implementation schedule for ON and OFF-Season treatments.

IPM	Fruit category	Implementation day
OFF season	Spring citrus Apricot VE	1 70
ON season	Peach E Peach M Peach L CitrusVL	90 90 120 160

NO IPM scenario: The simulation results of uncontrolled development of medfly population (scenario WITHOUT IPM) are outlined in Figure 6 and 7A. In the first quarter of the year, the weather conditions were moderately suboptimal, and both population density and activity of medfly remained low. Overwintering females, both adult and immature, were subject to mortality, and by the time their oviposition begun (day 64th), 37% of them had died, leaving 556 females scattered over an area of 9ha of the farm (less then 62/ha) as effective founders of a new population. During the first two months of the year, ripe citrus fruit, although still present on the farm, was rarely attacked by the then largely inactive females. In March, medfly activity increased and the still remaining citrus fruits was infested with 4 322 eggs (2,400/hectare). Assuming an average of 5 eggs per clutch and 2-3 egg deposits per infested fruit, this means around 192 infested fruits per hectare. Further assuming an average yield of 12 tonnes per hectare and single fruit weight

180 g, this means approximately 0.3% of the whole citrus crop. In the second quarter, weather conditions quickly approached optimal, flies become very active, although due to low densities (Figure 6a) they were still rarely caught in monitoring traps (Figure 6b). The flies remained on citrus fruits left until April and laid approximately 13 000 eggs (approx. 7 200/ha), which means additional damage to approximately 580 fruits/ha, or 0.9% of the entire citrus crop. It must be noted that usually citrus fruits are harvested gradually, most between December-February, and by late March and early April only a small fraction remains on the trees. In such a situation the relative infestation of the fruit still left or abandoned on the trees will be proportionately greater. By late April, most flies moved to the earliest apricot and peach, where they oviposited giving raise to most of the post-winter generation. Approximately 155 000 eggs (86 000/ha) were laid on the earliest apricot, and then about 509 000 eggs (283 000/ha) on early peach (Figure 7A), which resulted in noticeable two successive peaks of larval population (Figure 6d) and substantial fruit damage, 14.9% and 47.3%, respectively (Figure7A). In the third quarter, weather conditions became optimal, the medfly was very active, although with occasional midday slowdown caused by excessive temperatures (above 35 °C), frequent in August and September. In the absence of any control, medfly females actively

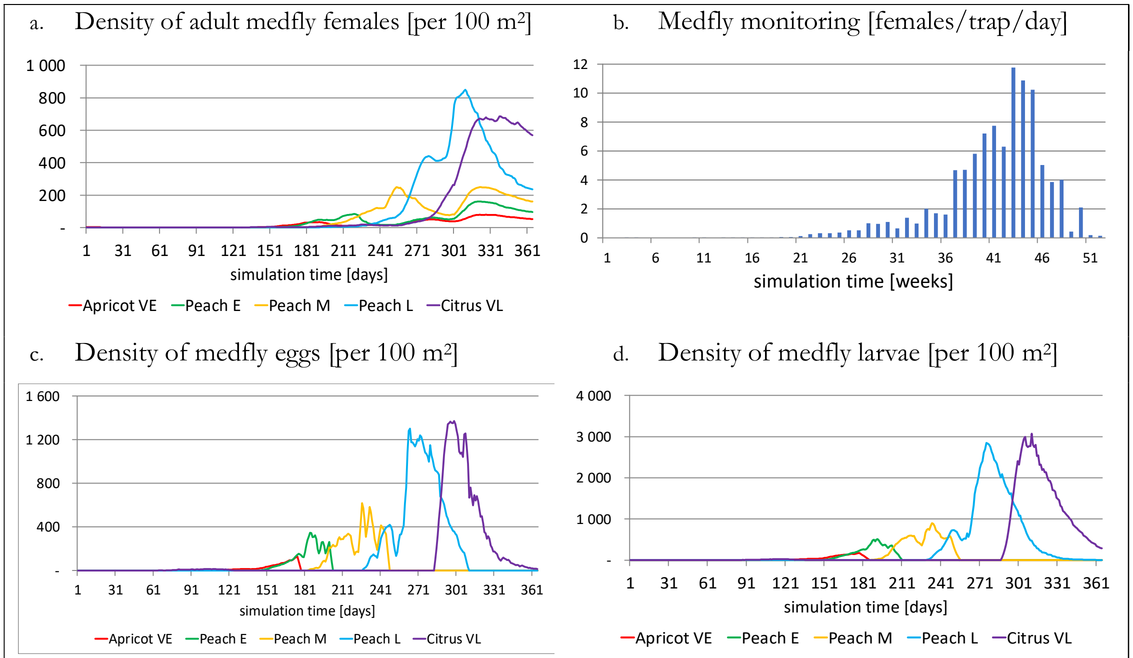
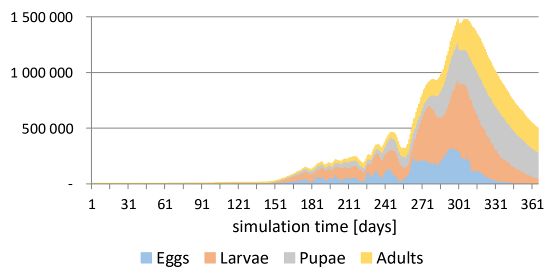


Figure 6. Paterno, Sicily, Italy: Annual patterns of medfly population on successive hosts under **NO IPM** scenario.

followed seasonal fruits, mid- and late-season peaches (Figure 6a), leaving behind subsequent peaks of eggs and larval offspring, dramatically enlarged on the late peach (Fig. 6c, d), and causing very severe fruit destruction (65.3 and 97.2%, respectively) (Fig. 7A). In total, approximately 1 057 000 and 2 340 000eggs were laid, and 904 000 and 1 936 000 larvae hatched in the mid- and late-season peach, respectively. Of these, approximately 474 000 and 926 000 entered the soil and pupated, from which 112 000 and 419 000 adult females emerged, respectively (Figure 7A). In October, the density of medfly population reached its peak (over 80 000/ha and 65 000/ha on late peach and citrus plots, respectively) (Fig. 6a). The flies gradually shifted from late peach to citrus plots, where they laid about 1 600 000 eggs. From these, about 1 264 000 larvae emerged, resulting in nearly 100% infestation of the citrus fruit (Fig. 7A). Shortly thereafter, the weather conditions gradually deteriorated, resulting in a slow decline in population density and a sharp decline in fly activity, which was reflected in dropping and ultimately negligible catches from monitoring traps. (Fig. 6b). By year's end, the overwintering medfly cohort consisted primarily of large numbers of adult females and pupae present mainly in citrus plots and, to a lesser extent, late-season peaches (Figure 6a).

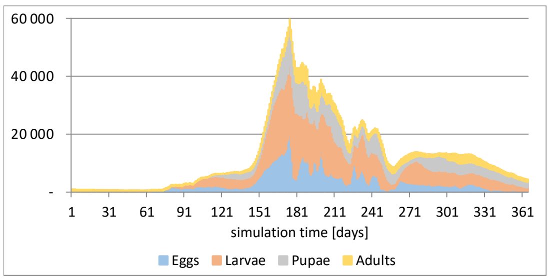
Medfly population size [whole farm, all stages] | Outline of medfly development on successive fruits

A. NO IPM



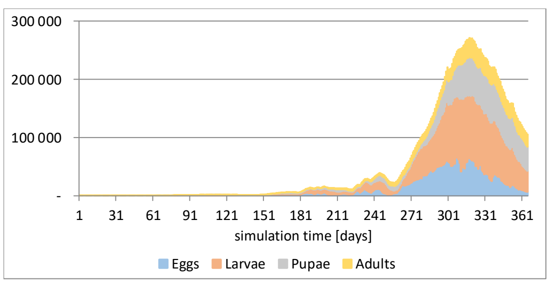
NO IPM	Apricot V-E	Peach E	Peach M	Peach L	Citrus V-L	Total
Fruit infestation at harvest	14.94%	47.31%	65.34%	97.17%	100.00%	
Eggs laid	155 368	509 121	1 057 368	2 339 968	1 621 177	**5 683 002**
Larvae hatched	132 464	431 755	903 741	1 936 395	1 264 588	**4 668 943**
Pupae (pupated larvae)	65 245	211 201	474 019	925 724	414 270	**2 090 459**
Adults emerged	16 642	36 272	112 042	419 498	15 149	**599 603**
IPM Cost & benefit [Euro]	Harvest value		IPM cost		Profit (harvest value)	
	6 124		0		6 124	

B. ON season IPM



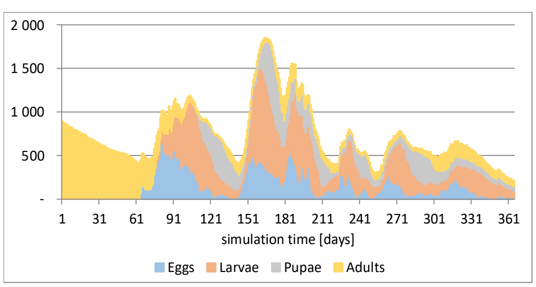
ON season IPM	Apricot V-E	Peach E	Peach M	Peach L	Citrus V-L	Total
Fruit infestation at harvest	10.57%	11.85%	12.22%	4.16%	12.22%	
Eggs laid	100 896	95 408	100 854	39 769	30 160	**367 087**
Larvae hatched	86 115	81 062	86 069	32 860	20 721	**306 827**
Pupae (pupated larvae)	42 932	40 308	45 902	15 751	5 293	**150 186**
Adults emerged	11 035	6 907	10 020	7 102	2 168	**37 232**
IPM Cost & benefit [Euro]	Harvest value		IPM cost		Profit above NO IPM	
	46 627		3 960		36 543	

C. OFF season IPM



OFF season IPM	Apricot V-E	Peach E	Peach M	Peach L	Citrus V-L	Total
Fruit infestation at harvest	0.62%	4.66%	8.01%	20.69%	92.75%	
Eggs laid	4 263	41 820	80 531	347 656	450 854	**925 124**
Larvae hatched	3 631	35 403	68 858	285 120	299 233	**692 245**
Pupae (pupated larvae)	1 836	17 353	35 687	123 290	49 781	**227 947**
Adults emerged	594	3 189	9 380	38 321	851	**52 335**
IPM Cost & benefit [Euro]	Harvest value		IPM cost		Profit above NO IPM	
	39 961		1 980		31 857	

D. OFF+ON season IPM



OFF+ON season IPM	Apricot V-E	Peach E	Peach M	Peach L	Citrus V-L	Total
Fruit infestation at harvest	0.48%	0.56%	0.32%	0.21%	0.92%	
Eggs laid	3 235	3 945	2 244	1 846	3 688	**14 958**
Larvae hatched	2 730	3 322	1 877	1 529	2 412	**11 870**
Pupae (pupated larvae)	1 425	1 696	1 021	763	671	**5 576**
Adults emerged	456	316	243	429	416	**1 860**
IPM Cost & benefit [Euro]	Harvest value		IPM cost		Profit above NO IPM	
	84 600		5 940		72 097	

Figure 7. Paterno, Sicily, Italy: Comparison of medfly management options

Until mid- June, catches in monitoring traps were erratic and only on the day 168th approached the IPM alert threshold of about 2 flies per trap per week (ca. 0.3/day) (Fig. 6 b). However, at that day, 4 544 adult females were already active on the farm, and in addition, 31 716 eggs, 48 699 larvae and 16 053 female pupae were present on different plots of the farm, ready to complete their development soon after. As a result, by the day of the IPM alert, the population of adult females had already increased over 8 times, and after taking into account all immature stages, by more than 181 times compared to the 556 females of the effective initial population.

ON-Season scenario: The simulation results are outlined in Figure 6B. The A&K panels implemented on early, medium and late peach plots accelerated the shift of medfly f7males from apricot, resulting in slight reduction in its infestation (from 14.9 to 10.5%) despite lack of control on these plots (Fig. 7B). Compared to the NO IPM scenario, the seasonal maximum of medfly population (all stages combined) present on the entire farm was substantially reduced, approximately 25 times. In the protected plots, the number of developing medfly stages decreased 5 times on early peach, 10-11 times on medium peach, 59 times on late peach, and 7-78 times on citrus. Even on the unprotected plots with apricot, the reduction was 2-fold.

Despite such a significant reduction in the medfly population, the infestation of all fruits, although much lower compared to the NO IPM scenario, was still severe and ranged from 4.2 to 12.2%, enough to substantially reduce the market value of the harvested fruit from the potential value of about €90,000 to €36,543. (Fig. 7B).

OFF-Season scenario: The simulation results are outlined in Figure 7C. As expected, the density of all medfly stages developing on apricots was reduced about 28-36 times compared to the standard ON season scenario. This very early suppression, applied on spring citrus and apricot only, also affected medfly on early and medium peaches, where its density was reduced by approximately 12-13-fold, respectively, despite the absence of any control on these plots. Later however, population growth accelerated, and at the peak the number all medfly stages present on the farm was almost 5 times higher than in the ON season scenario, although still about 5 times lower compared to the NO IPM case (Fig. 7C). The seasonal density peak was postponed by two weeks compared to the NO IPM case, and consequently, much smaller number of larvae completed their development on citrus before winter. Also, pupal development was slowed by the onset of cooler temperatures in November, so the number of adults that emerged from the citrus plots decreased by over 18-fold.

All this, although it significantly protected the early fruits, did not manage to save the late peaches and citrus fruits, which were very severely infected, about 21 and 93%, respectively. Despite the latter, the final effect, i.e. the value of the harvested crop (31,857 Euro) was comparable compared to the ON-Season scenario (€36,543) (Fig. 6C).

OFF+ON scenario: The simulation results are outlined in Figure 7D. Compared to the 'standard' ON season scenario, the number of immature stages and emerging adult females decreased by 24-32 times on the plots with very early apricots, 22-24 times on early peaches, 41-45 times on medium peaches, 17-22 times on late peaches, and 5-8 times on autumn citrus. Throughout the year, the density of medfly population was very low or negligible, and even during the peak period the seasonal maximum of medfly population (all stages combined) present on the entire farm was over 30 times lower compared to the ON Season scenario. So radically reduced population density was also reflected in negligible infestation (less ten 1%) of all fruits present on the farm.

The final effect of the combined use of A&K panels both in the OFF and ON season mode was very good (net benefit €72,097) (Fig. 7D).

5.4.3. Mid-Range of Medfly Presence in Europe - Lazio Case

The Cori area in Lazio is representative of the medfly's mid-range area in Europe with mild climate, when winter temperatures only occasionally fall a few degrees Celsius below zero and only sometimes exceed the medfly's optimal range in summer. On a typical farm, fruits suitable for medfly oviposition and larval development are available for about 6-7 months in summer and autumn, starting with apricots in May, through various cultivars of summer peaches, and ending with apples ripening from September to October (Fig. 8). Apples that are not harvested in autumn may remain in good condition till early next spring and harbour some immature medfly stages. In a site-typical year (2009), favourable weather allowed for 214 days (1,858 hours) of medfly activity, starting with short episodes in March and culminating in 8-11 hours daily in June-August (Fig. 8). Our research has shown that the earliest apricots and early peach are rarely noticeably infested and usually remain not protected. Regular medfly control begins in late June or early July with 2-3 pesticide sprays on medium peaches, 3-4 on late peaches, and 4-5 sprays on apple. With an estimated cost of pesticide treatment ranging from €70 to €120 /hectare, the cost of typical IPM implemented on our hypothetical farm ranges from €1,134 to €2,808/farm/season.

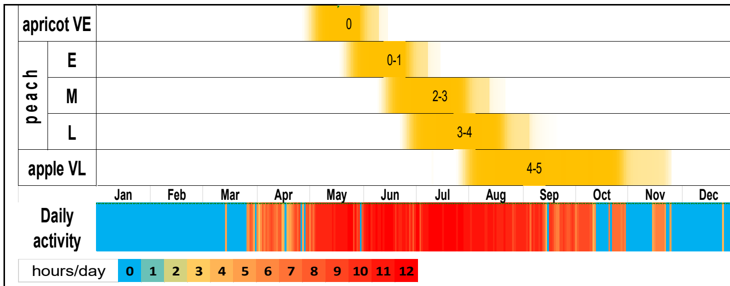


Figure 8. Cori, Lazio, Italy: Annual patterns of fruit availability with number of pesticide sprays, and days with Medfly activity.

The ON and OFF seasonal IPM implementation schemes, adopted in the simulations presented below, are presented in Table 5. The ON season scenario reflects farmers' usual practice in years with typical seasonal weather (protection of fruit that would otherwise be infested above 4-5%). With an estimated cost of A&K panels €550 /ha (at 100 A&K panels/ha), the cost of IPM implemented on our hypothetical farm equals €1,980 for the OFF season, €2,970 for ON season, and €4,950 for the combination OFF+ON season.

Table 5. Cori, Lazio, Italy: Implementation schedule for ON and OFF-Season treatments.

IPM	Fruit category	Implementation day
OFF season	Apricot VE Peach E	75
ON season	Peach M Peach L	110
	Apple VL	150

NO IPM scenario: The simulation results of uncontrolled development of medfly population are outlined in Figure 9 and 10A. Overwintering females, both adult and immature, were subject to mortality, and by the time their oviposition begun (day 126th), 65% of them had died, leaving only 319 females scattered over an area of 9 ha of the farm (less then 36/ha) as effective founders of a new population. In the second quarter, weather conditions quickly approached optimal, and, in April, the flies moved to the apricot and peach plots, where they oviposited giving raise to the first post-winter generation. Approximately 17 000 eggs (9 400/ha) were laid on the earliest apricot, and then about 35 200 eggs (19 500/ha) on early peach, which resulted in barely noticeable two successive peaks of egg and larval population (Figure 9 c, d) and negligeable damage on apricot (0.9%) and very low on early peach (3.5%) (Fig. 10A). In the third quarter, after 12 589 adult females emerged from the apricot and early peach plots, the still uncontrolled medfly population entered a phase of exponential growth. Adult females actively followed seasonal fruits (Fig. 9a), leaving behind subsequent loads of eggs and larval offspring (Figure 9 c, d), and causing severe fruit destruction, 18.2% and 66.8% of medium and late peach, respectively. In total, approximately 245 800 and 941 300 larvae hatched, of these, approximately 123 500 and 488 600 entered the soil and pupated, from which 79 350 and 286 500 adult females emerged on the plots with medium and late peach, respectively (Fig. 10A). At its peak in early September almost 1.4 million females, in various stages of development, were present on the farm (Fig. 10A). Later, the flies shifted from late peach to apple plots, where they laid about 1 542 200 eggs. From these, about 1 311 700 larvae emerged, resulting in 100% infestation of the apple fruit (Fig. 10A). Shortly thereafter, weather conditions deteriorated, resulting in a decline in population density and a sharp decline in fly activity, which was reflected in dropping and ultimately negligible catches from monitoring traps. (Fig. 9 a, b). By year's end, the overwintering medfly cohort consisted primarily of large numbers of adult females, present mainly in apple plots.

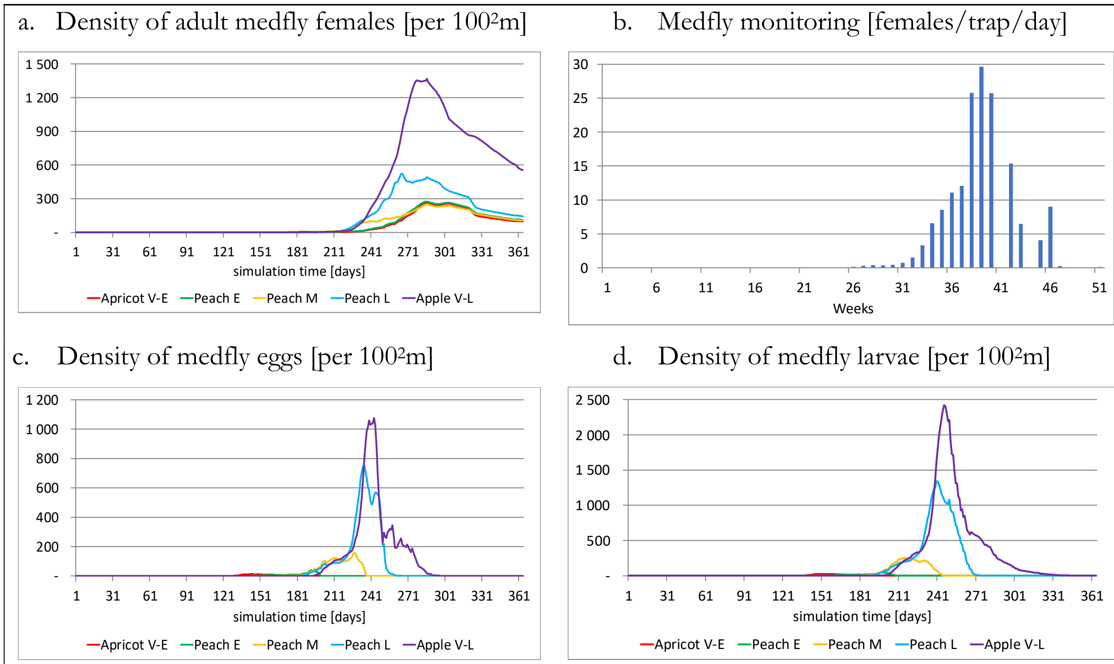


Figure 9. Cori, Lazio, Italy: Annual patterns of medfly population on successive hosts under **NO IPM** scenario.

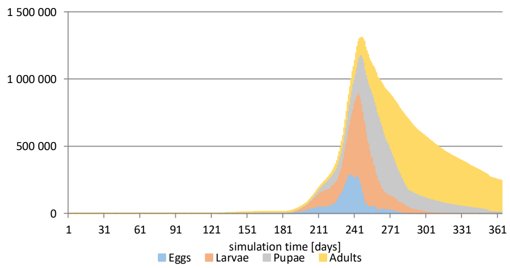
Until end of June, catches in monitoring traps were erratic and only in mid-July, on the day 189th, approached the IPM alert threshold of about 2 flies per trap per week (ca. 0.3/day) (Fig. 9 b). However, at that day, 3 068 adult females were already active on the farm, and in addition, 8 738 eggs, 7 917 larvae and 4 263 female pupae were present on different plots of the farm, ready to complete their development soon after. As a result, by the day of the IPM alert, the population of adult females had already increased by almost 10 times, and after taking into account all immature stages, by more than 75 times compared to the 319 females of the effective initial population.

ON-Season scenario: The simulation results are outlined in Figure 10B. The attractive panels implemented on medium and late peach plots accelerated the shift of medfly females from early peach, resulting in slight reduction in its infestation (from 3.5 to 2.3%) despite lack of control on these plots (Fig. 10B). Compared to the NO IPM scenario, the seasonal maximum of medfly population (all stages combined) present on the entire farm was reduced approximately 5 times. In the protected plots, the number of developing medfly stages decreased 3-6 times. Despite significant reduction in medfly population, medium and late-season peaches, and even more so apples, were less but still severely infested at approximately 7, 17 and 39%, respectively (Fig. 10B).

Despite less fruit infestation, the end result of the use of A&K panels only in the ON season mode was only by €9,306 better than that with the complete lack of any protection (NO IPM) (Fig. 10B).

Medfly population size [whole farm, all stages] | Outline of medfly development on successive fruits

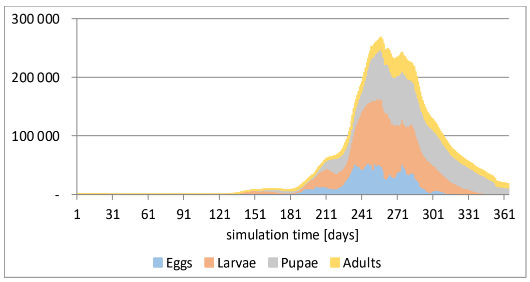
A. NO IPM



NO IPM	Apricot V-E	Peach E	Peach M	Peach L	Apple V-L	Total
Fruit infestation at harvest	0.94%	3.49%	18.24%	66.81%	100.00%	
Eggs laid	16 967	35 202	286 499	1 094 791	1 542 156	2 975 615
Larvae hatched	13 829	29 456	245 808	941 338	1 311 724	2 542 155
Pupae (pupated larvae)	6 653	12 644	123 531	488 637	730 543	1 362 008
Adults emerged	4 372	8 217	79 353	286 476	375 374	753 792

IPM Cost & benefit [Euro]	Harvest value	IPM cost	Profit (harvest value)
	26 379	0	26 379

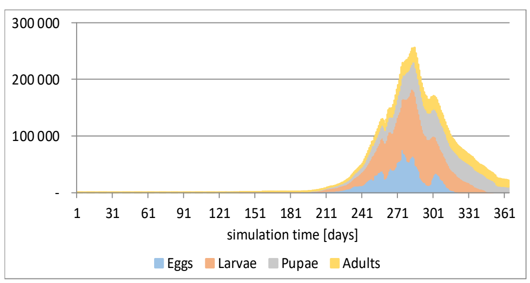
B. ON-Season IPM



ON season IPM	Apricot V-E	Peach E	Peach M	Peach L	Apple V-L	Total
Fruit infestation at harvest	0.91%	2.26%	6.68%	16.57%	38.65%	
Eggs laid	16 508	23 891	81 869	238 772	593 748	954 788
Larvae hatched	13 421	20 021	70 307	203 644	473 839	781 232
Pupae (pupated larvae)	6 503	8 235	34 803	100 410	197 141	347 092
Adults emerged	4 334	5 306	22 508	54 025	67 926	154 099

IPM Cost & benefit [Euro]	Harvest value	IPM cost	Profit above NO IPM
	38 655	2 970	9 306

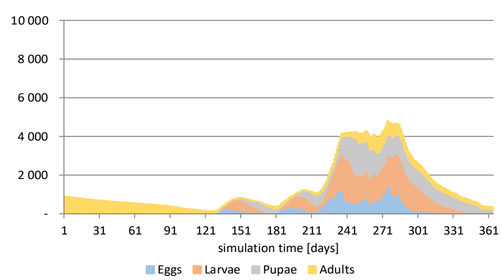
C. OFF-Season IPM



OFF season IPM	Apricot V-E	Peach E	Peach M	Peach L	Apple V-L	Total
Fruit infestation at harvest	0.11%	0.24%	2.43%	7.66%	33.47%	
Eggs laid	2 076	1 595	22 716	102 108	522 475	650 970
Larvae hatched	1 666	1 328	19 426	85 865	377 909	486 194
Pupae (pupated larvae)	775	659	9 411	37 993	95 234	144 072
Adults emerged	511	447	6 031	16 396	13 762	37 147

IPM Cost & benefit [Euro]	Harvest value	IPM cost	Profit above NO IPM
	56 054	1 980	27 695

D. OFF+ON Season IPM



OFF+ON season IPM	Apricot V-E	Peach E	Peach M	Peach L	Apple V-L	Total
Fruit infestation at harvest	0.08%	0.11%	0.28%	0.75%	1.72%	
Eggs laid	1 423	756	2 467	5 984	10 952	21 582
Larvae hatched	1 133	628	2 116	5 058	8 492	17 427
Pupae (pupated larvae)	563	286	1 037	2 593	2 891	7 370
Adults emerged	374	201	653	1 487	1 013	3 728

IPM Cost & benefit [Euro]	Harvest value	IPM cost	Profit above NO IPM
	80 453	4 950	49 124

Figure 10. Cori, Lazio, Italy: Comparison of medfly management options

OFF-Season scenario: The simulation results are outlined in Figure 10C. Compared to the standard ON season scenario, the density of all medfly stages present on apricots and early peaches was reduced about 8-9 and 18-22 times, respectively. This early suppression also affected medfly on medium and late peaches, where medfly density was also reduced by approximately 13 and 11-17-fold, respectively, despite the absence of any control on these plots (Fig. 10C). Later however, population growth accelerated, and at the peak the number all medfly stages present on the farm was comparable to the ON season scenario. Although the egg load and fruit infestation on medium and late peach was reduced 3-4 and 2 times, respectively, the difference in the egg load on apples was only minor, which resulted in similar, over 30% fruit infestation (Fig. 10C). But compared to the ON season scenario, the seasonal density peak was delayed by almost 30 days, and consequently, much smaller number of larvae completed their development on apples before harvest. Also, pupal development was slowed by the onset of cooler temperatures in October, so the number of adults that emerged from the apple plots decreased by about 5-fold. In conclusion, OFF season medfly suppression focused only on the plots with the earliest fruit, if applied alone, did not sufficiently protect all fruit on the farm, but importantly, its results on unprotected medium and late peaches were substantially better compared to the 'standard' ON season IPM.

Interestingly, the final effect (net benefit €27,695) of the use of A&K panels only in the OFF season mode was nearly 3 times better compared to the ON season scenario (€9,306) (Fig. 10C).

OFF+ON Scenario: The simulation results are outlined in Figure 10D. Compared to the 'standard' ON season scenario, the number of immature stages and emerging adult females decreased by 12 and 26-32 times on the plots with very early apricots and early peaches, in plots with medium and late peaches by 33-34 and 36-40 times, respectively, and 54-68 times on late apples. Throughout the year, the density of medfly population was very low or negligible, and even during the peak period the seasonal maximum of medfly population (all stages combined) present on the entire farm was over 50 times lower compared to the ON season scenario. So radically reduced population density was also reflected in negligible infestation of very early apricot and all peach cultivars (less ten 1%), and very low (less than 2%) infestation of the most vulnerable late apple.

The final effect (net benefit 49,124 Euro) of the use of A&K panels both in the OFF and ON Season mode was very good (Fig. 10D).

5.4.4. Northern Limit of medfly Presence in Europe - Trentino Case

The Avio area in Trentino is representative of the northern limit of medfly's range in Europe with temperate climate. Winter temperatures regularly drop several degrees Celsius below zero, and sometimes only reach the optimal medfly range in the summer and very rarely, almost never exceed it. On a typical farm, fruits suitable for medfly oviposition and larval development are available for about 4-5 months in summer and autumn, starting with apricots late in June – early July, through various cultivars of summer peaches, and ending with apples ripening from September till late October (Fig. 11). In a site-typical year, favourable weather allows for 145 days (1 186 hours) of medfly activity, starting with short and erratic episodes in April and culminating in 8-11 hours daily in July-August (Fig. 11). The earliest apricots, as well as early and medium peaches are usually not noticeably infested and are not protected. Regular medfly control begins in August with 3-4 pesticide sprays on late peaches, and 4-5 sprays on apple. With an estimated cost of pesticide treatment ranging from 70 to 120 Euro/hectare, the cost of typical IPM implemented on our hypothetical farm ranges from €882 to €1,944 /farm/season.

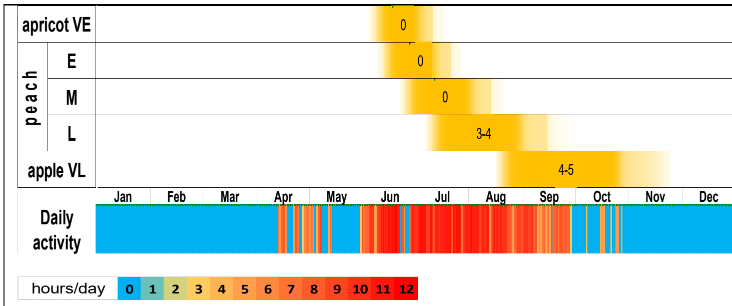


Figure 11. Avio, Trentino, Italy: Annual patterns of fruit availability with number of pesticide sprays, and days with medfly activity.

Table 6. Avio, Trentino, Italy: Implementation schedule for ON and OFF-Season treatments.

IPM	**Fruit category**	**Implementation day**
OFF season	Apricot VE Peach E Peach M	110
ON season	Peach L Apple VL	135 160

The ON and OFF Season IPM implementation schemes, adopted in the simulations presented below, are presented in Table 6. The ON season scenario reflects farmers' usual practice in years with typical seasonal weather (protection of fruit that would otherwise be infested above 4-5%). With an estimated cost of A&K panels €550 /ha (at 100 A&K panels/ha), the cost of IPM implemented on our hypothetical farm equals €2,970 for the OFF season, €1,980 for ON season, and €4,950 for the combination OFF+ON season.

NO IPM scenario: The simulation results of uncontrolled development of medfly population are outlined in Figure 12 and 13A. In the first half of the year, weather conditions were not favourable, and medfly's limited and irregular activity began only in mid-April and continued in this form until the end of May. Overwintering females were subjected to high mortality and by early June (day 153), when their egg laying began, 69% of them had died, leaving only 279 females scattered over an area of 9 ha of the farm (less than 32/ ha) as effective founders of a new population. In the third quarter, weather conditions improved rapidly with daytime temperatures fluctuating within the low-to-mid optimal range for medfly. Most of the flies moved to the plots with apricot and early and medium peach, where they oviposited giving raise to the first post-winter generation. About 11 000 eggs (6 100/ha) were laid on apricot, about 9 400 eggs (5 300/ha) on early peach, and about 10 500 eggs (5 800/ha) on medium peach (Figure 13A), which resulted in barely noticeable three successive peaks of egg and larval population (Figure 12 c, d) and negligeable damage on apricot (0.6%), very low on early and medium peach (1.5 and 1.2%, respectively) (Fig. 13A). In mid-late September, the population of medfly reached its annual maximum (about 100 000 for all stages), with most adults, eggs and larvae present on the plots with late peaches and apples (Fig. 12 a, c, d). About 60 000 eggs (33 400/ha) were laid on the late peach, about 161 300 eggs (89 600/ha) on apples, which resulted in moderate (ca. 7%) infestation of late peach and severe (ca. 22%) of apples (Fig. 13A).

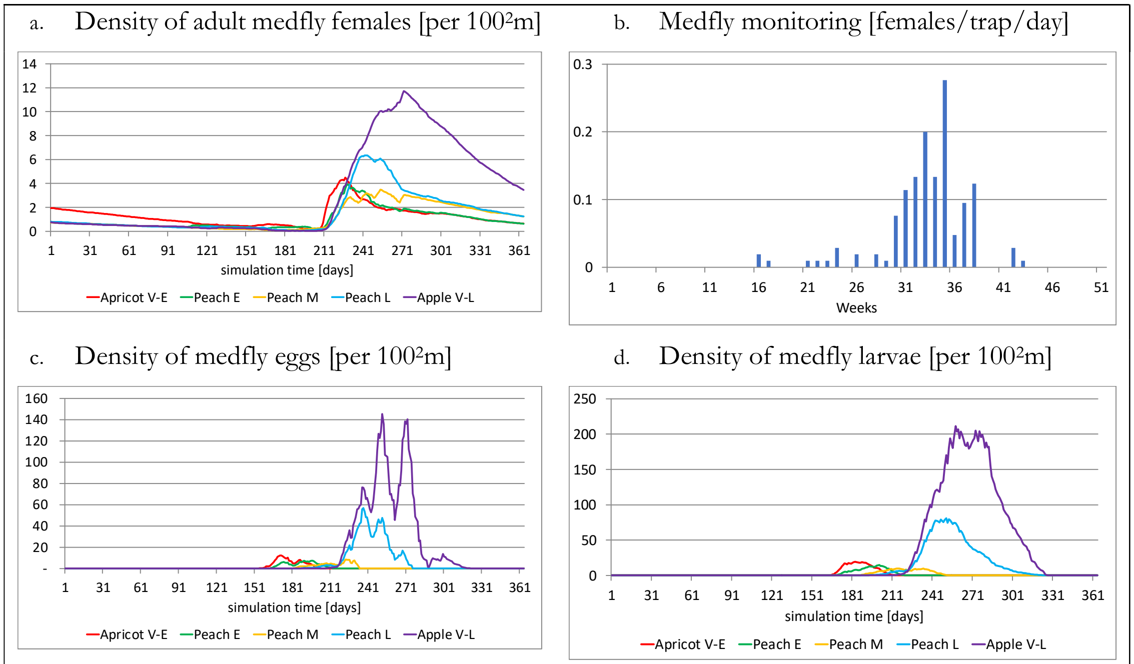


Figure 12. Avio, Trentino, Italy: Annual patterns of medfly population on successive hosts under **NO IPM** scenario.

Until early August, catches in monitoring traps were erratic and only early in September, on the day 245th, approached the IPM alert threshold of about 2 flies per trap per week (ca. 0.3/day) (Figure 12 b). However, on that day, 4 248 adult females were already active on the farm, and in addition, 17 118 eggs, 35 871 larvae and 6,957 female pupae were present on different plots, ready to complete their development soon after. As a result, by the day of the IPM alert, the population of adult females had already increased by almost 15 times, and after taking into account all immature stages, by more than 227 times compared to the 282 females of the effective initial population.

In Trentino, with no IPM, only the latest fruit (apple) was damaged at 22%, so the net profit to the farmer was €56,088 (Figure 13A).

ON season scenario: The simulation results are outlined in Figure 13B. The attractive panels implemented on medium and late peach plots accelerated the shift of medfly females from early peach, resulting in marginal reduction in its infestation (from 1.5 to 0.8%) despite lack of control on these plots (Fig. 13B). Compared to the NO IPM scenario, the seasonal maximum size of medfly population (numbers of all stages combined) present on the entire farm was reduced approximately 4 times. In the protected plots, the number of developing medfly stages decreased 2-7 times. This resulted in fairly good protection of late peaches (infestation: 2.3%), but not in apples, where infestation was barely acceptable (4.2%).

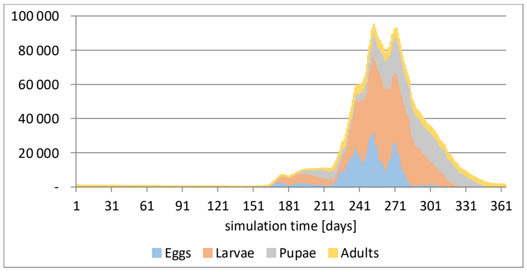
The end result of the use of A&K panels only in the ON season mode was substantial, after subtracting the IPM cost and compared to the NO IPM option, provided the net benefit of €21,371 (Fig. 13B).

OFF season scenario: The simulation results are outlined in Figure 13C. Compared to the standard ON season scenario, the density of all medfly stages developing on apricots was reduced about 7 -8 times, on early peaches. 12-13 times, and on medium peaches 14-19 times. This early suppression also affected medfly on late peaches and apples, where medfly density was also reduced by approximately 3-4 and 5-6-fold, respectively, despite the absence of any control on these plots (Fig. 13C). Also, the annual peak of medfly population size present on the farm (numbers of all stages combined) was reduced about 5 times compared to the ON season scenario. In effect, the infestation of all fruits, protected and unprotected, was very low, below 1% (Figure 13C).

Interestingly, the final effect (net benefit 21,633 Euro) of the use of A&K panels only in the OFF-Season mode was almost exactly the same as that of the 'standard' ON season scenario (Fig. 13C).

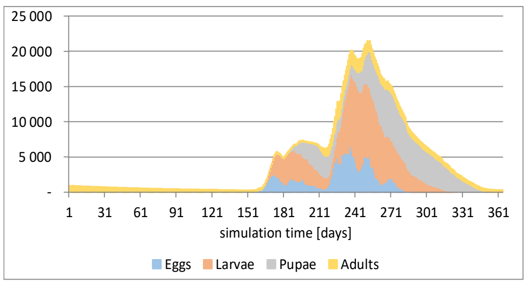
Medfly population size [whole farm, all stages] | Outline of medfly development on successive fruits

A. NO IPM



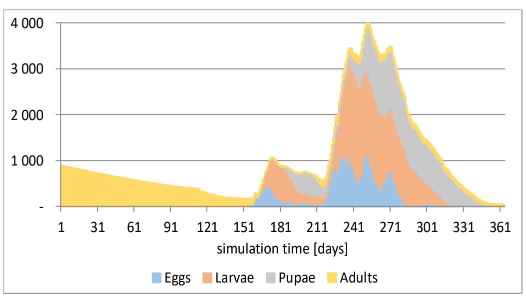
NO IPM	Apricot V-E	Peach E	Peach M	Peach L	Apple V-L	Total
Fruit infestation at harvest	0.63%	1.55%	1.18%	7.07%	22.15%	
Eggs laid	11 157	9 429	10 497	60 100	161 276	252 459
Larvae hatched	8 813	7 472	8 706	46 489	115 284	186 764
Pupae (pupated larvae)	3 702	3 388	3 847	13 611	23 558	48 106
Adults emerged	2 364	2 199	1 515	735	180	6 993
IPM Cost & benefit [Euro]	Harvest value		IPM cost		Profit (harvest value)	
	56 088		0		56 088	

B. ON season IPM



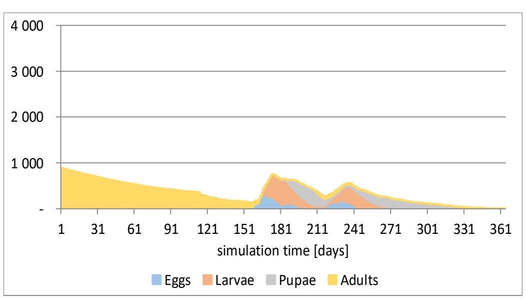
ON season IPM	Apricot V-E	Peach E	Peach M	Peach L	Apple V-L	Total
Fruit infestation at harvest	0.51%	1.02%	0.64%	2.29%	4.21%	
Eggs laid	9 469	6 163	5 931	17 533	26 732	65 828
Larvae hatched	7 389	4 936	4 924	13 614	20 319	51 182
Pupae (pupated larvae)	3 200	2 261	2 042	4 318	6 497	18 318
Adults emerged	2 105	1 521	771	230	60	4 687
IPM Cost & benefit [Euro]	Harvest value		IPM cost		Profit above NO IPM	
	79 439		1 980		21 371	

C. OFF season IPM



OFF season IPM	Apricot V-E	Peach E	Peach M	Peach L	Apple V-L	Total
Fruit infestation at harvest	0.08%	0.09%	0.04%	0.55%	0.91%	
Eggs laid	1 333	508	331	4 210	5 725	12 107
Larvae hatched	1 048	410	265	3 304	4 201	9 228
Pupae (pupated larvae)	443	173	132	1 140	1 089	2 977
Adults emerged	279	115	55	81	10	540
IPM Cost & benefit [Euro]	Harvest value		IPM cost		Profit above NO IPM	
	80 691		2 970		21 633	

D. OFF+ON season IPM



OFF+ON season IPM	Apricot V-E	Peach E	Peach M	Peach L	Apple V-L	Total
Fruit infestation at harvest	0.06%	0.10%	0.01%	0.07%	0.07%	
Eggs laid	898	524	76	506	434	2 438
Larvae hatched	710	409	59	400	351	1 929
Pupae (pupated larvae)	326	197	26	175	169	893
Adults emerged	196	118	7	20	3	344
IPM Cost & benefit [Euro]	Harvest value		IPM cost		Profit above NO IPM	
	80 952		4 950		19 914	

Figure 13. Avio, Trentino, Italy: Comparison of medfly management options

OFF+ON Scenario: The simulation results are outlined in Figure 13D. Compared to the 'standard' ON season scenario, the number of immature stages and emerging adult females decreased by 10-13 times on the plots with very early apricots and early peaches, in plots with medium and late peaches by 78-110 and 12-35 times, respectively, and 30-62 times on late apples. Throughout the year, the density of medfly population was very low or negligible, and even during the peak period it was over 20 times lower compared to the ON season scenario.

However, this drastic reduction in medfly population density and the resulting negligible (less than ten 0.1%) infestation of all fruit present on the farm did not translate into additional financial benefits. Compared to the OFF-season scenario, adding the ON season protection provided no additional benefits, in fact after deducting the IPM cost the net benefit was €1,719 lower (Fig. 13D).

5.4.5. Role of target fruit market and fruit infestation tolerance

The results of the net gain simulation (fruit value minus IPM cost) with respect to market demands and fruit infestation tolerance are presented in Table 7. As expected, the results show significant differences in fruit value and perception of benefits from IPM, highest in the southernmost regions where medfly is abundant, and among fruit growers focusing on the most restrictive export markets.

Table 7. Net profit in relation to target market and the infestation threshold.

Paterno	5%	10%	15%	20%	25%	30%
NO IPM	-	-	6 124	6 124	9 799	9 799
On season	4 665	9 841	42 667	60 293	60 293	60 293
OFF season	19 195	30 765	37 981	37 981	48 099	48 099
OFF+ON season	78 221	78 221	78 221	78 221	78 221	78 221

Cori	5%	10%	15%	20%	25%	30%
NO IPM	19 430	23 600	26 379	33 002	33 002	36 975
On season	20 775	31 149	35 685	43 193	46 217	50 722
OFF season	37 616	49 088	54 074	54 074	57 398	57 398
OFF+ON season	71 612	75 503	75 503	75 503	75 503	75 503

Avio	5%	10%	15%	20%	25%	30%
NO IPM	42 706	51 069	56 088	56 088	67 141	67 141
On season	64 459	73 666	77 459	77 459	77 459	77 459
OFF season	77 721	77 721	77 721	77 721	77 721	77 721
OFF+ON season	76 002	76 002	76 002	76 002	76 002	76 002

- The net-profit = fruit value - IPM cost

5.5. DISCUSSION

The IPM paradigm: The conceptual framework of the classical IPM paradigm was developed over 60 years ago in response to growing public concerns about the widespread overuse of pesticides in agriculture, the rapid development of pesticide-resistant pests, and the harmful consequences for producers, consumers, and the environment. The main goal was to rationalize and limit the use of synthetic pesticides and, where possible, integrate them with biological methods, giving priority to the latter. The decision-making process based on current pest monitoring results is the cornerstone of the logical framework of the IPM concept. It stipulates that a decision to undertake pest control is made only when population density actually exceeds predetermined economic inquiry levels or IPM action thresholds (Stern et al., 1959). While it was recognized that in some cases of regularly occurring and very harmful pests it may not always be necessary to base pest management decisions on population sampling results (Poston et al., 1983; Nyrop et al., 1989), this did not change the overarching principle and operational criterion to undertake control only when and where there is a present and real need to avoid imminent and unacceptable crop loss.

The concept of a rational, need and criteria-based approach to plant protection have gained widespread acceptance, and in 2009, in Europe, strict compliance with the principles of the IPM paradigm was enforced by the European Directive 2009/128/EC and subsequent legislative amendments in all Member States.

Medfly management in Europe: Under the regulations, also in the case of invasive tropical tephritid fruit flies, such as medfly, fruit growers are officially obligated to follow the IPM principles and advised to implement pest monitoring and action thresholds (Cavalloro and Prota 1983; Dekker and Messing 2019; Garcia 2009; Vincenot and Quilici 1995). Yet our current surveys have shown that, over 10 years after the Directive, the majority of farm owners still use a simplistic, reactive approach based on experience and habit: "control where and when the problem usually occurs", mostly reduced even further to a routine practice of regular pesticide cover sprays on summer and autumn fruit (Colacci et al. 2022). Even if some monitoring traps are deployed on a farm, the reality is that this is more often driven by the need for "nominal IPM compliance" than by actual use of their decision support functions.

This pesticide dependence persists despite the availability of highly acclaimed biology-based methods for medfly control, such as mass trapping or Attract & Kill, Sterile Insect Technique, predator conservation, and the use of entomopathogenic fungal and bacterial pathogens or nematodes. In this context, the continuing reluctance to adopt and implement these methods is intriguing, which inspired us to investigate its causes.

Medfly annual cycle: The results of our simulations, carried out for three locations (Sicily, Lazio and Trentino) over approximately 1 000 km of the latitudinal transect of medfly occurrence in Italy, reflect well the known trends and are consistent with our empirical data and published information (Papadopoulos et al. 2001, Israely 1997, Giunti at al. 2023, Zanoni etc). The timing and intensity of the simulated prolific phase follows latitudinal weather gradients, with delayed and smaller annual peaks at the northernmost parts of the medfly range. This allows us to take a closer look at specific aspects of the IPM process with some confidence.

IPM decision-making and timing: Fruit growers and commonly advised to base IPM decisions on medfly monitoring and action thresholds (Cavalloro and Prota 1983; Dekker and Messing 2019; Garcia 2009; Vincenot and Quilici 1995). But our simulations revealed, that for trap catches to reach the IPM threshold, the overwintering medfly must first reproduce and increase its density. In each location, by the day of the 'IPM alert', the population of adult females active on the farm had already increased 10-20 times compared to the starting spring cohort. The actual population increase was in fact much higher because it is also necessary to include the immature stages, already present on the farm in the plots with the earliest fruits and ready to complete their development soon. Therefore, the effective pre-alert increase can be estimated as 100-200 times, depending on location. This was despite the assumption of a much higher trap density (15 traps /6 ha farm) compared to the prevailing practice (2-5 traps/farm) and the strict "alert" threshold (2 females/trap/week) used in our simulations, that was significantly below the usually recommended 7-10 females/trap/week. Therefore, in normal practice (fewer traps and higher thresholds), the moment of decision and initiation of control will usually come even later, with an even larger population of active adult females that have emerged from the soil in the meantime.

Our simulations demonstrated, that by following the recommended routine of pest monitoring and acting at the IPM alert time, in the case of medfly, the farmer invariably gets his warning late and starts control when the medfly has already multiplied significantly and is much more difficult to control. It is therefore not surprising that in such a situation, concerned farmers resort to the use of immediate-acting pesticides to save their crops. Even synthetic pesticides, while usually effective, in years with exceptionally mild winters and medfly-favourable weather frequently fail when used at such late stage.

Biological methods as an alternative to pesticides: The 'ON-Season' application of pesticides to protect summer and autumn fruit plots is a well-established and widespread practice maintained by both the habits of farmers and the recommendations of the classic IPM paradigm. It broadly complies with the common-sense IPM principle: 'take action only where and when needed'. However, the basic IPM recommendation: 'replace the use of pesticides with biological methods whenever possible' is very rarely implemented. To investigate the causes, we simulated the effects of replacing pesticide treatments with well-established and recognized Attract & Kill method. Our preliminary simulations with A&K panels implemented at the recommended IPM alert time, have shown discouraging results. Therefore, to take full advantage of the long-term activity of the panels (up to 180 days in field conditions) and provide a head-start advantage, the simulations presented in this paper assumed a much earlier implementation of the panels, well before IPM alert date (78-8 days for Paterno, 79-39 for Cori and 110-86 days in Avio), and higher than usually recommended density (100 panels/ha *vs* 70/ha). The results seemed very promising. Compared to the NO IPM option, both the peak seasonal medfly densities and fruit infestation were much reduced (population peak: 4-25 times, fruit infestation: 4-7 times). However, this apparent success did not always translate into a real profit for the farmer. The acceptable profits were achieved only in Avio, the northernmost location, where medfly's population growth was already constrained by mostly suboptimal weather conditions. In other locations, with longer fruiting season and more suitable weather, final fruit infestation was still too severe, which reduced the commercial value of the harvest and overall profit to unacceptably low levels.

Our simulations and experience show that in the ON-Season implementation mode, in most cases, even highly acclaimed biological methods are not effective and reliable enough to become a practical alternative to replacing pesticides. In the following, we discuss the causes and possibilities of mitigating this situation.

Peculiarity of tropical tephritid fruit flies: Temperate fruit flies are oligophagous, univoltine with obligatory diapause. At the beginning of summer, within 1-4 weeks, the single annual cohort emerges from the ground and during this process, before reaching its maximum, the trap catches usually exceed the IPM alert threshold. The emerging individuals are still immature and need a few to a dozen or so days to mature and start laying eggs into then available fruit. After reaching a maximum, population density gradually declines due to natural mortality. Early alert and the early use of biological methods acts on this downward trend, accelerating the population decline process (Fig. 14).

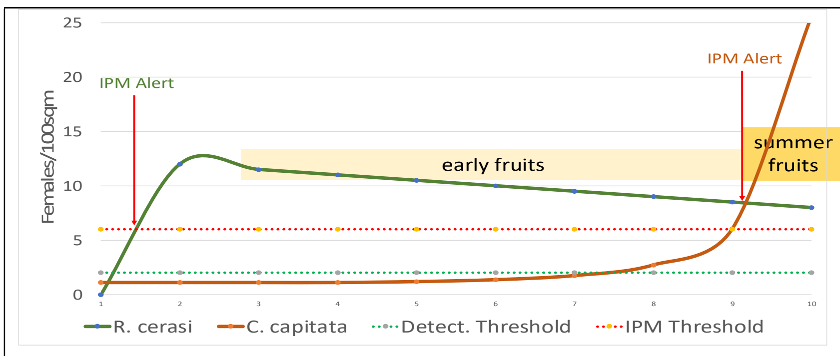


Figure 14. The difference in early population trends between temperate and tropical fruit flies and its implications for IPM.

In contrast, invasive tephritids of tropical origin, such as the medfly, are highly polyphagous and multivoltine, with the capacity for rapid population growth. Due to the lack of obligatory diapause, their daily activity depends solely on current weather conditions. In mild climates, it may appear occasionally, even on warm winter days. As soon as the earliest fruits become available, already mature females lay eggs while still in the cryptic phase, "invisible" in monitoring traps due to the very low density. When the IPM alert threshold is reached, medfly is already in the phase of its expansive population growth (Figure 14). While immediate-acting pesticides are usually able to cope, gradually acting biological methods are not able to reverse the seep upward population trends.

Misleading measures of IPM success - discrepancy between researcher's and farmer's perspective: The poor performance of the standard ON-Season scenario, in which A&K panels were used as an alternative to pesticides, calls into question the feasibility of the key ambition of the classic IPM: "replace pesticides with biological methods ". Such statement may seem to contradict the extensive literature reporting good control of medfly using biological methods such as A&K panels. This apparent inconsistency is due to the particular mode of operation of biological methods and the common discrepancy between the researcher's and the farmer's criteria and perceptions of IPM success. Unlike pesticides, biological methods suffer from inherent shortcoming of gradual mode of action. With sufficient time, they can reach even pesticide-comparable suppression of medfly population, but meanwhile, the remaining and still alive flies can significantly damage crops. Scientists focus on suppressing the medfly population and typically use trap catches and, rarely, fruit infection to measure it. Invariably, several-fold reductions in trap catches and/or fruit infestations are heralded as proof of success (Gonçalves 2015). But experience shows that for a farmer, information about a reduced pest is welcome, but of marginal importance. What really matters is the final net profit, measured by the market value of the fruit minus the cost of IPM. In highly competitive fruit markets, the wholesale price drops rapidly to almost zero with even moderate fruit damage. This value threshold varies for different countries, target markets and seasons, but exceeding it makes the fruit harvest unprofitable. Only for amateur growers a small amount of saved fruit can be considered satisfactory. The above explains the common misconception that literature-acclaimed biological methods are simply ready substitutes for pesticides. Their gradual mode of action, combined with the ability of tropical fruit flies to multiply significantly before reaching the IPM threshold, makes biological methods unable to cope with rapidly expanding medfly populations when used at such a late time, which in turn also explains the continued reluctance to use them and the persistent dependence on pesticides.

The results of our simulations reflect the above relationships and showed that even a several-fold reduction in pest density did not necessarily translate into a significant reduction in fruit infestation. Moreover, even if a similar reduction in fruit damage was achieved, it did not always translate into an increase in the final profit for the farmer. In a broader sense, it points to a fundamental problem of operational insufficiency of biological control methods when used against tropical fruit flies according to the classical IPM paradigm.

OFF-Season shift in medfly IPM: The disappointing results of simple substitution of pesticides with biological methods within the framework of classic IPM inspired us to look for other implementation possibilities. Hence, departing from the principles of classical IPM and common practice, OFF Season scenarios were tested that were based on a seemingly irrational idea: "start control in early spring, before the pest can even be detected, and focus on the earliest fruit, which is usually undamaged". It was not our intention to propose a complete abandonment of the traditional protection of summer and autumn fruit, but to evaluate the possible benefits of acting against the sparse overwintering medfly population while it is still in the cryptic phase and incapable of causing significant damage to the early fruit.

The overall results of targeting medfly spring population were very encouraging. Despite leaving the most attacked summer and autumn fruits without any protection, in all locations the net benefit for the farmer was comparable or greater compared to implementing the same A&K method in the regular ON season mode, described above. The effect was location dependent, and in warmer locations, early suppressed and sparse medfly populations still managed to "bounce back" and increase on the unprotected late fruit and cause serious infestation. However, in the northernmost location, the overall result of the OFF-Season mode only (without any protection of summer and autumn fruit) was comparable to the ON seasonal mode, but also completely satisfactory, with fruit infestation below 1% throughout the farm.

OFF+ON - year-round medfly management: These scenarios were simulated to assess the advantages of comprehensive, year-round protection of all fruits present on farm, regardless of the risk or severity of their infestation by medfly. Importantly, the time schedule for the implementation of A&K panels was not based on the classic IPM criteria such as real risk of fruit damage, pest monitoring results and IPM thresholds, but solely guided by the phenology of the fruit and the time of its potential susceptibility to medfly attack, regardless of the real risk of fruit damage. To take advantage of the long working time of A&K panels, in each case the implementation was planned to ensure an early start and, if possible, also a post-harvest activity margin.

The overall results of targeting both the spring and summer/autumn medfly populations exceeded our expectations. The net benefits were highly location-dependent, with the greatest overall benefits to the farmer in the southernmost locations, where the medfly population was highest. In Paterno (Sicily), the overall profit was about 2 times higher compared to the OFF-Season only application or the standard IPM-guided ON-Season scenario. Remarkably, all fruit on the farm was infested less than 1%, a result rarely achieved even under intensive pesticide control. In Lazio (Cori) the net result was similar, almost 2 times greater compared to the OFF-Season case and nearly 5 times better compared to the standard IPM-guided ON-Season scenario. Only in the northernmost location (Avio, Trentino) no increase was noted, actually the overall benefit was slightly smaller compared to the OFF-Season scenario. The very good results previously achieved in both On and OFF only scenarios left a very narrow margin for further improvement and therefore only marginal incremental improvements achieved by combining OFF & ON treatments did not offset the increased costs of the more comprehensive IPM.

The role of target fruit market and fruit infestation tolerance: In competitive markets, the wholesale value of fruit drops rapidly with even moderate fruit infestation, and beyond a certain threshold, the cost of harvesting and selecting fruit (removing infected fruit) is no longer compensated by the market value of the fruit, and so the overall value of the crop drops to zero. The thresholds and benefit perception vary substantially depending on the target fruit market and grower's approach. The simulated results show the in the southernmost locations where medfly is abundant, the gains from any IPM are the greatest, as compared to central of northern regions. The value and perception of benefits from IPM is the greatest in the case of fruit producers targeting highly demanding export markets, where typically very restrictive infestation thresholds and rigorous penalties for even single infested fruits found int eh exported commodity are applied. Smaller scale local producers selling their fruit at local markets or direct retailing on their farm who just select not infested fruit and tolerate much greater degrees of crop damage. At the opposite extreme, there are amateur producers who grow fruit for their own use in home gardens, who are usually satisfied with even a relatively small amount of non-infested fruit, are willing to tolerate much greater infestation and are less motivated to appreciate the benefits from IPM.

Local specificity and the need to optimise: Our intention was to illustrate the general possibilities and benefits of early medfly control, and the factors contributing to the low adoption of biological control methods. Taking into account the results of our empirical work carried out directly on fruit growers' farms, it is clear that to obtain optimal results, specific IPM scenarios need to be adapted to the local climate and conditions, farm topography, fruit succession and phenology, neighbourhood and target market or fruit grower goals.

The developed Virtual-Farm approach and decision support and simulation tools enable not only the *in silico* generation of various IPM scenarios, but also their advanced optimization to local conditions.

5.6. CONCLUSIONS

- Our empirical work carried out on the farms in Greece, Italy and Spain and the results of *in silico* generated IPM scenarios selected by individual farmers and applied on their own farms corroborated our initial hypothesis challenging the guidelines of the classical IPM paradigm, based on medfly monitoring and economic action thresholds, and confirmed the merits of the postulated OFF-Season shift in medfly management.

- Our extensive simulations of various IPM scenarios revealed that the classical IPM paradigm is not optimal for the management of tropical fruit flies mainly because it ignores their capacity for substantial cryptic population increase on the earliest fruit, a process that goes unnoticed by the farmer and escapes ordinary monitoring systems.

- Recommending control actions only after the number of medflies caught in monitoring traps exceed IPM action thresholds results in a much-delayed warning to farmers that comes at the time when the greatly increased medfly population has already entered a phase of exponential growth and when only immediate-acting pesticides can save the vulnerable summer and autumn fruit.

- The acclaimed control methods based on medfly biology, such as A&K or mass trapping, have an inherent disadvantage of gradual mode of action and, if implemented according to the classical IPM paradigm, are unable to cope with the steep upward trend of medfly growth and prevent fruit infestation.

- The OFF season shift in medfly control, targeting the overwintering population, results in a very substantial reduction in population build-up, and when combined with the traditional (ON-Season) summer medfly control into a comprehensive (OFF + ON) management system is not only very effective, but also allows gradually acting biological methods to show their full potential and work on par with or substitute synthetic pesticides.

- The recommended OFF+ON medfly management should start in early spring, before the medfly can even be detected in monitoring traps, focus on the earliest fruits regardless of their potential damage, and then gradually continue to protect subsequent fruits according to their phenology.

- The ultimate effects of medfly control with biology-based methods and relative effects of its OFF and ON components are site specific, and depend on the local climate and actual weather patterns, the size of the spring medfly population, the landscape structure, the duration and continuity of the availability of local fruit, etc. Local optimization of the IPM schedule - timing, spatial combination and intensity of individual control treatments - can significantly increase the overall effectiveness of IPM and reduce its cost.

- The developed decision support and service system, based on the Virtual Farm toolkit and PESTonFARM modelling platform, can effectively take into account complex local conditions, such as site-specific weather patterns, fruit spatial structure and phenology, and simulate IPM scenarios based on different combinations of IPM treatments in accordance with the farmer's preferences regarding the selection of control methods, and taking into account his production goals and the rigors of target markets.

- Medfly monitoring, while not needed for planning and executing the OFF+ON medfly management operations, can play a vital role as a ‘safety’ mechanism for verifying the actual effects of the implemented IPM. Applied from mid-summer to autumn, if necessary, it will alert to undertake corrective actions that may be needed, for example in years of unusual occurrence of the fly.

5.7. REFERENCES

CABI (Centre for Agriculture and Bioscience International) (2023) invasive species compendium. https://doi.org/10.1079/cabicompendium.12367 . Accessed April 1, 2023

Cavalloro R, Prota R. Integrated control in citrus orchards: sampling methodology and threshold for intervention against the principal phytophagous pests. In: Cavalloro R, Prota R, Eds. Proceedings E.C. Experts' Meeting "Integrated control in citrus: comparison of results achieved by applying a standardized methodology"; 1982: Siniscola - Muravera, 1983.

Colacci M., Forleo M.B., Lux S.A., Sciarretta A. 2022. The status of Medfly and IPM practices based on case studies in Italy. Acta Hortic. 1352. ISHS 2022. DOI 10.17660/ActaHortic.2022.1352.13

Dekker, L., Messing, R., & No, H. B. (2019). Pest Management Guidelines. *HITAR Brief*, (114).

De Meyer M., Copeland R. S., Lux S. A., Mansell M., Quilici S., Wharton R., White I. M., Zenz N. 2002a Annotated checklist of host plants for afrotropical fruit flies (Diptera: Tephritidae) of the genus Ceratitis. Documentation zoologique, Musée royal de l'Afrique centrale, Tervuren 27: 91pp.

De Meyer, M., Copeland, R. S., Wharton, R. A., McPheron, B. A., & Barnes, B. N. (2002b). On the geographic origin of the Medfly Ceratitis capitata (Wiedemann)(Diptera: Tephritidae). In *Proceedings of the 6th International Fruit Fly Symposium, Stellenbosch, South Africa* (pp. 45-53).

Egartner, A., Lethmayer, C., Gottsberger, R.A. and Blümel, S., 2019, January. Recent records of the Mediterranean fruit fly, Ceratitis capitata (Tephritidae, Diptera), in Austria. In *Joint Meeting of the IOBC-WPRS Working Groups "Pheromones and other semiochemicals in integrated production" & "Integrated Protection of Fruit Crops" at* (Vol. 146, pp. 143-152).

Garcia Marí F. Plagas de cítricos y sus enemigos naturals. Valencia: Phytoma-España, Valencia 2009.

Gasperi, G., Bonizzoni, M., Gomulski, L. M., Murelli, V., Torti, C., Malacrida, A. R., & Guglielmino, C. R. (2002). Genetic differentiation, gene flow and the origin of infestations of the Medfly, Ceratitis capitata. *Genetica*, *116*, 125-135.

Giunti G., Benelli G., Campolo O., Canale A., Kapranas A., Liedo P., De Meyer M., Nestel D., Ruiu L., Scolari F., Wang X ., Papadopoulos N.T. (2023). Biology, ecology and invasiveness of the Mediterranean fruit fly, *Ceratitis capitata*: a review. Entomologia Generalis, Volume 43 (2023), Issue 6, 1221–1239.

Gonçalves, M.A., 2015, August. Mass trapping for the control of the Mediterranean fruit fly Ceratitis capitata (Diptera: Tephritidae) on fig trees in Southern Portugal (Algarve). In *V International Symposium on Fig 1173* (pp. 269-272).

Israely, N., Yuval, B., Kitron, U. and Nestel, D., 1997. Population fluctuations of adult Mediterranean fruit flies (Diptera: Tephritidae) in a Mediterranean heterogeneous agricultural region. *Environmental Entomology*, *26*(6), pp.1263-1269.

Lux S.A. (2014). PESTonFARM - stochastic model of on-farm insect behaviour and their response to IPM interventions. J Appl. Entomol., 138: pp 458-467. DOI: 10.1111/jen.12083 (Fist published online: 24 Sep 2013)

Lux, S. A., Wnuk, A., Vogt, H., Belien, T., Spornberger A., Studnicki M. (2016). Validation of individual-based Markov-like stochastic process model of insect behaviour and a 'virtual farm' concept for enhancement of site-specific IPM. Front. Physiol. 7:363. doi: 10.3389/fphys.2016.00363, https://doi.org/10.3389/fphys.2016.00363

Lux, S. A. (2018). Individual-based modelling approach to assessment of the impacts of landscape complexity and climate on dispersion, detectability and fate of incipient Medfly populations. *Frontiers in Physiology*, *8*,1121. https://doi.org/10.3389/fphys.2017.01121

Mitchell, W. C. (1977). *The Mediterranean Fruit Fly and Its Economic Impact on Central American Countries and Panama: A Multidisciplinary Study Team Report*. University of California.

Nyrop, J.P., Shelton, A.M. and Theunissen, J., 1989. Value of a control decision rule for leek moth infestations in leek. *Entomologia experimentalis et applicata*, *53*(2), pp.167-176.

Poston, F.L., Pedigo, L.P. and Welch, S.M., 1983. Economic injury levels: reality and practicality. *Bulletin of the ESA*, *29*(1), pp.49-53.Siebert, J. B. (1990). Economic Analysis of the Establishment of Medfly in California. *This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.*, *1*(2,566), 10-60.

Stern, V.M.R.F., Smith, R., Van den Bosch, R. and Hagen, K., 1959. The integration of chemical and biological control of the spotted alfalfa aphid: the integrated control concept. *Hilgardia*, *29*(2), pp.81-101.Szyniszewska, A. M., & Tatem, A. J. (2014). Global assessment of seasonal potential distribution of Mediterranean fruit fly, Ceratitis capitata (Diptera: Tephritidae). *PLOS one*, *9*(11), e111582.

Vincenot D., Quilici S., Lutte raisonnée en vergers d'agrumes à la Réunion : expérimen- tation et développement, Fruits 50 (1995) (1) 27–38.

Zanoni, S., Baldessari, M., De Cristofaro, A., Angeli, G. and Ioriatti, C., 2019. Susceptibility of selected apple cultivars to the Mediterranean fruit fly. *Journal of Applied Entomology*, *143*(7), pp.744-753.