Climatic Consequences on Bactrocera oleae

Subjects: Entomology
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Worldwide, the exclusive key insect pest of the olive tree is the tephritid fly Bactrocera oleae. Bactrocera oleae is a monophagous pest on the genus Olea that causes direct damage to olive yield since its larval stages feed on drupe pulp. It causes serious economic losses that have been estimated at more than USD 1 billion per year in the Mediterranean alone. In this area, B. oleae can complete several generations that vary from one to four depending on temperature and area characteristics (e.g., elevation, distance to sea). Among the environmental factors, temperature is the key parameter influencing B. oleae phenology and the relation with O. europaea. High temperatures in summer induce B. oleae mortality and slowdown on pest activity, since adult physiological processes cease at 35 °C. However, other patterns such as weather conditions, season extension and crop–pest synchrony impact temporal changes in pest abundance. The tight relation that links B. oleae to Olea species makes this system a proper scenario for studying the climatic change in the Mediterranean Basin.

Keywords: Bactrocera oleae ; climate emergency ; Mediterranean Basin ; Olea europaea ; olive pest

1. Prediction Models of B. oleae Population Dynamics

The global climate change may influence insects' population dynamics and pest outbreaks [Marchi et al., 2016]. The ability of *B. oleae* to fly for long distances and the poor knowledge on the overwintering generation may influence the monitoring of the pest and consequently the prediction of infestation risk [Petacchi et al., 2015]. In this scenario, the use of prediction models is essential to improve pest control strategies, deal with environmental impact and ameliorate product quality [Park and Tollefson, 2005; Carriere et al., 2006; Petacchi et al., 2015]. Models based on long-term datasets, concerning both insect population dynamics and weather parameters, are relevant for organizing proper pest control strategies [Marchi et al., 2016]. Even if *B. oleae* is the major insect pest of the olive tree worldwide, few studies have been currently done about predictive modeling of olive fly population dynamics, particularly in a climate change scenario. Below, models based on cumulative degree day, *B. oleae* physiology, endogenous and exogenous factors influencing *B. oleae* demography and machine learning models are analyzed.

1.1. Cumulative Degree Day Models

Bactrocera oleae evolves from pupae to adult when the cumulated degree day (CDD) reaches the value of 379.02 from oviposition, which usually takes place in October (base temperature of 8.99 °C) [Crovetti et al., 1982; Petacchi et al., 2015; Marchi et al., 2016]. The heat unit accumulation by CDD has always been used as a temperature-dependent method to predict the adult emergence [Petacchi et al., 2015], even if an error of 10–15% is estimated [Higley et al., 1986; Petacchi et al., 2015]. In order to reduce errors in the CDD model, accurate calibration of the starting date is needed, and proper monitoring of *B. oleae* flight during the previous winter and spring seasons is essential [Petacchi et al., 2015]. Furthermore, the availability of long-term insect monitoring greatly influences the prediction quality [Bale et al., 2002]. In Liguria (northwest Italy), Petacchi et al. (2015) [Petacchi et al., 2015] demonstrated that the CDD model, supported by GIS approach and agrometeorological regional network, gave a reliable prediction of *B. oleae* emergence, highlighting the *B. oleae* diversity at the local scale and the strong coastal influence in pest distribution. According to Volpi et al. (2020) [Volpi et al., 2020], the olive fruit fly finds advantageous conditions in coastal areas characterized by cool summers and mild winters, and the probability of infestation becomes low if the olive is cultivated far from the coast. The output of the CDD model was mapped with regression correlation, providing a precise description of *B. oleae* diversity and reporting the high spatial climatic variability of Liguria [Petacchi et al., 2015]. Additionally, Marchi et al. (2016) [Marchi et al., 2016] described an important relationship between the degree of *B. oleae* infestation and temperature-based indices in Tuscany (central Italy), using 13 years (2001–2014) of monitoring data and a CDD model. In this temporal span, the highest attack by *B. oleae* was recorded in 2007 and 2014, years in which mild winters were observed. Indeed, in the last years, an increase in winter temperatures with few frost days has been registered in the Tuscany region [Moonen et al., 2002; Marchi et al., 2016]. These conditions usually cause a reduction in pest mortality and an acceleration in recovering from overwintering [Volpi et al., 2020,Bale and Hayward, 2010]. Furthermore, during summer 2014, temperatures rarely overpassed the thermic threshold of 35 °C. In this context, adult physiological activities remained undamaged, and great consequences on olive yield were reported [Marchi et al., 2016]. The CDD model has also been used in northeast Portugal to predict the second generation of *B. oleae*, the most threatening in the Trás-os-Montes region, using data from 2005 to 2008 [Goncalves and Torres, 2011]. The model was suitable for predicting in advance *B. oleae* infestation both in 2006 and 2008. In 2007, the same model was not so efficient, probably in consequence of abnormal low summer temperatures (average 20.7 °C) [Goncalves and Torres, 2011]. Despite this unusual condition, the model was demonstrated to be a potential tool for *B. oleae* management, allowing the prior identification of the second-generation activity and consequently the estimation of the infestation risk [Goncalves and Torres, 2011].

1.2. Machine Learning Models

Machine learning (ML) algorithms are used for various purposes (e.g., data mining, image processing, predictive analytics) and allow the users to manage complex datasets and target trend analysis [Dey, 2018; Volpi et al., 2020]. In agronomical studies, they are generally employed to build predictive models from regression or classification analysis depending on the variables [Ip et al., 2018]. For this purpose, large datasets are required over several years [Hill et al., 2014]. Volpi et al. (2020) described an ML model based on a long-running sampling network (2002–2019) to predict, in Tuscany, the occurrence of the first summer generation of *B. oleae*. The algorithm selected for the model was greatly able to distinguish both the presence and the absence of the infestation, reaching an accuracy of 85% and 78%, respectively [Volpi et al., 2020]. The model properly identified the mechanism that drove the occurrence of the olive fly summer generation, highlighting a good ability as a preventive tool in IPM of *B. oleae*. However, it did not show a clear relationship between summer temperatures and the olive fruit fly infestation [Volpi et al., 2020].

Among ML techniques, the maximum entropy (ME) is a statistical–probabilistic technique that, except for its complex math, does not require high precision and huge datasets to accurately estimate species distributions [Kornejady et al., 2017]. It has been used to model the climatic suitability of *B. oleae* in the Iberian Peninsula and its probability of occurrence, determining a priori the presence or the absence of *O. europaea* (see Benhadi-Marín et al., 2020). In the model, the climatic suitability of the olive fruit fly was negatively influenced by high precipitation values recorded in the coldest quarter, and precipitation of the driest month agrees with the adaptation of the olive fly and the olive tree to the Mediterranean drought occurring in summer since it is in harmony with *B. oleae* bioecology [Benhadi-Marín et al., 2020]. Limiting environmental factors for both *B. oleae* and the olive tree are the main drivers influencing the habitat requirements for olive fly survival [Benhadi-Marín et al., 2020]. Additionally, temperature deeply contributes to the model, predicting a strong decrease in *B. oleae* suitability at a mean diurnal range >10 °C and an optimal for the mean temperature of the coldest quarter at 4.5 °C [Benhadi-Marín et al., 2020].

1.3. Physiologically Based Demographic Models

The management of a pest must include realistic estimates about its phenology and potential distribution in time and space and an evaluation of the damage [Gutierrez et al., 2010]. These estimates are based on the multifactor time-varying complexity of pest systems, which are often tricky to assess, particularly in a climate change scenario [Tylianakis et al., 2008]. For these purposes, mechanistic models, such as physiologically based demographic models (PBSMs), could be successfully used [Ponti et al., 2015]. Gutierrez et al. (2009) described the Italian distribution and abundance of olive and *B. oleae* using a PBDM under observed weather, considering 84 locations covering the whole peninsula, and climatic data from 1999 to 2005. The model created three warming scenarios by increasing daily mean temperature (+1 °C, +2 °C, +3 °C) and assuming all other variables as unaltered. The model estimated an increase in olive yields in the entire Italian territory, especially in the northern currently inhospitable areas (e.g., Po Valley), in all warming scenarios. However, some reductions in olive tree adaptability are predicted in southern areas due to excessively hot temperatures [Gutierrez et al., 2009]. The PBDM estimated higher damages due to *B. oleae* with a 1 °C increase in temperature, particularly in northern Italy since the weather was predicted favorable for the species and also for the olive tree. Increases of +2 °C and +3 °C, instead, seem to cause inhospitable conditions for olive fly reproduction and survival, especially in the southern areas of the peninsula [Gutierrez et al., 2009].

1.4. Model Based on Exogenous and Endogenous Factors Influencing Insect Population Dynamics

Insect population dynamics can be well investigated when global climatic indicators are considered together with local weather conditions [Aluja et al., 2012]. Among global indicators, the North Atlantic Oscillation (NAO) is an important factor influencing plant and animal populations in the Mediterranean Basin [Hodar et al., 2012]. Ordano et al. (2015) [Ordano et al., 2015] investigated and modeled the joint role of exogenous (e.g., local climatic factors, NAO) and endogenous (e.g., intrinsic population dynamics) factors involved in the autoregressive process and population dynamics of *B. oleae* in five locations within Palestine and Israel. The model revealed that the main exogenous driver in all populations was the local climatic variation measured as night land surface temperature, while NAO was influential in only one of the studied populations [Ordano et al., 2015]. The same population was also significantly influenced by olive fruit availability [Ordano et al., 2015]. However, despite the strong influence of exogenous factors, the model indicated endogenous factors as the main driver influencing *B. oleae* population dynamics since it showed recurrent olive fly infestations revealing density-dependent population feedback [Ordano et al., 2015].

2. Climate Influence on B. oleae Parasitoids and Predators

The current knowledge about the influence of climatic factors on *B. oleae* parasitoid and predator complex is extremely patchy, despite the high interest in olive fly natural enemies as bio-controllers [Picchi et al., 2017]. Among *B. oleae* parasitoids, *Psyttalia concolor* (Szépligeti) (Hymenoptera: Braconidae) has been the most studied [Wang et al., 2011; Garantonakis et al., 2017]. It was introduced in Europe in the early 1900s as a natural enemy of the olive fruit fly, but unsuccessfully [Hoelmer et al., 2011; Garantonakis et al., 2017]. Low winter temperatures may contribute to this failure, since *P. concolor* survival is negatively influenced by cold [Garantonakis et al., 2017]. Furthermore, the climate breakdown may limit the success of *B. oleae* parasitoids [Abd El-Salam et al., 2019]. Recently, Abd El-Salam et al. (2019) [Abd El-Salam et al., 2019] described the influence of temperature and relative humidity on *P. concolor* survival in two Egyptian localities vulnerable to climate change. The study showed that the adverse change of temperature and relative humidity negatively influenced the relationship between the young stages of *B. oleae* and their parasitoid *P. concolor* [Abd El-Salam et al., 2019]. Furthermore, temperature had a key role in determining *P. concolor* survival compared to relative humidity [Abd El-Salam et al., 2019].

Soil arthropods (e.g., carabids, staphylinids, ants, spiders, opilionids, centipedes, earwigs, chilopods) are included in the predator complex of *B. oleae*, since the olive fly larvae leave the drupe to pupate in the soil before the winter [Orsini et al., 2007; Albertini et al., 2017; Picchi et al., 2017]. The soil environment is highly dynamic, both because it hosts a huge number of plants and arthropods and because it is susceptible to changes in moisture, temperature and fluctuating redox states [Jansson and Hofmockel, 2020]. Even if most climate studies refer to the atmospheric conditions, climate change strongly influences soil characteristics (e.g., temperature, soil organic carbon) [Dimou et al., 2003; Zhang et al., 2005] and, consequently, arthropods dwelling in the ecosystem. However, to the best of our knowledge, no studies have been currently carried on about climate heating and soil predators of *B. oleae*.

3. Control Strategies of B. oleae under Global Warming

Climate change is one of the main factors that contribute to the use of pesticides and influences their behavior in the environment (e.g., transformation, degradation, volatilization, runoff, leaching) [Tudi et al., 2021]. Historically, the control of *B. oleae* has been mainly based on the use of chemicals, even if it has changed over time [Montiel-Bueno and Jones, 2002; Nestel et al., 2016]. Nowadays, since global heating influences the biology and distribution of *B. oleae* [Ragaglini et al., 2005], its control methods must be adjusted according to this phenomenon. In autumn, the current extension of the period in which temperatures are favorable to *B. oleae* oviposition (>12 °C) increases the risk of yield loss for Mediterranean olive producers [Petacchi et al., 2021] Marchini et al. (2017) declared that olive fly females can complete one generation in spring, adding new evidence on the reproductive behavior of this species and pointing out the necessity of proper control strategies. Accordingly, preventive adulticide treatments (e.g., attract and kill techniques with canopy traps, bait traps) that cause a decrease in *B. oleae* reproductive activity are recommended to reduce *B. oleae* population in the following summer when olive fruits are set [Marchi et al., 2017].

Moreover, the recent discovery of insecticide residues in olive oil and in the environment and the growing resistance to chemicals encourage the shift to eco-friendly control methods (e.g., botanical insecticides, insect growth regulators, semiochemicals) and conservation biological control programs (e.g., the enhancement of generalist predators) [Montiel-Bueno and Jones 2002]. The implementation of a decision support system (DSS), together with reliable monitoring of the pest, allows bridging the gap between prediction models and extension services and technically supports the olive farmers in suggesting suitable management for the orchard [Marchi et al., 2016]. In accordance with this, scheduled calendar treatments are abandoned, and chemical applications are reduced in time and space in favor of integrated pest management [Marchi et al., 2016,Miranda et al., 2019] (**Figure 1**). Furthermore, the recent development of advanced data process technologies allows monitoring and managing insect pests following an ecofriendly approach [Nestel et al., 2016]. For instance, precision agriculture in olive fly control drives the chemical application directly on the hot spot area, limiting the treatment just to a few trees per orchard [Pontikakos et al., 2010; Nestel at al., 2016]. This causes a decrease in pesticide application and consequently a limitation of environmental pollution, since the chemical drift is reduced and the use of fossil fuel (CO_2 emission) for the sprayer machines is limited [Fenger et al., 2009; Pontikakos et al., 2010].

Therefore, in the olive orchard, the adoption of new technologies together with alternative and eco-friendly control strategies might contribute to limit global heating thanks to a more sustainable use of pesticides and a reduction in air pollutants, limiting the carbon dioxide emission overall.

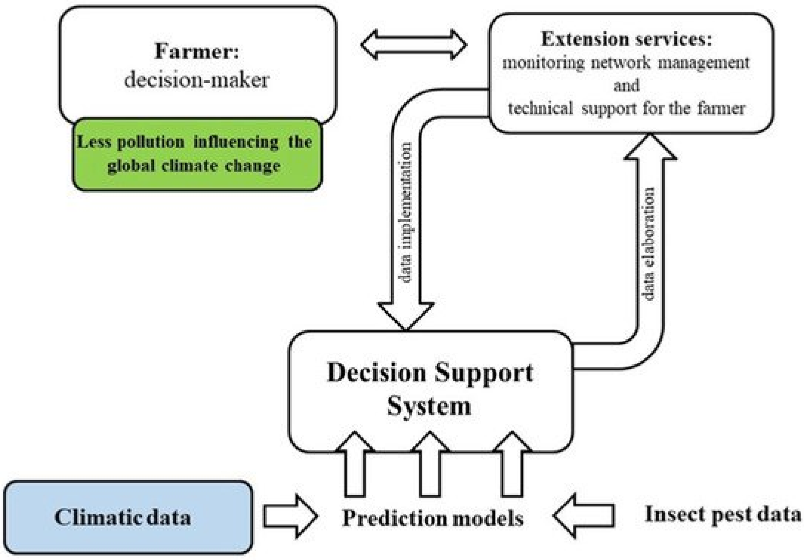

Figure 1. Long-term climatic data are the basis of insect pest prediction models together with insect data obtained by proper monitoring [Marchi et al.,2016]. The decision support systems (DSSs), which bridge the gap between prediction models and extension services, have the task of technically supporting farmers in olive orchard management. In order to abandon scheduled treatments and then to avoid the risk of carrying out unnecessary chemical uses, farmers need a good scenario of the current status of the pest and its potential future trend. As a consequence of a conscious olive orchard management, positive outcomes on the environmental impact and global heating can be recorded (e.g., less air pollution) [Park and Tollefson, 2005; Carriere et al., 2006; Fenger, 2009; Petacchi et al., 2015].