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# SULLA PROTEZIONE DELLE PIANTE
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# SULLA PROTEZIONE DELLE PIANTE
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## V GIORNATE DI STUDIO SUI MODELLI PER LA PROTEZIONE DELLE PIANTE

**Convegno organizzato da grimpp**
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**27-29 maggio 2009**

2009

# INDICE

## V GIORNATE DI STUDIO
## SUI MODELLI PER LA PROTEZIONE DELLE PIANTE
## Piacenza, 27-29 maggio 2009

# THE OLIVE–*BACTROCERA OLEAE* (DIPTERA TEPHRITIDAE) SYSTEM IN THE MEDITERRANEAN BASIN: A PHYSIOLOGICALLY BASED ANALYSIS DRIVEN BY THE ERA-40 CLIMATE DATA

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## Summary

This paper reviews applications of weather-driven physiologically based demographic models (PBDMs) used to analyze a major Mediterranean crop-pest system, namely olive (*Olea europaea*) and the olive fruit fly (*Bactrocera oleae*) (http://cnr.berkeley.edu/casas/). The Mediterranean Basin is expected to be particularly vulnerable to climate change including pronounced climate warming and desertification. A preliminary analysis of this system in the Mediterranean Basin using a new climate dataset is reported that provides direction concerning deficiencies and future extensions of the models.

The tight co-evolution links of drought-resistant olive and its major pest the olive fly, and their wide distribution make the system a suitable model for climate change studies. The weather-driven PBDMs used in this study use ERA-40 climate data for two periods (1958-1967 and 1988-1997) as drivers. The ERA-40 data are down-scaled using the regional climate model RegCM3 that is coupled to the MIT ocean model. PBDM predictions of olive bloom dates and yield, total season-long olive fly pupae, and percent fruit attacked by the fly are mapped using the open source GIS GRASS (http://grass.osgeo.org/). Mediterranean wide simulation data are summarized using multivariate regression.

The major deficiency of the integrated PBDM/GIS approach is the need for extensive weather and edaphic factor data to drive the models, and hence a major achievement of this study is to link PBDM/GIS technology with increasingly reliable, high resolution down-scaled fields for assessing on-ground ecosystem-level problems over large geographical areas such as the Mediterranean Basin.

**Key words:** olive, olive fly, Mediterranean Basin, physiologically based models, agroecosystem analysis, climatic change, multitrophic interactions, GIS, ERA-40, RegCM3, MIT ocean model.

## 1. Introduction

This paper reviews applications of weather-driven physiologically based demographic models (PBDMs) of olive (*Olea europaea*) and the olive fruit fly (*Bactrocera oleae*) to the analysis of this system in the Mediterranean Basin. A new basin-wide climate dataset is used in a preliminary analysis that identifies deficiencies of the approach and provides direction for future analyses. Previous applications of PBDMs to the olive-olive fly system include regional analyses targeting Arizona, California and Italy (Gutierrez *et al.*, 2006b, 2008, 2009), and the Mediterranean island of Sardinia (Ponti *et al.*, 2009).

Analytical tools that provide a synthesis of ecological data are increasingly needed to design and maintain sustainable agroecosystems increasingly subjected to disruption by *global change* in the form of agro-technical inputs, invasive pests, and climate change. This is especially so for the Mediterranean Basin, a region expected to be particularly vulnerable to climate change including pronounced climate warming (Giorgi, 2006; Giorgi & Lionello, 2008) and desertification (Montaldo *et al.*, 2007; EEA, 2008; Gao & Giorgi, 2008). Olive (*Olea europaea* L.) is of prominent ecological and socioeconomic relevance in the Mediterranean region (Marcuzzi, 1996; Montiel Bueno & Jones, 2002) and is considered a sensitive indicator of the degree of climatic change (Osborne *et al.*, 2000; Besnard *et al.*, 2007). Olive and olive fly are of African origins, but Mediterranean Basin is the centre of domestication of the crop and currently includes most of the global olive acreage (Harwood & Aparicio, 2000; Vossen, 2007). The olive fly *Bactrocera oleae* (Rossi) is a host specific invasive species and is a major pest of olive inducing economic losses worldwide totaling about 800 million US dollars per year (Montiel Bueno & Jones, 2002). The biology, distribution and evolution of olive and olive fly are tightly linked (Nardi *et al.*, 2005), and this system is an excellent example for studying of how crop domestication impacts trophic dynamics (Wang *et al.*, 2009). These characteristics make it a highly suitable system for investigating climate change impact on the Mediterranean climate region.

Despite a high degree of confidence that climatic change is affecting living systems (Walther *et al.*, 2002; Parmesan, 2007; Rosenzweig *et al.*, 2008), the analysis of climate effects on species distribution and dynamics is still confined to purely climate-based approaches (Pearson & Dawson, 2003; Ibáñez *et al.*, 2006) that overlook both the biology of the species involved and their multitrophic interactions (Gutierrez & Baumgärtner, 1984; Gutierrez *et al.*, 1994; Davis *et al.*, 1998; Parmesan, 2006; Araujo & Luoto, 2007). This gap can be breached using realistic ecosystem models that include not only physiological and climatic requirements but also the interactions of key species (Schmitz *et al.*, 2003; Gutierrez *et al.*, 2005; Merrill *et al.*, 2008). In this paper, PBDMs of olive and olive fly (Gutierrez *et al.*, 2009; Ponti *et al.*, 2009; see also http://cnr.berkeley.edu/casas/) are used to analyze this crop-pest system across the Mediterranean Basin (see fig. 1). ERA-40 climate data for the period 1958-1967 and 1988-1997 that have been down-scaled using the coupled regional climate model RegCM3 and the MIT ocean model (Artale *et al.*, 2009) are used as model drivers. The PDBM approach used here includes interactions between species as altered by their differing responses to weather (Gutierrez & Baumgärtner, 1984; Gutierrez *et al.*, 1994; Gutierrez & Baumgärtner, 2007; Gutierrez *et al.*, 2008). This approach addresses the long standing criticisms of the “climate envelope” approach raised by Davis *et al.* (1998), and lays the groundwork to link in a dynamic fashion important biophysical factors into an integrated tool for the assessment of desertification of the region as proposed by Reynolds *et al.* (2007).

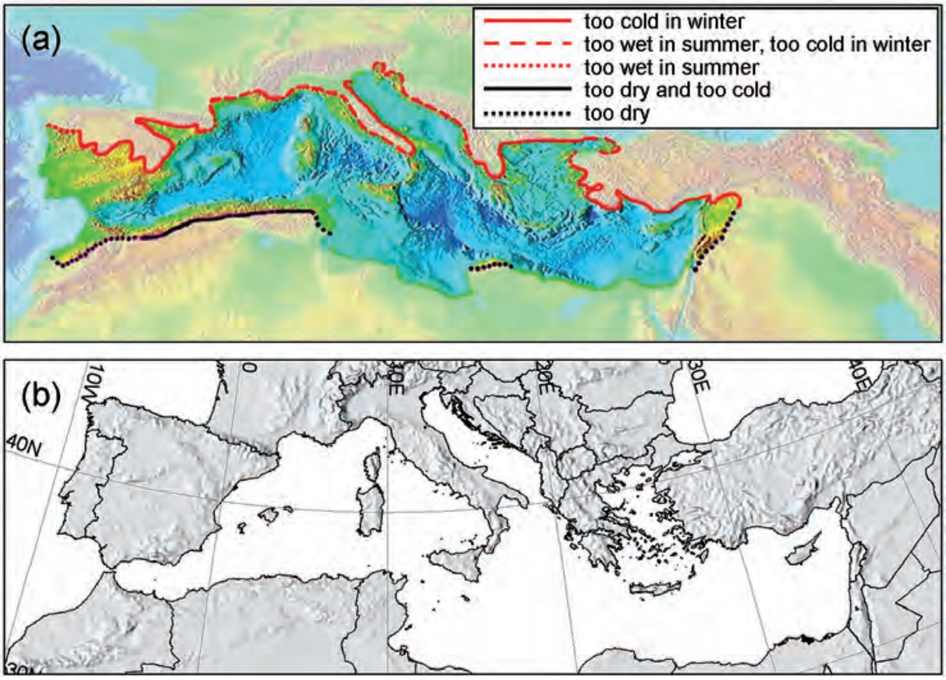

Fig. 1 - The Mediterranean Basin: (a) current olive range with indication of the main climatic limits to its distribution (modified form image available at the following web page: http://www.grabovrat.com/mapsViews/mapsViews82.html; see also Dallman, 1998); and (b) domain of the present analysis.

## 2. Materials and methods

### 2.1. Modeling the dynamics of olive and olive fly

A weather-driven PBDM has been used to simulate the phenology, growth and population dynamics of olive and olive fly at different geographic locations and scales (see Gutierrez *et al.*, 2009; Ponti *et al.*, 2009; see also http://cnr.berkeley.edu/casas/). Here we use this model to analyze this plant-pest system in the Mediterranean Basin, a region that is expected to suffer dramatically from climate warming and desertification (Gao & Giorgi, 2008) as one of the most prominent “hot-spots” of future climate change (Giorgi, 2006). The present analysis provides a summary of previous work on PBDMs of olive and olive fly, and indicates future research directions.

The PBDM approach identifies common processes across trophic levels and imbeds them in models having the same functional (resource acquisition model) and numerical (birth-death rates) response models (Gutierrez & Baumgärtner, 1984; Gutierrez, 1992, 1996). The model captures the biology and physiology of organisms in a general way describing the acquisition (i.e. the *supply, S*) and allocation of resources in priority order to egestion, conversion costs, respiration (i.e., the $Q_{10}$ rule in poikilotherms) and growth and reproduction, using site specific weather to drive the population dynamics. The physiology of assimilation falls under the rubric of the metabolic pool (Petrusewicz & MacFayden, 1970). The biology of biomass acquisition (i.e. the *supply*, *S*) is captured using a ratio-dependent functional response model where the sum of maximal genetic demand (*D*) is the major parameter (Gutierrez & Baumgärtner, 1984). The 0£*S/D*<1 ratio measures the extent to which assimilation demands are met and turns out to be always less than unity due to imperfect consumer search. The *S/D* ratio is used in the model to scale maximal vital rates of species (Gutierrez & Wang, 1977; Gutierrez & Baumgärtner, 1984).

The models driven by weather have been used to simulate the dynamics of species in broad variety of systems as reviewed in Gutierrez & Baumgärtner (2007). The model for olive growth and development is a plant canopy model with subunit populations of leaves, stem, root and healthy and attacked fruit that allows capturing the bottom-up effects on the dynamics of olive fly. The model simulates age-mass structured population dynamics of nine functional populations (n = 1…9): the dynamics of olive leaf mass and numbers {sub models n=1, 2}, stem plus shoots {n = 3}, root {4} and fruit mass and number {5, 6}, olive fly in fruit {7}, and reproductive and dormant adults {8, 9}. The mathematics of the model are reported in Gutierrez *et al.* (2009). [As an aside, the underlying model has also been used to explore economic theory (Regev *et al.*, 1998)].

Olive is a long-lived species known for its tolerance to drought, with a distribution limited mostly by frost and high temperature, and to a lesser extent by soil water and other factors (Bongi, 2002; Vitagliano & Sebastiani, 2002; Fiorino, 2003; see fig. 1a). Temperature influences nearly all aspects of olive's biology (see Gutierrez *et al.*, 2009) and in the model this is captured by a concave scalar function of temperature that represents the normalized net of the photosynthetic and respiration rates that also define the optimum and upper and lower thermal thresholds for development. The olive model predicts flowering phenology that is controlled by vernalization, age structured growth and yield, and fruit mortality due to temperature and fly attack. Flowering is believed to be a sensitive indicator of climate warming (Osborne *et al.*, 2000).

Olive fly is endemic in the Mediterranean Basin and the Middle East (Katsoyannos, 1992), and is the major pest in most commercial olive-growing regions of the world (Nardi *et al.*, 2005). Its biology is closely linked to olive fruit age and availability, and as in olive, the effect of temperature on olive fly's vital rates is captured by a concave scalar function (Gutierrez *et al.*, 2009).

### 2.2. THE CLIMATE DATASET

Olive system dynamics in our study across the Mediterranean basin were driven by data for the period 1958-1967 and 1988-1997 generated by a regional coupled system (i.e. the PROTHEUS system) composed of the RegCM3 atmospheric regional model and the MITgcm ocean model coupled using the OASIS3 coupler (for details see Artale *et al.*, 2009). Lateral boundary conditions for the RegCM3 simulations are supplied by 6-hourly large scale horizontal wind component, temperature, specific humidity and surface pressure. The boundary conditions for the climate period (1958-1997) came from the ERA-40 project that reanalyzed meteorological observations using the weather forecast model of the European Centre for Medium-Range Weather Forecasts (http://www.ecmwf.int/) and all available surface, upper-air and satellite observations. PROTHEUS was used to down-scale the ERA-40 dataset from the previously available 125 km grid to a 30 km grid resulting in 4,401 grid points with daily weather for the two decades in the geographic domain of the analysis (fig. 1b). Weather variables used to drive the olive-olive fly dynamics models include daily maximum and minimum temperature at 2 m and solar radiation. Rainfall, daily run of wind at 10 m and relative humidity were used to compute soil water balance.

### 2.3. Simulation runs

Although many aspects of the daily age structured dynamics of olive and olive fly are computed by the model, only Julian bloom dates, season yield, cumulative season long olive fly pupae, and the percent of fruit attacked are used in the present analysis. We included model runs of olive alone and others with the fly in the absence of pest control as a proxy for measuring the fly's potential damage. In our study, soil moisture is assumed non-limiting given the ability of olive to resist prolonged drought (Fernandez & Moreno, 1999; Sofo *et al.*, 2008). Using weather data as input, model runs were carried out via batch processing across years and locations, and the geo-referenced output data were written to an output file for GIS processing and mapping. The same initial conditions for olive and olive fly were used at all locations, and the model was run continuously for each of the two simulation periods (1 January 1958 to 31 December 1967 and 1 January 1988 to 31 December 1997). The first year of simulation was used to allow the model dynamics to equilibrate to local weather, and hence the first year data were not used to compute means and coefficients of variation.

### 2.4. GIS and marginal analysis

All GIS datasets used in the analysis are available in the public domain. The open source GIS software GRASS (GRASS Development Team, 2008; see http://grass.osgeo.org/) was used to map data at locations below 700 m. The digital elevation model used is the NOAA "Global Land One-km Base Elevation" (GLOBE) (www.ngdc.noaa.gov/mgg/topo/globe.html). State boundaries from the National Geospatial Agency (Vector Map Level 0, http://earth-info.nga.mil/publications/vmap0.html) were used. Because inverse distance weighting interpolation used to map the simulation data, the patterns reflect not only the site specific effects of weather on the biology of the species but also the resolution of the weather grid.

Simulation data across years and locations were analyzed using linear multivariate regression (implemented in R using function lm; R Development Core Team, 2008) retaining only independent variables having slopes significantly greater than zero (*t-values*, $p < 0.05$).

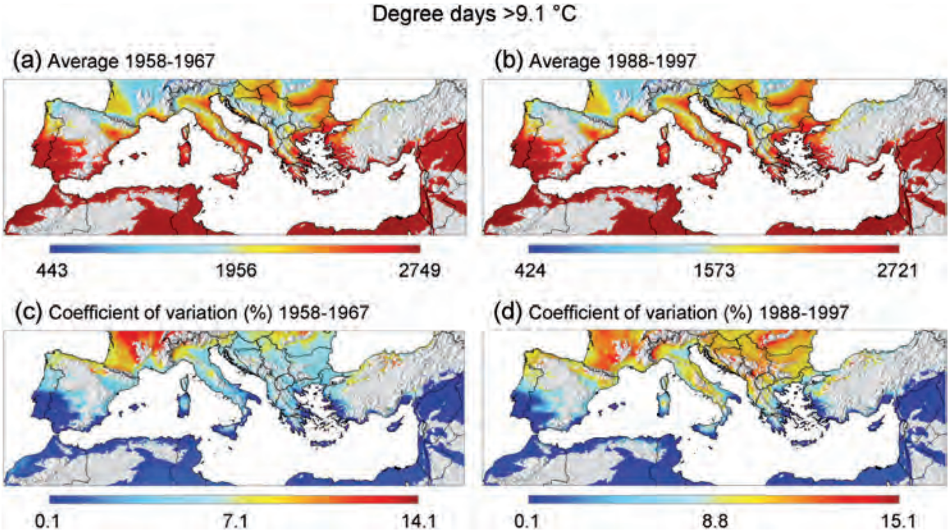

Fig. 2 - Degree days > 9.1 °C in the Mediterranean Basin: average (a, b) and % coefficient of variation (c, d) for the period 1958-1967 and 1988-1997.

## 3. Results

### 3.1. Season length

Season length is summarized in units of physiological time (i.e. degree-days for olive: *dda* > 9.1 °C computed using a non linear model, Gutierrez *et al*., 2009) (fig. 2a-b). The data range is large reflecting the extreme geographic variability of the region that includes the Alps (lower end on the range; see fig. 2a, b) as well as deserts in northern Africa and the Middle East (upper end of the range; see fig. 2a, b). Variability of season length expressed as coefficient of variation (CV %; fig. 2c, d) is lowest in the southern coasts of Europe, northern Africa, and the Middle East. The upper end of the data range is similar to that found for Arizona, California and Italy (Gutierrez *et al.*, 2009), and for Sardinia (Ponti *et al.*, 2009), while the lower end has a considerably lower value compared to previous analyses. This occurred because the weather grid used here covers with equal density very unfavorable sites. The references cited in this section are assumed as the comparative standard in the following sections.

### 3.2. Olive

#### *3.2.1. Blooming patterns*

Blooming did not occur at all locations and years across the Mediterranean Basin. Simulated mean bloom dates range from a minimum similar to previous analyses to a maximum that exceeded previous bloom dates in very cold areas where olive is not

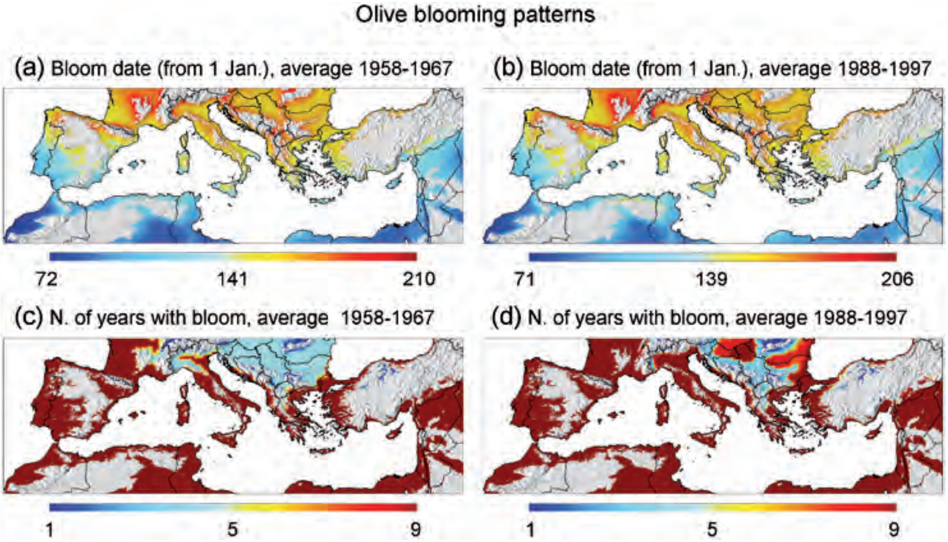

Fig. 3 - Average olive bloom dates (from 1 January) (a, b) and number of years in which blooming occurred (c, d) in the Mediterranean Basin for the period 1958-1967 and 1988-1997.

cultivated (fig. 3 a, b). Very late blooming did occur during some years in these cold areas but it was not reliable (fig. 3c, d). More years of blooming in some unfavorable areas occurred in the second than in the first decade (fig. 3d vs. c).

### *3.2.2. Yield without olive fly*

Mean yields (kg fruit dry matter per tree) in the absence of olive fly are predicted to be highest in areas of northern Africa that are too dry for olive (fig. 4a, b; cf. fig. 1a). This occurred because soil moisture was assumed non-limiting in our study (e.g. deserts). Given the ability of olive to resist severe and prolonged drought (Fernandez & Moreno, 1999; Sofo *et al.*, 2008), our assumption holds in most other areas of our study (see fig. 1a). With this exception, predicted yield patterns illustrate well current olive distribution (fig. 4a, b vs. fig. 1a). Lowest yields are predicted at high altitudes in inland areas which also had the highest CV (fig. 4c, d). Previous analyses on Italy and Sardinia showed similar results in terms of yield patterns and range (Gutierrez *et al.*, 2009; Ponti *et al.*, 2009).

Regression analysis – The effects of season length ($dda > 9.1$ °C), total $ddb < 0$ °C, date of bloom ($Blm_{day}$), and cumulative yearly rainfall ($mm$) on yield (g dry matter) across all locations were estimated using linear multiple regressions (eqn. 1). No obvious biological interactions were apparent among the variables, and hence none were included in the regression analysis. Means for the independent variables are given in brackets as a reference to help estimate average effects.

All variables were highly significant ($P < 0.001$) with the effect on yield being positive

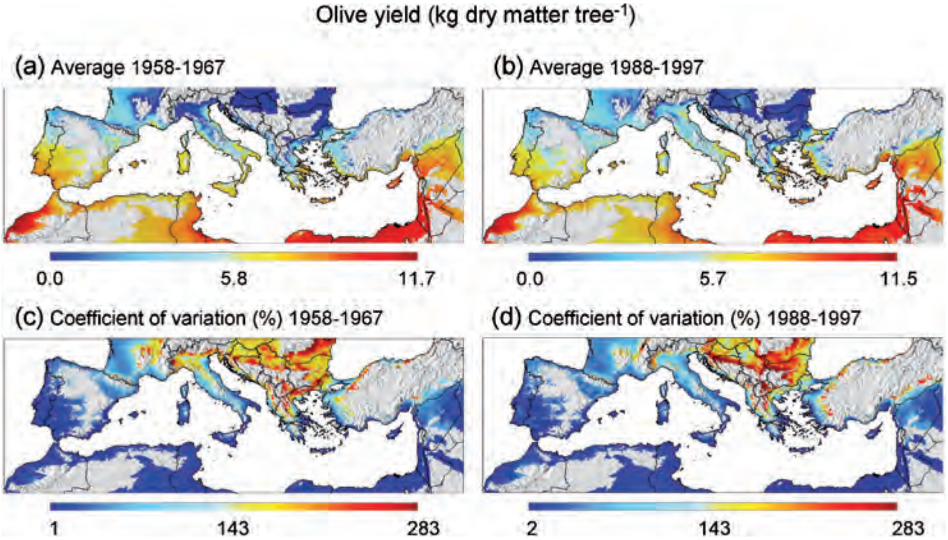

Fig. 4 - Olive yield (kg dry matter tree$^{-1}$) in the Mediterranean Basin: average (a, b) and standard deviation (c, d) for the period 1958-1967 and 1988-1997.

for *dda* (2089.7) and negative for *ddb* (82.4), $Blm_{day}$ (137.9) and *mm* (1824.5) (eqn. 1). By replacing average values for the independent variables, *dda* contributes 2142.6 g while *ddb*, $Blm_{day}$, and *mm* decrease yield by 2409.6, 6593.1 and 224.9 g respectively. An average yield of 4459.9 ± 3654.4 g tree$^{-1}$ is predicted across all sites in the Mediterranean region. These yield estimates are presented for heuristic purposes only as yield may vary with tree age, variety, cultural practices and other factors.

$$yeld = 10828.0 + 1.0\mathrm{dda} - 29.2ddb - 47.7Blm_{day} - 0.12mm$$
$$R2 = 0.86, \quad F_{4,7526} = 12020, \quad P < 0.001 \qquad (1)$$

### 3.3. OLIVE FLY

### 3.3.1. *Olive fly density*

Cumulative numbers of pupae produced over the season (thousands per tree) without pest control are used to examine geographic distribution and relative abundance of the fly, which are driven by bottom-up effects of olive fruit abundance and phenology, and temperature. Areas of highest favorability for olive fly are predicted along mild coastal areas of southern Europe and northern Africa, while mountainous inland areas are unfavorable due to colder winter temperatures (fig. 5a, b). Results are coherent to what has been showed by previous analysis (Gutierrez *et al.*, 2009; Ponti *et al.*, 2009).

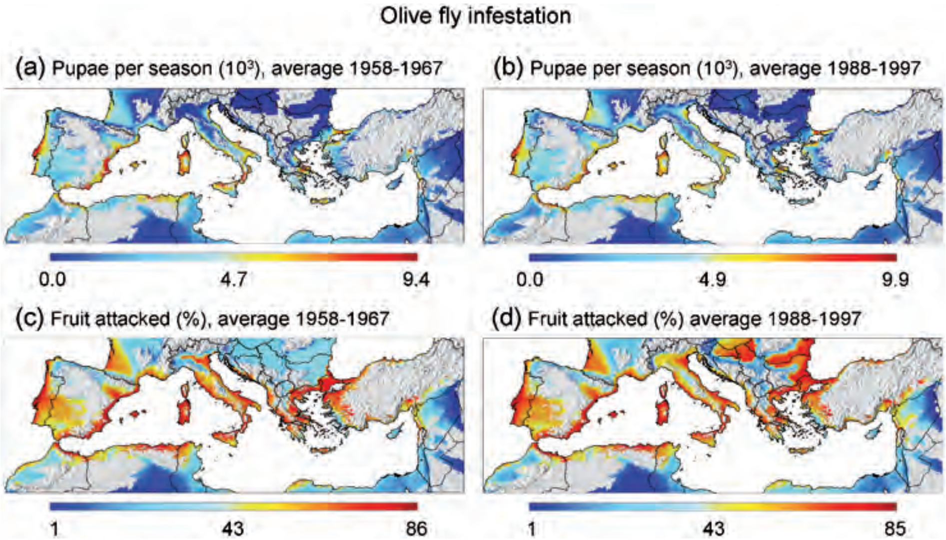

Fig. 5 - Average cumulative olive fly pupae (season$^{-1}$ tree$^{-1}$) (a, b) and percent fruit attacked (e, f) in the Mediterranean Basin for the period 1958-1967 and 1988-1997.

Regression analysis – The linear multiple regression analysis (eqn. 2) shows highly significant coefficients ($P < 0.001$) for all independent variables considered including $\log_{10}$ olive fly pupae on season length ($dda > 9.1$ °C), total $ddb < 0$ °C, date of bloom ($Blm_{day}$), and cumulative yearly rainfall (*mm*). Only the coefficient for *ddb* was negative. Substituting average values for the independent variables shows that *ddb* (-1.23) has a negative average effect on log pupal density, while *dda* (2.42), bloom date (1.72), and *mm* (0.29) have positive effects resulting in an average of 1686.9 ± 1918.6 pupae tree$^{-1}$.

$$\begin{aligned} &log_{10}pupae = -1.35 + 0.0011dda - 0.015ddb + 0.012Blm_{day} + 0.00016mm \\ &R2 = 0.84, \quad F_{4,7526} = 10130, \quad P < 0.001 \\ &(\text{means: } dda = 2089.7;\ ddb = 82.4;\ Blm_{day} = 137.9;\ mm = 1824.5) \end{aligned} \tag{2}$$

### *3.3.2. Percentage of fruit attacked*

The results for percentage of fruit attacked should be interpreted with caution as the values are dimensionless, and hence they are used here to illustrate the risk of fly damage irrespective of potential yield.

The simulated percentage of fruit attacked (fig. 5c, d) is lower in areas unfavorable for olive fly and higher in areas of high fly density (cf. fig. 5a-b). Very hot areas in northern

Africa are very unfavorable due to temperatures above the upper thermal threshold of the fly, with very low levels of infestation similar to that observed in the desert regions of southern California and Arizona (Gutierrez *et al.*, 2009).

### 3.4. DECADE EFFECTS (1988-1997 VS. 1958-1967)

The effect of 1988-1997 vs. 1958-1967 decade was assessed using a paired t-test (pairs of values from the two decades for the same location) for season length ($dda > 9.1$ °C), total $ddb < 0$ °C, date of bloom ($Blm_{day}$), olive yield, cumulative olive fly pupae, and cumulative of yearly rainfall (*mm*). Average *dd* in 1988-1997 (2078.6) were 22.1 lower than in 1958-1967 (2100.7) ($t_{4400} = 38.70$, $P < 0.001$, 95% *C.I.* = 21.0-23.2, mean = 2089.7). Average *ddbZero* in 1988-1997 (81.7) were 1.3 lower than in 1958-1967 (83.0) ($t_{4400} = 2.33$, $P < 0.05$, 95% *C.I.* = 0.2-2.3, mean = 82.4). An unpaired t-test was performed for $Blm_{day}$ because missing values occur when olive does not bloom which results in an unbalanced dataset. Although a paired test could still be feasible on a subset, the unpaired test was chosen because it is conservative and allows the full dataset to be used. Average $Blm_{day}$ in 1988-1997 (138.6) was 1.4 higher than in 1958-1967 (137.2) ($t_{7462.5} = 2.08$, $P < 0.05$, 95% *C.I.* = 2.82-0.08, mean = 137.9). Average cumulative olive yield (g dry matter) in 1988-1997 (4431.1) was 57.5 g lower than in 1958-1967 (4488.7) ($t_{4400} = 4.75$, $P < 0.001$, 95% *C.I.* = 33.8-81.3, mean = 1686.9). Average cumulative number of olive fly pupae in 1988-1997 (1745.9) was 117.9 higher than in 1958-1967 (1628.0) ($t_{4400} = 15.76$, $P < 0.001$, 95% *C.I.* = 132.6-103.2, mean = 1686.9). Average *mm* in 1988-1997 (1892.6) was 136.2 higher than in 1958-1967 (1756.3) ($t_{4400} = 13.06$, $P < 0.001$, 95% *C.I.* = 156.6-115.7, mean = 1824.5).

## 4. Discussion

Climate change effects on living systems (Walther *et al.*, 2002; Parmesan, 2007; Rosenzweig *et al.*, 2008) occur in ways that are largely unknown (Visser & Both, 2005; Deutsch *et al.*, 2008; Visser, 2008). The analysis of climate effects on species distribution and abundance is still largely confined to purely climate-based approaches (Pearson & Dawson, 2003; Ibáñez *et al.*, 2006) that overlook both the biology of the species involved and their multitrophic interactions (Gutierrez *et al.*, 1994; Davis *et al.*, 1998; Parmesan, 2006; Araujo & Luoto, 2007). The Mediterranean Basin is a region where a better understanding of climate effects on ecosystems is urgently needed in light of the expected severe climate change including pronounced climate warming (Giorgi, 2006; Giorgi & Lionello, 2008) and desertification (Montaldo *et al.*, 2007; EEA, 2008; Gao & Giorgi, 2008). This knowledge gap can be filled by using realistic ecosystem models such as PBDMs (Gutierrez, 1996; Gutierrez *et al.*, 2005; Gutierrez *et al.*, 2006a; Gutierrez *et al.*, 2008) that are able to simulate not only physiological and climatic requirements but also the interactions of key species (Schmitz *et al.*, 2003; Gutierrez *et al.*, 2005; Merrill *et al.*, 2008). In this paper, a PBDM of olive and olive fly (Gutierrez *et al.*, 2009; Ponti *et al.*, 2009; see also http://cnr.berkeley.edu/casas/) was used to analyze this crop-pest system in the Mediterranean region (see fig. 1) based on ERA-40 climate data for the period 1958-1967 and 1988-1997 down-scaled via the regional climate model RegCM3 coupled to the MIT ocean model (Artale *et al.*, 2009). This new analysis provided a framework to review previous studies carried out using a PBDM of olive and olive fly (Gutierrez *et al.*, 2006b; Gutierrez *et al.*, 2008; Gutierrez *et al.*, 2009; Ponti *et al.*, 2009).

### 4.1. OLIVE

Olive flowering is considered a sensitive indicator of climate warming in the Mediterranean (Osborne *et al.*, 2000) with little response to rainfall pattern (Spano *et al.*, 1999). The area where blooming occurs in all years increased in 1988-1997 compared to the 1958-1967 decade, and this is most evident in the Balkans and in the Po Valley in Italy as these areas become more favorable to olive. This would indicate climate warming with consequent decrease in the upper end of the range of bloom dates in the second decade (fig. 3b vs. a). The warming effect is not immediately apparent when looking only at regional average values, because average season length actually decreases and average bloom date increase in 1988-1997 vs. 1958-1967 (see t-test in section 3.4). This is a good illustration of the importance of maps in regional ecosystem analysis beyond their aesthetic value. On the other hand, an overall decrease in *dd* < 0°C shows that warming mostly occurs for low temperatures (see again t-test), which increases favorability of previously unfavorable areas such as the Balkans and the Po Valley (map of *dd* < 0°C not shown). Average olive yield decreases as expected due to a shorter average season length in 1988-1997 vs. 1958-1967, and this may be interpreted as a consequence to olive range expanding into previously unfavorable areas with short season length, late bloom dates, and consequently low yields. In addition, average precipitation increased in 1988-1997 vs. 1958-1967 and this implies a higher cloud cover with lower dry matter accumulation as a net result.

A caveat of this and previous studies is that climate variability in the Mediterranean Basin and related environmental problems such as desertification are due to not only warming but also a pronounced decrease in precipitation (Gao & Giorgi, 2008). We used present climate data to analyze areas of favorableness for the olive-olive fly system, and although olive is a model for drought tolerance in Mediterranean climates (Sofo *et al.*, 2008), expected severe decreases in precipitation over the Mediterranean region (>25–30%; see Giorgi & Lionello, 2008) and current soil moisture limitations in desert areas suggest the need to include an updated plant water balance model in future analysis. In the current analysis, the predicted area of favorability for olive has a good match to the observed range of the crop in the Mediterranean region (see fig. 1), with the exception of desert areas where olive growth is severely limited by soil moisture that in the model is assumed non-limiting.

### 4.2. OLIVE FLY

Current distribution of olive fly in the Mediterranean Basin is limited by low winter temperatures in high elevation inland areas, while high summer temperatures allow large population densities only in milder coastal areas. High summer temperatures increase fly mortality, reduce reproduction, and induce reproductive dormancy, and as a consequence, an even mildly warmer climate extends the range of olive fly into previously unfavorable colder areas inland or at higher elevation as it is evident for the Balkans and the Po Valley in 1988-1977 vs. 1958-1967 (fig 5b vs. a; fig. 5d vs. c). The Balkans and northern Italy including the Po Valley were more favorable for olive fly in 1988-1977 than in 1958-1967 due to increasing presence of host fruit and milder winters (i.e. a decrease in *dd* < 0°C), while most coastal areas remain highly favorable with high fly density and infestation. Even though climate variability between the two decades appears small compared to current predictions of climate change in the Mediterranean Basin (Giorgi & Lionello, 2008), significant effects on olive and olive fly were predicted by the model.

## 5. Concluding remarks

An extensive review of climate change projections over the Mediterranean region indicates a trend toward substantial drying and warming of the Mediterranean region with warming exceeding 4-5°C (Giorgi & Lionello, 2008). When compared to state-of-the-art climate predictions, climate change between the two decades considered in our analysis was small but still provided sound indications of the magnitude and direction of expected changes in the olive-olive fly system. Because PBDMs include the dynamics and interactions of the plant and the pest, we were able to detect important phenological changes even under small climatic changes in our analysis. PBDMs overcome the limitations imposed by models using mean weather data (Venette *et al.*, 2000; vs. Gutierrez *et al.*, 2006a).

Currently, a major limitation to implementing the physiologically based modeling approach is the lack of infrastructure for systematically collecting the requisite biological and weather data. The cost to correct these deficiencies is relatively small, while the potential benefits are large. The comparative analysis of Giorgi (2006) places the Mediterranean among the most fragile regions susceptible to global climate change with potentially devastating effects on all ecosystems. The availability of climate datasets with extensive spatial and temporal coverage (Mínguez *et al.*, 2007; Giorgi & Diffenbaugh, 2008; Maurer & Hidalgo, 2008) coupled with multi-trophic PBDMs integrated in a GIS should be important tools to help develop the dynamic interdisciplinary understanding of global change biology required to design sustainable management strategies for Mediterranean olive systems in the face of climate change.

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## Riassunto

*Il sistema olivo-*Bactrocera oleae *(Diptera Tephritidae) nel Bacino del Mediterraneo: un'analisi basata sulla fisiologia e condotta sulla base dei dati climatici ERA-40*

Questo articolo passa in rassegna le applicazioni dei modelli demografici basati sulla fisiologia ("physiologically based demographic models", PBDMs) e vincolati alle condizioni meteorologiche, all'analisi di uno dei principali sistemi pianta-fitofago mediterranei, costituito dall'olivo (*Olea europaea*) e dalla mosca delle olive (*Bactrocera oleae*) (http://cnr.berkeley.edu/casas/). È noto che il Bacino del Mediterraneo sarà particolarmente vulnerabile ai cambiamenti climatici, ivi compresi riscaldamento del clima e desertificazione accentuati. Viene pertanto riportata un'analisi preliminare di questo ecosistema nel Bacino del Mediterraneo basata su un nuovo set di dati climatici, così da fornire indicazioni riguardo a difetti e future applicazioni dei modelli.

L'olivo è una coltura arido-resistente che ha sviluppato stretti legami co-evolutivi con il suo fitofago chiave, la mosca delle olive, e la loro ampia distribuzione geografica li rende un modello idoneo per studi sui cambiamenti climatici nel Bacino del Mediterraneo. I PBDMs utilizzati in questo studio utilizzano dati climatici ERA-40 relativi a due periodi (1958-1967 e 1988-1997) come driver. La risoluzione dei dati climatici ERA-40 è stata aumentata mediante modello climatico RegCM3 accoppiato a modello oceanico MIT. Le simulazioni del PBDM relative a data di fioritura e resa dell'olivo, densità cumulata stagionale di pupe di mosca, e infestazione percentuale dei frutti, sono rappresentate su mappa mediate il GIS a sorgente aperta GRASS (http://grass.osgeo.org/). I risultati della simulazione su scala mediterranea vengono riassunti utilizzando la regressione multipla.

Il difetto principale dell'approccio integrato PBDM/GIS è la gran quantità di dati meteorologici ed edafici necessaria al funzionamento dei modelli, e quindi un risultato notevole del presente studio è l'aver collegato la tecnologia PBDM/GIS con un nuovo set di dati climatici con risoluzione migliore rispetto agli altri esistenti, per valutare problemi ecologici su vaste aree geografiche come il Bacino del Mediterraneo.

**Parole chiave:** olivo, mosca delle olive, Bacino del Mediterraneo, modelli basati sulla fisiologia, analisi degli agroecosistemi, cambiamenti climatici, interazioni multitrofiche, GIS, ERA-40, RegCM3, modello di oceano MIT.

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