Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Olive agroecosystems in the Mediterranean Basin: multitrophic analysis of climate effects with process-based representation of soil water balance

Luigi Ponti[a,b,*], Andrew Paul Gutierrez[b,c], Bruno Basso[d,e], Markus Neteler[f], Paolo Michele Ruti[g], Alessandro Dell'Aquila[g], Massimo Iannetta[a,]

[a]Technical Unit for Sustainable Development and Innovation of the Agro-Industrial System, Italian national agency for new technologies, energy and sustainable economic development (ENEA), Casaccia Research Center, Italy.
[b]Center for the Analysis of Sustainable Agricultural Systems (CASAS), Kensington, California, USA (http://cnr.berkeley.edu/casas/).
[c]Division of Ecosystem Science, Dept. of Environmental Science, Policy & Management, University of California, Berkeley, USA.
[d]Department of Geological Sciences and W.K. Kellogg Biological Station, East Lansing, Michigan, USA.
[e]Department of Crop Systems, Forestry and Environmental Sciences, University of Basilicata, Potenza, Italy.
[f]GIS and Remote Sensing unit, Edmund Mach Foundation – Research and Innovation Center, Trento, Italy.
[g]Technical Unit for Energy and Environmental Modeling, ENEA, Casaccia Research Center, Rome, Italy.

Abstract

Olive is of major eco-social importance for the Mediterranean Basin, a climate change and biodiversity hotspot of global relevance where remarkable climate change is expected over the next few decades with unknown ecosystem impacts. However, climate impact assessments on terrestrial ecosystems have long been constrained by a narrow methodological basis (ecological niche models, ENMs) that is correlative and hence largely omits key impact drivers such as trophic interactions and the effect of water availability, the latter being especially relevant to desertification-prone Mediterranean ecosystems. ENMs use correlative measures of water availability unsuitable for making projections about the future. To bridge this gap, mechanistic approaches such as physiologically-based weather-driven demographic models (PBDMs) may be used as they embed by design both the biology of trophic interactions and a mechanistic representation of soil water balance. Here we report progress towards assessing climate effects on olive culture across the Mediterranean region using mechanistic PBDMs that project regionally the multitrophic population dynamics of olive and olive fly as affected by daily weather and soil water balance.

* Corresponding author. Tel.: +39-06-3048-6459; fax: +39-06-3048-6308.
E-mail address: luigi.ponti@enea.it

1. Introduction

Modeling of ecosystems usually ignores the influence of soil moisture on plant growth and development, and the bottom up effects on higher trophic levels. Here we examine these effects on olive (*Olea europaea*) and its major obligate pest, olive fly (*Bactrocera oleae*) that are ubiquitous in the Mediterranean Basin. The Basin is deemed a climate change [1] and biodiversity hotspot [2] where climate change in the next few decades will result in substantial warming and significant decrease in precipitation [3, 4], and this may cause major ecological, economic, and social disruptions. The model proposed below is a work in progress designed to capture the effects of future climate change on the olive system.

Assessments of climate change on terrestrial ecosystems have historically been constrained by the use of narrow, correlative methodological approaches that fall under the ambit of ecological niche models (ENMs). These methods largely omit basic biology and trophic interactions [5], as well as the effects of water availability that is a major driver of climate impact [6] in desertification-prone ecosystems such as the Mediterranean basin [7]. ENMs use correlative measures of water availability that are unsuitable for making projections about the future [8]. These lacunae may be corrected using mechanistic approaches such as physiologically-based weather-driven demographic models (PBDMs, e.g. [9]) that embed by design both the biology of trophic interactions [10] and a mechanistic representation of soil water balance, see [11]. The PBDM captures the effects of weather, and hence can be applied to the analysis of current weather or to future weather under climate change. The capacity to assess the limiting effects of water will be particularly important for assessing climate change effects in arid areas.

In this paper, we assess the effects of current daily weather including soil water balance on olive culture across the Mediterranean region using mechanistic PBDMs designed to examine the multitrophic population dynamics of olive and olive fly. We note that a range of weather data sources are available (including satellite remote sensing [12] and state-of-the-art regional climate change projections [4]) that may be used to explore the dynamics of PBDM systems.

2. Methods

2.1. The olive system model

PBDMs build on the idea that all organisms are consumers and all have similar resource acquisition functions and allocation priorities; a notion that allows use of the same resource acquisition model and birth-death dynamics models to describe the biology of the species in all trophic levels [13-15] including the economic one [16] (Fig. 1). The inflows and outflows processes respectively are analogous, and similar shape functions are used to describe them. Resource acquisition (i.e. the supply, S) is a search process driven by organism assimilation demands (D), with allocation occurring in priority order to egestion, conversion costs, respiration, and reproduction, growth, and reserves (i.e., the metabolic pool model [17]), with weather driving the physiological and population dynamics. The ratio $0 \leq S/D < 1$ measures the extent to which assimilation demands are met, and is used to scale growth rates of species from maximal demand values [13, 18, 19]. $S/D < 1$ is due to imperfect consumer search. We also use this supply-demand approach to model the limiting effect of soil water, with the photosynthetic rate modified by shortfalls in water (S_w, i.e. transpiration) relative to plant demands (D_w) (see application [9] for further

detail). We modified the soil water balance model developed by Ritchie [11] (see [9]) as a mechanistic representation of hydrological processes in the soil-plant-atmosphere system that are particularly important for assessing the effects of climate change in arid areas.

The plant canopy model for olive has subunit populations of leaves, stem, root and healthy and attacked fruit that capture the bottom-up effects on olive fly dynamics [20, 21]. 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}, and immature olive fly in fruit {7} and reproductive and dormant fly adults {8, 9}. Temperature influences nearly all aspects of olive's biology [20], and the model captures this via a concave scalar function of temperature that represents the normalized net of the photosynthetic and respiration rates, and defines the optimum, and upper and lower thermal thresholds for development. The olive model predicts flowering phenology controlled by vernalization, age-structured growth and yield, and fruit mortality due to temperature and fly attack. Olive fly's 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 [20].
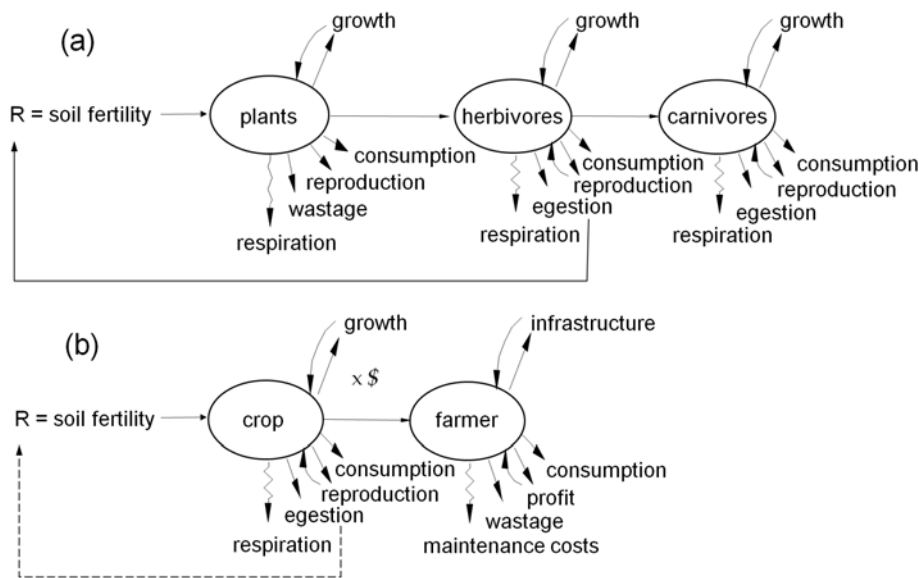

Fig. 1. Multitrophic mass (i.e., energy) flow in the consumer-resource population dynamics model [15]: (a) a natural system and (b) an agroecosystem [16])

2.2. Weather data

Weather data used to drive olive-olive fly dynamics were obtained from the following sources: the global surface summary of daily weather from the US National Climatic Data Center, available at http://www.ncdc.noaa.gov/; the HelioClim solar radiation data provided for a fee by the SoDa consortium http://www.soda-is.com/; E-OBS gridded observed temperature and precipitation data obtained from the ENSEMBLES (http://ensembles-eu.metoffice.com) and ECA&D (http://eca.knmi.nl) projects; gauge-based analysis of global daily precipitation data sourced from the US Climate Prediction Center, available at ftp://ftp.cpc.ncep.noaa.gov/; data present in the climatology resource for agroclimatology, obtained at

http://power.larc.nasa.gov from the NASA Langley Research Center POWER Project funded through the NASA Earth Science Directorate Applied Science Program.

Weather data include daily maximum and minimum temperature, solar radiation, precipitation, relative humidity and wind for the period 1990-2000 for 507 weather stations across the Mediterranean Basin (Fig. 2). Rainfall (Fig. 3) as well as relative humidity and wind are key variables in the soil water balance model [11].
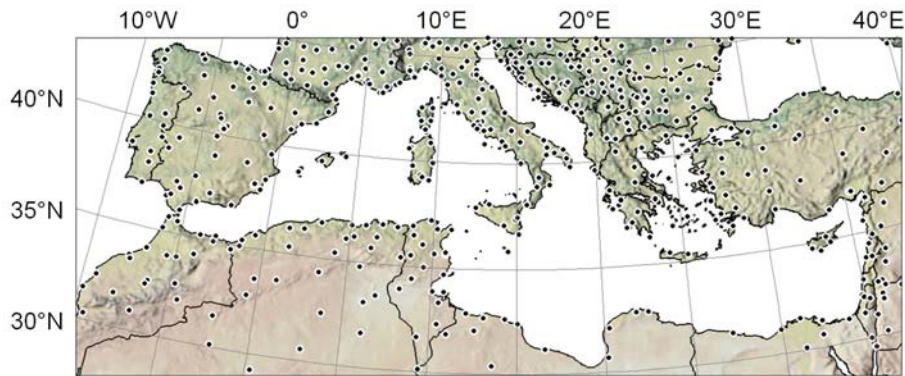

Fig. 2. Location of the weather stations used to run the analysis (n = 507) using data for the period 1990-2000. Land cover coloring form http://www.naturalearthdata.com/
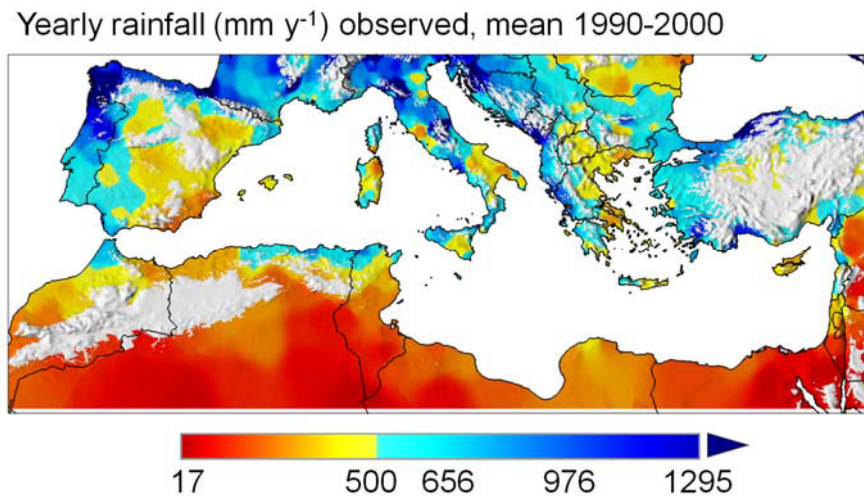

Yearly rainfall (mm y^{-1}) observed, mean 1990-2000

Fig. 3. Observed geographic distribution of mean yearly rainfall below 900 m for the period 1990-2000 in the Mediterranean Basin. The reference precipitation value of 500 mm y^{-1} shown is the lower limit for commercial olive yields under rain fed conditions [22].

2.3. Soil data

The soil data layer of the present analysis is based on the Harmonized World Soil Database (HWSD) [23, 24] from which we generated hydraulic characteristics of the soil (e.g., Fig. 4) at each weather station's location using algorithms proposed by Ritchie et al. [25] and Suleiman and Ritchie [26], and accounting for soil depth as given in the HWSD.

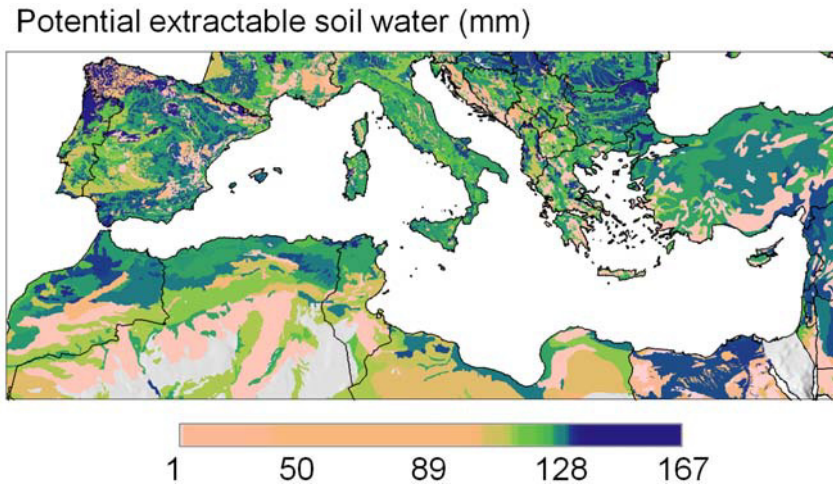## Potential extractable soil water (mm)

Fig. 4. Potential extractable soil water (PESW, mm) in the Mediterranean Basin (grey areas have no data). Values of PESW include soil depth as provided by the HWSD.

2.4. Simulation and GIS

The model was run continuously for the period 1 January 1990 to 31 December 2000, using the same initial conditions all locations, and weather and soil data as input. To allow model dynamics to equilibrate to local weather, the first year of simulation data was not used to compute means. We used GRASS GIS software [27] to map model output data at locations below 900 m [28] using inverse distance weighting interpolation, and hence the patterns reflect not only the site-specific effects of weather on the biology of the species, but also the spatial distribution of weather stations. Base GIS layers used in the analysis (digital elevation model, see http://www.ngdc.noaa.gov/mgg/topo/globe.html; and state boundaries, see http://www.naturalearthdata.com/) are feely available.

We used the observed geographic distribution of olive yield (Fig. 5) as reference for comparing results of the simulations.
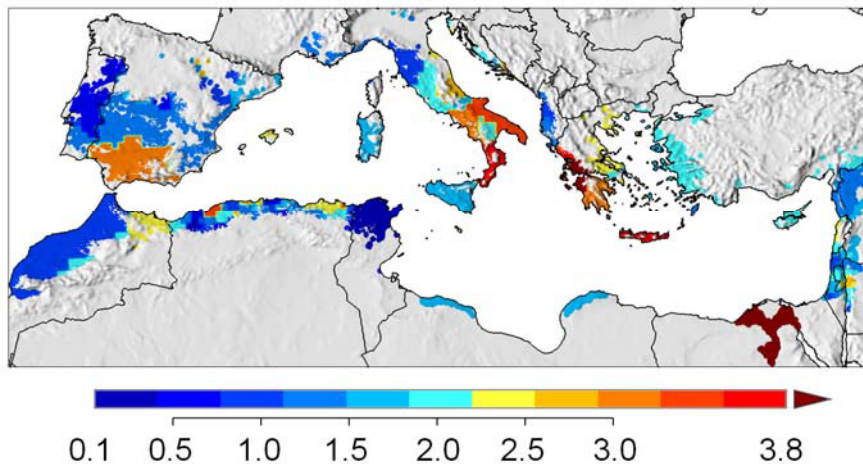
Observed olive yield (t ha⁻¹), reference year 2000

Fig. 5. Observed olive yield (t fresh olive fruit ha⁻¹) in the Mediterranean Basin: map of yields (agricultural statistics for years 1997-2003 turned in into an average data set representative of the year 2000, see Monfreda et al. [29]) where values >3.8 are shown as outliers (identified using R boxplot function; http://www.r-project.org/) for presentation purposes (yield range is 0.1-9.4) (see Ponti et al. [30]).

The observed olive yield map is that developed by Ponti et al. [30], and is mainly based on Corine land cover data (http://goo.gl/zTavS), and on the land use data set by Monfreda et al. [29] that represented the global area and yield of 175 distinct crops in the year 2000 using agricultural statistics for the period 1997-2003.

3. Results

3.1. Olive yield

The limiting effect of water on olive is evident when comparing olive yield simulated across the Mediterranean Basin computed using the water balance model (Fig. 6a) and assuming non limiting water (Fig. 6b). In particular, water constrains olive cultivation in the southern and eastern part of the Basin, and keeps the simulated distribution of olive within its observed range with good approximation of yield except for Egypt where irrigation is used to overcome the limitations of low rainfall (Fig. 6a vs. 5). Also note that yield differences are seen for Andalucía in Spain where drip irrigation is used. This suggests further calibration and additional site-specific irrigation parameters are required. Further, the model simulates an average tree while observed yield is recorded on a per-area basis and includes the effects of factors such as planting density, cultivar and especially irrigation (Andalucía and Egypt).

(a) Olive yield (kg dry matter tree⁻¹), with water balance (mean 1991-2000)

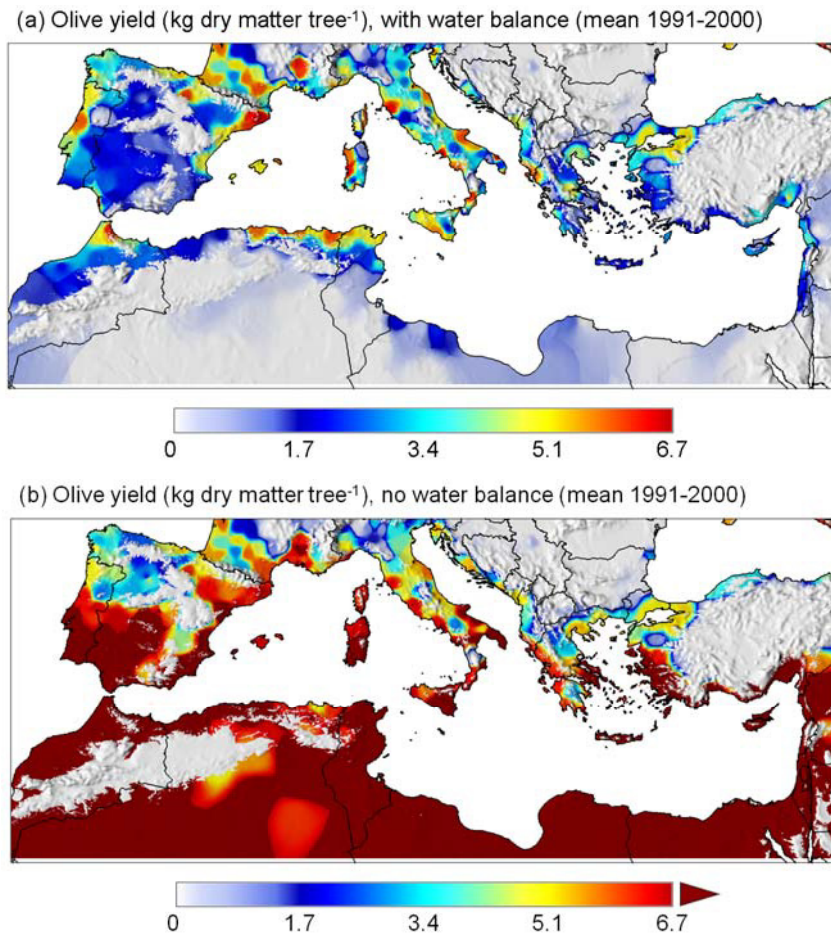(b) Olive yield (kg dry matter tree⁻¹), no water balance (mean 1991-2000)

Fig. 6. Mean olive yield (kg dry matter tree⁻¹) under observed weather for the period 1991-2000 with (a) and without (b) constraints of soil water. Values in subfigure (b) (data range 0-10.4) were mapped to color as in subfigure (a) for ease of comparison, with values exceeding 6.7 shown as outliers using a darker shade of red.

3.2. Olive fly dynamics

Olive fly abundance is affected by the bottom up effects of olive drupe density and directly by temperature. We note that the fly has narrower thermal tolerance than olive. Simulated distribution of abundance of olive fly across the Mediterranean Basin with the water balance model implemented shows the bottom-up effect of limiting water on olive as well as the direct effects of temperature (Fig. 7a vs. b), see [20, 21]. The model with limiting water provides a better representation of the distribution of the pest.
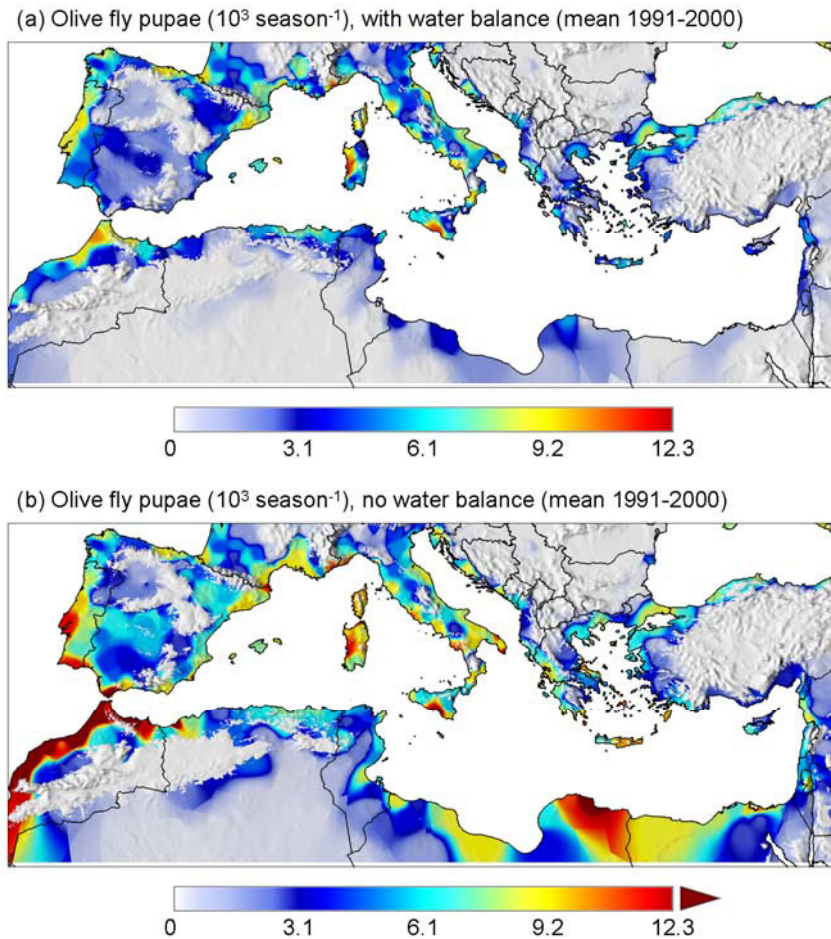
(a) Olive fly pupae (10³ season⁻¹), with water balance (mean 1991-2000)

(b) Olive fly pupae (10³ season⁻¹), no water balance (mean 1991-2000)

Fig. 7. Mean cumulate number of olive fly pupae (x10³ season⁻¹) under observed weather for the period 1991-2000 with (a) and without (b) constraints of soil water. Values in subfigure (b) (data range 0-20.9) were mapped to color as in subfigure (a) for ease of comparison, with values exceeding 12.3 shown as outliers using a darker shade of red.

4. Discussion

The goal of our analysis was not to predict olive yield precisely, as yield is influenced by a plethora of local factors: varieties and agronomic practices (e.g., age structure, planting densities, nutrients and irrigation) whose inclusion in the olive system model is prevented by the lack of suitable data. Our goal was to show the progress on assessing climate effects on olive culture across the Mediterranean region using mechanistic PBDMs that project regionally the multitrophic population dynamics of olive and olive fly as affected by daily weather and a mechanistic soil water balance model. Our PBDM simulates the effects of daily maximum and minimum temperatures and water balance on olive physiology, and the bottom-up effects on olive fly. The PBDM approach is an alternative to more widely-used correlative ENM approaches.

The simulated distribution of olive yield including the limiting effects of water accords well with the observed geographic distribution of olive yield in the Mediterranean Basin (Fig. 6a vs. 5), especially in

the southern and eastern part of the Basin. Differences are evident in simulated vs. observed yield patterns (Fig. 6a vs. 5), particularly for Egypt and the Province of Andalucía, Spain where irrigation is used to overcome the soil water limitations. Furthermore, no suitable yield records are available for validation at the scale of the Mediterranean Basin.

However, olive bloom date is the major factor determining season length and potential yield, and this was well captured in a previous analysis where the model was tested against field data [21]. Similarly, the olive model (without soil water balance) detected the production of olive in the microclimates along the northern Italian lakes and explained the distribution of olive fly in California and Arizona, USA [20].

5. Conclusions

Olive is a major feature in the landscape of the Mediterranean Basin where it has considerable ecological, economic, and social importance. The inclusion of a process-based model for soil water balance in a mechanistic PBDM of olive and olive fly improves our capacity to assess the effects of weather on olive production and pest levels. The model also provides the basis for assessing the impact of climate changes expected in the Basin in the next few decades. These changes will include substantial warming (about 1.5°C in winter and 2°C in summer) and a significant decrease in precipitation (about 5%) [3, 4]. Prospective analysis is needed of the impact of climate change on olive (and other crops) that will result in profound ecological and social changes.

Acknowledgements

References

[1] Giorgi F. Climate change hot-spots. *Geophys Res Lett* 2006;**33**:L08707.

[2] Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J. Biodiversity hotspots for conservation priorities. *Nature* 2000;**403**:853-858.

[3] Gualdi S, Somot S, Li L, Artale V, Adani M, Bellucci A, Braun A, Calmanti S, Carillo A, Dell'Aquila A. The CIRCE simulations: a new set of regional climate change projections performed with a realistic representation of the Mediterranean Sea. *B Am Meteorol Soc* 2012;DOI 10.1175/BAMS-D-1111-00136.

[4] Dell'Aquila A, Calmanti S, Ruti P, Struglia MV, Pisacane G, Carillo A, Sannino G. Effects of seasonal cycle fluctuations in an A1B scenario over the Euro-Mediterranean region. *Climate Res* 2012;**52**:135-157.

[5] Dawson TP, Jackson ST, House JI, Prentice IC, Mace GM. Beyond predictions: biodiversity conservation in a changing climate. *Science* 2011;**332**:53-58.

[6] Thuiller W, Lavorel S, Araújo MB, Sykes MT, Prentice IC. Climate change threats to plant diversity in Europe. *Proc Natl Acad Sci USA* 2005;**102**:8245-8250.

[7] Colonna N, Lupia F, Iannetta M. Severe environmental constraints for mediterranean agriculture and new options for water and soil resources management. in: P. Zdruli, M. Pagliai, S. Kapur, A. Faz Cano (Eds.) *Land Degradation and Desertification: Assessment, Mitigation and Remediation*: Springer Netherlands; 2010, p. 477-491.

[8] Hickler T, Fronzek S, Araújo MB, Schweiger O, Thuiller W, Sykes MT. An ecosystem model based estimate of changes in water availability differs from water proxies that are commonly used in species distribution models. *Global Ecol Biogeogr* 2009;**18**:304-313.

[9] Gutierrez AP, Pitcairn MJ, Ellis CK, Carruthers N, Ghezelbash R. Evaluating biological control of yellow starthistle (*Centaurea solstitialis*) in California: A GIS based supply-demand demographic model. *Biol Control* 2005;**34**:115-131.

[10] Wisz MS, Pottier J, Kissling WD, Pellissier L, Lenoir J, Damgaard CF, Dormann CF, Forchhammer MC, Grytnes JA, Guisan A, Heikkinen RK, Høye TT, Kühn I, Luoto M, Maiorano L, Nilsson M-C, Normand S, Öckinger E, Schmidt NM, Termansen M, Timmermann A, Wardle DA, Aastrup P, Svenning JC. The role of biotic interactions in shaping distributions and realised assemblages of species: implications for species distribution modelling. *Biol Rev* 2012;DOI 10.1111/j.1469-1185X.2012.00235.x.

[11] Ritchie JT. Model for predicting evaporation from a row crop with incomplete cover. *Water Resour Res* 1972;**8**:1204-1213.

[12] Neteler M. Estimating daily Land Surface Temperatures in mountainous environments by reconstructed MODIS LST data. *Remote Sens* 2010;**2**:333-351.

[13] Gutierrez AP, Baumgärtner JU. Multitrophic level models of predator-prey energetics: I. Age-specific energetics models - pea aphid *Acyrthosiphon pisum* (Homoptera: Aphididae) as an example. *Can Entomol* 1984;**116**:924-932.

[14] Gutierrez AP. The physiological basis of ratio-dependent predator-prey theory: the metabolic pool model as a paradigm. *Ecology* 1992;**73**:1552-1563.

[15] Gutierrez AP. *Applied population ecology: a supply-demand approach*. New York, USA: John Wiley and Sons; 1996.

[16] Gutierrez AP, Regev U. The bioeconomics of tritrophic systems: applications to invasive species. *Ecol Econ* 2005;**52**:383-396.

[17] Petrusewicz K, MacFayden A. *Productivity of terresrtial animals: principles and methods*. Oxford, UK: Blackwell; 1970.

[18] Gutierrez AP, Wang YH. Applied population ecology: models for crop production and pest management. in: G.A. Norton, C.S. Holling (Eds.) *Pest management*, Oxford, UK: (International Institute for Applied Systems Analysis. IIASA Proceedings Series; vol 4), Pergamon Press; 1977, p. 255-280.

[19] de Wit CT, Goudriaan J. *Simulation of ecological processes*. 2nd ed. The Netherlands: PUDOC Publishers; 1978.

[20] Gutierrez AP, Ponti L, Cossu QA. Effects of climate warming on olive and olive fly (*Bactrocera* oleae (Gmelin)) in California and Italy. *Climatic Change* 2009;**95**:195-217.

[21] Ponti L, Cossu QA, Gutierrez AP. Climate warming effects on the *Olea europaea–Bactrocera oleae s*ystem in Mediterranean islands: Sardinia as an example. *Global Change Biol* 2009;**15**:2874-2884.

[22] Fernandez JE, Moreno F. Water use by the olive tree. *J Crop Prod* 1999;**2**:101-162.

[23] Food and Agriculture Organization of the United Nations (FAO), International Institute for Applied Systems Analysis (IIASA), ISRIC-World Soil Information, Institute of Soil Science – Chinese Academy of Sciences (ISSCAS), Joint Research Centre of the European Commission (JRC). *Harmonized World Soil Database (version 1.1)*. FAO, Rome, Italy and IIASA, Laxenburg, Austria; 2009.

[24] Fischer G, Nachtergaele F, Prieler S, Velthuizen HTv, L. Verelst DW. *Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008)*. IIASA, Laxenburg, Austria and FAO, Rome, Italy; 2008.

[25] Ritchie J, Gerakis A, Suleiman A. Simple model to estimate field-measured soil water limits. *Trans ASAE* 1999;**42**:1609-1614.

[26] Suleiman A, Ritchie J. Estimating saturated hydraulic conductivity from soil porosity. *Trans ASAE* 2001;**44**:235-239.

[27] GRASS Development Team. *Geographic Resources Analysis Support System (GRASS) Software, Version 6.4.0*. Open Source Geospatial Foundation. URL http://grass.osgeo.org; 2010.

[28] Vermoere M, Vanhecke L, Waelkens M, Smets E. Modern and ancient olive stands near Sagalassos (south-west Turkey) and reconstruction of the ancient agricultural landscape in two valleys. *Global Ecol Biogeogr* 2003;**12**:217-235.

[29] Monfreda C, Ramankutty N, Foley JA. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochem Cycles* 2008;**22**:GB1022, DOI 1010.1029/2007GB002947.

[30] Ponti L, Gutierrez AP, Ruti PM, Dell'Aquila A. Effects of climate warming on olive profitability in the Mediterranean Basin. 2013;(submitted).