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Analysis of Grape Production in the Face of Climate Change

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Received: 18 January 2018; Accepted: 19 March 2018; Published: 21 March 2018

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Abstract: Grape, olive, and wheat are traditional Mediterranean Basin crops that have immense cultural, economic, and ecological importance, and are the basis for producing wine, olive oil, and pasta and bread products. Of fruit crops, grape has the largest area and the highest economic importance globally. These traditional Mediterranean crop systems and related food products have global relevance, and yet globally, all regions with Mediterranean climate are especially vulnerable to climate change that threatens this Mediterranean bio-cultural heritage. However, how to analyze the complex tripartite ecological, economic, and social effects of climate change on these systems has been vexing and largely unexplored. Here we review how a bioeconomic approach using physiologically-based demographic models in the context of geographic information systems may be an important step in examining the complexity of these factors on grape. We show that with relatively modest data and funding, regional bioeconomic analysis of grape production under present weather and climate change is possible, and that management-relevant complexity can be included in a mechanistic way.

Keywords: ecosystem modeling; physiologically-based demographic models; *Lobesia botrana*; ecological assessment; economic assessment

1. Introduction

Grape (*Vitis vinifera*) is an important cultural, economic and ecological feature of the Mediterranean Basin but also a cosmopolitan crop with the largest acreage and the highest economic value among fruit crops globally [1]. With olive (*Olea europaea*) and wheat (*Triticum durum* and *T. aestivum*), grape forms the core of traditional Mediterranean crop systems that are the basis for producing olive oil, pasta, and wine [2–4]. Olive oil, pasta, and wine are unique in that they are both food commodities with a global market and are hallmarks of the Mediterranean diet; they are part of the UNESCO intangible cultural heritage of humanity [5–7]. These crops and related food products are of utmost ecological, economic, and cultural relevance to the Mediterranean region and globally [8]. Yet globally, all regions with Mediterranean climate are especially vulnerable to climate change [9], and the associated ecological, economic, and social effects threaten this Mediterranean bio-cultural heritage [10,11]. However, how to analyze the tripartite ecological, economic, and social effects of climate change has been vexing and largely unexplored [12]. Here we review how a bioeconomic approach using physiologically-based demographic models (PBDMs) in the context of a geographic information system (GIS) may be an important step in examining the complexity brought about by these tripartite factors, albeit with different levels of precision. A PBDM-based bioeconomic analysis of olive was completed [12] that demonstrated the importance of including the ecological complexity of trophic interactions between species in assessing biological and economic impacts of climate change over large geographic areas, and provides a template for assessing climate change impact in other agroecosystems such as grape [13]. This paper reviews the ecological and geographic complexity involved in assessing the bioeconomics of grape production under climate change with a focus on the European grapevine moth *Lobesia botrana*, the principal native pest of grape in the Palearctic region. The goal is to show that with relatively modest data and funding, regional bioeconomic analysis of grape production under climate change is possible that includes management-relevant complexity in a mechanistic way. Specifically, the present paper is conceived as a companion paper that complements Gutierrez et al. [13] as follows:

- It illustrates the ecological and geographic complexity involved in assessing the bioeconomics of grape production under climate change, including an expanded overview on ongoing and prospective work in PBDM analysis of the pest/vector/disease complex of grape (Figure 1);
- It pinpoints key ecological differences that drive different levels of management and external input intensity in olive and grape, the two major perennial traditional cropping systems of Mediterranean agriculture (Section 2);
- It provides a broad overview on how PBDMs in a GIS context can be used to explore mechanistically otherwise mostly intractable complex problems such as crop-pests interactions that lie at the interface between global change and biological systems (i.e., global change biology) based on the paradigm of ecological analogies (Section 3);
- It reviews the GIS context for PBDMs by illustrating how GRASS GIS [14] can be linked to the free software environment for statistical computing and graphics R [15] to analyze (Figures 2 and 3) and assess (Figure 4) the observed geographic distribution of grape (or any other crop) production in the Euro-Mediterranean region (or any other region including globally);
- For each of the major grape growing countries of the Euro-Mediterranean region (Figure 2) it shows the probability distribution of changes in grape yield and grapevine moth infestation (Figures 5 and 6), as well as the fraction of grape growing area in each country where these changes are expected to be positive or negative (Tables 1 and 2);
- It ranks the 18 major Euro-Mediterranean grape growing countries in terms of the following bioeconomic measures of climate risk: (a) mean climate change impact on grape yield and grapevine moth infestation (Figures 5 and 6); (b) relative share of the grape growing area in each country where grape yield and grapevine moth infestation are expected to be negative or positive (Tables 1 and 2).

2. Olive vs. Grape

Olive and grape are the two major perennial crop systems traditionally grown in the Mediterranean Basin [16]. They are ecological, socioeconomic, and cultural assets of Mediterranean landscapes [17] developed over centuries of human-nature interaction [18], and show considerable ecological resilience [19] when properly managed [4,18,20–22].

Olive and grape are to some extent complementary agroecosystems. In olive, the usually conflicting goals of biodiversity conservation and agricultural production largely converge (see e.g. supplementary materials in [12]). In contrast, the economic drivers in grape production have turned it into an industrial monoculture that currently is an important source of ecological disruption and pollution in the agricultural landscape [23]. Specifically, olive is an evergreen plant with a relatively stable associated pest/pathogen complex in which only the olive fruit fly *Bactrocera oleae* causes economic damage requiring ongoing management [24,25], whereas grape is deciduous and seasonally colonized by herbivores, and requires relatively high pesticide use to prevent economic damage from a variety of pests and pathogens [26] (Figure 1) leading to environmental and health concerns. Overall, pesticide inputs in grape are expected to increase under climate change [27] unless better management practices can be developed.

3. The PBDM Approach

Complexity is intrinsically high in grape, and is a major barrier to analysis and management (see Figure 1; modified from [13]), with climate change further complicating issues [28,29]. To fully understand the consequences of current and future management practices requires a holistic analysis of the system [30], but while this is often advocated [31–36] it is rarely achieved. As a result, management strategies for critical pest problems often fail because holistic analyses that underpin sound decision making at the field level are unavailable [37].

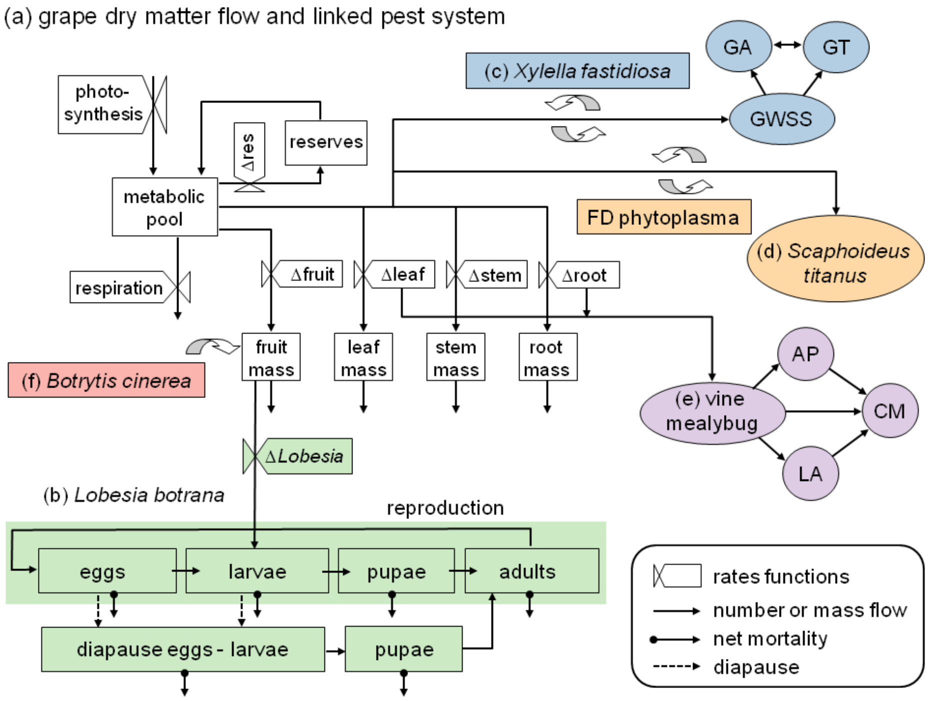

Figure 1. The grape system model including major pests, vectors, and diseases that have been modeled and included in the extant or developing system. (**a**) Dry matter flow in grapevine [38,39]; and (**b**) the linkage of European grapevine moth (*Lobesia botrana*) life-stages including diapause induction and termination [13,40]. Linkages of three vascular feeding Homoptera; (**c**) the glassy-winged sharpshooter (GWSS) with its natural enemies the parasitoids *Gonatocerus ashmeadi* (GA) and *G. triguttatus* (GT), and the transmission of the bacterium *Xylella fastidiosa* that causes Pierce's disease [41]; (**d**) the leafhopper *Scaphoideus titanus* and the transmission of the phytoplasma that causes flavescence dorée disease (currently being modeled) [42]; and (**e**) the vine mealybug with its natural enemies the parasitoids *Anagyrus pseudococci* (AP) and *Leptomastidea abnormis* (LA), and a coccinellid predator, *Cryptolaemus montrouzieri* (CM) [43]; (**f**) Linkage of the fungus *Botrytis cinerea* that causes grey mold disease developed by González-Domínguez et al. [44]. (Figure modified from [13]).

One way to tackle complex problems such as crop-pests interactions that lie at the interface between global change and biological systems (i.e., global change biology) is to analyze them using a mechanistic description of their biology (i.e., a model) based on the unifying paradigm that all organisms including humans acquire and allocate resources by analogous processes (the paradigm of ecological analogies, see [30], and http://www.casasglobal.org/). PBDMs are based on the notion that analogous weather-driven sub-models for resource acquisition and birth-death dynamics can be used to predict explicitly the biology and dynamics of heterotherm species across trophic levels [30,37,45,46], including the economic level [47,48]. PBDMs include bottom-up effects of plant growth and development on herbivore dynamics, and the top-down action of natural enemies [28,49]. Realistic PBDMs have been used as the production function in bioeconomic analyses in agriculture including invasive species under observed and climate change scenarios at various spatial scales and with different degrees of economic focus [12,50,51]. General bioeconomic PBDMs of renewable resource exploitation including the economic consumer can also be used to examine the stability and bioeconomic properties of natural and agro-ecosystems [45,52–54]. Bioeconomic analysis using PBDMs is based on theoretical foundations that include a set of analogies between natural and human economies [47,48].

When driven by weather including climate change scenarios, PBDMs predict the phenology, age structure and abundance dynamics, and the distribution of the interacting species across wide geographic areas [37,55]. Several weather data sources can be used to drive weather-driven PBDMs [56], including satellite remote sensing [57,58] and regional climate change projections [59,60], while the geographic information system (GIS) GRASS (http://grass.osgeo.org) [14] is used to perform geospatial analysis and produce maps.

A significant fraction of the management-relevant complexity included in the grape agroecosystem has been or is being modeled using the PBDMs in a GIS context (Figure 1) [13,38–41,43], and hence the reader is referred to the original papers for a full description. Here we focus on how the interaction of grape and its major insect pest *L. botrana* is expected to change as a result of climate warming [see 13] in the major grape growing countries of the Euro-Mediterranean region (Figure 2). It is worth noting that although feeding by *L. botrana* larvae causes relatively small direct yield losses, the associated indirect damage may be economically large and be possibly exacerbated by the grey mold fungus *Botrytis cinerea* (Sclerotiniaceae) (Figure 1).

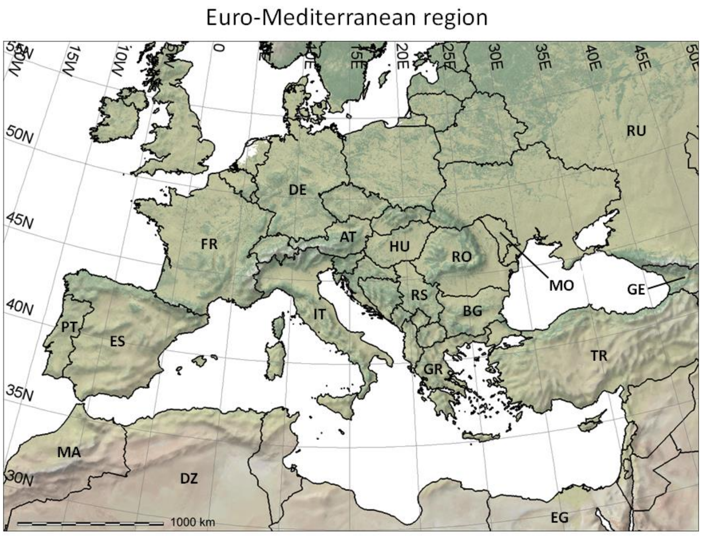

Figure 2. The Euro-Mediterranean part of the Western Palearctic region considered in the present paper, including shaded relief and land cover coloring based on satellite observations (form http://www.naturalearthdata.com/), and two-letter country codes (i.e., ISO 3166-1 alpha-2 codes, https://en.wikipedia.org/wiki/ISO_3166-1_alpha-2) used in this study to identify countries of interest. DZ = Algeria; AT = Austria; BG = Bulgaria; EG = Egypt; FR = France; DE = Germany; GR = Greece; HU = Hungary; IT = Italy; MO = Moldova; MA = Morocco; PT = Portugal; RO = Romania; RU = Russia; RS = Serbia; ES = Spain; TR = Turkey.

4. The GIS Context for PBDMs

GIS have the capacity to integrate digital data layers into joint databases and to provide data analysis and visualization techniques for ecological data, whether field observations or PBDM predictions. We use the free and open source GIS software GRASS [14]. A number of factors affecting species distribution and abundance may be integrated into ecosystem models as digital data using joint geo-referenced databases in a GIS [30]. Another important component in the PBDM data management system is R [15] which is a software environment for statistical computing and graphics that is also free and open source, and that enables a two-way interface to GRASS functionality and data [61].

A first geographic step in studying grape production in the Euro-Mediterranean region is to assess the observed geographic distribution and yield of the crop. To achieve this, we used GRASS to process and analyze state of the art datasets on the distribution of grape (Figure 3) and of grape yield (Figure 4).

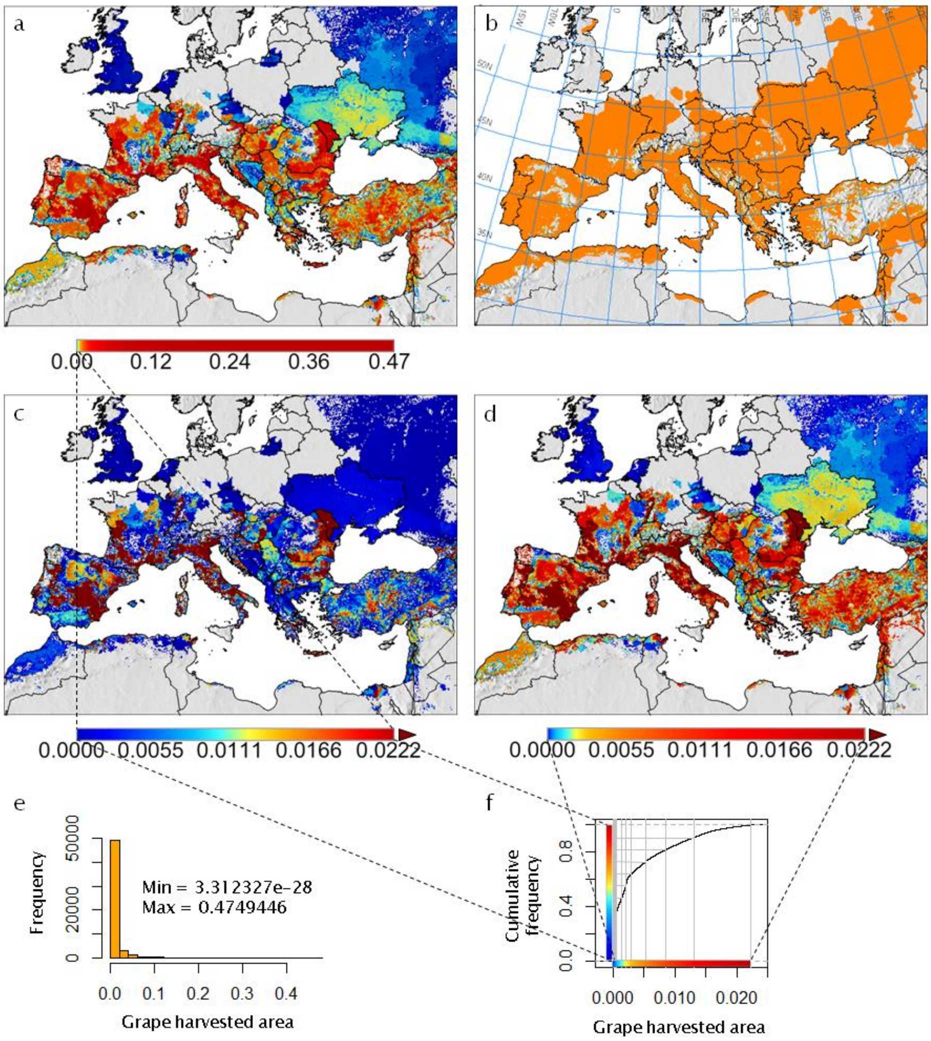

Figure 3. Analysis of the observed geographic distribution of grape production for the reference year 2000 using the fraction of ~10 km × 10 km cell covered by vineyards (data from [62]) mapped only if fraction is ≥0.0001 (i.e., each raster cell that covers ~10^4 ha of land is considered part of the grape growing area if it includes at least one ha of vineyard): (**a**) map with histogram-equalized color coding (**f**) where each color covers an equal share of land; (**b**) derived potential grape distribution with uniform color to highlight the grape growing area (note that missing data for Sicily in [62] were filled using Corine Land Cover 2000 raster data [63]); (**c**) map where statistical outliers selected via the *boxplot* R function [15] are mapped in very dark red (i.e., symbol ►) to improve visual detection of differences within non-outlier data [64]; (**d**) map with histogram-equalized color coding restricted to non-outlier data, and where each color covers an equal share of land but only for areas covered by non-outlier data cells (**f**); (**e**) frequency histogram of data in (**a**–**d**); (**f**) cumulative frequency used to assign an equal number of cells to every color in the legend of plot (**d**).

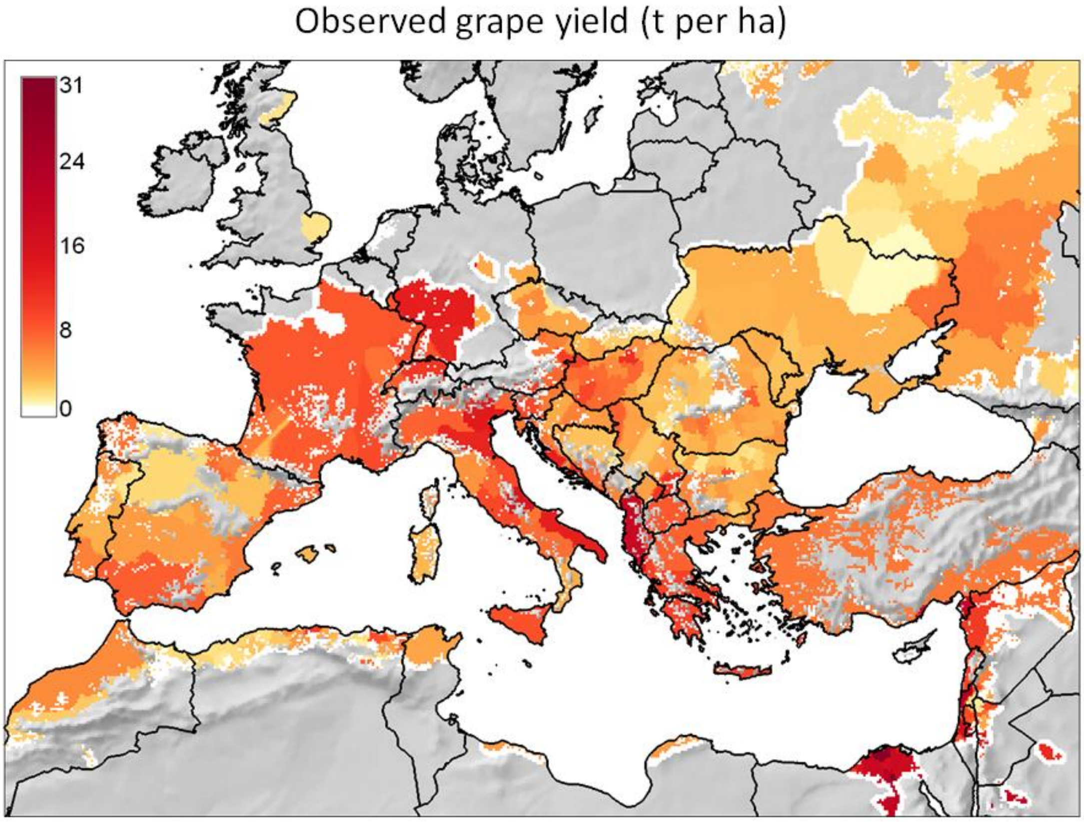

Figure 4. Observed grape yield (*t* per ha) for the reference year 2000 (data from [62]) mapped for the observed geographic distribution shown in Figure 3. Note that missing data for Sicily in [62] were filled using AGRO-MAPS data [65].

5. Climate Change Effects on Grape and Its Major Insect Pest

PBDMs are driven by daily weather, and hence a climate modeling scenario is required to assess the effects of projected climate change on grape and *L. botrana* [40]. In this study, we used the A1B regional climate change scenario that posits +1.8 °C warming for the Euro-Mediterranean region [60]; a scenario that is towards the middle of the Intergovernmental Panel on Climate Change [33] range of greenhouse gas (GHG) forcing scenarios [66]. This fine-scale weather dataset at ~30 km resolution was developed by Dell'Aquila et al. [60] using the regional climate model PROTHEUS [59]. PROTHEUS is a coupled atmosphere-ocean regional model that allows simulation of local extremes of weather via the inclusion of a fine-scale representation of topography and the influence of the Mediterranean Sea [59]. The PROTHEUS A1B scenario is a fine-scale projection of future climate change for the Euro-Mediterranean region, and the daily weather data for the periods 1960–1970 (reference baseline) and 2040–2050 (climate change) was used to run the grapevine/*L. botrana* system across the Euro-Mediterranean region [13]. Here we provide further analysis of the data presented in [13], with emphasis on regional bioeconomic analysis. Specifically, we present an overview of changes in grape yield (Figure 5) and *L. botrana* density (Figure 6) as driven by climate warming for each of the 18 Euro-Mediterranean countries (Figure 2) having a grape growing area larger than 32×10^3 ha [67]. The present paper provides information that complements that found in [13].

The present analysis shows that climate warming effects on grape and its major insect pest may be positive and/or negative in the different countries (Figures 5 and 6). With the notable exception of France where vineyards extend beyond 50° North (Figure 3b), Mediterranean countries (i.e., Algeria, Greece, Portugal, Morocco, Turkey, Spain, Italy, and Egypt) are projected to experience a negative average effect of climate warming on grape yield (Figure 5). A general detrimental effect of climate change on viticulture in the Mediterranean region has previously been shown, although without consideration of the pest level [11,68–71]. Countries such as Spain, Bulgaria, and Italy where the median effect of climate warming on grape yield is close to zero, are projected to have positive or negative yield changes on equal shares of their respective vineyard areas (Figure 5). Spain is expected to have the highest variability in climate warming effects on yields, with the lowest variability expected in Egypt (Figure 5). Projected climate warming will increase grape yield to some extent in all countries except Egypt, but yield increases are expected over the entire grape growing area only in Germany and Hungary (Figure 5).

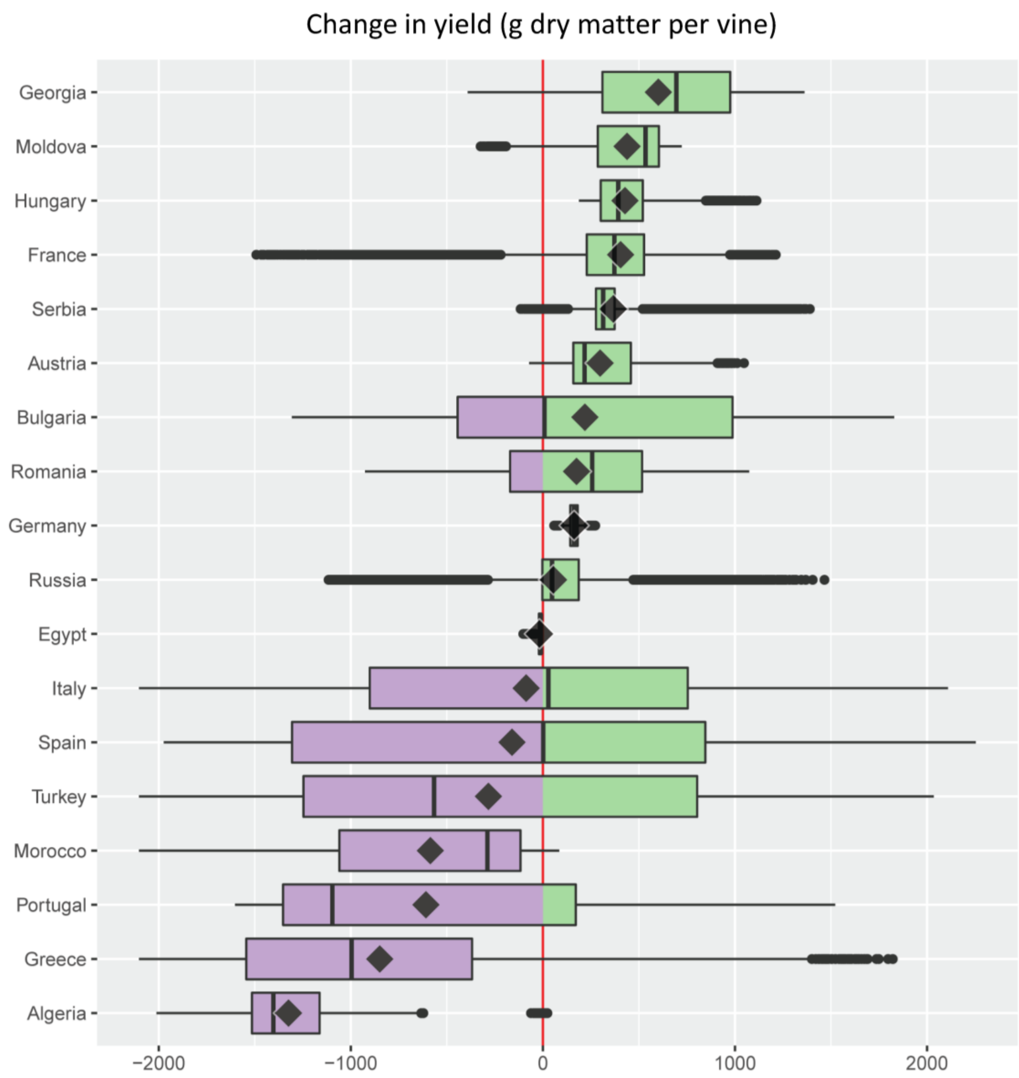

Figure 5. Change in grape yield (g dry matter per plant) under an A1B scenario of 1.8 °C average climate warming in the Euro-Mediterranean region illustrated as a series of stacked boxplots (graphics produced using the R package *ggplot2* [72]), one for each of the 18 Euro-Mediterranean countries (Figure 2) having a grape growing area larger than 32×10^3 ha [67]. Box-and-whisker plots (boxplots) indicate the distribution of data with the vertical black line inside the box representing the median value, the left and right limits of the box being the 25th and 75th percentile (the lower and upper quartiles, respectively), and the whiskers indicating the minimum and maximum value unless outliers are shown as black points, in which case whiskers represent the lower quartile − (1.5 × the interquartile range) (IQR, a measure of statistical dispersion equal to the difference between upper and lower quartiles) and/or the upper quartile + (1.5 × IQR). The superimposed diamonds indicate the mean climate change impact, and boxplots are ordered using this parameter. The red line is a reference for no impact with violet filling indicating a negative change (decrease) and green a positive one (increase). Color palette from ColorBrewer [73].

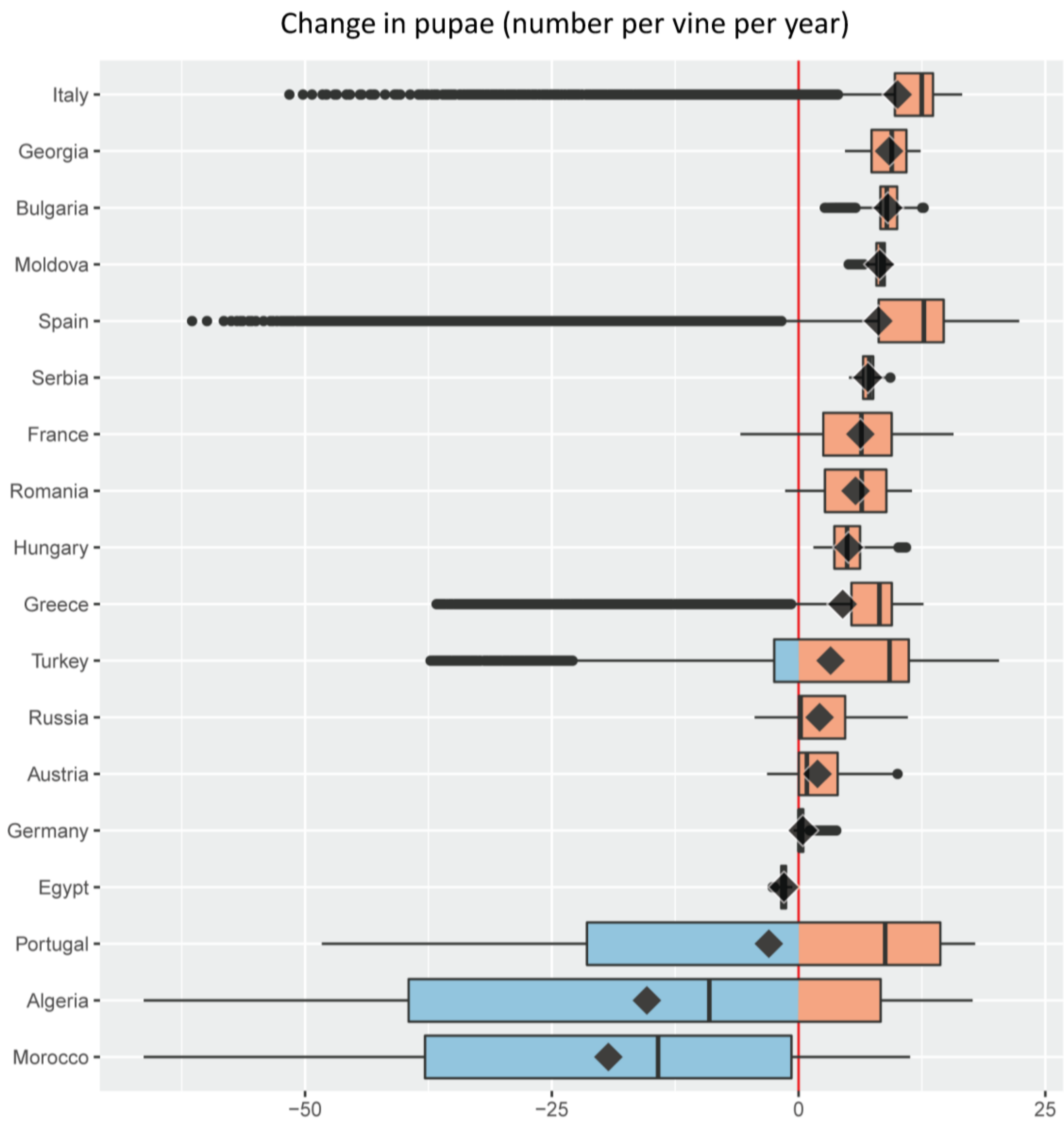

Figure 6. Change in the density of the grapevine moth *Lobesia botrana* (cumulative number of pupae per plant per year) under an A1B scenario of 1.8 °C average climate warming in the Euro-Mediterranean region illustrated as a series of stacked boxplots (graphics produced using the R package *ggplot2* [72]), one for each of the 18 Euro-Mediterranean countries (Figure 2) having a grape growing area larger than 32×10^3 ha [67]. Box-and-whisker plots (boxplots) indicate the distribution of data with the vertical black line inside the box representing the median value, the left and right limits of the box being the 25th and 75th percentile (the lower and upper quartiles, respectively), and the whiskers indicating the minimum and maximum value unless outliers are shown as black points, in which case whiskers represent the lower quartile − (1.5 × the interquartile range) (IQR, a measure of statistical dispersion equal to the difference between upper and lower quartiles) and/or the upper quartile + (1.5 × IQR). The superimposed diamonds indicate the mean climate change impact, and boxplots are ordered using this parameter. The red line is a reference for no impact with blue filling indicating a negative change (decrease) and pink a positive one (increase). Color palette from ColorBrewer [73].

An average increase in infestations by *L. botrana* is projected in most countries because of climate warming, with the pest expected to increase across all vineyards of Hungary, Serbia, Moldova, Bulgaria, and Georgia (Figure 6). Some Mediterranean countries with hotter climates where negative yield change is expected on average under climate warming, are also projected to experience decreased average pest infestations: this is the case of Morocco, Algeria, Portugal, and Egypt (Figure 6). On average, others such as Greece, Spain, and Italy are projected to face both decreases in yield and increases in pest infestation (Figure 6). Algeria shows the largest variability in climate warming effects on pest infestations, while Egypt the smallest (Figure 6). Climate warming is predicted to increase pest levels in a total of 14 countries vs. only 10 countries where increased yield is expected (Figure 5 vs. Figure 6).

Additional information that complements estimates of the variability, median, mean, and extreme values in yield and pest level changes under climate warming, is the relative share of the grape growing area in each country that is expected to experience these changes (Tables 1 and 2).

Table 1. Percent fraction (%) of the grape growing area where negative or positive changes in yield (Δ yield) are projected under an A1B scenario of 1.8 °C average climate warming in the 18 Euro-Mediterranean countries with the largest vineyard area.

Country	% Grape Growing Area	
	Δ Yield < 0	Δ Yield > 0
Germany	0.0	100.0
Hungary	0.0	100.0
Serbia	0.5	99.5
Austria	2.1	97.9
France	2.5	97.5
Moldova	5.0	95.0
Georgia	12.0	88.0
Romania	26.7	73.3
Russia	27.3	72.7
Italy	49.3	50.7
Bulgaria	49.7	50.3
Spain	50.0	50.0
Turkey	65.2	34.8
Portugal	73.2	26.8
Greece	84.6	15.4
Morocco	96.9	3.1
Algeria	99.9	0.1
Egypt	100.0	0.0

Table 2. Percent fraction (%) of the grape growing area where negative or positive changes in the density of grapevine moth (*Lobesia botrana*) (Δ pupae) are projected under an A1B scenario of 1.8 °C average climate warming in the 18 Euro-Mediterranean countries with the largest vineyard area.

Country	% Grape Growing Area	
	Δ Pupae < 0	Δ Pupae > 0
Moldova	0.0	100.0
Hungary	0.0	100.0
Bulgaria	0.0	100.0
Serbia	0.0	100.0
Georgia	0.0	100.0
France	3.7	96.3
Russia	3.8	96.2
Romania	4.4	95.6
Italy	8.0	92.0
Spain	11.5	88.5
Germany	13.0	87.0
Greece	16.0	84.0
Austria	21.0	79.0
Turkey	27.4	72.6

Table 2. *Cont.*

Country	% Grape Growing Area	
	Δ Pupae < 0	Δ Pupae > 0
Portugal	41.2	58.8
Algeria	58.9	41.1
Morocco	81.3	18.7
Egypt	100.0	0.0

Note the absence of areas where no change in yield and pest level is expected under climate warming (Tables 1 and 2). This is due to the use of the single value zero to separate positive and negative changes. An alternative approach would be to use an interval including zero and a range of small positive and negative values of change that would be considered negligible.

6. Discussion

Determining the direction and magnitude of change in tri-trophic natural and agro-ecosystems due to climate change is a major challenge for developing sustainable management strategies. These changes may be in phenology, yield, pest levels, natural enemy efficacy, and other measurable aspects of the system. To assess the underlying causes of these changes requires that we analyze the population dynamics of plant, herbivorous and carnivorous species and their interactions under extant weather and climate change [12,30]. The literature is replete with analyses that fail to include the appropriate level of system complexity, and that yield solutions having little relevance to develop a general understanding of the problems. Among the ecosystem level problems that will be complicated by global change and climate change will be changes in the dynamic interactions of ecosystem components [28,74] as weather may affect each in different ways, and these changes will challenge our capacity to develop timely solutions.

An efficient way to address holistically ecosystem level analyses that are robust to climate change effects is the development of mechanistic physiologically-based demographic models (i.e., PBDMs) of the biology of the interacting species in a weather-driven GIS context [30]. The problem of developing PBDMs is simplified by the fact that all species in all trophic levels (including the economic one) have by analogy the same resource acquisition and allocation strategies [30,47,48]. These PBDMs can be used as the economic objective function to perform realistic bioeconomic analyses that include usually neglected core ecological issues that determine socio-economic outcomes. Two recent examples under extant and climate change weather scenarios are the bioeconomic analysis of olive/olive fly in the Mediterranean Basin [12] and the impact of weather and new biotechnologies in Indian cotton on increases in economic distress and in Indian farmer suicides [51]. Applications with a more traditional economic bent are also possible, leading to estimates of the economic gains and losses of extant and new technologies at local and regional level in crop/pest systems [50]. Bioeconomic models based on sound PBDMs have firm theoretical, ecological and economic foundations with known stability and bioeconomic properties [45,47,48,52–54] and can readily be applied to natural and agro-ecosystems as affected by changes in climate, and biological and technological innovations.

This paper focused on grape in the Palearctic region, but globally, grape is the fruit crop with the largest acreage and the highest economic value [1]. Grape has a variety of pests and pathogens that cause economic damage [75–77] and that require control interventions. As a result, chemical use in grape is among the highest among agricultural crops [23,26]. To assess the impact of pests, a model for grapevine was developed based upon extensive field data [38,39], while models for the pests were developed based on modest data and funding ([13,38–41]; Figure 1). Because the PBDMs capture the weather driven biology of the different species and their interactions, the same system model can be used to analyze grape and the pest species globally where they co-occur under observed and climate change weather. These models have a modular structure, and as such models of additional pest species can be added as required; e.g., the major fungal disease *Botrytis cinerea* [44].

The principal native insect pest of grape in the Palearctic region is the grapevine moth *L. botrana*, and was the focus of our analysis in the Mediterranean Basin in the face of extant weather and of climate warming [13]. The analysis predicts that grape yield and *L. botrana* densities may increase or decrease across the major grape growing countries of the Euro-Mediterranean region (Figure 2). On a finer scale, the analysis predicts that climate warming effects on grape and *L. botrana* may vary widely across countries and within ecological zones within a country (Figures 5 and 6; Tables 1 and 2; see Figure 9 in [13]). Because the grape/*L. botrana* PBDM system is driven by weather, the model may be applied at various levels (e.g., field or regional) and used to develop management strategies. Applications at the field level, however, require development of infrastructure to provide field level estimates of initial conditions for plant, pests and diseases, and site-specific weather data to drive the model.

Pest problems such as *L. botrana* have required chemical inputs to control it (and other pests and diseases), resulting in chemical use that is one of the highest among crops, and that is expected to increase under climate change [27] in a time and place specific manner. The PBDM system could also be used to develop and test alternative control strategies. For example, the grape/*L. botrana* system was used to evaluate the use of pheromone-based control strategies [13,40]. PBDM grounded holistic bioeconomic models and analyses are well suited to address such evolving problems due to various causes in a timely manner; especially in the face of climate change where prior experience may provide little guidance.

Our study on grape is the most recent of a long series of analyses carried out using PBDMs worldwide in systems as diverse as alfalfa, cassava, coffee, grape, olive, mosquitoes, rice, screwworm, and tsetse fly (http://www.casasglobal.org/). This progress was made possible by the identification of core conceptual, semantic, and algorithmic patterns discussed above [13,38–43]. The development of unified plug and play software for PBDM development would empower researchers globally to perform rapid and low-cost holistic bio-economic analyses of eco-social problems of many crop systems.

Acknowledgments: Funding for the modeling/GIS analysis was provided by Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA), Rome, Italy and by the Center for the Analysis of Sustainable Agricultural Systems (CASAS Global), Kensington, California, USA. This research contributes to the knowledge hub titled Modelling European Agriculture with Climate Change for Food Security (MACSUR; www.macsur.eu/) within the Joint Programming Initiative on Agriculture, Food Security and Climate Change (FACCEJPI; www.faccejpi.com/); to the agreement between ENEA and the Italian Ministry of the Environment and Protection of Land and Sea (Convezione tra ENEA e Ministero dell'Ambiente e della Tutela del Territorio e del Mare); and to the project titled Turning climate-related information into added value for traditional MEDiterranean Grape, OLive and Durum wheat food systems (MED-GOLD) that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 776467. An earlier version of this paper was presented at the international conference "Wine sustainability", Pescara, Italy, 1–2 September 2017.

Author Contributions: L.P. and A.P.G. designed and performed the analysis; all authors contributed to analyzing the data; M.N. contributed analysis tools and A.B. contributed economics expertise to the analysis; L.P. wrote the initial draft of the manuscript and all authors contributed to the final version.

Conflicts of Interest: The authors declare no conflict of interest.

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