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CLIMATE CHANGE AND CROP-PEST DYNAMICS IN THE MEDITERRANEAN BASIN

RT/2016/27/ENEA

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ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES,
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L. Ponti, A.P. Gutierrez, M. Iannetta

Riassunto

A causa dei cambiamenti climatici valutare e gestire sistemi coltura-parassita nel Bacino del Mediterraneo sarà più difficile che altrove a livello globale. Il Bacino del Mediterraneo è infatti per molti versi un hot spot in termini di cambiamento globale, poiché in quest'area del pianeta i cambiamenti climatici attesi sono più intensi della media e minacciano una diversità biologica e culturale estremamente ricca ed intrecciata, oltre ad incrementare la vulnerabilità nei confronti delle invasioni biologiche. Di conseguenza per affrontare efficacemente i problemi causati da parassiti in questo hot spot sarà sempre più necessario un approccio olistico, tale da consentire un'analisi dettagliata di quelle complesse e spesso sfuggenti interazioni che sono alla base di ogni decisione sensata a livello di campo. Partendo da oltre trent'anni di progresso scientifico multidisciplinare ispirato a studi pionieristici effettuati presso l'Università della California, il progetto ENEA GlobalChangeBiology in collaborazione con CASAS Global sta sviluppando uno strumento interdisciplinare per descrivere in maniera meccanicistica (ossia descrivere processi mediante un modello), analizzare e gestire problemi agro-ecologici basandosi sul paradigma unificante che tutti gli organismi, esseri umani compresi, acquisiscono e allocano risorse mediante processi analoghi. Si tratta del paradigma delle analogie ecologiche che è intrinsecamente olistico. Recenti analisi sviluppate utilizzando questo paradigma mostrano come lo strumento messo a punto abbia fornito e continuerà a fornire alle agenzie governative la base scientifica necessaria per integrare la resilienza eco-sociale ai cambiamenti climatici in sistemi agricoli presenti nel Bacino del Mediterraneo e altrove.

Parole chiave: cambiamento globale, insetti parassiti delle colture, specie invasive, modelli di ecosistema, modelli demografici con base fisiologica.

Abstract

Climate change will make assessing and managing crop-pest systems in the Mediterranean Basin more difficult than elsewhere on the globe. The Basin is in many ways a hot spot of global change, as higher than average projected climate change threatens an extremely rich and intertwined biological and cultural diversity, and increases its vulnerability to biological invasions. As a consequence, pest problems in this hot spot will require a holistic approach to deconstruct the elusive complex interactions that are the underpinning basis for sound decision making at the field level. Building on 30+ years of multidisciplinary progress inspired by pioneering work at University of California, the ENEA GlobalChangeBiology project in collaboration with CASAS Global is developing an interdisciplinary tool to mechanistically describe (i.e., model), analyze and manage agro-ecological problems based on the unifying paradigm that all organisms including humans acquire and allocate resources by analogous processes – the paradigm of ecological analogies that is holistic by design. Recent analyses using this approach show how the tool provided and will continue to provide governmental agencies with the scientific basis for building eco-social resilience to climate warming into agricultural systems across the Mediterranean Basin and elsewhere.

Keywords: *global change, insect pests, invasive species, ecosystem modeling, physiologically based demographic models*

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The Mediterranean Basin as a hot spot of global change

Climate change is expected to increase temperatures globally and alter patterns of rainfall [1] and other derivative factors that can alter species distribution, abundance and impact in natural, agricultural and medical/veterinary vector/disease systems in unknown ways [2]. Plant and arthropod species are heterothermic, and hence in the short run their local phenology, dynamics and abundance are largely determined by weather and interacting species (e.g., [3,4]), with climate (i.e., long run weather) and interacting species determining their potential geographic range. The effects of climate change on insect pest populations can be direct through impacts on their physiology and behavior, or indirect through biotic interactions with other species [2,5]. For crop pests, climate effects may be mediated by the host plant (bottom-up effects from the lower trophic level), by natural enemies (top-down effects from the higher trophic level), or by species having a degree of niche overlap (competition effects at the same trophic level) [2,6,7].

The physiology and behavior of pest insects and interacting crop plants is influenced by climate change, and even modest warming can dramatically affect the energy budget of all stages and diapause specifically [8] via increased respiration and decreases in growth, reproduction and survival [2], and hence impact the species' geographic distributions and relative abundance. Projected climate changes could modify extant relationships and interactions in food chains and webs (i.e., crop-pest-natural enemy interactions) (e.g., [9]) and effects on any trophic level may cascade to lower and higher levels in food chains and webs affecting system regulation, stability and resilience (*sensu* [6]). This is of general significance because despite crop protection, worldwide crop losses to animal pests (mainly insects) in major crops range 5 to 22%, with potential losses without crop protection ranging 7 to 41% [10]. How climate change will affect these losses is of considerable concern. The question of how best to study the effects of climate change on complex biological systems (*sensu* [11]) such as crop-pest systems across spatial and temporal scales is only now being resolved [9] (see below).

The Mediterranean Basin is a global change hot spot for a number of reasons, including expected higher than average climate change in the region, the extremely rich biodiversity it harbors, and its high vulnerability to biological invasions [12]. The region's status as a climate change hot spot was assessed by robust analysis [13] and from a consensus of climate projections [14,15] across forcing scenarios, future time periods, and a range of global and regional climate models [16,17]. As a result, the Mediterranean Basin is at increased risk of exotic species invasions (e.g., pests) that is exacerbated by a high density of shipping ports of entry and airports with voluminous incoming traffic from regions with similar climates that have rendered geographical barriers to species spread mostly ineffective [18,19]. This combination of factors is projected to increase invasive species establishment [18] as illustrated by the recent arrival and establishment of several insect species [20] including serious agricultural pests (e.g., the tomato leafminer *Tuta absoluta*, see [21]).

Climate change brings additional complexity to crop-pest systems

Complexity is intrinsically high in agricultural systems, and remains the main barrier to their study and management, with climate change and invasive species being additional factors that complicate management issues further [2,22]. Robinet and Roques [20] point out that understanding and managing insects under climate change is vexing as contradictory results likely arise in field studies, large-scale experiments are challenging, and driving factors include interactions with other species such as host plants, competitors and natural enemies that each respond differently to climate change. This latter point is illustrated in Fig. 1 which shows that control by a natural enemy might be compromised by a 2°C increase in temperature that decreases its growth rates relative to that of the pest herbivore. To fully understand the consequences of such changes requires a holistic analysis of the system, but while often advocated [23–26] this 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 (see [27]).

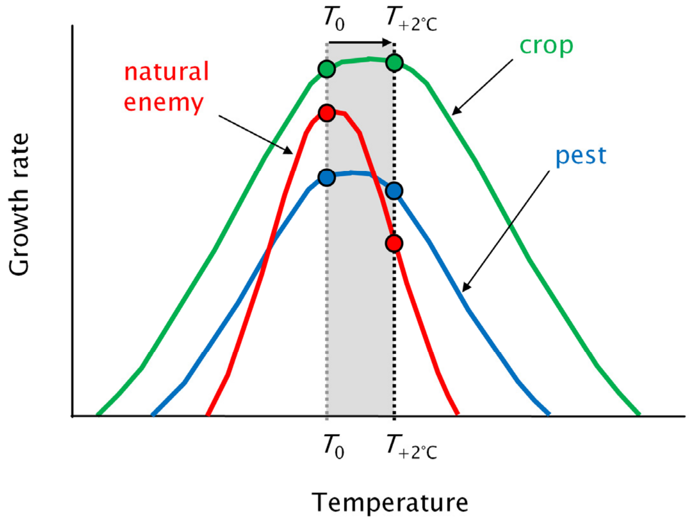

Figure 1. Plots of the growth rates on temperature of a crop, pest and natural enemy to intuitively illustrate how an increase in average temperature from T_0 to $T_{+2°C}$ may affect the physiological basis of trophic interactions. With temperature warming, biological control of the pest may decrease due to the narrower temperature tolerance of the natural enemy compared to the pest. Source: [2].

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 (paradigm of ecological analogies; see [28] and http://www.casasglobal.org/). This approach was implemented in Europe by the project GlobalChangeBiology [29] that framed a collaboration between ENEA and the University of California at Berkeley that continues through the nonprofit scientific consortium CASAS Global [30].

The following section briefly reviews recent and prospective holistic analyses of climate change effects on crop-pest systems in the Mediterranean Basin performed under the joint auspices of GlobalChangeBiology project and CASAS Global. The approach involves using physiologically based demographic modeling (PBDM) of crop-pest-natural enemy interactions in the context of a geographic information system (GIS) (see e.g., [27,28,31]). A major goal is to link the PBDM/GIS technology with increasingly available biophysical datasets from global modeling and satellite observations, and use them to bridge the gap between bottom-up (primarily physiological and population dynamics) and top-down (climatological) GIS approaches for assessing on ground ecosystem level problems such as agricultural pests [32].

PBDM example of some crop-pest systems in the Mediterranean Basin

The olive/olive fruit fly (*Bactrocera oleae*) system. Olive is an ancient, ubiquitous crop of considerable ecological and socio-economic importance in the Basin, and olive fly is its major obligate pest. Climate change will impact the interactions of olive and olive fruit, and alter as a consequence the economics of olive culture across the Basin [33]. The effects of climate warming on olive and olive fly dynamics in the Mediterranean Basin [22] were assessed using a PBDM of the crop-pest system [34] as driven by daily weather data from the ERA40 reanalysis of meteorological observations for years 1958-2000 [35] downscaled to a 30km grid using the PROTHEUS regional climate model [36], and a climate warming scenario obtained from the same data by increasing daily temperatures +2°C. Olive fly abundance in the absence of control is influenced by olive fruit phenology and abundance, and temperature. Under present climate, mild coastal areas across the Basin show highest favorability for olive fly, whereas lower favorability is found either at higher inland elevations where winter temperatures are unfavorable (e.g. areas of Europe) or in areas of Morocco and the Middle East where high summer temperatures approach the upper thermal limits of the fly, increase its mortality, decrease reproduction and induce reproductive dormancy (Fig. 2a). With +2°C climate warming, olive fly abundance decreases in many of the areas that show highest favorability under present climate, and increases in higher altitude inland areas due to warmer temperatures (Fig. 2b). Fruit infestation levels by the fly may decline in currently hot areas as a consequence of warming, whereas levels may increase in milder inland areas, especially at high altitudes that become more favorable for both the plant (not shown) and fly (Fig. 2c). Changes in olive yield and fly abundance can increase or decrease, affecting fruit attack rates and fruit quality, and control costs. Combining all of these factors in a bioeconomic analysis enabled estimations of the economic impact of climate change on olive [22,33]. The same PBDM of the crop-pest system [34] was used to assess eco-social resilience to climate warming in olive systems across the Mediterranean Basin [37], and was extended to include a mechanistic water balance model to explore the effects of water availability on crop-pest interactions [38].

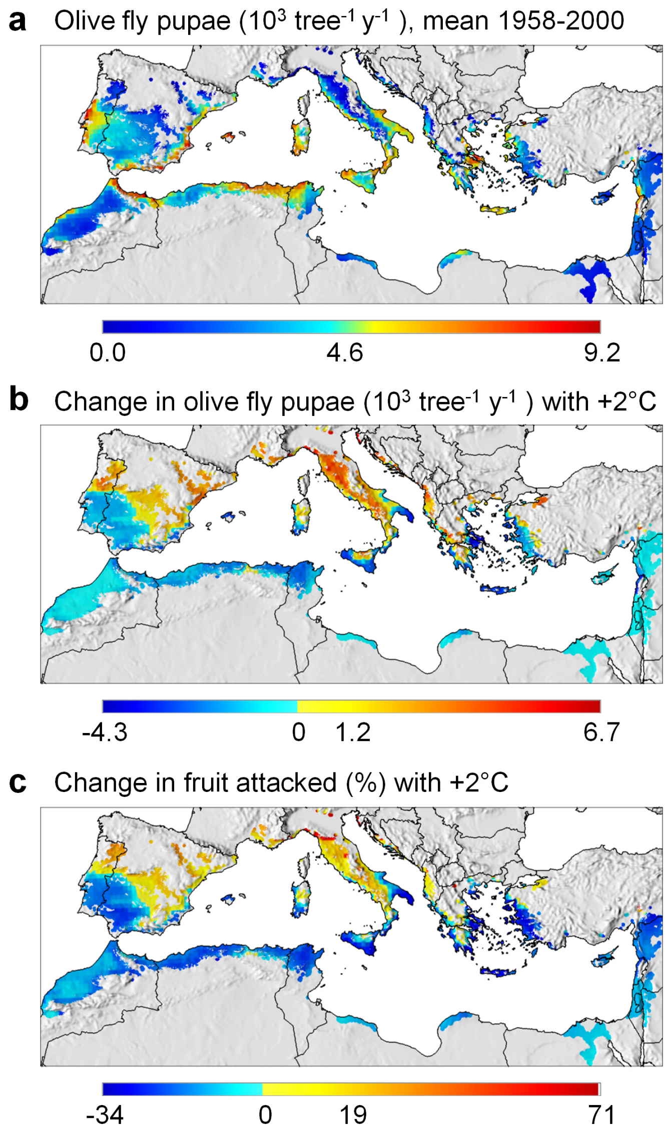

Figure 2. Simulated dynamics of olive fly (*Bactrocera oleae*) as influenced by bottom-up effects of olive and driven by present climate (years 1958-2000) or in a +2°C climate warming scenario: cumulative number of pupae (10^3 tree^{-1} year^{-1}) under present climate (a), and change of this number with +2°C climate warming (b); effects of climate warming on percent olive fruit attacked by the fly (c). Source: modified from [22].

The olive/insect vector/*Xylella fastidiosa* system. Insects can also cause indirect damage to crops, as is the case when they act as vectors of pathogens. The bacterial pathogen *Xylella fastidiosa* is simply one of the growing number of exotic invasive species that challenge the Mediterranean Basin [39,40]. The bacterium is widespread in the Americas, has been on Europe's quarantine list since 1981 [41], and was detected in olive in the Mediterranean Basin in the Italian region of Apulia in 2013 [42]. *Xylella* is a threat of utmost importance for organic and sustainable olive culture with most of the management focus currently on chemical (insecticides) and mechanical (soil tillage) control of vectors and alternate host plants. This disease is currently the center of a controversial eradication program involving destruction of infected olive trees, this despite the fact that numerous plant species host the disease and several vectors transmit it. *Xylella fastidiosa* is limited to the xylem system of plants from where it is mechanically transmitted by xylem-sap feeding insects [43]. In California, it causes Pierce's disease in grape and scorch-like diseases in other plants such as citrus and olive. Virtually all insects that feed on the xylem sap of these plants are potential vectors of *X. fastidiosa*, and there are tens of candidate vectors in the Mediterranean region [44] that must be evaluated for vector competency. For example, one way of excluding vectors are the laboratory trials where a dominant xylem-sap feeding insect species in olive orchards, the meadow spittlebug *Philaenus spumarius*, failed to transmit *Xylella* to olive [45]. The bacteria is found in a very broad range of plants including cultivated and wild species, and some plants may carry the bacteria without showing disease symptoms [46,47]. This makes the olive/*Xylella* system extremely complex and difficult to assess and manage, particularly in the Mediterranean region where olive plays a vital role in maintaining the rich natural and agricultural biodiversity [33,37].

A holistic analysis based on the ecological requirements for growth, survival and reproduction of olive, *X. fastidiosa*, its identified insect vectors and their natural enemies is required to determine the potential geographic distribution, abundance, and impact of this disease. These methods can be used to develop sustainable management strategies and tactics to address the disease on a regional basis. The PBDM approach provides a basis for making such assessments (see [28]), and a good example is the PBDM model developed for grape and the invasive polyphagous glassy-winged sharpshooter (GWSS; *Homalodisca vitripennis*) that is a vector of *X. fastidiosa* that causes Pierce's disease in grape in California, and for two egg parasitoids (*Gonatocerus ashmeadi* and *G. triguttatus*) introduced for biological control of GWSS [48]. In California, *Xylella* is endemic whereas the insect vector extended its range from other regions of the USA and Mexico, while in contrast, *Xylella* is exotic to olive in Italy. The model predicts that the potential range of *X. fastidiosa* in California is considerably less than that of GWSS, but with biological control of GWSS, the potential range of the pathogen was reduced still further to the desert regions of southern California. PBDM analysis was able to separate and quantify the biotic and abiotic factors that affect the distribution and abundance of *X. fastidiosa* in grape at the geographic scale of California, and similar analyses are expected to achieve comparable results for the pathogen in olive at the scale of the Mediterranean Basin. Recent projections of the potential geographic distribution of *Xylella*, with no consideration of vector biology, were obtained using the correlative ecological niche modeling tool Maxent [49], and show that the potential distribution of the pathogen roughly coincides with the currently infected area of Salento (Fig. 3) where an ongoing eradication program is in progress (see Fig. 2 in [50] vs. the official infection map [51]). The results suggest that more effort should be put into screening vectors and developing the data on their developmental biology, and in preventing invasion of areas at high risk of establishment in Italy [50] and the rest of the Mediterranean Basin [52].

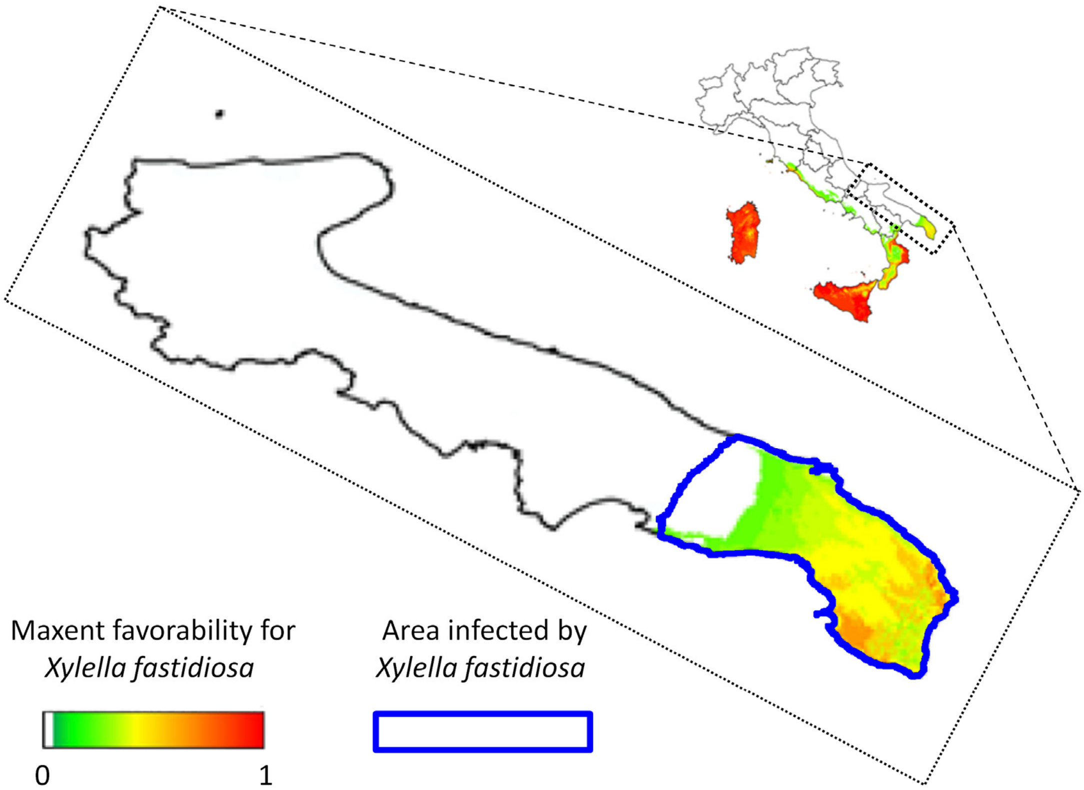

Figure 3. Geographic distribution of favorability for *Xylella fastidiosa* in Italy estimated using the Maxent model from climatic correlates of occurrence of the species [50], with an expanded view of the Apulia region including the current area of *X. fastidiosa* infection [51] obtained and processed from the web server of Apulia Phytosanitary Observatory using GRASS GIS [53]. Source: modified from [51] using data from [53].

The citrus/Asian citrus psyllid (*Diaphorina citri*)/*Candidatus* Liberibacter asiaticus system. Asian citrus psyllid is considered the most important pest of citrus worldwide [54] because in addition to being a destructive invasive species causing direct feeding damage to species of citrus and other species in 25 genera of Rutaceae, it is a vector of the phloem-limited bacterium *Candidatus* Liberibacter asiaticus and other species of the genus (*Candidatus* L. africanus and *Candidatus* L. americanus) that cause greening disease (huanglongbing, HLB) in citrus (see [55,56]). HLB is one of the most serious diseases of citrus in many countries across Asia, Africa, and North and South America [57] (Fig. 4), and is considered a threat to the survival of the citrus industry in the Mediterranean basin where the disease is not yet present [58,59] (see Fig. 4). The presence of African citrus psyllid, *Trioza erytrae*, in the Canary and Madeira islands (Fig. 4) threatens the western Mediterranean basin, while Asian citrus psyllid with *Candidatus* L. asiaticus and *Candidatus* L. africanus are present in Iran and the Arabian Peninsula and threaten the eastern Mediterranean region [58].

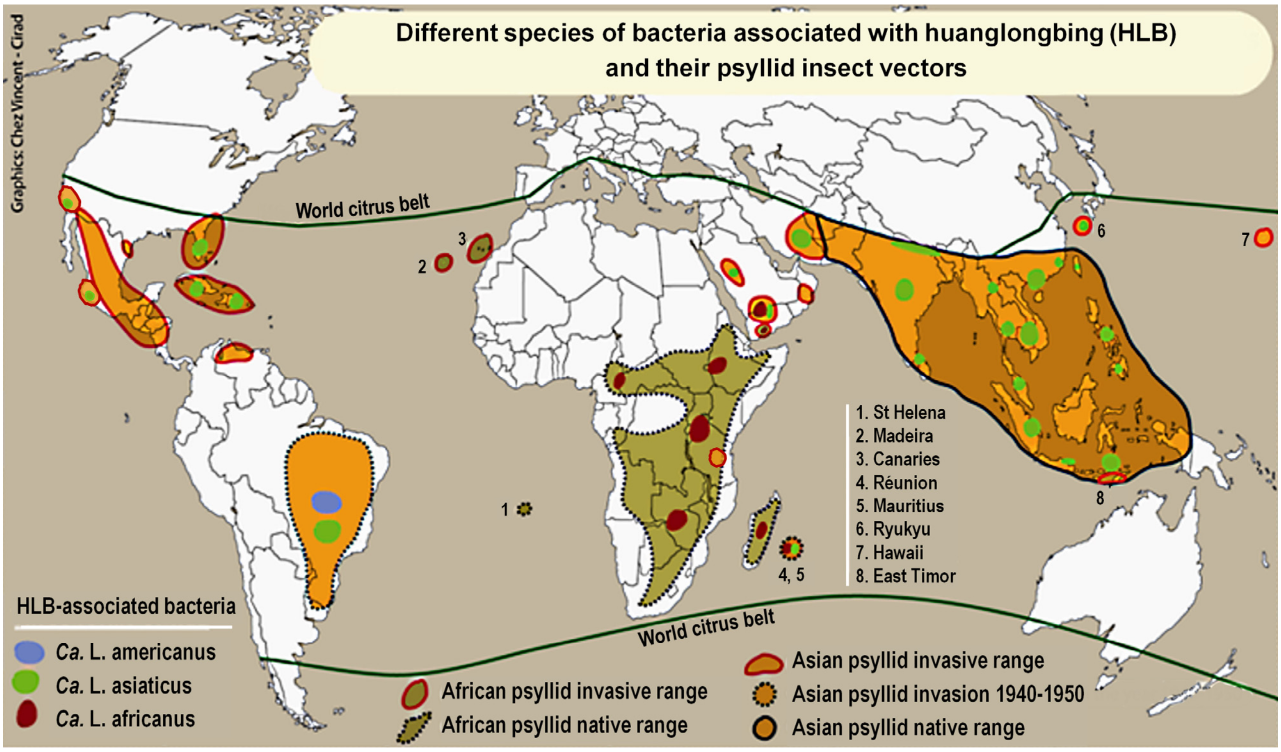

Figure 4. Map showing the global distribution of the different pathogens and vectors associated with huanglongbing (HLB) citrus disease. Source: modified and updated from [59] including first records of Asian citrus psyllid in California, USA and in Tanzania in 2014 (first record for Africa) [60]) as well as the first report of the HLB disease in California in 2012 [61] and additional record for Mexico [62].

A PBDM of the citrus/Asian citrus psyllid/*Candidatus* L. asiaticus system was developed to summarize the available data in the literature, and used to assess prospectively the geographic distribution and relative yield of citrus, the relative densities of the psyllid, its parasitoid (*Tamarixia radiata*, currently used in classical biological control programs, see e.g. [63]), and the potential severity of HLB in North America and the Mediterranean Basin [55]. The model captures the potential citrus growing region in the Mediterranean Basin in the upper half of the distribution of yield quite well (Fig.5a). The prospective distribution of favorability for citrus greening disease is greatest in North Africa, southern Spain and the Middle East (Fig. 5b), with the countries in southern Europe, including Turkey being intermediate in favorability. These results are consistent with recent predictions made using a Maxent model [62] based on climatic correlates of occurrence for both organisms. However, unlike the PBDM [55], the Maxent model provided little biological insights useful for management of the disease/vector system, whereas the PBDM modeled the mechanistic linkages and environmental requirements of the pathogen, the plant, the vector and its parasitoid (see Fig. 2e in [55]; see also [27,64]). The PBDM predicts prospectively that the distribution of Asian citrus psyllid is more restricted (Fig. 5c) than that of the disease, and estimated the prospective joint distribution using the product of normalized psyllid days (i.e., from Fig. 5c) and the disease index (DI x CPI, Fig. 5d). Prospectively, the joint favorability suggests the eastern Mediterranean region is at greatest risk with only Sicily and small areas of southern Spain included in the upper half of the range [55].

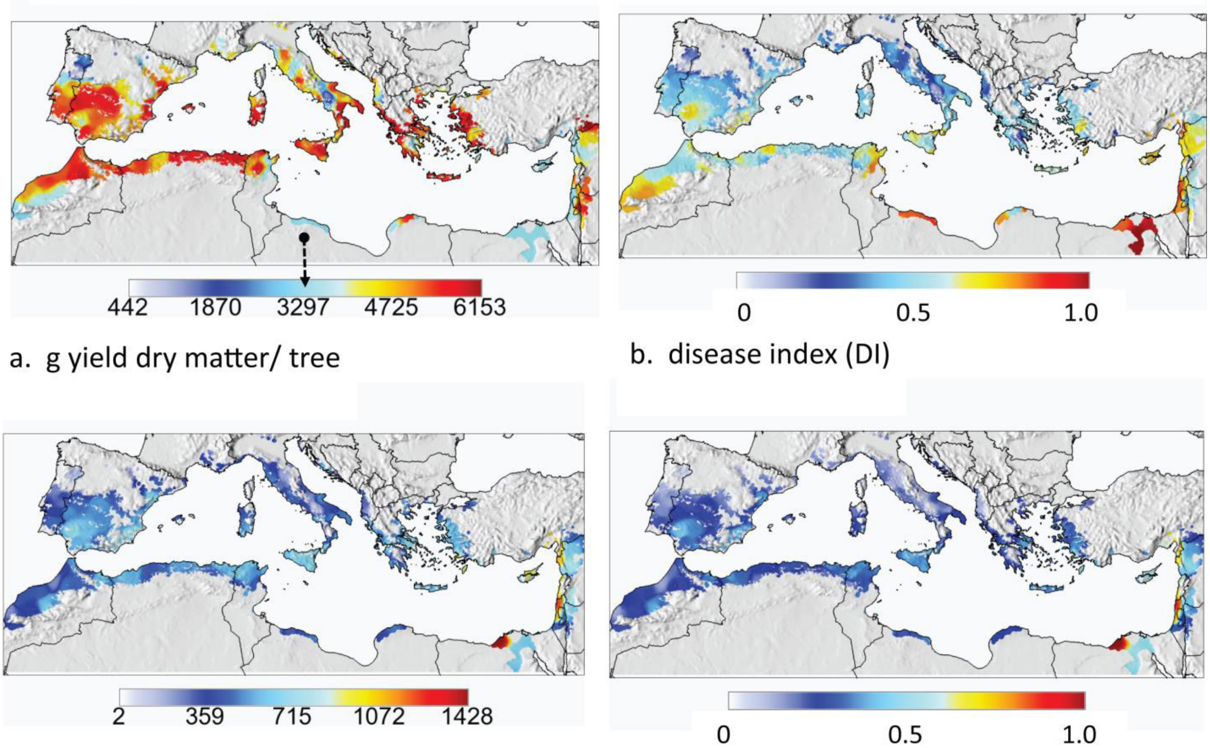

Figure 5. The simulated average dynamics of the citrus/citrus psyllid/greening disease system across the Mediterranean Basin below 1000m: (a) simulated yield in g dry matter per tree, (b) the normalized cumulative growth rate of greening disease (DI), (c) psyllid nymph days per tree given the effects of coccinellid predation and *Tamarixia radiata* parasitism, and (d) the product of DI and normalized psyllid density (i.e., CPI) computed from data used in Fig. 5c. Source: [55].

Other PBDM assessments

Other recent prospective PBDM assessments of crop-pest systems relevant to the Mediterranean Basin include: fruit tree hosts/Mediterranean fruit fly (*Ceratitis capitata*) [65] (see also [66]), grapevine/European grapevine moth (*Lobesia botrana*) [67], tomato/tomato leaf miner (*Tuta absoluta*) [12], alfalfa/interacting pests [68], cotton/pink bollworm (*Pectinophora gossypiella*) [27] (see [69] for eco-social consequences), and spotted wing Drosophila (*Drosophila suzukii*). Only in the case of *D. suzukii* was the host plant not modeled as it attacks more than 80 hosts and as some are widely available for *D. suzukii* reproduction when temperatures are in the favorable range [70,71].

Conclusions

The Mediterranean Basin is a global change hot spot because in addition to being a repository of bio-cultural diversity of global relevance [37], it is also being particularly challenged by climate change and biological invasions [12]. This makes assessing and managing crop-pest dynamics in the region extremely complex and difficult relative to other areas globally. ENEA's GlobalGhangeBiology project in collaboration with CASAS Global has begun to tackle panoply of global change multifaceted pest problems using physiologically-based weather-driven geospatial modeling tools that enable mechanistic description of their biology (i.e., modeling), analysis of their dynamics and impact, and the development of environmentally sound management options. The success story for olive and olive fly [72] is a template for analyses that provide governmental agencies with the scientific basis for developing sound policy required to adjust to global change including climate change in Europe and elsewhere [73].

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