

Predicted effect of climate change on the invasibility and distribution of the Western corn root-worm

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- Abstract**
- 1 Insect pests, biological invasions and climate change are considered to represent major threats to biodiversity, ecosystem functioning, agriculture and forestry. Deriving hypothesis of contemporary and/or future potential distributions of insect pests and invasive species is becoming an important tool for predicting the spatial structure of potential threats.
 - 2 The western corn rootworm (WCR) *Diabrotica virgifera virgifera* LeConte is a pest of maize in North America that has invaded Europe in recent years, resulting in economic costs in terms of maize yields in both continents. The present study aimed to estimate the dynamics of potential areas of invasion by the WCR under a climate change scenario in the Northern Hemisphere. The areas at risk under this scenario were assessed by comparing, using complementary approaches, the spatial projections of current and future areas of climatic favourability of the WCR. Spatial hypothesis were generated with respect to the presence records in the native range of the WCR and physiological thresholds from previous empirical studies.
 - 3 We used a previously developed protocol specifically designed to estimate the climatic favourability of the WCR. We selected the most biologically relevant climatic predictors and then used multidimensional envelope (MDE) and Mahalanobis distances (MD) approaches to derive potential distributions for current and future climatic conditions.
 - 4 The results obtained showed a northward advancement of the upper physiological limit as a result of climate change, which might increase the strength of outbreaks at higher latitudes. In addition, both MDE and MD outputs predict the stability of climatic favourability for the WCR in the core of the already invaded area in Europe, which suggests that this zone would continue to experience damage from this pest in Europe.

Keywords BIOCLIM, biological invasion, climate change, climatic favourability, *Diabrotica virgifera virgifera*, insect pest, Mahalanobis distances.

Introduction

In recent decades, there has been an increase in research on pest prevention and eradication, as well as on the impacts of biological invasions and climate change on natural resources. Insect pests have had some of the greatest ecologically and economically adverse impacts on agriculture and forestry (Vidal *et al.*, 2005). Biological invasions and climate change also

can affect human health, ecosystem functioning and global biodiversity (Gewin, 2005; Vidal *et al.*, 2005; Borges *et al.*, 2006; Millennium Ecosystem Assessment, 2006; Tatem *et al.*, 2006). Techniques developed aiming to detect areas of climatic favourability, such as those used in species distribution models, are considered to represent useful approaches for preventing invasions (Thuiller *et al.*, 2005; Tatem *et al.*, 2006; López-Darias *et al.*, 2008). In the same way, these types of predictive models have been used recurrently to detect range shifts under climate change scenarios (Thomas *et al.*, 2004) and species turnover (Aragón *et al.*, 2010a), and empirical studies

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have shown that climate change has already caused range shifts in many species (Parmesan & Yohe, 2003; Battisti *et al.*, 2005).

A common challenge for studies on the prediction of the impacts of pests, biological invasions and climatic change is that they are inherently associated with different sources of uncertainty. When it is expected that all of these issues are acting jointly in additive or synergistic ways in a given species, the challenge is even more pronounced. The case of the western corn rootworm (WCR) *Diabrotica virgifera virgifera* LeConte is a paradigmatic example because it is an insect pest of maize in North America that has recently invaded Central Europe through multiple independent invasions (Ciosi *et al.*, 2008; European and Mediterranean Plant Protection Organization, <http://www.eppo.org>). This subspecies had received increasing attention in recent years because of its aggressive invasive nature and adaptability to various management actions (Meinke *et al.*, 2009; Spencer *et al.*, 2009) as well as its potential economic impact in North America and Europe (Dillen *et al.*, 2010a, b; Dun *et al.*, 2010; Wessler & Fall, 2010). Considering that climate is one of the most important environmental factors affecting, through physiological constraints, the phenology, demography and colonization success of insect species (Parmesan & Yohe, 2003; Battisti *et al.*, 2005; Chown & Terblanche, 2007), we previously estimated the climatically favourable zones for the WCR in the Northern Hemisphere (Aragón *et al.*, 2010b). That previous study highlighted the usefulness of combining distribution models (such as multidimensional envelopes and Mahalanobis distances) with physiological spatial projections (using empirical physiological data), aiming to evaluate models and/or infer causality. In the present study, we projected these models with respect to a future climate scenario to estimate the potential dynamics of invasion risk areas through time (i.e. combining current and future model outputs).

Materials and methods

Data sources

The recorded presence of the WCR in its native region (mainly northern Mexico and U.S.A.) was georeferenced from Krysan and Smith (1987) at 5-km resolution ($n = 1029$). In addition, the current area of influence in the invaded Europe (as of 2008) was digitized from Edward and Kiss (2008) to test whether climatic stability regarding the used scenarios may partially explain the most important outbreaks in Europe. Environmental variables at the same resolution were generated by the WorldClim source for the current (Hijmans *et al.*, 2005) and future (Govindasamy *et al.*, 2003) scenarios. The climate change scenario is a Community Climate Model scenario (CCM3) for the year 2100. This is a 'business as usual' prediction assuming a duplication of greenhouse gas emissions that is approximately equivalent to the average of the current scenario families proposed by The Intergovernmental Panel on Climate Change (Dai *et al.*, 2001; Seavy *et al.*, 2008). This scenario originates from high resolution simulations of global warming with an atmospheric general circulation model (Govindasamy *et al.*, 2003).

Mapping climatic favourability and physiological thresholds for current and future scenarios

To generate maps combining current and future estimations of invasion risk areas for the Northern Hemisphere, we used a previously developed protocol for estimating current climatic favourability (Aragón *et al.*, 2010b). In brief, we used complementary techniques to assess the biological relevance of predictors and obtain areas of climatic favourability. For the case of invasive species, the main aim should be always to characterize potential areas of invasion. Therefore, we used presence-only methods because it has been argued that their outputs are more related to the potential distribution of the organism whereas presence-absence or presence-pseudoabsence data are generally more appropriate to represent the realized distribution (Jiménez-Valverde *et al.*, 2008). The biological relevance of climatic variables was first assessed by accounting for two main components of the Grinnellian niche (marginality and specialization) using ecological niche factor analysis (Hirzel *et al.*, 2002; Calenge & Basille, 2008). Then, the most relevant predictors were used to obtain either multidimensional envelope modelling procedure (MDE; Busby, 1991) or Mahalanobis distances (MD; Farber & Kadmon, 2003) with respect to the native range of the WCR. MDE outputs correspond to the grid cells that lay inside the environmental range of the WCR (i.e. within the maximum and minimum for the variables considered). MD outputs are distances from each grid cell to the mean of the hypervolume of the selected variables, with reference to the presence records of the WCR. Model outputs and predictor relevance were independently assessed in the currently invaded region of Europe and through the spatial projection of proposed physiological temperature thresholds for key fitness components from previous empirical studies. These thresholds were set for oviposition (optimal at ≥ 16 °C; EPPO report, PRA document 97/6445, <http://www.eppo.org>), hatching (reduced to 0 by 1 week at -15 °C; Chiang, 1973) and immature development (detrimental ≥ 30 °C; Jackson & Elliott, 1988). Next, we presented global zones of climatic favourability and invasion risk for the WCR. Model evaluations revealed that our methodology was efficient for predicting future potential invasions, spreads and secondary contact zones of insect pests (for a more detailed description on the methodology, see Aragón *et al.*, 2010b). This procedure revealed the most relevant predictors as: the mean temperatures of the wettest and warmest quarters, and the precipitation of the warmest quarter, minimum temperature of the coldest month, temperature annual range, maximum temperature of the warmest month and isothermality. Therefore, in the present study, these variables were also used to project climatic favourability areas using the future climatic scenario.

We generated risk categorical maps of climatic favourability from the projected physiological thresholds and MDE and MD outputs. Thus, for each map, we obtained different categories of climatic favourability for the WCR: (i) climatic favourability only in the current conditions; (ii) only in the future conditions; and (iii) in both time periods (climate stability). Because the MD output is a continuous variable, we obtained a threshold value for discriminating between lower and higher climate favourability and then applied it over the Northern Hemisphere. The threshold proposed from the histogram of WCR presence in America along the corresponding MD was set at the first

distance at which only 1% of presences were associated. This threshold encompassed 93% of all presences (Aragón *et al.*, 2010b).

Results and Discussion

Using a previously developed protocol to estimate potential areas of invasion for the WCR (Aragón *et al.*, 2010b), we extrapolated our models to a future scenario for the year 2100 to generate combined maps of current and future estimations of climatic favourability. We used the available future scenario that provides the same variables as those estimated to be most relevant for model building with respect to current conditions. We present three types of outputs in the Northern Hemisphere for the current and future conditions: (i) geographical projections of temperature physiological thresholds based on key fitness components, which were obtained from empirical studies; (ii) MDE outputs; and (iii) MD outputs categorized as of lower or higher climatic favourability.

Change in the spatial patterns of physiological projections

Our physiological projections in the Northern Hemisphere revealed that there is a northward shift of the temperature thresholds considered under the future scenario used (Fig. 1a). This is of special relevance because those potential invasions that might occur in the current physiological limit may change in terms of colonization success. Sink populations that might be easier to eradicate (i.e. because they are in the border of their suitable conditions) would shift to source populations as the

physiological limits move northward. This is in agreement with a previous study where the physiological thresholds of the WCR were projected to the future in the U.S.A. through predictors such as growing degree days (Diffenbaugh *et al.*, 2008). This same previous study also predicted an appreciable increase in suitable conditions in the North of U.S.A. By contrast, although a qualitative comparison with this previous study is feasible, more detailed quantitative comparisons are less evident because both studies used different climatic predictors. In our case, we were restricted only to the current and future climatic predictors available for the entire Northern Hemisphere. Therefore, it is important to note that global data on other predictors such as growing degree days might reveal more subtle patterns.

Agreement between projections

The MDE model outputs were also consistent with the direction pattern observed for the physiological projections (Fig. 1b). In this case, the MDE model under the future scenario predicts the appearance of new climatically suitable areas in the North of America, Europe and China. The predicted areas of current and future climatic favourability for the MDE were smaller than those projected with the physiological thresholds. This is not an unexpected result because distribution models, such as MDE, should retain more information than our projections based on the partial information regarding physiology. In terms of values relative to the total suitable area in both time periods, these predicted future expansions (mainly northward) were 12% for MDE and 18% for physiologically based projections.

Interestingly, both MDE and MD models coincide when predicting a permanent climatic favourability (current and future

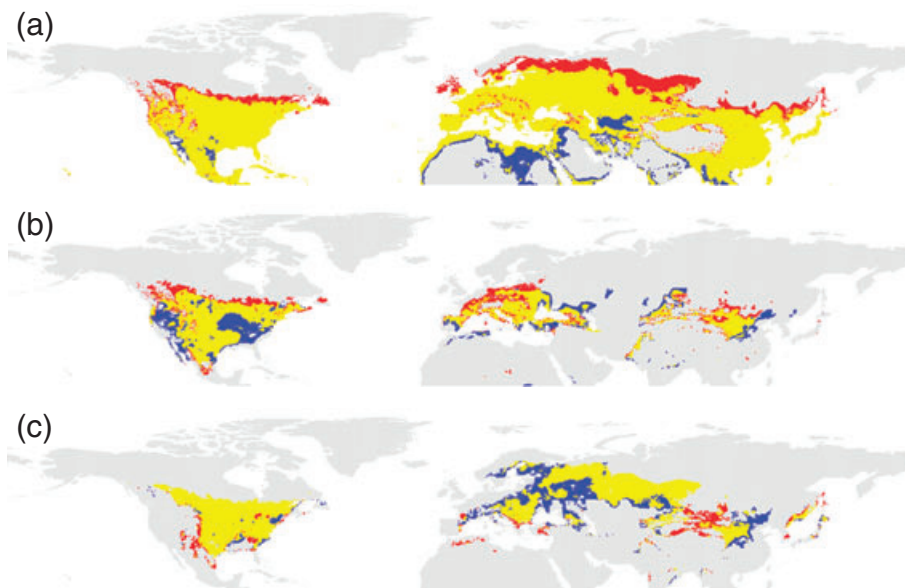


Figure 1 Northern Hemisphere maps showing the estimated current and future climatic ranges of *Diabrotica virgifera virgifera*. Projections were based on the WorldClim scenario for the current conditions (1950–2000) and on a WorldClim CCM3 scenario for future conditions (2100). Areas of climatic favourability are labelled in blue for current conditions and red for future conditions, and the concordance between both periods is shown in yellow. Climatic favourability was estimated with respect to the most biologically relevant predictors: (a) geographical projections of the temperature physiological thresholds based on key fitness components; (b) using the multidimensional envelope technique; and (c) using Mahalanobis distances within the independently estimated partial physiological range (for additional methodological details, see Aragón *et al.*, 2010b).

conditions) within most of the area encompassed by the current area of invasion in Europe (yellow area within the black contour shown in Fig. 2). These zones of stability in the Northern Hemisphere represent 59% for MDE and 69% for MD with respect to the total suitable areas in both time periods. Considering only Europe, these values were 60% and 51% for MDE and MD, respectively. Although climatic fluctuations in a given area are often considered a risk for many species, the stability of climatic favourability for invasive species should be considered as a situation of concern. In an area where the invasion has already occurred, the stability of climatic favourability may be even more risky than in new suitable areas where the species had not yet arrived. Accordingly, the area invaded in the Italian–Hungarian–Serbian core, which is currently one of the most problematic zones in Europe in terms of economic costs (Dillen *et al.*, 2010a, b; Wessler & Fall, 2010), will also be more difficult to eradicate. Another important question arising from this pattern is whether the strongest outbreaks relative to other less aggressive invasions have evolved because of a previous stability of climatic favourability subsequent to the first invasions in 1992. The present study cannot answer this question, however, because we only contrasted current and future conditions, and not those of the recent past. Thus, this conjecture would hold validity if previous stability in climatic favourability (subsequent to 1992) is correlated with the stability of future climatic favourability in the zone.

Finally, both models also coincide in predicting stability of climatic favourability in the North of China (Fig. 1), and also to some extent the appearance of new suitable areas toward the North in Mongolia. These patterns might represent a real risk because the growing economy of China and an associated increase in air transport, which is the dispersal vector of the WCR for transcontinental invasions (Ciosi *et al.*, 2008), is both causing and accelerating biological invasions (Ding *et al.*, 2008).

Variability of model outputs

The most apparent discrepancy between the outputs of MDE and MD models is from Finland to Western Russia and Northern Kazakhstan. Whereas MDE outputs do not predict climatic favourability in these zones (grey in Fig. 1b), the MD outputs predict large areas of stability in climatic favourability (yellow in Fig. 1c). In this case, to reduce uncertainty with respect to maize plantings, as the main host of the WCR, we can only refer to the information on observed contemporary maize cultivation, as well as to the comparison between the current and future potential distribution of maize suitability: currently, the main maize areas are not located in this zone (Monfreda *et al.*, 2008; <http://www.geog.mcgill.ca/~nramankutty/index.html>). By contrast, estimations of the potential maize suitability performed by the Food and Agriculture Organization of the United Nations and the International Institute for Applied Systems Analysis reveals a northward increase in the area suitable for maize in Western Russia. These estimations assumed rain-fed intermediate inputs for both current climate and a future increase of

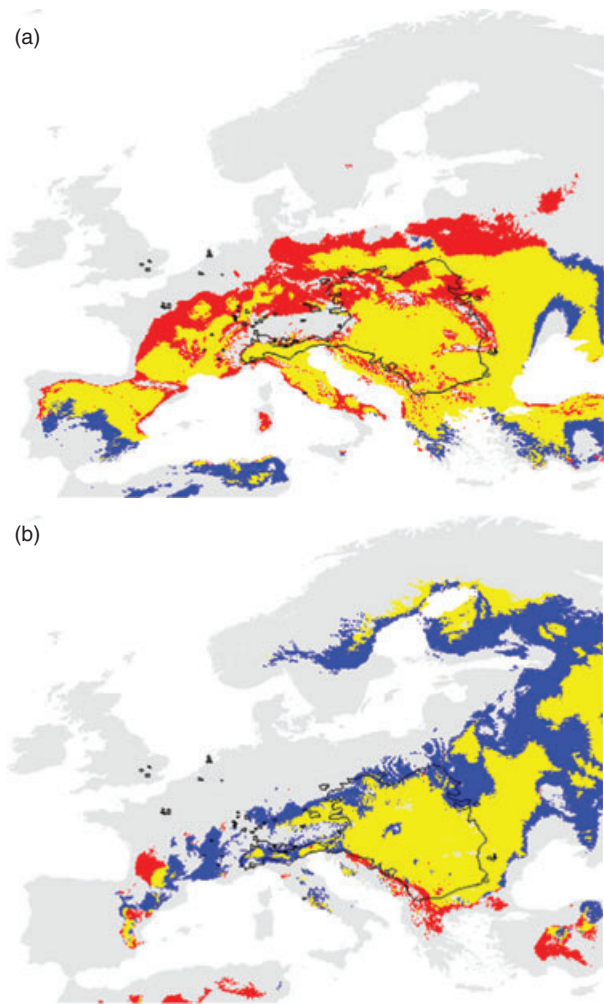


Figure 2 Map of Europe showing the estimated current and future climatic ranges and the current area of invasion of *Diabrotica virgifera virgifera*. Projections were based on the WorldClim scenario for the current conditions (1950–2000) and on a WorldClim CCM3 scenario for future conditions (2100). Areas of climatic favourability are labelled in blue for current conditions and red for future conditions, and the concordance between both periods is shown in yellow. Climatic favourability was estimated with respect to the most biologically relevant predictors: (a) using the multidimensional envelope technique and (b) using Mahalanobis distances (for additional methodological details, see Aragón *et al.*, 2010b). The black contour represents the current area of invasion observed in 2008.

2 °C (<http://www.fao.org/geonetwork/srv/en/main.home>). The suitability of areas for maize cultivation also depends on climatic conditions (Payero *et al.*, 2006) and subsequently on climatic change, and it is known that the uses of cropland areas are dynamic (Foley *et al.*, 2005).

In conclusion, despite the widely recognized uncertainties and limitations associated with species distribution models and climate change scenarios (Govindasamy *et al.*, 2003; Araújo *et al.*, 2005; Jiménez-Valverde *et al.*, 2008), the results obtained in the present study give some insights on the potential future trends of colonizations by the WCR; specifically, a northward movement of the physiological optimal for the WCR in the

Northern Hemisphere. The results also allow us to predict, based on a stability of favourability, some of the colonization events in the area already invaded in Europe that may be more problematic.

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