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Potential distributional changes of invasive crop pest species associated with global climate change

Yingwei Yan [a], Yi-Chen Wang [a], Chen-Chieh Feng [a, *], Peng-Hui Maffee Wan [b], Klarissa Ting-Ting Chang [b]

[a] Department of Geography, 1 Arts Link, National University of Singapore, Singapore, 117570, Singapore
[b] Department of Information Systems, 13 Computing Drive, National University of Singapore, Singapore, 117417, Singapore

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ABSTRACT

This study investigated the potential global distributional shifts of poikilothermic invasive crop pest species associated with climate change, aiming to understand if their overall global distributions will expand or contract, and how the species distributions will vary across different regions. An ecological niche modelling analysis was conducted for 76 species. The potential distributional changes of the species in 2050 and 2070 were scrutinized for two climate change scenarios, which were further examined across different temperature and precipitation ranges. Results showed that averages of the mean probabilities of presence of the 76 crop pest species were predicted to increase. Higher species turnovers were predicted mostly to occur in areas with increasing predicted species richness. Lower species turnovers, however, were predicted mostly to occur in areas with decreasing predicted species richness. Species richness increases were predicted to occur more often in currently lower temperature (annual mean temperature approximately < 21 °C) or lower precipitation (annual precipitation approximately < 1100 mm) regions. Areas with the current annual mean temperatures at around 27 °C and 7.5 °C, respectively, were predicted to experience the highest decrease and increase in species richness as the climate warms. In conclusion, climate change is likely to expand the pest species' overall distribution across the globe. It could have more profound impacts on the species distributions of those regions where species richness increases are expected, by altering the species' community compositions.

1. Introduction

The world's human population is estimated to increase by 70 million per annum (Popp, Pető, & Nagy, 2013). As the human population grows, so will the problem of the global food supply. Sustainable agricultural productions are therefore critical. However, agriculture in its diverse forms and large extent across the globe are highly sensitive to climate change (Howden et al., 2007). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has suggested that global mean surface temperature is expected to increase maximally 4.8 °C by the end of the 21th century (IPCC, 2013). Precipitation pattern will change, and extreme weather will become more frequent. Climate change can influence crop yields through effects mediated by changes in crop pest distributions, especially those invasive pest species (Bebber, Ramotowski, & Gurr, 2013; Estay, Lima, & Labra, 2009; Ziska, Blumenthal, Runion, Hunt, & Diaz-Soltero, 2011). Managing invasive species for securing cropping activities is challenging because such species can survive in diverse environments, mature quickly, and compete with local species for resources to affect ecosystem functioning (Bradley, 2009; Hoddle, 2014). The dispersal of invasive crop pest species is also likely to be incremental due to global warming (Thomson, Macfadyen, & Hoffmann, 2010; Ziska et al., 2011).

Among the invasive crop pests, poikilothermic (cold-blooded) species are recognized for the large area of agricultural losses that they cause. Temperature has been considered as the most important abiotic limiting factor that governs their distributions (Fand, Choudhary, Kumar, & Bal, 2014; Pimentel, Lach, Zuniga, & Morrison, 2000; Ziska et al., 2011). Poikilothermic pest species can thrive in warmer environments, so climate warming can

* Corresponding author.
E-mail addresses: yanyingwei@u.nus.edu (Y. Yan), geowyc@nus.edu.sg (Y.-C. Wang), geofcc@nus.edu.sg (C.-C. Feng), maffeewan@gmail.com (P.-H.M. Wan), changtt@comp.nus.edu.sg (K.T.-T. Chang).

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potentially enhance their overwintering survivability (Maxmen, 2013) and facilitate the accumulation of degree-days required by their growths (Herms, 2004). However, when temperature exceeds the upper threshold of a species' tolerance, it can result in a decreased growth and reproduction, thereby increasing the mortality for the species (Netherer & Schopf, 2010). Precipitation can also influence the species distributions as it alters ambient humidity, affecting the moisture needed for pest growths. Furthermore, precipitation extremes can negatively impact on pest growths, such that the resulting floods can wash off eggs and larvae and drown young pests (Kobori & Amano, 2003).

Climate change thus have both positive and negative effects on the pests. Numerous studies have examined the possible climate change effects on the distributions of various species at regional levels, such as plants (Garcia, Lasco, Ines, Lyon, & Pulhin, 2013), mammals (Alamgir, Mukul, & Turton, 2002), birds (Tingley, Monahan, Beissinger, & Moritz, 2009), reptiles (Araújo, Thuiller, & Pearson, 2006), amphibians (Thomas et al., 2004) and insects (Hongoh, Berrang-Ford, Scott, & Lindsay, 2012). Prior work has suggested that many species are likely to move poleward in latitude or upward in elevation as the climate warms (Estay et al., 2009; Jepsen, Hagen, Ims, & Yoccoz, 2008; Tingley et al., 2009). Regarding crop pests, recent effort has described the patterns and trends in their global spread with a temporal focus on the second half of the 20th century (Bebber, Holmes, & Gurr, 2014). Nevertheless, little is known if the overall global distributions of poikilothermic species of invasive crop pests will expand or contract as a result of future climate change, and to what extent will climate change influence the species richness across different regions. Research is thus needed to analyze the possible consequences of future climate change on the global distributions of the invasive crop pest species.

To estimate potential range and direction of distributional changes for invasive species, ecological niche model (ENM) has been suggested as a useful tool (Jeschke & Strayer, 2008). ENMs fall into two classes: mechanistic (or process-based) approach assesses physiological aspects of species; and correlative approach considers correlations between observed species distributions and environmental variables (Morin & Thuiller, 2009). Although both approaches have demonstrated their predictive capabilities (Kriticos, Morin, Leriche, Anderson, & Caley, 2013; Thuiller, Lavorel, Araújo, Sykes, & Prentice, 2005), correlative ENMs are frequently used in analyzing multiple species for at least three reasons. First, the lack of relevant knowledge on the physiological tolerance for all species of concern compromises the precision of mechanistic models (Mokany & Ferrier, 2010; Wiens, Stralberg, Jongsomjit, Howell, & Snyder, 2009). Second, species presence data for correlative ENMs are widely available, while data based on which mechanistic ENMs can be parameterized are often lacking (Morin & Thuiller, 2009). Third, the complexity of mechanistic models is high, requiring a relatively long time to fit a mechanistic model with appropriate data (Elith, 2014).

A correlative modelling program commonly applied to construct ENMs is maximum entropy modelling, or Maxent (Phillips, Anderson, & Schapire, 2006). It is a presence-only machine learning algorithm that estimates the probability distribution of species based on occurrence records and randomly generated background points by finding the maximum entropy. Prior work has demonstrated its better performance than other modelling methods in predicting invasive species distributions outside their native ranges (Bidinger, Lötters, Rödder, & Veith, 2012). This study thus uses species presence data to construct the correlative ENMs in Maxent, in order to contribute to the understanding of the impacts of climate change on the global distributions of poikilothermic invasive crop pest species. Specifically, this study addresses three research questions. First, will the overall global distribution of the pest species expand or contract as a result of climate change? Second, what are the spatial patterns of distributional changes in pest species richness? Third, how will temperature and precipitation variations across different regions affect the distributional changes of the pest species? Insights into the possible direction and range of the distributional changes of invasive crop pests are essential for adapting the current agricultural systems to climate change, so as to prevent world food insecurity and long-term nutritional emergencies.

2. Materials and methods

2.1. Study area

The spatial extent of the current global croplands (Appendix 1) was obtained from Pittman, Hansen, Becker-Reshef, Potapov, and Justice (2010) as the boundary of the study area. As it is uncertain if this extent will increase or decrease in the future (IPCC, 2013), this study assumed that the extent will remain the same. This study therefore focused on examining the species' distributional changes within the boundary of existing global cropping activities. This provides a reference for how decisions and planning can be made for adapting the existing agricultural activities to the species' distributional changes.

2.2. Ecological niche modelling

This study focused on modelling each species' fundamental niche (i.e., the maximum invasive potential within the boundary of the study area), rather than realized niche (i.e., a subset of the fundamental niche that the species can actually reach as a result of various uncertain constrains) (Tingley et al., 2009). For example, land use change and habitat fragmentation can form natural barrier to species movements and thus affect the rates of dispersal. Biotic interactions (e.g., competitors and predators) involved in realized niche can also limit the dispersals, although prior work has suggested that the effects of biotic interactions appear to be less important than the effects of climate in coarse-resolution and broad spatial extent analyses (Pearson & Dawson, 2003).

Maxent tool 3.3.3k (https://www.cs.princeton.edu/~schapire/maxent/) was used to construct ENMs. Following Moffett, Shackelford, and Sarkar (2007), random test percentage was set as 25%. The logistic output format was enabled in the modelling, which produced the predicted probability of presence (between 0 and 1) for a species on each pixel. The default regularization multiplier (1.0) was used, which was tuned and validated on diverse datasets by Phillips and Dudík (2008). A smaller regularization multiplier than the default of 1.0 may lead to overfitting due to increased model complexity, while a larger one may affect training accuracy.

For model evaluation, two tests were performed. First, the area under the receiver operating characteristic (ROC) curve values, or AUC, was used. The ROC curve is a plot of the sensitivity against 1-specificity (commission error) at all possible threshold probabilities for a positive prediction that ranges from 0 to 1. A model with an AUC above 0.8 was considered having "good" discrimination abilities (Swets, 1988). Second, a binomial probability test of omission was conducted to determine the statistical significance of the prediction of each model (Moffett et al., 2007).

2.3. Species occurrence records

Analyzing the complete cropping ecological system is almost impossible because of the large number of species. For example,