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Estimate global risks of a forest disease under current and future climates using species distribution model and simple thermal model – Pine Wilt disease as a model case

Makihiko Ikegami[a,*], Thomas A.R. Jenkins[b]

[a] National Institute of Environment Studies, Tsukuba, Japan
[b] Forest Research Agency, Wales Research Unit, UK

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ABSTRACT

Predicting distributions of a pest species is an important part of Pest Risk Analysis, but it is not always an easy task. Expert knowledge may help, yet, validation with field data is essential. Pine Wilt Disease (hereafter PWD) caused by the presence of the Pine wood nematode (hereafter PWN), *Bursaphelenchus xylophilus* is one of the most severe forest diseases in the world. The symptom development of this disease only occurs in a warmer region while the nematode itself could be widely distributed in cooler regions in its native range. Isotherm approaches have been used to estimate the distribution of this disease, but these models have not been well tested with field data. A correlative species distribution model, MaxEnt, is used to evaluate the climatic suitability for PWD at a global scale, along with a simple thermal model. The MaxEnt analysis indicated that most of the current distribution of PWD is explained by the average monthly mean temperatures of the warmest three months and aridity. The thermal model suggested larger PWD risk zones, particularly in hot and arid areas. The current distribution of some susceptible host species (*e.g., Pinus sylvestris*) is largely outside the area suitable for the development of PWD, but results using projected future climate showed that half of those areas become at risk from PWD in future. Species distribution models such as MaxEnt are useful tools for the evaluation of not only the likely potential distributions of pests but also areas where symptom development could occur under various climatic conditions, even exotic pests not yet present in a region. Our results suggest that PWD will undoubtedly pose a major threat to European pine species if climate change proceeds as currently projected.

1. Introduction

Since globalization increases the chances of pest species incursion worldwide (Hulme, 2009; Perrings et al., 2005) and climate changes alter the distributions of pest species (Dukes and Mooney, 1999; Walther et al., 2009), developing effective Pest Risk Analysis (PRA) is a key to take quick and proper quarantine planning for emerging pest species. Recent developments in computer-aided tools and large-scale database facilitate this task (see Venette, 2012), but data limitations for a focal species could hinder the use of such tools. Expert knowledge could help PRA, but such knowledge and predictions need to be validated. One of the challenges for exotic pest species is that estimating distributions of a pest species is not always equal to estimating the areas where damage could occur. Some pest species distribute far beyond the infested areas and cause little or no damage on the hosts in their native ranges, or they could cause damage only to "exotic" hosts. Under such circumstances, data from native ranges or expert knowledge have their limitations. Species Distribution Models (hereafter SDMs), a.k.a. Environmental Niche or Climate Envelope models, are commonly used to evaluate the relations between climate and species distributions (Elith and Leathwick, 2009; Franklin, 2009). These models are used to find statistical relationships between the current distribution of a species and environmental variables to predict distributions of the species. Today, predicting the potential distribution of a pest species using SDMs is becoming a common approach in Pest Risk Analysis (Jiménez-Valverde et al., 2011; Venette, 2012).

Pine Wilt Disease (PWD), caused by Pine wood nematode *Bursaphelenchus xylophilus* (Steiner & Buhrer) Nickle (PWN), is one of the most devastating forest diseases in the world and originated from North America (Mota and Vieira, 2008; Webster and Mota, 2007). The expression of PWD (*i.e.,* whether pine trees succumb to the disease) is a result of host-vector-pathogen species interactions in combination with climatic factors. The disease has caused high mortality in pine trees in Japan for a hundred years (Futai, 2008) and has spread to China (Zhao,

* Corresponding author.
E-mail addresses: Makihiko.ikegami@gmail.com (M. Ikegami), tom.jenkins@forestry.gsi.gov.uk (T.A.R. Jenkins).

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2008) and Korea (Han et al., 2008; Shin, 2008) in last few decades. Despite the quarantine efforts taken to prevent this disease from reaching European countries, the disease was found in Setubal, 50 km south of Lisbon, Portugal in 1999 (Mota et al., 1999), and has slowly but steadily spread towards central Portugal and the northern part of Spain, Galicia (Abelleira et al., 2011). Since various commercially important European pine species are highly susceptible to this disease (*e.g., Pinus sylvestris* and *P. pinaster*), it is essential to evaluate the potential risks of this disease in Europe and the rest of the world to build proper pest control schemes. Several authors have evaluated the PWN risks in different regions; using multi-variate analysis on climate and pine mortality (Li et al., 2010; Pérez et al., 2008), or applying a spreading model to identify the entry points of PWD in Europe (Robinet et al., 2011), or evaluating potential risk of PWD under current and future climates in China (Robinet et al., 2009; Roques et al., 2015), or in Europe (Gruffudd et al., 2016) but no study has so far evaluated the potential risks of PWD under current and future climates at a global scale. Isotherm approaches have been used to estimate the distribution and the risks of this disease (e.g., Rutherford and Webster, 1987), but these models are not well tested with field data.

Like many other tree diseases, PWD symptom development is primarily controlled by climate, especially temperature (Rutherford and Webster, 1987). In the native range of PWN in North America symptom development occurred mostly in warm regions on exotic pine species (Rutherford and Webster, 1987), despite the fact that PWN has been detected in northern colder areas. In Japan, pine trees growing at high elevation show low or no mortality from PWD, probably due to the lower temperatures experienced at altitude (Futai, 2008). Inoculation experiments have shown that host trees did not wilt at temperatures below 20 °C but showed significant wilt when temperatures exceeded 25 degrees (*e.g.,* Braasch, 2000). Another driving force behind mortality caused by PWD is water stress experienced by host trees (Suzuki and Kiyohara, 1978). A number of studies have shown lower mortality in well-watered trees under controlled climatic conditions and analysis of field data suggests that a dry summer increases mortality from PWD (Suzuki and Kiyohara, 1978). Rutherford and Webster (1987) qualitatively evaluated the potential risks of PWN for Northern hemisphere using summer temperatures (*i.e.,* isotherm). Recently Hirata et al. (2017) applied this method to evaluate the global risks of PWD under current and future climate (Hirata et al., 2017). However, both studies used a temperature threshold obtained from studies in Japan and did not consider water stress on host trees. Thus, it is not clear if the same temperature threshold could be applied to other pine species in other parts of the world, especially susceptible European pine species.

The average global temperature rose 0.4 °C at the end of last century and this trend is projected to continue through the 21st century (IPPC, 2013). Such a climate trend will influence the distribution of many species, including pests (Evans et al., 2002; Sturrock et al., 2011). The 5th Annual Report of the IPCC estimated that, by the end of 21st century, the global average increase in annual temperature would exceed between 1.0 °C (under RCP2.6 scenario) and 4.0 °C (RCP8.5) relative to the 1986–2005 period. Because PWD is temperature sensitive, if future average summer temperature regularly exceeds 20 °C in a currently cooler area, then, PWN is likely to cause high mortality of susceptible pine trees in the region where PWN is present. Identifying these areas is essential to evaluate the potential impacts of this disease. If the expression of PWD is essentially limited by environmental factors, an SDM is able to predict the potential distribution area of PWD (*i.e.,* "risk area") under current and future climatic conditions.

In this study, the current distribution of PWD in East Asia, North America and Europe is first analysed under current climatic conditions. The PWD distribution under projected future climatic conditions is then predicted for those same geographic regions. This is achieved using MaxEnt, a machine learning-based species distribution model widely used in the field of ecology and conservation (Phillips et al., 2006). In addition to the MaxEnt model, the risk of PWD expression is evaluated using average monthly mean temperatures of the warmest three months under current and projected future climatic conditions. We analyse the current distributions of PWD with MaxEnt and then determine a threshold value for our thermal model. Unlike SDMs, a simple thermal model analysis does not require distribution data of host/pest species and thus easy to build but potentially inaccurate. We believe it is worth to validate the thermal model and compare the results from two approaches to discuss the effective model developments. Finally, the likely extent of the PWD risk area under current and projected future climatic conditions is estimated for twenty-one PWD-susceptible pine species at a global scale.

2. Model & data

2.1. Distribution data

Pine wood nematode (PWN) is distributed widely in Japan, although it is absent from cooler climatic regions, such as the island of Hokkaido (43.0 N, 142.0 E) and at higher elevations. For the current study, the locations of confirmed PWD in Japan and Korea were identified from maps in the published literature (*e.g.,* Forest Conservation Departmental Meeting of Tohoku Forestry Research Institute Liaison Council, 2014; Futai, 2008; Shin, 2008). The presence of PWD in China was determined from sampling data and maps (Robinet et al., 2009; Zhao et al., 2014), and for the USA and Taiwan regional occurrence data were obtained from reports or regional news found on the internet. The challenge of gathering the occurrence records of PWD is separating data from the occurrence of PWN. Numerous survey data in the USA are dropped from the analysis since those data did not clearly identify if the samples were collected from trees showing PWD symptoms or not. Presence data for Portugal were obtained from the PHRAME/Re-PHRAME reports (Evans, 2015, 2007), ICNF (the Portuguese Forestry Authority) website (http://www.icnf.pt/portal/florestas/prag-doe/ag-bn/nmp/infgeo access on 20170716), Valadas et al. (2012), and Zhao et al. (2014). Data for Garcia in Spain are obtained from Abelleira et al. (2011).

Fig. 1 shows the locations of the occurrence data we gathered in this study. Obtaining location data directly from existing maps is generally less accurate than using actual distribution points (geographic coordinates). In addition, PWD occurrences were reported at a regional scale in the USA (at county level), Portugal (in district level at data from ICNF) and Taiwan (prefecture). For such data, we identified a forested area inside or around the largest city (in the US and Taiwan) or plantation forest (at Portugal) in each region as a PWD occurrence point using Google Earth. Although the accuracy of occurrence data is crucial to the accurate predictions of SDMs (Dormann et al., 2008), we have to bear the risk of using rather coarse occurrence data for our study due to the data limitation, especially in the PWN native range (USA). Nonetheless, because our climate data are at 2.5 arc minute resolution (about 4 km in these countries) and PWD tends to be more widely observed than this in infested areas, the resolution of occurrence data was deemed sufficient for our analyses at a global scale.

To evaluate the likely risk to pine species from PWD, twenty-one PWD-susceptible species from temperate zones were included in this study: four species from Europe (*Pinus mugo, P. nigra, P. pinaster, and P. sylvestris*), seven species from East Asia areas (*P. densiflora, P. koraiensis, P. luchuensis, P. massoniana, P. parviflora, P. pumila, and P. thunbergii*), ten species from Central or North America (*P. ayacahuite, P. caribaea, P. engelmannii, P. leiophylla, P. monticola, P. muricata, P. oocarpa, P. ponderosa, P. radiata and P. strobiformis*). These species are listed as PWD-susceptible species by Sathyapala (2004) or Furuno (1982) based on inoculation experiments and field observations, but some species showed conflicting results. For those species, we selected the focal species based on their economic or conservation importance (e.g., *P. radiata*). Distribution data (range maps) for the European pine species were downloaded from the EUFORGEN website (http://www.