Global threat to agriculture from invasive species

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Edited by Harold A. Mooney, Stanford University, Stanford, CA, and approved April 28, 2016 (received for review February 13, 2016)

Invasive species present significant threats to global agriculture, although how the magnitude and distribution of the threats vary between countries and regions remains unclear. Here, we present an analysis of almost 1,300 known invasive insect pests and pathogens, calculating the total potential cost of these species invading each of 124 countries of the world, as well as determining which countries present the greatest threat to the rest of the world given their trading partners and incumbent pool of invasive species. We find that countries vary in terms of potential threat from invasive species and also their role as potential sources, with apparently similar countries sometimes varying markedly depending on specifics of agricultural commodities and trade patterns. Overall, the biggest agricultural producers (China and the United States) could experience the greatest absolute cost from further species invasions. However, developing countries, in particular, Sub-Saharan African countries, appear most vulnerable in relative terms. Furthermore, China and the United States represent the greatest potential sources of invasive species for the rest of the world. The analysis reveals considerable scope for ongoing redistribution of known invasive pests and highlights the need for international cooperation to slow their spread.

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Significance

A key scientific and policy challenge relating to invasive species at the world level is to understand and predict which countries are most vulnerable to the threat of invasive species. We present an analysis of the threat from almost 1,300 agricultural invasive species to the world (124 countries). The analysis examines the global distribution of these species, international trade flows, and each country’s main agricultural production crops, to determine potential invasion and impact of these invasive species. We found the most vulnerable countries to be from Sub-Saharan Africa, while those countries representing the greatest threat to the rest of the world (given the invasive species they already contain, and their trade patterns) to be the United States and China.

Author contributions: D.R.P., A.W.S., D.C.C., P.J.D.B., S.P.W., and M.B.T. designed research; D.R.P. performed research; D.R.P. and D.C.C. contributed new reagents/analytic tools; D.R.P. analyzed data; and D.R.P., A.W.S., D.C.C., P.J.D.B., S.P.W., and M.B.T. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. Freely available online through the PNAS open access option.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1602205113/-/DCSupplemental.

www.pnas.org/cgi/doi/10.1073/pnas.1602205113
pest and pathogen species in the analysis, we calculated the invasion threat to a particular country only if that country grew an agricultural crop that was a known host of that pest or pathogen species and that species was not already present in the country. The invasion threat (IT_{ps}) of one species, p, from one source country, s, to a recipient (or threatened) country, t, was calculated as the product of the arrival and establishment indices. We calculated the total invasion threat (TT_{ps}) of one species, p, from all possible source countries to a given threatened country, t (SI Appendix, Fig. S1). We then combined the TT values for all species to calculate an overall invasion threat (OT_{t}) to a country, t, incorporating all pests and pathogens from all possible source countries (trading partners).

Having defined the threat from invasive species to a country, we then calculated the potential cost from invasive pests and pathogens on each crop, c, in each country, t (crop invasion cost—CIC_{pct}). It was not possible to determine the potential impact of all species in all countries as such data are not available. As an alternative, we obtained the maximum reported percentage impact for 140 species (of the 1,297 species in our analysis) on one of its main agricultural hosts. We assumed this represented the range of possible impacts of all species in our dataset. For each species, p, and each crop, c, and in each country, t, we sampled from this range 100 times (with replacement) to get a mean potential impact (MI_{pct}). We therefore generated more than 37,000 unique mean potential impact values, for each possible combination of species, crop, and country. The mean was then multiplied by the TT_{ps} and the value of the crop in that country to generate the potential financial impact of that pest on that crop in that country. This was subsequently summed over all pests and all crops to determine the total invasion cost (TIC_{t}) to that country.

We were also able to identify not just threatened countries, which have the most to lose from these invasive species, but also those countries that represent the greatest threat to the rest of the world, given their trade patterns and the invasive species they already have present within their borders. To estimate source-TIC (TIC_{s}) for an individual source country, s, we followed a similar method used to generate TIC_{t} for threatened countries, except we used the crop data of countries they export to and those invasive species present within their own country, which could spread to trading countries.

**Results**

**Invasion Threat.** We found that 40 of the 124 countries assessed (32%) had a likelihood index of being invaded (OT_{t}) by any one insect or pathogen species greater than 0.80 (Fig. 1A and SI Appendix, Table S1). Only 10 countries (8%) had OT_{t} values <0.4.

**Invasion Cost.** As expected, countries that are large agricultural producers such as China, United States, India, and Brazil exhibit the highest potential cost from these 1,297 invasive species (Fig. 1B and SI Appendix, Table S2). However, the economic significance of an invasive species following introduction will likely depend not only on the value of the threatened commodity but also the ability to manage or mitigate the impact via means such as pest management, plant breeding, crop substitutions, imports, or subsidies (22). To provide an estimate of this relative cost, we divided a country’s TIC_{t} by its mean gross domestic product.
Source Countries. As with the rankings by TIC, we found that China and the United States ranked first and second as potential source countries (Fig. 1D and SI Appendix, Table S4). Furthermore, exactly one-half (10) of the countries ranked in the top 20 source countries were also ranked in the top 20 for threatened countries (Fig. 1B and SI Appendix, Table S2).

Discussion

We saw little pattern in which countries had higher or lower OTi values, indicating the complex interplay between the types of crops grown in a country, the level of trade with other countries, and the particular invasive species present in those trading countries. For example, neighboring countries can have surprisingly different OTi values. Italy has a low OTi, whereas its immediate neighbors, Switzerland and Austria, both have high OTi values (Fig. 1D and SI Appendix, Table S1), despite Italy’s importing approximately twice the value of either Switzerland or Austria (IT = $371,349M, CH = $151,835M, AT = $188,494M). This is partly driven by the fact that fewer invasive species threaten Italy (IT = 147, CH = 170, AT = 264), but also by the particular species that are threatening (and their establishment indices), as well as the different trading partners of these countries. Furthermore, although it would be expected that import dollars will strongly influence a country’s TICi, we found a number of examples where this is not the case. India and Sweden have similar mean import dollars ($138,542M and $109,479M, respectively), but very different TICi values (Fig. 1B and SI Appendix, Table S2), as a result of the number of species threatening each country (190 and 58, respectively), which is a function of the crops grown and the invasive species present in trading countries. Finally, examining TICi shows that, although export dollars can influence a country’s TICi value, it can also be the number of threatening invasive species. Mexico and Pakistan have very different TICi values (Fig. 1D and SI Appendix, Table S4) but similar numbers of invasive species present (379 and 377, respectively). The difference in TICi values for these two countries is influenced by the large differences in mean export dollars ($217,484M and $12,464M, respectively). Alternatively, India and Czech Republic have similar mean export dollars ($97,034M and $86,478M), yet different TICi values (Fig. 1D and SI Appendix, Table S4), driven by large differences in the number of invasive species present in each country (627 and 212, respectively).

Despite these apparent complex interactions, when examining TICi as a proportion of GDP, countries in Sub-Saharan Africa were clearly identified as the most vulnerable to the potential impact of invasion by the agricultural pests and pathogens included in this analysis. These countries (and many of the highly ranked developing countries) generally do not have diverse economic industries and are consequently disproportionately more dependent on agriculture (24). As a result, any threat from invasive species can potentially have a greater relative impact on these countries. Wealthy regions where agricultural activity represents a smaller proportion of GDP have a much smaller relative TICi, even where invasion threat is large. To illustrate, North American and Scandinavian countries all have a high OTi (Fig. 1D), yet, when potential impact (TICi) as a proportion of GDP is considered (Fig. 1C), these countries are placed in the lowest category.

The United States and China were identified as the two most important source countries to the rest of the world. These countries are characterized by large and diverse trade volumes and have been confirmed as network hubs in the international agrofood trade network (25). They also have diverse agroecosystems and host a substantial number (52% and 56%, respectively) of the pool of invasive pests and pathogens, more than any other country in this analysis. As such, they can be considered central nodes in the worldwide network of invasive species spread. Other countries, such as Japan, Germany, France, and Republic of Korea, also ranked highly as potential source countries [Germany and France have also been identified as network hubs (25)]. At the other end of the scale, numerous developing countries ranked low as potential sources of invasive species. This contrasts to their position as generally the most vulnerable countries to invasion as a function of GDP (Fig. 1C).

Uncertainties are an intrinsic feature of any model-based assessment of ecological invasions (26), and it is important to quantify the impact of these uncertainties in any model outputs. There were four key parameters in our model (arrival index, establishment index, mean potential impact, and crop production value), and we examined their impact on TIC for both threatened and source countries (TICi and TICi, respectively).

We found little change in the rankings with the introduction of these errors (SI Appendix, Figs. S2–S9). We also found only small changes in TICi and TICi values. The largest change was a decrease in TICi for Mongolia by 16% with the introduction of uncertainty to mean annual crop value, although this country’s ranking only dropped by one place as a result (from 111 to 112). Overall, the mean change in TICi and TICi varied from 0.24% to 3.94% depending on the type of uncertainty introduced (i.e., arrival index, establishment index, mean potential impact, or mean annual crop value) (SI Appendix, Table S5).

Predicting invasion by a species with no known invasion history or with no previous pest impact is extremely challenging because they are likely to be unknown before invasion of the new region. However, the invasive species assessed here are a substantial subset of the known global species pool of economically significant pests. We would therefore expect the patterns revealed in this analysis to be robust to the inclusion of more species.

The presence/absence data used in the Centre for Agriculture and Bioscience International (CABI) Crop Protection Compendium (CPC) include species that may be recorded in a country from a restricted range (one location only) up to a widespread range. As such, we have been unable to consider whether a species establishes and does not spread or if there is a lag phase before spread. Our predictions therefore only consider whether a species can establish in a country and not the more complex dynamic invasion processes that could follow. Furthermore, predicting the impact of an individual pest species is extremely challenging due to spatial and temporal uncertainty. The same pest species can have a major impact in one location yet a minor impact in another. The rate of spread of a pest species will also influence any economic impact assessment. Accordingly, we feel our use of mean potential impact drawn from the range of reported impacts for a subsample of species in this analysis is a parsimonious approach to analyzing global patterns.

To our knowledge, this is the first analysis summarizing the invasive species threat to global crop production on a country-by-country basis. We find that fast from being “saturated” or “homogenized,” many countries are open to substantial ongoing threat of invasion from known pests and/or pathogens. Countries that are large crop producers are most at risk in absolute terms, whereas numerous developing countries are disproportionately vulnerable to invasion in relative terms. Countries with diverse commodities and/or large trade volumes are likely the greatest source of invasive pests and pathogens, whereas countries with developing economies likely play less of a role as sources of invasion. As trade volumes continue to increase and more trade connections are made between countries, the pressures from invasive species will only intensify. The formation of an international
body responsible for invasive species could not only enable the management of invasive species at the global scale but also provide those countries identified here as most vulnerable, with the information, and possibly the resources necessary to protect their borders and limit the further spread of invasive species (27).

Materials and Methods

Species and Country Data. Species data were extracted from the CABI CPC (18). Species in this database fall into one of two categories in terms of the quality of data (basic data sheets and full data sheets). Basic data sheets are generated by a process of data mining and have not been manually checked. Full data sheets have been written specifically for the compendium by a range of specialists. These full data sheets are then edited and checked by additional experts. Only those insect and fungal pathogen species in the database with a full data sheet available were extracted.

Countries were included in the analysis only if both crop data from the Food and Agriculture Organization of the United Nations (FAO) (21) and direction of trade data from the International Monetary Fund (17) were available. For some country-to-country combinations, no direction of trade data were available (e.g., Burkina Faso and Azerbaijan). These were relatively infrequent, and rather than remove both countries from the analysis, we assumed the value of trade between the two countries was zero.

Arrival Index. An arrival index was generated from direction of trade data (17), which has consistently been shown to be related to the number of invasive species in a country or region (4, 12–16). For each country, we generated a mean importation value (in millions of US dollars) from the trading country by the mean total import value from all trading countries, a proportion was generated by dividing the mean import value from the trading country by the mean total import value from all trading countries. This proportion was used as a proxy for likelihood of a species arriving at the threatened country over the course of 1 y.

Establishment Index. The species distribution for each of the 1,297 invasive species in 124 countries was extracted (18) and placed into a 124 × 1,297 matrix, in which each neuron represents a species being present in a country and 0 represents absence.

An SOM (28) was used to analyze this matrix. An SOM is a type of artificial neural network capable of converting high-dimensional data into a 2D map, pictorially showing which data points are most similar. The SOM therefore is a clustering method and full details can be obtained from Refs. 10 and 28, pictorially showing which data points are most similar. The SOM is an elastic network of neurons that are projected into this multidimensional space and which interact with the regions. The vector that determines each neuron’s position in this space is termed the neuron weight vector. The number of neurons in an SOM is partially determined by the heuristic rule, \( n = \sqrt{p} \), where \( n \) is the number of samples (in our case, this is 124 countries) and \( p \) in which each neuron represents a species being present in a country and 0 represents absence.

When the analysis is initiated, each country is assessed and the closest neuron to this country in multidimensional space is identified as the best matching unit (BMU). The neuron weight vector of the BMU is adjusted so that the neuron moves closer to the country. The BMU is reassessed every iteration, and the recommended number of iterations is 500 × number of species (for this analysis, 500 × 54 = 27,000). With each iteration, the gravitational effect of one neuron on neighboring neurons decreases and the distance a BMU is moved closer to a country also decreases. As the analysis approaches the final iterations, the SOM spreads out to occupy approximately the same area that the countries occupy in the multidimensional space. When the analysis is complete, each country will be assigned to a BMU that is its closest neuron. Some countries will have the same BMU, because they have similar assemblages of invasive species and hence are found close to each other in the multidimensional space. Each of the 1,297 elements of the neuron weight vector of a BMU corresponds to each of the 1,297 invasive species in the analysis and will have a value between 0 and 1, which is a measure of the strength of association of the invasive species with the assemblage of invasive species of any country assigned to that BMU. The strength of association for a species can be interpreted as an index of establishment likelihood for that species in a region (10, 19, 20). On completion of the analysis, an establishment index can be determined for every species in every country included in the analysis.

Mean Crop Value. The mean annual value (2000–2009) of each agricultural crop (in millions of US dollars), for each of the 124 countries, was obtained from the FAO (21). For each country, crop categories were ranked by value and those crops that comprised the top 75% of total agricultural production were used. For each crop category, a list of the insect pests and fungal pathogens using that crop as a host was extracted from the CABI CPC (18). Some crop categories were too general to determine what species of crop was included (e.g., dry beans), whereas for other crop categories there was no information available in the CABI CPC (e.g., mushrooms and truffles). These crops were therefore omitted in the calculation of the top 75% of agricultural production.

Invasion Threat. The invasion threat, \( \text{IT}_{\text{th}} \), for each threatened country, \( t \), for each invasive species, \( p \), from each source country, \( s \), conducting trade with the threatened country was calculated only if that invasive species was present in the source country, absent from the threatened country, and a known pest or pathogen of a crop grown in the threatened country:

\[
\text{IT}_{\text{th}} = \frac{p_{\text{th}} \cdot E_{\text{th}}}{p_{\text{th}} \cdot E_{\text{th}} + p_{\text{th}} \cdot E_{\text{th}} + p_{\text{th}} \cdot E_{\text{th}}},
\]

where \( p_{\text{th}} \) is the arrival index of a species to a threatened country, \( t \), from source country, \( s \), and \( E_{\text{th}} \) is the establishment index of species, \( p \), in threatened country, \( t \).

Threatened Countries. The \( \text{TT}_{\text{tp}} \) for a threatened country was calculated for one species, \( p \), from each possible source country, \( s \), to a given threatened country, \( t \):

\[
\text{TT}_{\text{tp}} = \frac{1 - \left[ \frac{\text{IT}_{\text{th}}}{\text{IT}_{\text{th}} + 1} \right] }{1 - \left[ 1 - \frac{\text{IT}_{\text{th}}}{\text{IT}_{\text{th}} + 1} \right] }.
\]

In addition, the total invasion threat, \( \text{TT}_{\text{ts}} \), from all species known to be a threat to a particular crop, \( c \), grown in a threatened country, \( t \), was calculated as follows:

\[
\text{TT}_{\text{ts}} = \frac{1 - \left[ \frac{\text{IT}_{\text{th}}}{\text{IT}_{\text{th}} + 1} \right] }{1 - \left[ 1 - \frac{\text{IT}_{\text{th}}}{\text{IT}_{\text{th}} + 1} \right] }.
\]

Threatened Countries—Invasion Cost. Before estimating the invasion cost, we first estimated the potential impact of species, \( p \), on crop, \( c \), in country \( t \). To do this, we searched the CABI CPC (30) and found the maximum reported percentage impact on crop production for 140 species. Damage estimates are not reported for most species and the 140 species were selected to include a representative diversity of pest taxa from the complete list, and to span the range of possible impacts any species could have on any crop in any country (SI Appendix, Table S6). For each country on each crop, we sampled from this range 100 times (with replacement) and calculated the mean potential impact, \( \text{MI}_{\text{pct}} \), generating more than 37,000 unique mean potential impact values.

The crop invasion cost, \( \text{CIC}_{\text{pct}} \), of all invasive species that are known pests or pathogens of an agricultural crop, \( c \), grown in a threatened country, \( t \), was then calculated as follows:

\[
\text{CIC}_{\text{pct}} = \frac{\text{TT}_{\text{ts}} \cdot \text{MI}_{\text{pct}} \cdot \text{CV}_{\text{th}}}{\text{TT}_{\text{ts}} \cdot \text{MI}_{\text{pct}} \cdot \text{CV}_{\text{th}}}.
\]

where \( \text{CV}_{\text{th}} \) is the mean annual value of crop, \( c \), in threatened country, \( t \).
The total invasion cost for each threatened country, $\text{TIC}_s$, was calculated from the sum of $\text{CIC}_{sc}$ of all crops grown in the threatened country:

$$\text{TIC}_s = \sum_t \text{CIC}_{st}.$$

**Source Countries.** The total invasion threat from all species found in a source country, $\text{TT}_{sc}$, to a particular crop, $c$, grown in a threatened country, $t$, was calculated as follows:

$$\text{TT}_{sc} = 1 - \prod_t [1 - \text{IT}_{st}].$$

**Source Countries—Invasion Cost.** The crop invasion cost from a source country, $\text{CIC}_{st}$, of all invasive species that are known pests or pathogens found in the source country, $s$, and threatening an agricultural crop, $c$, grown in a threatened country, $t$, was calculated as follows:

$$\text{CIC}_{st} = \text{TT}_{sc} \times \text{MI}_{st} \times \text{CV}_{st},$$

where $\text{CV}_{st}$ is the mean annual value of crop, $c$, in threatened country, $t$.


The total invasion cost from each source country, $\text{TIC}_s$, was calculated from the sum of $\text{CIC}_{sc}$ of all crops, $c$, grown in threatened countries:

$$\text{TIC}_s = \sum_t \text{CIC}_{st}.$$