Journal of Environmental Management 180 (2016) 301–309

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Border control for stowaway alien species should be prioritised based on variations in establishment debt

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ARTICLE INFO

Article history:
Received 9 December 2015
Received in revised form 26 April 2016
Accepted 9 May 2016
Available online 1 June 2016

Keywords:
Biological invasion
Prioritised inspection strategies
Border control
Climatic similarity
Resource allocation
Inspection effort

ABSTRACT

Border control is one of the major approaches used by countries to limit the number of organisms introduced as stowaways. However, it is not feasible to inspect all passengers, cargo and vehicles entering a country, and so efforts need to be prioritised. Here we use South Africa as a case study to assess, based on tourism and trade data and climate matching techniques, the number of stowaway species that might be introduced ('colonisation pressure') and the likelihood that once introduced, these organisms will establish ('likelihood of establishment'). These results were used to explore how the number of species that are likely to establish ('establishment debt') varies across donor regions and seasons. A simple theoretical model was then used to compare four strategies for prioritising border control inspections: no prioritisation; based on colonisation pressure; based on likelihood of establishment; and based on both colonisation pressure and likelihood of establishment. Establishment debt was greatest in southern hemisphere spring and autumn when South Africa is climatically similar to northern hemisphere countries with which there are strong, consistent trade and tourism links (i.e. colonisation pressure varied little seasonally, but likelihood of establishment did vary across the seasons). Prioritising inspections based on both colonisation pressure and the likelihood of establishment was clearly the most effective strategy, with this strategy detecting at least 6% more potential invaders than the other strategies. While there are many practical limitations to the implementation of such prioritised inspection strategies, the results highlight the importance of national and regional studies of establishment debt.

1. Introduction

The movement of goods and people around the globe is increasing, leading to an increase in the introduction of organisms to regions where they are not native (Levine and D'Antonio, 2003; Westphal et al., 2008). Organisms are often unintentionally introduced as stowaways on or in transport vectors (Hulme et al., 2008). Some of these stowaway organisms become invasive and have undesirable ecological and economic impacts (Pimentel et al., 2001; Simberloff et al., 2013). Where an effort is made to prevent these unintentional introductions, likely vectors (e.g. goods, traveller's luggage and vehicles) are identified and inspected at the border.

Inspection services, however, face many obstacles and while the number of vectors requiring inspection has increased (Bacon et al., 2012; McCullough et al., 2006), the resources available for these inspections (budget and personnel) are limited (Simberloff, 2006). Consequently, only a small proportion of the potential vectors can actually be inspected (Bacon et al., 2012; McCullough et al., 2006) and a large number of organisms go undetected (Stanaway et al., 2001; Work et al., 2005). Inspection services also often only target agricultural pests, neglecting organisms that will have environmental impacts (Bacon et al., 2012). The development and implementation of prioritised inspection strategies could improve this situation and, if based on underlying risks or the potential costs of pest introduction, could result in more efficient and effective border control (Areal et al., 2008; Bacon et al., 2012; Surkov et al., 2008). Unfortunately evaluations tend to be at a global

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http://dx.doi.org/10.1016/j.jenvman.2016.05.023
0301-4797/

scale—there has been little effort to link evaluations of the underlying risks to prevention strategies at regional scales (but see Bacon et al., 2012; Keller et al., 2011; MacIsaac et al., 2002).

Attempts to consider the underlying risks have largely focused on the likelihood that organisms will be introduced from one region to another (e.g. Bacon et al., 2012; Drake and Lodge, 2004; MacIsaac et al., 2002). As the number of organisms that are introduced is rarely known with accuracy, these endeavours use proxies (e.g. the number of people or goods transported) that are positively correlated with the likelihood of introduction (Drake and Lodge, 2004; Liebhold et al., 2006; Tatem et al., 2006a). Such research has proposed that prevention strategies should prioritise vectors traveling from regions from which a large number of organisms are introduced. However, this approach neglects two potentially important factors that may have consequences for the efficient allocation of resources. Firstly, the number of organisms introduced is likely to change over time (e.g. increasing during the peak tourism season; Tatem and Hay, 2007). Secondly, introduced organisms need to be able to establish in order to become invasive, and the likelihood of establishment will vary spatially and seasonally. To establish, an introduced organism must survive in the recipient environment upon introduction and thus the donor and recipient regions must be sufficiently climatically similar. The higher the climatic similarity the higher the likelihood that an introduced organism will establish (Andow, 2003). For stowaway organisms that are sensitive to small changes in climate (e.g. arthropods and micro-organisms, referred to here as 'climatically sensitive organisms') this might be a substantial barrier to invasion, with establishment only possible during seasons when the donor and recipient environments have a high climate match. Due to these two factors, the number of alien species that are introduced and establish should vary across donor regions and over time, and will be greatest during periods of the year when the number of introductions and the likelihood of establishment are highest (Tatem and Hay, 2007).

As developing countries have few resources available for border control (Mumford, 2002), inspection strategies need to be effectively prioritised, requiring national-level assessments of underlying risks. Here, South Africa is used as a case study to evaluate the risk of invasion posed to natural and semi-natural environments by climatically sensitive organisms that are introduced as stowaways. As a country that relies heavily on imports, South Africa should be particularly at risk of such invasions (Tatem, 2009) and in line with this there has been a recent increase in the number of established arthropods (Giliomee, 2011). Our aim was to explore how the number of species that could be introduced and establish in a region varies across donor regions and seasons, and to assess the implication of any variation when developing inspection strategies.

2. Materials and methods

The number of species that are likely to establish in South Africa (referred to as 'establishment debt' (Rouget et al., 2016)) was assessed by taking into account two key stages of the invasion continuum (i.e. introduction and establishment (Blackburn et al., 2011)). For each season the number of stowaway species that would be introduced from a foreign country to South Africa was assessed, and the likelihood that these species would establish was evaluated. These results were combined to determine how establishment debt varies seasonally and how donor regions vary in their contribution to this debt. In this paper, colonisation pressure refers to the number of species introduced (Lockwood et al., 2009), and the likelihood of establishment is the likelihood that a species will be introduced to an area with a suitable climate and establish. Note, the eventual impact of the species is not considered here (see supplementary materials for the full methodology).

2.1. Colonisation pressure

Trade and tourism data were used as a proxy for colonisation pressure. Monthly country-level data on the number of foreign tourists and the value of commodity imports (in South African Rand) were obtained from Statistics South Africa and the South African Department of Trade and Industry for 2007 to 2011. These data were used to determine the monthly colonisation pressure posed by each foreign country to South Africa. Let $j \in M$, where M is the set of months of the year, and let H_j be average tourism and W_j be average imports for month j. The monthly colonisation pressure posed by each country was calculated using the formula below which weighted tourism and imports equally:

$$M_j = \frac{1}{2}\left(\frac{H_j}{\sum_{i \in M} H_i} + \frac{W_j}{\sum_{i \in M} W_i}\right)$$

Seasonal results were obtained by averaging across months that fall into southern hemisphere seasons (i.e. winter is June–August; spring is September–November etc.). The relative seasonal colonisation pressure posed by each country was designated as low, medium or high (colonisation pressures greater than or equal to the 75th percentile were high; greater than or equal to the 50th percentile were medium; and the remainder were low).

2.2. Likelihood of establishment

The likelihood that organisms introduced from foreign countries could establish in South Africa (given that they had survived transportation and were introduced) was assessed using two climate matching techniques. The climatic similarity between South Africa and foreign countries was firstly evaluated at a city level using a point-based technique, and secondly at a country level using a grid-based method. The two climate matching techniques measured the likelihood of different extents of establishment. The point-based technique measured the likelihood that introduced organisms will survive and reproduce at the point of introduction, while the grid-based method measured the likelihood that introduced organisms will survive and reproduce a significant distance from the point of introduction. The results of the two methods were then combined to obtain a measure of likelihood of establishment.

2.2.1. Point-based climate matching technique

Gridded monthly mean temperature and precipitation data from the CRU CL 2.0 dataset at a spatial resolution of 10 min (New et al., 2002) were used to calculate the monthly climatic distance between large South African and large foreign cities (organisms are often transported between large cities; for example, mosquitos most often enter New Zealand through Auckland (Derraik, 2004)). As recommended by Bradie et al. (2015) unweighted Euclidean distance was calculated following standard methods (Barry et al., 2008) using the 'stats' package in R (R Core Team, 2013) (see Figs S1–S4 in supplementary materials for examples of pairwise-comparison results). Seasonal, pairwise results were obtained by averaging the Euclidean distance values for months that fall into southern hemisphere seasons. For each season, the Euclidean distance value from the city in each country that is the most climatically similar to a South African city (i.e. that with the lowest Euclidean distance) was utilised as a measure of climatic similarity between the two countries. This value represents the maximum likelihood that an organism transported from a foreign country to South Africa will find a suitable climate at the point of introduction. For each season, countries were designated as having a low,