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Invasive species control in a one-dimensional metapopulation network

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ABSTRACT

The growth and spread of established Invasive Alien Species (IAS) cause significant ecological and economic damages. Minimising the costs of controlling, and the damages from, IAS depends on the spatial dynamics and uncertainty regarding IAS spread. This study expands on existing modelling approaches by allowing for varying stock sizes within patches and stochastic spread between patches. The objective of this study is to demonstrate the added value from this more detailed modelling approach. This is achieved in the context of coastal and riparian systems, which can be accurately modelled one-dimensional landscape, i.e., a series of patches connected in a line. The model allows for two types of intervention, namely (1) partial or complete removal of the population in within any patch; and (2) containment to reduce spread between patches. We analyse the general properties of the model using a two-patch setup to determine how the optimal policy depends on both the location and size of the invasion in patches. We find that allowing for varying stock sizes within patches facilitates optimal timing of the application of containment. We also identify two novel optimal policies: the combination of containment and removal to stop spread between patches and the application of up to four distinct policies for a single patch depending on the size of the invasion in that patch.

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1. Introduction

Invasive Alien Species (IAS) are species that proliferate, spread, and persist after introduction into a natural environment (Mack et al., 2000). IAS can cause dramatic changes in ecological systems and have profoundly altered terrestrial and marine ecosystems worldwide (Gurevitch and Padilla, 2004; Hulme, 2006). Although invasions are not necessarily human-driven, the number of invasions has grown substantially as a result of global travel and trade (Mack et al., 2000). Invasions can lead to significant losses in terms of human health, biodiversity, and ecological services (Frésard and Boncoeur, 2006; Pimentel et al., 2005; Scalera, 2010). These losses can be mitigated by appropriate management in response to invasions, informed by scientific decision support (Carrasco et al., 2010a). A better understanding of the costs and benefits of controlling IAS improves management efficiency (Genovesi, 2005). A particular aspect requiring more attention is our understanding of the spatial aspects of invasion control (Albers et al., 2010; Epanchin-Niell and Hastings, 2010; Savage and Renton, 2014).

Much of the literature concerning spatial dynamics is concerned with the interaction of multiple jurisdictions in response to invasive species and the actions of other jurisdictions. These include Huffaker et al. (1992), Albers et al. (2010), Sanchirico et al. (2010), Zhang et al. (2010), Carrasco et al. (2012), McDermott et al. (2013), Fenichel et al. (2014) and Kovacs et al. (2014). The literature considering single jurisdictions consisting of multiple spatial areas has the shortcoming that it either does not allow for varying stock sizes within areas (i.e., areas are modelled in binary terms: either invaded or not invaded) or restricts removal of invasions in a given area to complete eradiction only (Carrasco et al., 2010a; Finnoff et al., 2010; Epanchin-Niell and Wilen, 2012; Epanchin-Niell et al., 2012). Restricting removal of the invasive population to complete eradication only is particularly problematic in the marine context because marine invasions can very rarely be eradicated (Vitousek et al., 1997).

The binary restriction (areas are modelled as either invaded or not invaded) limits modelling richness as it excludes within-patch density dependence of damages. Further, the binary restriction limits the set of potential management options. When patches are

Abbreviations: IAS, Invasive Alien Species; NR, No Removal; PR, Partial Removal; FR, Full Removal; IE, Immediate Eradication.

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either invaded or not invaded, the set of management options in terms of reducing the size of the stock is restricted to doing nothing or completely eradicating the invasion in that area. This precludes the identification of optimal management policies which maintain an intermediate invasive population in a given patch.

We therefore construct a model which allows for varying stock sizes in patches and removal of any amount of the population from any patch (cf. Salinas et al., 2005; Burnett et al., 2007), as opposed to being invaded or non-invaded in a binary sense (as in Epanchin-Niell and Wilen, 2012; Chadès et al., 2011), in a single jurisdiction setting. Additionally, we allow for a second intervention which we term containment. Containment reduces the probability of spread between patches without affecting the population size within the patch. This paper therefore builds on Burnett et al. (2007), who consider varying population size within patches (but do not allow for measures to directly contain the spread of the invasion) by allowing for a containment intervention, such as employed by Sharov (2004).

Allowing for varying stock sizes in patches increases the dimensionality of the problem. In a network of two patches which can only be invaded or non-invaded there are only four possible states. However, if a patch can either be invaded, invaded at an intermediate population size, or fully invaded, (thus, three possible states for a given patch) then there are nine possible states for the network as a whole. Thus, the computational burden of modelling more complex systems can quickly become problematic. This burden is further increased by our use of two interventions; removal and containment. In this paper, we consider the case of a one-dimensional network, which limits the increased computational burden resulting from varying population size within patches. A one-dimensional network consists of a series of patches connected in a line. Chadès et al. (2011) refers to such a spatial arrangement as a line network and employs line-networks to analyse invasive species management. A one-dimensional network consists of two end patches which are linked to only one other patch, and all other patches are linked to only two other patches such that all the patches, visually, form a line. A one-dimensional network is therefore fully defined by the number of patches. We assume that an invasion can only spread between patches for which there is a connection. Hence, if there are three patches with Patch 1 and 3 as the end patches and Patch 1 is invaded, then Patch 3 can only become invaded after Patch 2 is invaded.

Invasions spreading in coastal and riparian systems are suitable to be modelled as one-dimensional networks. The modelling approach of this study is influenced in particular by two cases; that of the Pacific Oyster (*Crassostrea gigas*) in the Wadden Sea and the Chinese Mitten Crab (*Eriocheir sinensis*) in European rivers. The Pacific Oyster can affect commercial mussel yields and cause injury to recreationists due to its sharp shells (Troost, 2010). Further, the increase in substrate which may result from Pacific Oyster invasions can form a platform for the establishment of future invasions of other species (Haydar and Wolff, 2011). Barriers to spread between parts of the Wadden Sea exist due to the presence of tidal basins. Tidal basins are systems of coastal currents which form a barrier to the spread of the Pacific Oyster larvae and thus the spread of the invasion through the Wadden Sea (Kraft et al., 2010). The Chinese Mitten Crab causes damage to manmade structures such as flood defences via burrowing, damages nets and traps by feeding on the fish caught within them and increases the competition for food with native species (Herborg et al., 2003). In riparian habitats, the spread of the Chinese Mitten Crab can be impeded by installing traps at weirs (Herborg et al., 2003), although, this method is not totally effective at preventing further spread.

The two case studies considered above share a common theme: that of barriers to spread. Barriers to spread imply that the rate at which patches are invaded is not constant. Instead it depends on the invasive population size in adjacent patches. The model therefore employs a stochastic spread process as an intuitive way to link the size of the invasion within a given patches to the probability of spread to an adjacent patch. Such a relationship can be conceptualised in two ways. Firstly, a stochastic spread processes conforms to the principle of propagule pressure, whereby the probability of a species becoming established in a new patch increases with the number of arrivals (Kolar and Lodge, 2001). Hence, a greater population in one patch leads to a great number of arrivals in a connected patch, and thus that the probability of successful establishment of the invasion in the new patch increases. Alternatively, a greater population in an invaded patch implies a greater number of possible attempts to cross the barrier, and thus a greater total probability of success.

In order to analyse optimal control of IAS with varying stock size within patches, we construct a model which is solved using Stochastic Dynamic Programming. We assume that it is always possible (if not necessarily optimal) to remove all or some of an invasion in specific patches. In practise then, the invasion can be harvested or destroyed in a given patch. We do not assume that there are always feasible methods to restrict the ability of the invasion to spread. For example, it is difficult to conceive a realistic containment technology to limit the spread of Pacific Oyster spat between tidal basins. It is however, reasonable to attempt to trap invasive Chinese Mitten Crab as they cross a weir. Therefore, unlike Epanchin-Niell and Wilen (2012), we do not assume that the spread can be prevented with certainty, rather that the probability of spread can only be reduced.

We construct a generalised model of N patches in one-dimensional space. Under the assumption that the invasion always arrives at one end of the line network, and spreads patch by patch through the network, a two-patch model is sufficient to analyse the optimality of removal, containment and combining both removal and containment. Two-patch models have been shown to provide useful insights in related settings by Salinas et al. (2005) and Sanchirico et al. (2010). We explore the effects of heterogeneity of damage costs between patches and the costs of interventions on optimal policies and thus demonstrate the added value from considering varying stock size within patches. We proceed to demonstrate how the invasion grows with, and spreads between, patches in a three-patch system under the optimal policy. This also demonstrates the generalisability of the modelling approach to larger systems.

2. The model

We consider the spread of an invasive species over time, indexed t, in a line network, with N patches, indexed by i. The state of the system in a given time period is described by the size of the invasion in each patch and is given by $\mathbf{S}_t = \left[s_{1,t}, s_{2,t} \ldots, s_{N,t}\right]$. The values which $s_{i,t}$ can take (stock sizes) are determined by the set of values in the vector $\mathbf{Q} = [q_1, q_2, .., q_M]$ such that $s_{i,t} \in \mathbf{Q} \forall i, t$. The final element of $\mathbf{Q}$, q_M, is the maximum possible size of the stock in any given patch. Because we use a discrete approach, M gives the number of different values which stock in a given patch can take. Where j indexes the elements of $\mathbf{Q}$, the properties of $\mathbf{Q}$ are, firstly, $0 \le q_j \le 1$ and secondly, $q_1 = 0$. The second property means that if $s_{i,t} = q_1$ then $s_{i,t}$ is non-invaded.

The stock within a patch increases deterministically according to a vector, $\mathbf{G} = [g_1, g_2, .., g_M]$. As described above, the state of any patch is equal to an indexed element of $\mathbf{Q}$. If the current stock size of a given patch is equal to the jth element of $\mathbf{Q}$ then the jth element of $\mathbf{G}$ gives stock size in the next period for that patch. To illustrate, let us consider the example of a single patch ($N = 1$) with state given by $s_t = 0.4$. Taking the example of $\mathbf{Q} = [0, 0.2, 0.4, 0.6, 0.8, 1]$, we see that $0.4 = q_3$. Hence, the jth element of interest is the 3rd element.

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