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SCENARIO ANALYSIS FOR SEEKING COST-EFFECTIVE MANAGEMENT USING A CELLULAR AUTOMATON-BASED MODEL OF INVASIVE SPECIES

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Abstract

In this study we evaluate and compare different invasive species management scenarios in order to investigate a cost-effective management strategy over space and time. Cost effectiveness matters because budget constraints limit the area that can be treated to mitigate the risk of invasion in any given year. The spatial nature of invasive species spread makes it important to effectively allocate budget resources to control spread over space and time. We develop and use a simulation model to examine and compare the affect of various management strategies on the pattern and extent of invasive species spread, as well as management costs. Our model is based on a biological model that captures the dynamic and spatial aspect of invasion, integrated with a spatially explicit dynamic decision tool. Our model explicitly integrates the tradeoff between management intensity and management cost, and quantifies this tradeoff, which is important information for allocating management efforts efficiently and effectively over space and time.

Keywords: Invasive species, Spatial and dynamic model, Simulation model, Management costs

Özet

Bu çalışmada değişen zaman ve mekan koşullarında düşük maliyetli bir yönetim stratejisi araştırmak amacıyla farklı istilacı türlerin yönetim senaryoları karşılaştırılıp değerlendirilmiştir. Düşük maliyet önemlidir çünkü, yıllık bütçenin kısıtlı olması, istilacı türlerin yayılma riskinin hafifletileceği alanı sınırlar. İstilacı türlerin mekansal dağılımcı doğası, bu türlerin zamansal ve mekansal dağılım hakimiyetlerinin kontrolünü sağlayabilmek için, bütçenin etkin bir şekilde paylaşımını / kullanılmasını önemli kılmaktadır. Bu çalışma kapsamında geliştirilen benzetim modelini kullanılarak farklı yönetim stratejilerinin istilacı türlerin yayılma düzeni ve büyüklüğü üzerindeki etkisi ve bunun maliyeti irdelenip karşılaştırılmıştır. Geliştirilen model, istilanın gidişatını enerjisi ve boyutu açısından algılayabilen bir biyolojik model esasına dayanmakta ve istilanın mekansal – zamansal değişmine uygun etkin karar mekanizmasına sahiptir. Model; zaman ve mekan içindeki yönetim etkinliklerinin verimli ve etkili tahsisi için önemli bilgi olan yönetim yoğunluğu ve yönetim maliyeti arasındaki değişimi net bir şekilde entegre eder ve bu değişimi sayısallaştırır.

Anahtar Kelimeler: İstilacı türler, Konumsal ve dinamik model, Simülasyon modeli, Yönetim maliyetleri

INTRODUCTION

The entry, establishment, and spread of invasive species often result in loss of biodiversity and associated economic damage. Worldwide, Pimentel et al. (2001) estimate the damage at more than US$ 1.4 trillion per year. Furthermore, some invasive plants increase the risk of other ecosystem disturbances, such as fire (Knick and Rotenberry 1997). Cost effective management of invasive species is therefore an important global issue, especially when limited resources are allocated for such management. Generally speaking, there are three approaches for invasive species management—prevention, eradication, and control. Although prevention is generally more cost-effective than eradication and control (Mack et al. 2000; Leung et al. 2002), relying exclusively on prevention is not realistic because there are so many potential invasion pathways (Mehta et al. 2007) and it is often too late for this option to be applied (Taylor and Hastings 2004). Eradication is effective at the initial stages of invasion, but to be cost-effective early detection is required (Rejmánek and Pitcairn 2002; Mehta et al. 2007), which is quite challenging in many cases. Landscape-level control and containment appear to be a more appropriate and effective goal in cases where invasion has already occurred to some extent (Menz and Auld 1977; Lodge et al. 2006). In this study we focus on "control & containment," emphasizing efficient control of existing invasion to mitigate extensive damage.

Once invasive species establish, they cause additional damage over time by spreading to neighboring areas. However, the use of appropriate management strategies can control the rate of spread or temporarily halt additional establishment (Sharov, 2004; Williams et al., 2007; Alofs and Fowler, 2010). Barrier zones, or management areas located partially or directly adjacent to the invasion front intended to modify the spread rate (Sharov, 2004), are one commonly employed containment strategy. Because the spatial arrangement of management efforts affects the spread of invasive species over time, it is necessary to explicitly address the spatial and dynamic aspects of invasion risk management when developing an efficient and effective management strategy. Methods for projecting the spread of invasive species have been developed in the field of ecology, as have a number of spatially explicit dynamic spread models (Collingham et al. 1996; Cannas et al. 1999; Marco et al. 2002; Cannas et al. 2003; Murphy et al. 2008; Mercader et al. 2010). Recently, there have been several studies that simulate different management strategies to evaluate and compare the effectiveness of those based on a spatially explicit model (Wadsworth et al. 2000; Grevstad 2005; Carrasco et al. 2010). Other studies (e.g., Konoshima et al. 2008; Konoshima et al. 2010) have looked at disturbance agents, such as fire, that have a spatial impact across the landscape. These studies have explored optimal management regimes to mitigate fire risk by considering spatial and dynamic fire spread mechanisms. However, few studies have considered the influence of spatial management on the spread of invasive species (Vilà and Ibàñez 2011) and there is a need to explore management strategies that consider spatial spread patterns (Grevstad 2005).

Despite this ongoing work in the field of ecology, there are still few studies that use a dynamic and spatially explicit modeling framework to identify cost-efficient management strategies. The current study bridges this gap by integrating the latest findings from these ecological studies with a dynamic decision making tool. We examine various control strategies with differing intensity levels to explore the tradeoff between management cost and the spread of invasive species. We test management zones of varying width to represent different management intensity levels. Establishing smaller, narrow management zones will cost less, but may be inadequate to mitigate damage. On the other hand, it is costly to extend management areas far from the invasion front. This dilemma is highly relevant to land management agencies and policy makers faced with developing cost-effective long-term management programs. Because a management zone should be adjusted in response to movement of the invasion front (Sharov, 2004), we simulate management decisions using a dynamic decision making framework. This approach allows for an adaptive management strategy that considers the current spread pattern when developing a management zone to control future spread.

This paper is structured as follows: In Section 2 we describe our modeling approach. In Sections 3 we analyze and show our simulation results using relatively simple examples that illustrate important general features of a cost-efficient management strategy. Section 4 contains concluding remarks.

METHODS

Our integrated model explicitly considers spatial management activities and their affect on the spread pattern of an invasive species. By addressing the interactions between management activities and spread pattern, we can explore spatial tradeoffs and search for the most cost-efficient management strategy.

Dynamic spatial decision making aspect

We develop a cell-based model that captures interactions between spatial management activities and the spread of invasive species. Developing a model that considers the affect of spatially allocated management activities on the risk of invasive species spread is important because the risk in one area is not independent from management activities in adjacent areas. The model must also include a dynamic decision making framework because each year`s management decisions should reflect the current invasion condition, adjusting management zones in response to shifts in the invasion front over time.

Our study assumes a homogeneous landscape where an invasive species has recently established. These assumptions isolate the impact of other factors (e.g., topography), allowing us to examine the affect spatial management allocation has on the pattern and extent of invasive species spread. Thus, we can evaluate only those costs associated with varying management intensity levels. We assume the land manager seeks to control and contain the spread of invasive species. To reduce the rate of spread at the beginning of every management period t , the land manager can assign treatment to both invaded cells, as well as non-invaded cells (adjacent areas that have not been invaded), based on the invasion pattern observed in period $t - 1$. Various control methods, such as pulling seedlings, removing adult plants by mowing, or applying herbicides, can be considered to control the spread of invasive species (Taylor and Hastings 2004). Because this study focuses on the impact of the spatial allocation of management activities on spread pattern, we assume the manager implements only one control method in a management zone. In our cell-based model, each management unit is represented by a single cell; thus, a management zone consists of a set of cells where a single control method is implemented.

In this study, we consider eight different management zone widths around each invasion cell (Figure 1). We evaluate and compare the level of invasion and management costs associated with each of these eight management strategies, which also represent different management intensity levels. Management cost is based on a fixed rate per unit of area; thus, the cost of each management strategy is based on the total area managed during the planning period.

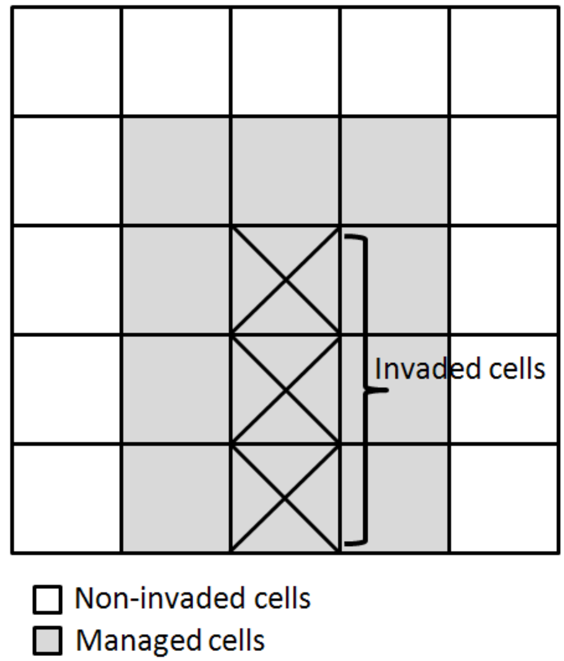

Figure 1: Management zone

Invasive species spread model

Our invasive species spread model is based on a model developed by Marco et al. (2002) and Cannas et al. (2003). We rebuild their model using Visual C++ TM 8 (Microsoft Corp., 1995) so that we can evaluate the effectiveness of various spatial management strategies. Because their model has already been described in detail (see Marco et al. 2002 and Cannas et al. (2003), we will only provide a brief overview.

Marco et al. (2002) and Cannas et al. (2003) considered life history traits relevant to species dynamics. Using field values corresponding to invasive species in their study area, they developed a cellular automaton model that projects the spread of invasive species over time. For our analysis we choose to use parameters reflecting the life history traits of the invasive species honey locust (*G. triachanthos*), which are outlined by Marco et al. (2002) and Cannas et al. (2003), and summarized in Table 1.

According to Marco et al. (2002) and Cannas et al. (2003), the probability of colonization at cell i is defined as follows:

$$p_i = 1 - (1 - P_s \times f_g)^{s_i}$$

Where s_i represents the number of seeds received by the cell i .

$$s_i = n \times g_i$$

Where g_i is a function of 1) the spatial location of the i^{th} cell, 2) the mean seed dispersal distance and, 3) the age of the species. When species in adjacent cells reach reproductive maturity, g_i in period t, $g_i(t)$ assumes a non-zero positive value. Figure 2 shows the relation between g_i and the distance from an invaded cell.

Table 1: Summary of the variables representing the life history traits of *G. triachanthos*.

Parameter	Description	Value
d (lattice units)	mean seed dispersal distance	3
t_{max}	maximum longevity	75
q	annual adult survival probability	0.96
t_m	age of reproductive maturity	7
n	mean seed production	14000
t_s	interval between masting seed crops	1
f_g	average age of saplings	0.2
P_s	juvenile survival probability	0.4
t_j	average age of saplings in the juvenile bank	5

Although Marco et al. (2002) and Cannas et al. (2003) modeled a complex mechanism of multiple species interactions, we focus on the spatial spread mechanism of a single invasive species. We extend their model to examine the interaction between spread patterns and the spatial aspect of management, assuming the implementation of a management zone slows the invasion rate (Sharov, 2004). Sharov and Liebhold (1998a) used historical data from the Appalachian Mountains to show that installing barrier zones reduced the average rate of spread by about 50-60%. In this study, we modify the parameter value related to the spread rate—the mean seed dispersal distance—assuming implementation of a management zone (management in a cell) shortens the dispersal distance (d) by 50%.

Simulation

For the purposes of this study, we use a hypothetical landscape consisting of 40,000 cells (200 by 200), each 5m square, managed by a single individual over 10 planning periods. The manager assigns one of the following eight management strategies, which create management zones of varying widths:

1) No Management (No-M)
2) 2-cell management zone (M2): A management zone 2 cell widths
3) 4-cell management zone (M4): A management zone 4 cell widths
4) 6-cell management zone (M6): A management zone 6 cell widths
5) 8-cell management zone (M8): A management zone 8 cell widths
   10-cell management zone (M10): A management zone 10 cell widths
6) 12-cell management zone (M12): A management zone 12 cell widths
7) 14-cell management zone (M14): A management zone 14 cell widths

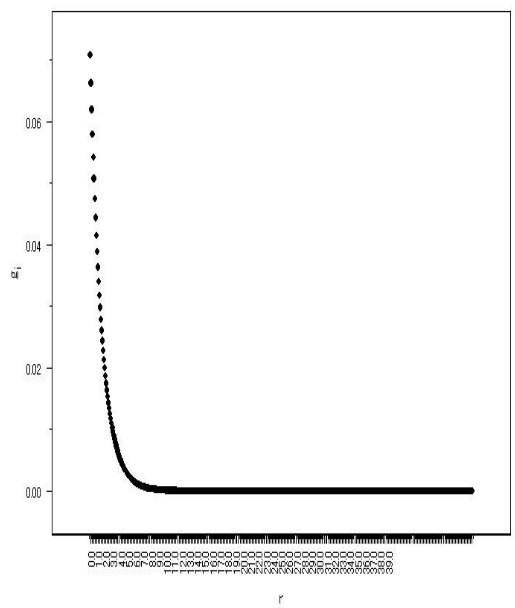

Figure 2: Relation between g_i and the distance from an invaded cell.

These strategies apply a management zone of the specified width to both invaded cells and non-invaded cells (adjacent areas that have not been invaded), reducing the spread rate when an invasive species enters the management zone. In our simulation we assume an invasive species invades and establishes from the left bottom corner of the landscape. We generate a random variable p_i^u from a uniform distribution of 0-1. If $p_i > p_i^u$, then the i^{th} cell will be invaded and colonized.

SIMULATION RESULTS

Invasive Species Spread

We evaluate and compare different spatial management strategies and the resulting spread patterns. Figure 3 shows the spread patterns at the end of the planning period. Figure 4 shows changes in the number of invaded cells over time for the eight different management strategies for one iteration of the simulation. In our simulation, if no management strategy is assigned during the 10-year planning period, more than 40% of the landscape is invaded at the end of the period (Figure 4). If the most intensive 14-cell management strategy is applied, the invaded area can be contained to the smallest of all strategies tested—about 10% of the landscape—over the planning period. Our simulation results show that applying a wider management zone can more efficiently contain the invasion front during each period. However, when the width of a management zone exceeds 10 cells, there is no appreciable difference among scenarios (the 10-, 12-, or 14-cell scenarios).

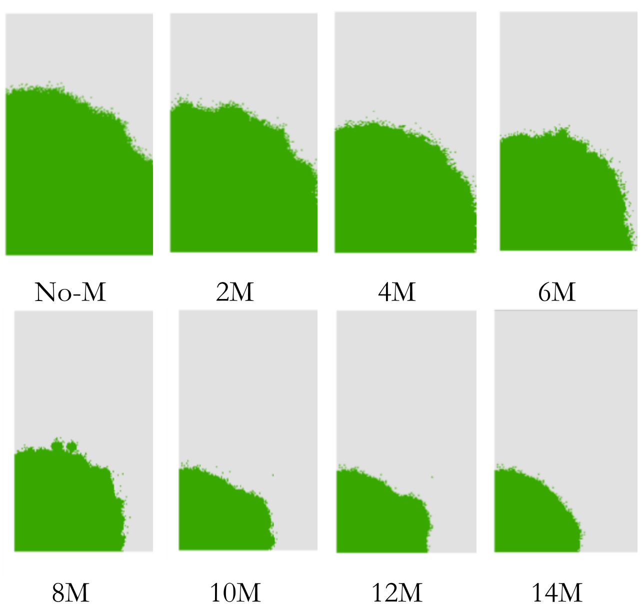

Figure 3: Spatial spread patterns for different management strategies at the end of the planning period

Management Cost

Figure 5 compares the number of management cells among the eight different strategies. If the "do nothing" strategy is applied, the number of managed cells during the planning period is zero. We can compare management costs by evaluating the number of management units, assuming a fixed cost for each cell. The greater the number of managed cells, the greater the cost. In our simulation setting, as Figure 5 shows, the 2-cell management strategy was most costly, followed by the 4-cell, the 6-cell, and the 8-cell. Less intensive management strategies (applying narrower management zones) are not as effective at containing the invasion in each period—comparatively more cells were invaded. As a result, the invasion front expanded more rapidly, requiring the addition of more management cells to maintain the narrower barrier. On the other hand, in our simulation setting, applying more intensive strategies (the 10-, 12-, or 14-cell scenarios), which result in wider management zones, costs more initially (Figure 5), but effectively minimizes the number of cells invaded in each period. As a result, fewer management cells are needed overall to maintain the prescribed (wider) barrier zone.

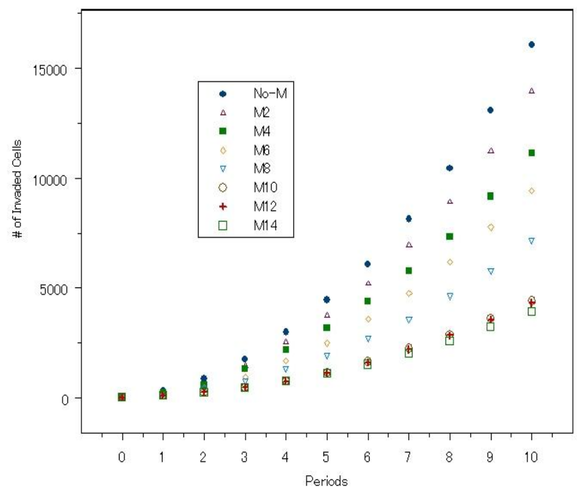

Figure 4: Changes in the number of invaded cells over time for the different management strategies for one iteration of the simulation.

CONCLUSIONS and DISCUSSION

Given the threat posed by invasive species and limited resources for mitigation activities, identifying and implementing cost-effective management strategies is of utmost importance. This study was designed to enrich our understanding of efficient spatial allocation of management activities to mitigate the damage caused by invasive species. We evaluated and compared different invasive species management scenarios in order to investigate a cost-effective management strategy over space and time using a model that explicitly considers the spread mechanism of invasive species. Our model was developed by integrating a dynamic decision making tool with the latest knowledge in the dynamic and spatial growth of invasive species.

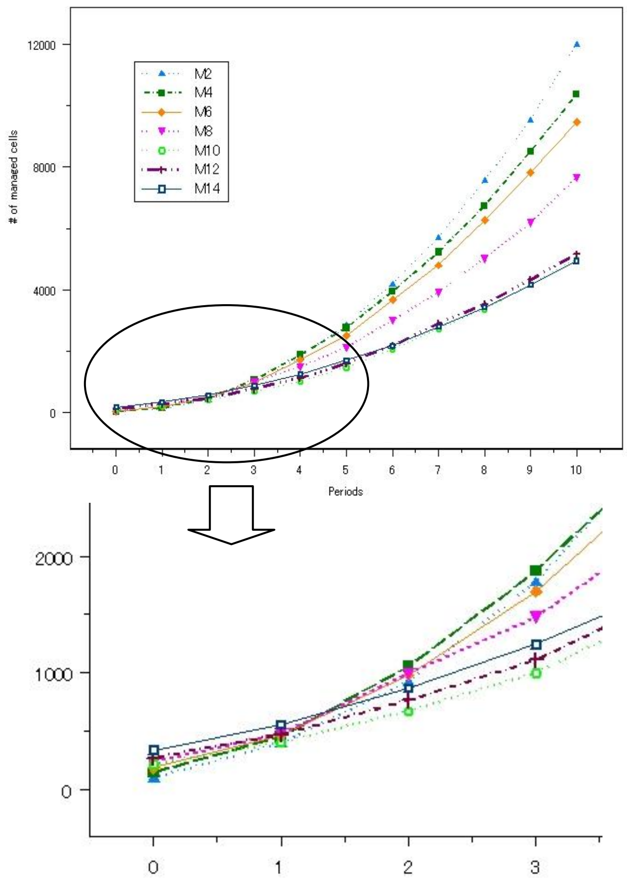

Figure 5: Changes in the number of management cells over time for the different management strategies

The distinctive characteristic of our model is that it addresses interactions between management activities and the risk of invasion in a spatially explicit and dynamic manner by modeling periodic responsive actions to the previous period`s spread pattern. This approach captures important trade-offs for achieving cost-effective management. In our simulation setting, our simulation results show that applying a wider management zone may prove cost-effective because they more efficiently contain the invasion front during each period. As a result, fewer management cells are needed overall to maintain the management zone and slow the spread rate. This simulation results imply that if a land manager fails to apply management at an appropriate level of intensity, he or she may waste money for little mitigation effect. However, our simulation also suggests there is an optimum management intensity level (i.e., a 10-cell management zone), above which there is little additional benefit. Our simulation results indicate that in order to effectively and efficiently control invasive species with management zones, it is important to consider trade-offs between management intensity and management cost over time.

Although our framework uses a hypothetical landscape consisting of 40,000 cells of equal size and shape, and we make other simplifications, the model captures important interactions between management activities and the spread of an invasive species in a spatially explicit and dynamic manner. One potential next step could be to consider and model long distance dispersal, which might occur rarely (With 2002; Epanchin-Niell and Wilen 2011) but could cause rapid, global expansion of invasive species (Cannas et al. 2006; Williams *et al.*, 2007). Currently, an increasing number of studies (Pearson and Dawson 2005; Cannas et al. 2006) are attempting to model long distance dispersal, but making accurate measurements has proven difficult (Williams and Wardle 2007); more work is needed in this area (Cain et al. 2000). Combining a dynamic decision tool with a model that simultaneously considers both short distance invasion and long distance dispersal could improve our understanding of efficient and effective invasive species management strategies.

Evaluating and comparing additional spatial management patterns could be another useful extension. Our study considered only eight different strategies based on varying management zone width. In a future study, we plan to integrate a cell automaton and an optimization model. This approach will allow us to evaluate and compare a broader range of spatial management allocation patterns to find an optimal management strategy that minimizes spatial expansion based on a given budget constraint. Such coupling models have only recently been developed and studied for invasive species management (Haight et al. 2011; Epanchin-Niell and Wilen 2011). Our simulation results highlight the importance of using a dynamic decision tool to explore the most cost-effective overall management strategy. In addition to providing a foundation for land managers to develop a cost-effective management zone over space and time, our model also provides a basis for designing a coupling optimization model.

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