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The design of nature reserves in the face of habitat loss

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ABSTRACT

When designing nature reserves, it is very difficult to find an intact landscape because of the prevalence of habitat loss. The FLOMS debate – should we have Few Large Or Many Small reserves – is a focus of the design of nature reserves. Thus, habitat loss may greatly influences the FLOMS debate. Selecting the given area of suitable habitats from the center of a fragmented landscape (caused by habitat loss), we present a theoretical model and Cellular Automata simulation is used to investigate whether several large or many small reserves should be established in these suitable habitats. The results suggest that if the environmental carrying capacity is high, many small reserves are optimal; if it is low, several large reserves are optimal. When the carrying capacity is intermediate, the effects of both habitat loss and migration must be considered, and the following apply. (1) If migration is not allowed between reserves, several large reserves are better. (2) If migration is allowed between reserves and habitat loss is not severe, many small reserves are optimal. (3) If habitat loss is severe, few large reserves are beneficial, regardless of whether migration exists between reserves. (4) Increasing the migration mortality rate tends to favor the implementation of several large reserves.

1. Introduction

As habitat loss increases, the survival of some valuable species, such as the giant panda and tiger, is becoming increasingly challenged. Nature reserves are attracting increasing attention as a tool for protecting valuable endangered species (Soule, 1991; Cuonga et al., 2017; Gong et al., 2017). When designing nature reserves, some important issues must be considered, including whether several large or many small reserves are optimal (Diamond, 1975; Soule and Simberloff, 1986; Wilson and Willis, 1975). And it is the famous FLOMS debate.

In the mid-1970s, six rules for reserve design were proposed (Diamond, 1975; May, 1975). The first of these rules stated that when the area is fixed, one large reserve is optimal (Terborgh, 1974; Wilson and Willis, 1975). However, after the mid-1970s, these rules were questioned, and the FLOMS debate became a focus of ecologists, biogeographers and conservationists for the next 40 years (McCarthy et al., 2005, 2011; Dapporto and Dennis, 2008; Baker et al., 2013; Lindenmayer et al., 2015). Ecologists, biogeographers and conservationists have conducted a large number of empirical and theoretical studies to investigate the FLOMS debate (Gilpin and Diamond, 1980).

The results of these studies have been varied and contradictory. Some results indicate that a few large reserves are most beneficial for species conservation (Burkey, 1995, 1997; Tjørve, 2010; McCarthy et al., 2011), whereas others indicate that many small (Honnay et al., 1999; Robert, 2009; Baker et al., 2013; Lindenmayer et al., 2015), an intermediate number (Lomolino, 1994; Etienne and Heesterbeek, 2000; Ovaskainen, 2002; Zhou and Wang, 2006), a mixed selection of several large and many small (Schei et al., 2013), or many small or an intermediate reserves (Roux et al., 2015) are most beneficial. Furthermore, some results suggest that the optimal reserve number increases with the environmental carrying capacity (Quinn and Hastings, 1987; Reed, 2004). Owing to the varied objectives and methods of these studies, no coherent conclusion has been drawn, and the FLOMS debate is still unresolved. However, the results show that the optimal reserve number is case specific and depends on several factors, such as the environmental carrying capacity, the extent of migration, and the extent of disturbance (Etienne and Heesterbeek, 2000; Ovaskainen, 2002; Robert,

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2009; Lindenmayer et al., 2015). Several additional factors may also greatly influence the FLOMS debate, such as the extent of habitat loss and the shape of individual nature reserves. However, the influences of these factors have not been well studied. Therefore, an exploration of the influences of these factors may be very useful.

With social and economic development, humanity has changed the world greatly, and habitat loss has become a common phenomenon. When establishing nature reserves, habitat loss has become an increasingly important issue (Johnstone et al., 2014; Barredo et al., 2016; Heinrichs et al., 2016), as it is very difficult to find intact regions in which to establish nature reserves because of the prevalence of habitat loss. Therefore, habitat loss influences the design of nature reserves. Several studies relating to habitat loss have been conducted that explore the effects of other factors on the FLOMS debate, such as migration and environmental carrying capacity (Pelletier, 2000; Reed, 2004; Robert, 2009). However, these studies are based on the assumption that the proportion of lost habitat within the region remains constant or changes with the number of reserves; therefore, they are limited in their generalizability. Therefore, an exploration of the effect of habitat loss is urgently needed and can help resolve the FLOMS debate.

Species migration also may be important for the FLOMS debate. Species migration between different reserves can increase the viability of species through demographic and genetic rescue (Richards, 2000) while helping species to tolerate environmentally induced fluctuations in population size. In addition to having positive effects, migration may also affect species negatively by introducing disease or parasites (Harding and McNamara, 2002). Even without considering diseases and parasites, previous works still offer two opposing conclusions regarding the effects of migration on species viability. The majority of results suggest that migration increases the viability of species (Gonzalez et al., 1998; Debinski and Holt, 2000), whereas others have found the opposite result (Quinn and Hastings, 1987; Burkey, 1997). One possible reason for this difference is that migration has two opposing influences. In small populations, migration has a "rescue effect", which is beneficial to the species; however, migration mortality increases the overall population mortality rate, which is detrimental to the species. If the migration mortality rate is low, the positive influence of migration may outweigh the negative one such that the net effect of migration is beneficial to the species; however, if the migration mortality rate is high, the negative influence of migration may outweigh the positive one. However, there are no sufficient evidences to support or negate this hypothesis. Thus, the effect of migration on endangered species' dynamics is important and urgently needed. And nature reserves are one important tool for species conservation (Soule, 1991) and the FLOMS debate is a focus of the design of reserves, thus species migration may greatly influence the FLOMS debate. Pelletier (2000) suggests that when no migration is allowed between reserves, many small, equally sized reserves are the optimal geometry, whereas when migration is allowed, the optimal geometry is a single large reserve when the migration mortality rate is high and a self-similar distribution when the migration mortality rate is low. However, Pelletier (2000) does not explore the influence of migration rate on the FLOMS debate, and studies that test these hypotheses are lacking.

To address the issues described above, we build a computer simulation model to systematically investigate the influences of habitat loss and migration on the FLOMS debate.

2. Model

The model description follows the Overview, Design concepts, Details protocol (ODD) for describing agent-based models (Grimm et al., 2006, 2010).

2.1. Purpose

In a fragmented landscape (caused by habitat loss), we select a region from the center of landscape, so that the area of suitable habitats in the region is fixed and constant, which means the selected region should be larger if habitat loss is severer. For these suitable habitats, a model is used to systematically investigate whether few large or many small reserves (the FLOMS debate) should be established.

2.2. Entities and state variables

The selected region includes two types of areas: suitable habitats and lost habitats, and all suitable habitats are established as reserves. The model contains three types of entities – reserves, local populations and lost habitats. Every reserve is characterized by its environmental carrying capacity and its $I-$ and $J-$ coordinates. The individuals living in a reserve are regarded as a local population, and thus every local population can be also characterized by its population size and the $I-$ and $J-$ coordinates of reserve. Every lost habitat is characterized its $I-$ and $J-$ coordinates.

2.3. Process overview and scheduling

The model is implemented as a discrete-event dynamical system representing a discrete-time process. Within every time step (Fig. 1), the environmental carrying capacity of every reserve grows; every local population grows; every reserve is affected by disturbance (disturbance rate, μ), where disturbance will affect the environmental carrying capacity and the local population living in the reserve; and some individuals in every reserve may migrate to neighboring reserves. If the number of individuals in all of the reserves is less than a (the minimum number of individuals of a species that it can save from extinction), then the species is considered extinct (see Submodel section below for details).

2.4. Design concepts

As we assume there is fixed land suitable that can be distributed among several large or many small reserves, the total area of reserves are given and constant. Reserves are not identical in environmental quality, area and geometry; however, here we assume that all of the reserves are identical with regard to these traits. And we assume the initial, local populations in reserves are also identical.

The species extinction probability is the standard of whether several large or many small reserves should be established. We should obtain the optimal reserve number associated with the minimum species extinction probability, then obtain the area of every reserves by the optimal number of reserves because the total area of reserves are given and constant and all reserves are identical in their area. According to the optimal number of reserves and the area of every reserve, we can determine whether several large or many small reserves should be established. We divide the suitable habitats into N_2 (N_2 should range from one to many) reserves, and 10,000 independent replicated simulations were run. For every N_2, the species extinction probability was estimated from these 10,000 independent replicated simulations as the ratio of the number of simulations where the protected species went extinct to the total number of simulations (i.e., 10,000). We then obtained the optimal reserve number associated with the minimum species extinction probability.

The stochasticity of the model involves two components of the model. One is disturbance events, wherein every reserve is affected by disturbance (disturbance rate, μ); the other is reserve location, which is randomly selected for every reserve. For observing the