Defining the Area-Number Pattern for Establishing Protected Areas in Fragmented Landscapes (Postprint)

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Abstract

Owing to increasingly severe habitat loss, it has become difficult to locate pristine habitats for the establishment of nature reserves; consequently, the impacts of habitat loss must be addressed in protected area design. On a landscape that has already experienced habitat loss, a square region is selected and its area is adjusted to ensure that the area of intact habitat within it remains a fixed constant, in order to investigate whether to configure the intact habitat as numerous small protected areas or a few large protected areas. The results demonstrate that: (1) Under random habitat loss, the higher the proportion of habitat loss, the more pronounced the advantage of the few large protected areas strategy. (2) Even when the proportion of habitat loss is held constant, the spatial distribution pattern of the lost habitat exerts a significant influence—the greater the degree of spatial clustering of the lost habitat, the more pronounced the advantage of the numerous small protected areas strategy. (3) Increasing the dispersal rate or decreasing the dispersal mortality can induce a transition from a scenario where few large protected areas are more beneficial for species to one where numerous small protected areas are more beneficial, and the greater the degree of clustering of the lost habitat, the larger the magnitude of this transition. These conclusions provide a theoretical foundation for nature reserve design.

Full Text

Preamble

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Defining the Area-Number Pattern for Nature Reserves in Fragmented Landscapes

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Abstract

As habitat loss increases, the survival of valuable species such as the giant panda and tiger is becoming increasingly challenged. Nature reserves are attracting increased attention as tools for protecting valuable endangered species. When designing nature reserves, important issues must be considered, including whether several large or many small reserves are optimal—which represents the famous few large or many small (FLOMS) debate. In a fragmented landscape, we selected a region from the center of the landscape and adjusted the area of the region so that the area of suitable habitats within it is fixed and constant. As such, the selected region should be larger if habitat loss is more severe. Subsequently, we explored whether several large or many small reserves should be distributed over these suitable habitats.

The results suggest that: (1) For random habitat loss, when the proportion of lost habitats is 0.2, the optimal reserve number is more than 170. As the proportion of lost habitats increases, the optimal reserve number also decreases sharply, and when it reaches 0.9, the optimal reserve number is less than 20. Because the area of every reserve is in inverse proportion to the number of reserves, when random habitat loss occurs, increases in the proportion of lost habitats tend to favor the implementation of several large reserves. (2) If the proportion of lost habitats is fixed and the degree of clustering of lost habitats is low, then the optimal reserve number is small. As the degree of clustering increases, the optimal reserve number will also increase sharply, and when it is high, the optimal reserve number will also be high. As a result, although the proportion of lost habitats is constant, the spatial distribution of lost habitats also greatly affects the FLOMS problem. In addition, increases in the degree of clustering of lost habitats tend to favor the implementation of many small reserves. (3) When the diffusion rate was 0, the optimal reserve number is also low. As the diffusion rate increases, the optimal reserve number also increases. If the degree of clustering of lost habitats is higher, then a greater increase in the optimal reserve number occurs under an increasing rate of diffusion. When the diffusion mortality rate is 0.9, the optimal reserve number is low. As the diffusion mortality rate decreases, the optimal reserve number also increases. If the degree of clustering of lost habitats is higher, then a greater increase in the optimal reserve number will occur with a decreasing diffusion mortality rate. As a result, increases in the diffusion rate or decreases in the diffusion mortality will tend to favor the implementation of many small reserves. When the degree of clustering of lost habitats is higher, a greater increase in the optimal reserve number will occur with increasing or decreasing diffusion rate.

These findings can provide a theoretical basis for the FLOMS debate and endangered species conservation, and reinforce the importance of habitat loss, providing insights for natural environmental protection.

Keywords: FLOMS problem; endangered species conservation; habitat loss; individual diffusion

Introduction

Due to changes in living environments, many species are facing increasing survival difficulties. More seriously, numerous rare wild animals and plants are on the brink of extinction, such as *Panthera tigris altaica* and *Ailuropoda melanoleuca*. Protecting endangered species has become a research hotspot. As effective tools for protecting endangered species, nature reserves have attracted widespread attention from researchers. When designing nature reserves, several issues are particularly noteworthy: Should available habitats be developed into a few large reserves or many small ones? Should corridors be established between reserves to connect isolated reserves into a network? The first issue is the famous FLOMS (few large or many small) debate, also known as SLOSS (single large or several small).

Researchers have debated this issue for decades. Early studies suggested that a single large reserve pattern was more beneficial for species survival, forming several design principles for nature reserves. However, these conclusions were subsequently challenged. Some studies indicated that a few large reserves were advantageous for species survival, while others argued that many small reserves were more beneficial. Some researchers believed that an intermediate number of reserves was optimal, while others suggested that the optimal number increased with environmental carrying capacity. Despite numerous studies, no unified conclusion has been reached due to different research objectives and methods. Synthesizing all results only yields that the optimal number of reserves is determined by species characteristics and their environment, including environmental carrying capacity, individual diffusion, and environmental disturbance.

Many factors may influence the FLOMS problem, but previous studies have not deeply investigated habitat loss and its interaction with individual diffusion. Exploring these factors can help researchers understand how species characteristics and environmental conditions affect the FLOMS problem and promote its ultimate resolution. Habitat loss is not only the primary factor of species extinction but also makes it difficult to find intact landscapes for establishing nature reserves. Habitat loss has become an important factor affecting reserve establishment. Habitat loss can influence the FLOMS problem by affecting individual diffusion, population growth, and environmental disturbance. Individual diffusion may also significantly impact the FLOMS problem. While diffusion can help species avoid extinction, it may also introduce diseases or parasites, negatively affecting species. Regarding individual diffusion (excluding disease and parasite introduction), there are opposing views: most studies consider diffusion beneficial, while others consider it detrimental. The reason for these contradictory conclusions may lie in mortality during diffusion. If mortality is low, diffusion can help species avoid extinction; if mortality is high, negative effects may outweigh positive ones.

Despite extensive research, several shortcomings exist in previous studies. Although the spatial distribution pattern of destroyed habitats is non-random, previous studies have assumed it to be random. Individual diffusion may interact with habitat loss to affect species, but few studies have addressed this issue. Although habitat loss may have direct effects on the FLOMS problem, most research has only explored indirect effects. This paper addresses these gaps by examining both the direct effects of habitat loss proportion and how the spatial distribution characteristics of destroyed habitats affect the FLOMS problem.

1. Model

The model description follows the ODD (Overview, Design concepts, Details protocol) framework for agent-based models.

1.1 Purpose

Based on an agent-based model approach, this study investigates how habitat loss and individual diffusion affect the FLOMS problem. In a landscape that has experienced habitat loss, we select a square region and adjust its area to ensure the area of intact habitat within it remains a fixed constant.

1.2 Entities and State Variables

The selected region contains two habitat types: destroyed and intact. All intact habitats will be established as nature reserves. The model includes three main entities: destroyed habitats, reserves, and protected species living in reserves. Each reserve has a maximum sustainable carrying capacity and spatial location. Each reserve contains a local population, and some individuals from local populations can diffuse between reserves, linking them into a metapopulation. Each destroyed habitat also occupies a spatial location.

1.3 Process Overview

A discrete-time and discrete-space model describes the entire ecological process. Environmental carrying capacity and population size grow in each time step. Each reserve may be affected by disturbances. If at any step the total number of protected species individuals falls below a threshold a, the species is considered ecologically extinct and the simulation terminates. The disturbance rate is . Some individuals in local populations may diffuse to adjacent reserves.

[Figure 1: see original paper] Processes, scheduling and pseudo-code

1.4 Design Concepts

Because the total area that can be developed into reserves is constant, the total area of all reserves is fixed. Although in reality the area, shape, and environmental carrying capacity of each reserve and the size of each local population would not be identical, these differences are ignored. Each destroyed habitat has the same area and shape as a reserve. The optimal number of reserves is determined based on the extinction probability of the protected species—the reserve number corresponding to the minimum extinction probability is optimal. This also yields the area of individual reserves, allowing decision-makers to determine whether to build many small or few large reserves.

The intact habitat is divided into N reserves of equal area, where N ranges from few to many. For each N value, 1000 independent simulation experiments are conducted to obtain the species extinction probability. The extinction probability is defined as the number of simulations where extinction occurred divided by the total number of simulations. Each N value corresponds to a species extinction probability, revealing the optimal N where extinction probability is minimized.

In each simulation, changes in protected species population size and corresponding time points from initial to termination are recorded. Each reserve has a probability of being affected by disturbance, making disturbance a random event and the source of stochasticity in the model.

1.5 Initialization

A cellular automaton simulates the model, where each cell corresponds to a reserve or destroyed habitat. Reserve numbers vary from few to many. The cellular automaton has N reserves and D destroyed habitats, where D is the ratio of destroyed habitat cells to total cells. Since all reserves and destroyed habitats have equal area, D also represents the ratio of total destroyed habitat area to selected region area—the habitat loss proportion.

Because each reserve' s initial environmental carrying capacity is identical, the total initial carrying capacity for all reserves is K_{TOT}. Thus, the initial environmental carrying capacity of a single reserve is $K = K$_{TOT}/N. Local population sizes are initially identical, assumed to be half of the reserve' s carrying capacity.

The spatial distribution of destroyed habitats is determined by D and q_{E/E} (clustering degree). If a destroyed habitat' s neighbor is randomly selected and is also destroyed with probability q_{E/E}, then q_{E/E} represents the clustering degree. Higher q_{E/E} values indicate more concentrated destroyed habitat distribution and more clustered reserve distribution. Reserve locations occupy remaining positions after destroyed habitats are placed.

2. Species Model

[Figure 2: see original paper] Two types of nature reserve models. (a-e) Few large reserves model; (f-j) Many small reserves model. In each figure, gray cells are reserves, white cells are destroyed habitats, black lines represent boundaries, and the total area of all reserves is constant.

Environmental carrying capacity growth follows: K_{I(t+1)} = K_{I(t)} + r × K_{I(t)} × (1 - K_{I(t)}/K), where r is the growth rate. This logistic growth pattern means actual growth rate decreases as carrying capacity is approached.

Each reserve experiences disturbance with probability . When reserve I is disturbed:

K_{I(t+1)} = K_{I(t)} - d × K_{I(t)}
N_{I(t+1)} = N_{I(t)} - d × N_{I(t)}

where d measures disturbance impact.

Individuals can only diffuse to adjacent reserves (Moore neighborhood: eight neighbors) and cannot cross destroyed habitats. The number of individuals diffusing from reserve I to reserve J is:

M_{I→J} = × (1/D_{IJ}) × (1 - D_{IJ}/8) × N_{I(t)}

where is the diffusion rate, D_{IJ} is the distance between reserve centers, and the diffusion probability decreases with distance. Diffusing individuals face mortality during movement.

[Figure 3: see original paper] Individual diffusion between reserve A and other reserves (only diffusion from reserve A is shown). Gray cells are reserves, black cells are destroyed habitats. The proportion of individuals diffusing to closer reserves is higher.

3. Results

3.1 Impact of Habitat Loss on the FLOMS Problem

Random or non-random habitat loss significantly affects the optimal reserve number. Under random habitat loss, when habitat loss proportion increases, the optimal reserve number decreases sharply. For example, when loss proportion is 0.2, the optimal number exceeds 170; when loss proportion reaches 0.9, the optimal number falls below 20. Since reserve area is inversely proportional to reserve number, higher habitat loss proportions favor the few large reserves model.

If habitat loss proportion is constant but clustering degree (q_{E/E}) changes, the spatial distribution of destroyed habitats also greatly affects the FLOMS problem. When clustering degree is low, the optimal reserve number is small; as clustering degree increases, the optimal reserve number increases sharply. When clustering degree is high, the many small reserves model becomes more advantageous. Thus, even with constant habitat loss proportion, the spatial aggregation of destroyed habitats significantly influences the optimal strategy.

3.2 Impact of Diffusion

Diffusion rate and mortality also affect the FLOMS problem. When diffusion rate increases, the optimal reserve number increases. This effect is more pronounced when destroyed habitats are highly clustered (clustering degree 0.7). When clustering degree is low (e.g., 0.2), the increase in optimal reserve number is smaller. Therefore, increasing diffusion rate can shift the optimal strategy from few large reserves to many small reserves, with higher clustering degrees causing more dramatic shifts.

When diffusion mortality is high (e.g., 0.9), the optimal reserve number is low. As diffusion mortality decreases, the optimal reserve number increases, especially when habitat clustering is high. Thus, decreasing diffusion mortality also favors the many small reserves model, with the shift being more pronounced at higher clustering degrees.

[Figure 4: see original paper] Effect of habitat loss proportion and clustering degree of lost habitats on optimal reserve number ($r = 1$, K_{TOT} $= 2000$, $= 0.01$, $= 0.1$, $d = 0.2$, $a = 50$, $b = 1100$).

[Figure 5: see original paper] Optimal number of reserves changes with diffusion rate and diffusion mortality rate ($r = 1$, K_{TOT} $= 2000$, $= 0.01$, $d = 0.2$, $a = 50$, $b = 1200$; and $r = 1$, K_{TOT} $= 2000$, $= 0.016$, $= 0.1$, $d = 0$, $a = 50$, $b = 1200$).

4. Case Study

The giant panda once widely inhabited North China, South China, and even northern Vietnam and Myanmar. However, due to rapid population growth and increasing land demand, much panda habitat has been converted to cities and villages. Remaining habitats have been severely damaged by excessive logging, causing panda numbers to plummet and the species to become endangered.

Since the establishment of the Wolong Nature Reserve, China has created 67 panda reserves. National surveys show that wild panda numbers have rebounded to 1864. However, economic development around reserves, expanding rural areas, and increasing transportation infrastructure have caused further habitat loss and reduced spatial clustering. To address this, China plans to integrate 67 panda reserves into a Giant Panda National Park comprising three sections (Minshan, Qinling, and Baishuijiang) to strengthen biodiversity conservation centered on pandas.

This real-world example demonstrates that increased habitat loss and decreased spatial clustering lead to the integration of many small reserves into fewer large reserves, supporting our conclusion that the few large reserves model becomes optimal under these conditions.

5. Discussion

Habitat loss not only threatens many rare species with extinction but also fragments their habitats. While ecological restoration techniques can help recover some destroyed habitats, restoring all habitats is impossible. Therefore, reserve establishment must address problems caused by habitat loss. This study selected a region in a habitat-loss-impacted landscape, fixed the area of intact habitat, and explored whether to develop it into few large or many small reserves.

Key findings: (1) Habitat loss proportion and spatial distribution jointly affect the FLOMS problem. Higher habitat loss proportions favor few large reserves. (2) With constant loss proportion, higher clustering of destroyed habitats favors many small reserves. (3) Increased diffusion rate or decreased diffusion mortality can shift the optimal strategy from few large to many small reserves, with more dramatic shifts at higher clustering degrees.

Previous studies often assumed random habitat loss distribution, which contradicts reality where loss is non-random. They also focused on indirect effects of habitat loss while neglecting direct effects and interactions with diffusion. This study addresses these gaps using a cellular automaton model to examine combined effects of habitat loss and individual diffusion on the FLOMS problem.

Results provide theoretical foundations for biodiversity conservation and reserve design, enhancing understanding of how species respond to habitat loss and raising awareness for environmental protection. However, limitations remain: individuals can disperse both short distances to neighboring areas and long distances via corridors, and habitat loss may interact with both dispersal types to affect population dynamics. Additionally, while reserves often focus on flagship species, they typically contain multiple species requiring protection, which deserves further investigation.

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Note: Figure translations are in progress. See original paper for figures.