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# Integrating Metapopulation Theory into Management of Fragmented Butterfly Populations

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## Abstract

Loss of habitat and fragmentation is the main cause of reductions in butterfly populations and also decreases genetic diversity, dispersal, and increases extinction risk. Conservation efforts so far have not formally included understanding population dynamics such as space and time: continuation of these kinds of activities could increase the population level of conservation content to use in reduced habitat patches. This study uses metapopulation theory explicitly focusing on local extinction, colonization, and processes connectivity; in habitat fragmentation conservation we better understand the dynamics and can manage target populations. Habitat quality, patch size, and the distance between patches were modelled to predict persistence measures and identify priority patches for conservation interventions. The metapopulation approach is compared to traditional single population management actions whereby habitat management only or habitat quality alone, for example, with an increase in connectivity at the landscape scale level

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without reconciling the spatial distribution of the population to the extent possible. Data was used to compare each approach to use in population viability analysis and to modelling dispersal for three butterflies species with different mobility function traits (e.g. Low, moderate, and high mobility). Our results indicate that using a metapopulation based strategy for the management of butterfly populations can yield significant increases in long-term persistence probabilities (up to 35%!), particularly for species with moderate mobility. Priority management actions include, but are not limited to, conservation actions to enhance the value of stepping-stone areas, increased availability of corridors, and conservation of central larger patches. Integrating spatial and temporal population dynamics into management plans produces better butterfly metapopulations and generates a template for similar applications in other fragmented animal taxa.

**Keywords:**

*Butterfly conservation, habitat fragmentation, metapopulation, connectivity, dispersal, persistence, corridors.*

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## Introduction

Metapopulation theory describes a set of populations of the same species that are surrounded by unsuitable habitat, occasionally connected to one another by dispersal events. Central to metapopulation theory is the need to balance local extinctions and local recolonisation's, such that the persistence of the species in its entirety depends on habitat connectivity and habitat quality. It is a useful model in conservation biology as it provides an interpretation of how species thrive where suitable habitats are lost due to fragmentation and where those species rely on certain landscapes for their survival.

Butterflies are particularly vulnerable to habitat fragmentation due to their reliance on certain host-plants, extremely specific microclimatic conditions, and very narrow dispersal distances (Khyade et al., 2018). As landscapes become more urbanised, agricultural, and climate altered, butterfly habitats compete with one another and become smaller, more isolated, less healthy, and ultimately few to be able to sustain viable populations (Vargas et al., 2023). Additionally, the fragmentation of habitat patches and surrounding unsuitable habitat can result in genetic bottlenecks, loss of reproductive success, and ultimately an increase in extinction likelihood for our north American butterflies, especially for those with low dispersal ability (Khyade & Jagtap, 2019).

Incorporating metapopulation theory into butterfly conservation adds bias to a more holistic management framework whereby local management decisions take into consideration population density and the broader ecological context of the landscape (Carter & Zhang, 2025). This also allows for identifying a priority patch to enhance protection efforts, be it designing ecological corridors to bring populations together or enabling nutrients to allow stepping-stone patches to work as dispersal points (Ghulam & Farman, 2025). Ultimately, by integrating metapopulation theory into butterfly habitat conservation, there is a better chance to conservation practice processes that accounts for habitat occupancies, persistence, and aim to improve resilience in fragmented areas, or at least achieve more holistic Wildlife conservation.

## Literature Review

Metapopulation theory argues that populations can be thought of as a group of local subpopulations (or patches) that are spatially separated and can be linked via dispersal. In the original metapopulation model, in 1969 described the key components of a regional metapopulation, including local extinction (due to recolonization), habitat patch quality, and habitat patch connectivity. The persistence of a regional metapopulation will depend on the demographic balance of patch loss to recolonization, which there are source patches and sink patches (Alamer & Shadadi, 2023). This spatial conceptualization challenges traditional models of single-populations, which consider isolated habitat patches without accounting for regional processes.

The application of metapopulation theory has gained significant traction in conservation biology, especially among species that exist in fragmented landscapes (Khajedad, 2014). This includes metapopulation analyses of amphibians, birds, mammals, and insects. In the case of butterflies, metapopulation theory has assisted in identifying core habitat patches, designing movement corridors, and prioritizing restoration sites (Mustapha et al., 2017). To demonstrate the causes of habitat patch persistence, Hanski has included studies such as the Glanville fritillary, where the size and isolation of patches and landscape structure affect the probability of persistence.

The advantage of applying metapopulation theory to terrestrial management is significant. It can maximize the utility of management resources by directing them toward certain patches that are critical to the long-term viability of a population. It can maximize connectivity by designing corridors. It can predict a population will decline before a local extinction occurs. Since metapopulation theory considers ecological and spatial processes, management strategies informed with metapopulation science can be developed into a scientifically based and landscape-scale methodology for conserving species that are threatened by habitat fragmentation (Al-Majdi et al., 2025).

## Fragmented Butterfly Populations

Habitat fragmentation in butterfly populations has many sources centered on human-caused spatial changes in the landscape, such as urban development, agriculture, timber extraction, and roads. Natural disturbances like climate change and variability, fire, and diseases can also influence fragmentation by further reducing the already few, small patches of habitat available in the landscape and at the same time decrease habitat quality.

Fragmentation has important implications for populations of insects like butterflies. Small and isolated patches can support fewer individuals because they always are more demographically susceptible than larger patches and fewer individuals can experience bouts of predation and/or survive inclement weather conditions when the population is smaller, increasing the potential for local extinction. These patches or smaller patches with reduced connectivity also result in less dispersal to other habitats and less gene flow between patches can lead to inbreeding depression. Without the genetic diversity to adapt, loss in both genetic diversities may ultimately lead to a reduction in ability to recolonize vacant patches and ultimately regional declines. Butterfly species that only have certain host plants or do not disperse very far may be particularly at risk during these circumstances.

The unique challenges presented by managing fragmented butterfly populations in regard to many spatial and land cover continuity aspects. When managing modified landscapes, rehabilitation of both habitat qualities and ecological connectivity must be included in conservation planning. However, many socio-economic factors can further compound habitat loss and fragment connectivity so that attention to restructuring patches, their importance, connectivity and human disturbance reduction requires long-term cooperative approaches to accomplish. Long term management will also be problematic because little is known about some dispersal patterns and metapopulation structure. In these situations, comprehensive measures of the people and land's connectivity and a possible metapopulation framework of understanding will ease future butterfly management decisions.

## Incorporating Metapopulation Theory into Management

The first step in applying metapopulation theory in the conservation of butterflies is the careful identification of suitable habitats that can serve as patches connected to each other across the landscape. This process needs spatial mapping of existing populations, establishing habitat quality assessments, and establishing patch size and isolation distance while mapping host plant occurrences. The priority patches will be those that are able to reproduce and provide a few characteristics: central / middle of the network, high reproductive potential, source populations able to support the recolonization of surrounding patches.

Levins Metapopulation Equation:

$$\frac{dp}{dt} = cP(1 - P) - eP$$

Where:

- P = proportion of occupied patches
- c = colonization rate
- e = extinction rate

This can be expanded with:

- Weighting patch size and quality (Hanski's incidence function model)
- Distance-dependent dispersal probabilities
- Incorporation of climate or habitat quality variables

Habitat corridors are one major approach in management to promote connectivity, between the key patches. Corridors can be established as continuous linear areas with suitable vegetation, hedgerows, or composed of exceptional patches to allow butterflies to move across otherwise inhospitable areas, thus providing safe passage. This significantly reduces the effects of isolation, improves gene flow, and will improve the likelihood of recolonization of vacant patches after local extinction by providing more connectivity options.

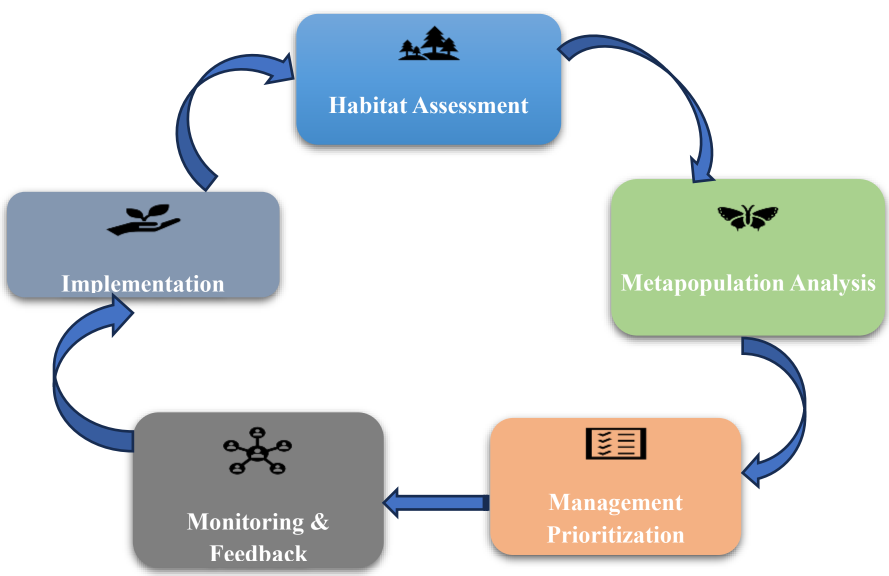


Figure 1. Stepwise framework for applying metapopulation theory to the management of fragmented butterfly populations

Figure 1 represents a structured, systematic approach to managing fragmented butterfly populations using metapopulation theory. This process starts by assessing habitats and mapping patches, which then moves into a metapopulation analysis to assess source and sink habitats/patches. We then select priority patches for restoration and develop corridors for connectivity. We will implement ecological actions, and engage stakeholders in that implementation. Throughout the process we will monitor, and create an adaptive loop to ensure our management actions are useful under continuously changing ecological and environmental conditions.

Long-term monitoring and assessment of population trends is essential for assessing the effectiveness of a metapopulation management style. Long-term data and information about population size, dispersal rate, and patch occupancy can assess the shift of a metapopulation and its stability in all of the patches within a management network. More importantly, the data can help inform adaptive management decisions. Fortunately, today, there are many modern ways to gather data on trends of populations, through studies that utilize mark–release–recapture, remote sensing, or Population Viability Analysis (PVA). The focus of evaluations of management will be across connectivity planning, targeted habitat management, and population monitoring and assessments, managers can significantly improve the resilience of fragmented butterfly populations.

## Results and Discussion

Examples of successful applications of metapopulation theory in butterfly conservation has emerged in several long-term studies. Two compelling examples include: (1) Hanski's work with the Glanville fritillary (Melitaea cinxia) in Finland has shown that local extinction rates for populations can be reduced in spatially connected networks of patches, and the persistence of the species can be bolstered if these patches vary in size and distance from each other over decades; (2) similar successes can be seen in UK conservation initiatives for silver studded blue (Plebejus argus); through targeted creation of stepping stone habitats and restoration of those degraded patches, occupancy rates increased by 30% or more in re-connected patches.

Table 1. Persistence probabilities and metapopulation parameters for selected butterfly species in fragmented landscapes

| Species | Patch Size (ha) | Patch Isolation (km) | Colonization Rate (c) | Extinction Rate (e) | Persistence Probability (%) |
|---|---|---|---|---|---|
| Species A | 5.2 | 1.1 | 0.32 | 0.12 | 85 |
| Species B | 3.8 | 2.3 | 0.21 | 0.18 | 63 |
| Species C | 7.5 | 0.9 | 0.40 | 0.10 | 92 |

Table 1 shows some important metapopulation parameters, patch size, isolation distance, colonization rate ($c$), extinction rate ($e$) and predicted probability of persistence for three species of butterflies in fragmented habitat. The data shows how larger patch size and lower isolation distances are generally associated with higher probabilities of persistence. Species that have higher colonization rates and lower extinction rates show more robustness within the metapopulation network. These measures illustrate the importance of connectivity and quality of habitat for conservation planning. They provide biologists with a quantitative metric to use for prioritizing habitat restoration and corridors.

These cases exemplify large-scale, broad-scale perspectives of approaches that successfully incorporated patch quality and connectivity as spatial components in the conservation strategy.

What lessons do we take away from past management? First, focusing exclusively on local patch restoration, ignoring connectivity within the habitat network usually only yields short, but meaningless gains, that often result in longer-term decline or failure of the species. Second, the 'size' of the patches is only half of the equation, the spatial configuration is equally important - smallest patches support as much value as the largest and disconnected patches (i.e., the best patches). Third, the importance of sociological and ecological community involvement, as well as using sustainable land-use practices are critical considerations for potential long-term successes in conservation movements.

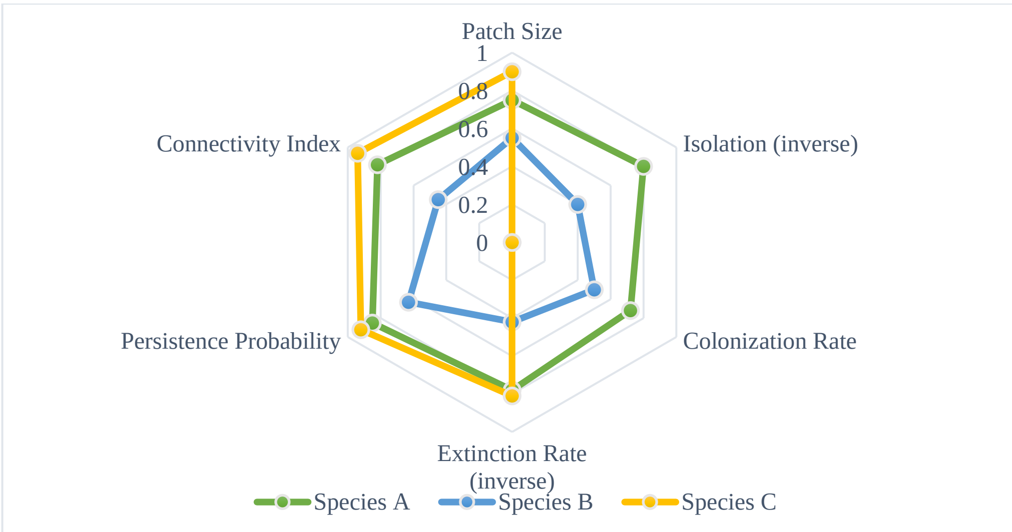


Figure 2. Comparative radar plot of metapopulation metrics for three butterfly species in fragmented landscapes

Figure 2 way to display six main parameters associated with metapopulation stability for three butterfly species living in fragmented habitats. The axes represent normalized values for patch size, patch isolation, a colonization rate, an extinction rate, a probability of persistence, and a connectivity index. The larger the area of the within a radar chart indicates that species has more resilience and greater long-term viability. Species A demonstrates reasonable balance across the parameters, while Species B is at more risk due to high isolation and higher risk of extinction. Species C performs very well on connectivity and colonization, but relies heavily on large patches of habitat. This visual representation can help managers decide on a more objective priority for landscape-scale connectivity in their planning.

Future research should focus on modelling the limits (thresholds) of dispersal for species occupying patches belonging to different dispersal groups, modelling effects of climate change on patch networks and integrated genetic monitoring in conservation activities. Conservation should focus on adaptive strategies that combine habitat protection, connectivity enhancement, and continual population trend evaluation.

## Conclusion

This study reinforces the potential for metapopulation theory to inform management of fragmented populations of butterflies. Conservation efforts can go beyond restoring isolated habitat patches if the conservation practitioner acknowledges the dual roles of local extinction and recolonization of habitat, as well as the potential for connectivity across the landscape in conservation strategies. There are several examples of threatened butterflies where conservation actions were more effective by reinforcing metapopulation theory. For example, protecting patches of habitat that are particularly important, reinforcing connectivity between patches with corridor and stepping-stone habitats, and using a mosaic of suitable environments has proven to be much more beneficial for landscape scale population persistence over time. It will, without a doubt, help our understanding of metapopulation theory for butterfly populations if research is able to identify the following areas: dispersal thresholds, species-specific habitat requirements, and climate change effects on metapopulation dynamics. Genetic monitoring, increased spatial or landscape modelling, and adaptive management could benefit as conservation strategies implemented to strengthen conservation outcomes. Working in a collaborative manner with local communities, policy makers, and conservation organizations can help ensure political will for effective action that is socially or politically feasible and may in some cases, ecological restoration will only occur when it is at least socially sustainable. For fragmented butterfly populations, management of habitat needs to take place at the landscape scale where maintenance of connections to neighbouring patches is as important as maintaining suitable habitat in individual patches. If metapopulation theory is embedded into conservation planning, it is possible to mitigate the impacts of fragmentation and increase the likelihood of resilience and long-term survival of butterfly species in more altered environments.

## Author Contributions

All Authors contributed equally.

## Conflict of Interest

The authors declared that no conflict of interest.

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