Designing Optimal Corridor Network for a Non-Contiguous Forest Landscape using Integer Programming Approach

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Abstract: Designing a corridor network for biodiversity concerns within forest landscape can be handled as a land-use allocation problem within an integer programming framework. In reality, a given landscape is often disturbed by manmade roads or water channels, which can transform the landscape into fragmented forest “islands”. In this paper, we propose a systematic modeling approach to explore the optimal corridor network for a non-contiguous forest landscape, characterized by several forest “islands”. Our approach first identifies if any separated forest “islands” exist as subgroups of landscape connection, and then looks for an optimal corridor network within each forest “island” or subgroup if any exist. We adapt the idea of maximum flow problems to identify forest “islands”, and then seek an optimal corridor in each forest “island” using integer programming. For demonstrative purposes, we conduct a computational experiment of our modeling approach using part of an existing forest landscape in Vietnam.

Keywords: Connectivity, corridor, GIS, non-contiguous forest landscape, spatial optimization model

1. Introduction

Habitat fragmentation has been one of the most debated issues in biodiversity conservation (Fretcher et al. 2018). Fragmentation of the forests reduces suitable habitat areas for forest dependent wildlife species. It also increases the length of the border between suitable habitats and fragments, which caused a so-called “edge effect” and have significant impact on the plant and animal communities because they are exposed to the altered physical environment (Collinge 1996). Furthermore, it has posed serious threat for the free movement of forest dependent wildlife species except for some bird species who traverse gaps between patches of suitable habitat. If species are trapped in a smaller suitable habitat with only a smaller population size, then, they can become genetically isolated, which can then increase their vulnerability of extinction (Reed 2004).

The provision of corridor is expected to facilitate the movement of forest dependent species between isolated populations and mitigate the negative effects of habitat fragmentation, by establishing the connectivity of habitats (Lindenmayer 1994). Designing a corridor network for protecting and preserving biodiversity is one of the global emerging environmental concerns.

Corridor is a “term” used to describe a linear strip composed of vegetation that is suitable for species habitat, and links dispersed patches of similar vegetation (Forman and Gordon 1986). For a given fragmented forest landscape, there are various locations and patterns that can be used to restore a linear strip corridor for establishing the link between dispersed habitats. However, resources available for conservation efforts are often limited. Therefore, it is important to explore the most efficient and cost-effective corridor network (Williams and Snyder 2005). Various studies have attempted to explore optimal corridor network (Conrad et al. 2010; Dilkina et al. 2017; St John et al. 2018). In this study we seek the optimal connection of suitable habitats for a given set of physically fragmented and isolated reserved habitats. Structural connectivity, which considers physical distance between habitats, has been used as the focal point in most of these studies (Chardon et al. 2003; Saura et al. 2011). One way to achieve structural connectivity is to first, identify the areas (often represented by polygons or grids) with suitable conditions for habitat. Once the spatial distribution of suitable habitats is identified, potential connectivity among them can then be explored. Physical connectivity is implemented by using adjacency relationships to seek an optimal corridor connection, where the landscape needs to be perfectly contiguous or connected by all available land-use for corridor connection.

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Non-forest land-uses such as logging roads or residential uses are known to fragment a contiguous forest landscape. When this occurs, a detour route of an alternative habitat type is required to connect two or more reserved areas (St. Clair et al. 1998; Bélisle and Desrochers 2002). The detour is necessary whenever a structurally separated landscape is physically connected by non-forest land-uses. In reality, there are many cases where man-made roads, water channels, extended non-forest zones, or a mixture of these, unnoticeably disconnect a forest landscape physically and subdivide it into multiple forest “islands” (or often called “patches”) (McIntyre 1995). Without considering this anomaly on contiguous connection, seeking an optimal corridor network may result in an infeasible model setting. This fact has been overlooked in most corridor optimization literature that searches for an optimal corridor connection for reserved area networks within a forest landscape. These studies apply an optimization model over a relatively simple landscape where non-forest land-uses do not completely fragment the area into smaller parts (Session 1992; Williams 1998; ¨Onal and Briers 2006; Jafari and Hearne 2013; Carvajal et al. 2013; St John et al. 2018) and implicitly assume that all forest units in the study area are spatially connected as a whole.

In this paper, we propose a systematic modeling approach to explore the optimal corridor allocation pattern for a non-contiguous forest landscape, characterized by several forest “islands”. Our approach first identifies forest “islands” or subgroups of the landscape connections within the optimization framework, and then seeks an optimal corridor network within each subgroup. We adapted the idea of a maximum flow problem (Harris and Ross 1955) for optimization to formulate a problem of subgroup identification as well as a corridor network problem using integer programming. For demonstrative purposes, we conducted a computational experiment using our modeling approach to a section of forest landscape in Vietnam. The forest management and land-uses in this area have recently received a lot of attention from the general public and international environmental organizations.

For maintaining the integrity of ecological systems and biodiversity, it has become increasingly important to carefully design and plan the spatial configuration of landscape (Collinge 1996) and developing a tool that helps develop landscape management plan and design is crucial (Landguth et al. 2012). Our proposed approach can serve as such a tool which is useful under fairly practical environment.

2. Materials and Methods

For a given forest landscape, we first investigate if the landscape meets complete adjacency network for corridor connection among fragmented habitats. The presence of roads and/or other contiguous non-forested units among forest units, may make their adjacency relationship incomplete. In such a case, we need to find out the least number of clusters with forest units for possible corridor connection. An optimal corridor network can be sought for each cluster based on the derived number of clusters. In what follows, we first propose a mathematical programming model to investigate if a given forest landscape is completely contiguous. This is conducted by seeking the least number of clusters in a given forest landscape. Following the first model, we then develop a second model to create an optimal corridor network for each cluster.

2.1. Clustering forest units for corridor connection

Our first model is constructed based on unit aggregation over a forest landscape. If a forest landscape is completely contiguous, the resultant number of clusters becomes 1. Let us consider an example of a forest map in Fig.1a. The circled numbers represent ID of each forest unit, while the values below the circle represent the area of each forest unit. The three grey polygons are those units assigned to a habitat unit where some protected habitat exists. From this forest map, we describe a forest unit as a node, and adjacency as an arc for connection between nodes in the flow network as shown in Fig.1b. In Fig.1b, we introduce an artificial super node indexed by “0”. Arcs are used as connection over common boundary between two adjacent forest units or nodes for connection. For clustering forest units, we interpret area of the i-th forest unit as a flow into node and out towards the super node. If a flow goes through an adjacent node towards the super node, those two adjacent nodes are merged as a part of cluster. An example of generating a cluster is provided in Fig.1c. Let us assume that arcs of 4–10, 2–9, 6–9, 5–8, 5–7, 3–7, are connected with a connection from 7, 9 and 10 to the super node. Thus, the resultant sets of (4, 10), (2, 6, 9) and (3, 5, 7, 8) generate three
clusters. Node 1 does not have any connection to adjacency nodes, so that it remains as single unit.

![Diagram](image1.png)

(a) an example forest map

(b) a flow network with nodes and arcs

(c) aggregation for a cluster

Figure 1. A forest map interpretation for maximum flow network.

![Diagram](image2.png)

(a) Landscape break by road (a bold line)

(b) Resultant incomplete network

Figure 2. Disturbance on a forest landscape.

In reality however, the forest map is often isolated by some disturbances and is divided into several forest zones, each of which consists of several forest units. Fig.2a shows disturbance caused by road construction (a bold line) in the forest landscape, so that those nodes above the road are not adjacent to those below it anymore, that is no arc exists between those two groups (see Fig.2b).
Table 1. Description of variables and coefficients used in the optimization models.

| Variables | Description |
|-----------|-------------|
| $y_{i0}$  | a binary variable with 1 for connecting arc from $i$-th to the super node |
| $y_{ij}$  | a binary variable with 1 for connecting arc from $i$-th to $j$-th node mutually adjacent over common boundary |
| $u_i$     | a binary variable with 1 for selecting $i$-th non-habitat unit for corridor connection |
| $w_{ij}$  | a non-negative variable for a flow from $i$-th to $j$-th unit (node) mutually adjacent over common boundary |
| $w_{ij}^c$| a non-negative variable for a flow from $i$-th to $j$-th unit (node) mutually adjacent over common boundary for corridor connection |

| Coefficients | Description |
|--------------|-------------|
| $L_i$        | an area of $i$-th unit |
| $\tilde{L}$ | a total area of forest map |
| $l_{ij}$     | the distance between centroids of two adjacent polygons assigned to $i$-th and $j$-th nodes |
| $m$          | the number of forest units |
| $\mathcal{NB}_i$ | a set of units adjacent to $i$-th unit over common boundary |
| $S_c$        | the index set of sources or habitat units for the network |

Table 1 shows variables and coefficients used to formulate the proposed model. The objective of clustering forest units is to minimize the number of connections from nodes to the super node weighted by each forest unit area. This is to investigate if a given forest landscape is completely contiguous.

$$\min_{\{y_{i0}\}} \sum_{i=1}^{m} L_i \cdot y_{i0}$$

Weighting method is used to avoid unnecessary multi-optima. If the resultant objective value becomes the smallest unit area, then we know that the number of clusters is 1, over a contiguous forest landscape map. Otherwise, it becomes non-contiguous, and an optimal corridor network has to be created for each cluster. The first set of constraints for arc connection is the following:

$$y_{ij} + y_{ji} \leq 1, \quad \forall j \in \mathcal{NB}_i, \forall i$$

$$y_{i0} + \sum_{j \in \mathcal{NB}_i} y_{ij} = 1, \quad \forall i$$

Eq. [2] restricts only one directional connection, while Eq. [3] ensures exactly one out-flow from the $i$-th node to one of its adjacent nodes including the super node. In order to complete the flow network, we associate the amount of flow over an arc with arc connection. That is, no flow is allowed over no arc connection.

$$w_{ij} \leq \tilde{L} \cdot y_{ij}, \quad \forall j \in \mathcal{NB}_i, \forall i$$

The flow balance is also attained by equating the amount of inflow to the outflow at each node using the following balance equation:

$$w_{i0} + \sum_{j \in \mathcal{NB}_i} w_{ij} = \sum_{j \in \mathcal{NB}_i} w_{ji} + L_i, \quad \forall i$$

To complete the flow network, the total area flow is ensured at the super node by;

$$\sum_{i=1}^{m} w_{i0} = \tilde{L}$$

This completes the formulation for unit clustering of a given forest landscape to investigate if a given forest landscape is completely contiguous.
2.2. Optimal corridor connection

Once we identify a set of clusters in a given forest landscape by the above first model for clustering, we can seek an optimal corridor connection within each contiguous cluster. Here, corridor connection can also be interpreted and solved through the flow network. The only difference is the amount of flow into the network. While the above clustering model regards forest unit area as a flow into the network, the corridor connection on the other hand uses a unit flow into those units assigned as a habitat unit. In Fig.3a, an example uses the grey units for habitat units where some habitat exists for preservation, and empty units for non-habitat units without such a habitat. Each habitat unit in the network is assumed to be a source into the network and the super node is assumed to be a sink from each habitat unit or source. Similar to clustering units, given the unit flow of 1 to each habitat unit for corridor connection, all flow ends up at the super node through the network.

Figure 3. Flow network for corridor connection.

Given a unit flow into the flow network from habitat units, we consider the flow amount collected at the super node. This is the number of habitat units, \( N^c \) within a generated cluster by the first model. For example, Fig.3a has 3 habitat units, while in Fig.3b one cluster has 2 habitat units and the other has 1 habitat unit. Setting \( S^c \) as the index set of unit ID numbers for habitat units in the network, Eq.[7] is to equate unit inflow and outflow at each node similar to Eq.[3], for all habitat units in \( S^c \). For a non-habitat unit, Eq.[8] is used to equate inflow from its adjacent unit and outflow to its another adjacent unit;

\[
y_{i0} + \sum_{j \in \text{NB}_i} y_{ij} = 1, \quad \forall i \in S^c
\]

\[
\sum_{j \in \text{NB}_i} y_{ij} = \sum_{j \in \text{NB}_i} y_{ji}, \quad \forall i \notin S^c
\]

With the flow amount by \( w^c_{ij} \) from the \( i \)-th node to the \( j \)-th node for the corridor connection, we associate \((y_{ij}, w^c_{ij})\) by;

\[
w^c_{ij} \leq N^c \cdot y_{ij}, \quad \forall j \in \text{NB}_i, \forall i
\]

\[
w^c_{i0} \leq N^c \cdot y_{i0}, \quad \forall i \in S^c
\]

Eq.[9] is to ensure that any flow of \( w^c_{ij} \) is allowed only when its corresponding arc is connected by \( y_{ij} = 1 \) in the network. Eq.[10] is only for habitat units to allow flow and arc connection to the super node. Finally, we equate the amount of inflow to the outflow for corridor connection at each node for consistent flow in the flow network;

\[
w_{i0} + \sum_{j \in \text{NB}_i} w^c_{ij} = \sum_{j \in \text{NB}_i} w^c_{ji} + 1, \quad \forall i \in S^c
\]

\[
\sum_{j \in \text{NB}_i} w^c_{ij} = \sum_{j \in \text{NB}_i} w^c_{ji}, \quad \forall i \notin S^c
\]
The total amount of flow for corridor connection is guaranteed at the super node or sink by the number of habitat units in the network:

\[ \sum_{i \in S^c} w_{i0}^c = N^c \]

The last constraint is to ensure only one connection from one of habitat units to the super node to complete corridor connection within a contiguous cluster:

\[ \sum_{i \in S^c} y_{i0} = 1 \]

We set the objective function to minimize the number of non-habitat units used for corridor connections weighted by their forest area:

\[ \min_{\{u_i\} \in \mathcal{S}^c} \sum_{i \in \mathcal{S}^c} L_i \cdot u_i \]

A new binary variable, \( u_i \), is introduced for unit selection. Selection of non-habitat units is controlled by the following:

\[ u_i = \sum_{j \in \mathcal{NB}_i} y_{ij}, \quad i \notin \mathcal{S}^c \]

If there is a flow over non-habitat units, then the corresponding unit selection takes place. With the above constraints (Eqs. [1] and [7] to [14] and [16]), we know which nodes (forest units) will become part of a corridor connection by the binary variables, \( \{y_{ij}\} \). Table 2 shows the two models proposed here for clustering units as well as corridor connection under non-contiguous forest landscape.

| The first model for clustering units | The second model for corridor connection |
|-------------------------------------|------------------------------------------|
| \[ \min_{\{y_{i0}\}} \sum_{i=1}^m L_i \cdot y_{i0} \] | \[ \min_{\{u_i\} \in \mathcal{S}^c} \sum_{i \in \mathcal{S}^c} L_i \cdot u_i \] |
| \[ \text{st} \] | \[ \text{st} \] |
| \[ y_{ij} + y_{ji} \leq 1, \quad \forall j \in \mathcal{NB}_i, \forall i \] | \[ y_{ij} + y_{ji} \leq 1, \quad \forall j \in \mathcal{NB}_i, \forall i \] |
| \[ y_{i0} + \sum_{j \in \mathcal{NB}_i} y_{ij} = 1, \quad \forall i \] | \[ y_{i0} + \sum_{j \in \mathcal{NB}_i} y_{ij} = 1, \quad \forall i \] |
| \[ w_{ij} \leq L \cdot y_{ij}, \quad \forall j \in \mathcal{NB}_i, \forall i \] | \[ \sum_{j \in \mathcal{NB}_i} y_{ij} = N^c \cdot y_{0i}, \quad \forall i \notin \mathcal{S}^c \] |
| \[ w_{i0} + \sum_{j \in \mathcal{NB}_i} w_{ij} = \sum_{j \in \mathcal{NB}_i} w_{ji} + L_i, \quad \forall i \] | \[ w_{i0}^c \leq N^c \cdot y_{0i}, \quad \forall i \in \mathcal{S}^c \] |
| \[ \sum_{i=1}^m w_{i0}^c = \bar{L} \] | \[ \sum_{i \in \mathcal{S}^c} w_{i0}^c = N^c \] |
| \[ y_{ij} \in \{0, 1\}, \quad \forall i, \forall j \] | \[ \sum_{i \in \mathcal{S}^c} y_{i0} = 1 \] |

Table 2. The proposed models for clustering units and corridor connection.
3. Data

3.1. Forest loss and fragmentation in Vietnam

Our study area is located in the North Central Coast region of Vietnam. The Vietnamese government launched a series of reforestation projects, such as “program 327”, “program 611”, and “program 5 million hectares” in the 1990’s in order to recover from the depletion of forested landbase. These government initiatives increased the total forested landbase by 39.1% in 2009, and further increased it by 41% of the total land area in 2015. The total forested landbase is now estimated to be about 14.68 million ha, of which plantation forest (4.4 million ha) accounts for roughly 30%. In spite of these impressive results, the government of Vietnam had not paid much attention to spatial configurations of forest landscapes, which allows Vietnam’s transition to market economy to trigger urbanization, road construction, housing development, and expansion of agricultural land, by converting forest lands (Raedig et al. 2017). The lack of attention to spatial configurations also allows forest preservation areas to be isolated and surrounded by intensive agricultural land-uses and road networks, which results in forest fragmentation (Cochard et al. 2017). In 2001, given the highly fragmented forest landscape in Vietnam, WWF initiated extensive studies in order to develop a corridor plan for preserving high-profile endangered species, tiger, (Long 2001). The study by van Schingen et al. (2020) also stressed on the importance of forest corridors for maintaining habitats for tropical lizard species in Vietnam. Currently, the government of Vietnam has recognized the importance and urgency of preparing spatial strategies and a master plan for biodiversity conservation, and has placed high priority on the development of corridor connecting habitats (Triệu et al. 2020).

3.2. Study site

The study site is the Mường Lát district in Thanh Hóa Province (Fig.4), which covers 815km$^2$. The district contains part of the Pu Hu Nature Reserve. Land-use types in the site can be classified into: 1) production forest (414km$^2$, 1,880 polygons), 2) protection forest (315km$^2$, 882 polygons), 3) special-use forest (53km$^2$, 81 polygons) (mainly for biodiversity conservation, Phuong and Dung, 2001), and 4) non forest (27km$^2$, 312 polygons). More than 50% of the study area is managed by individual households, and 20% and 10% of the study area are managed by the army and Forest Management Board, respectively. The rest of the study area is managed by the People’s Committee of Mường Lát district and others.

We obtained a geographic information system (GIS) data set of land-use types as well as owner types from Mường Lát Protective Forest Management Office, Vietnam. Our optimization model requires two types of adjacency relationships; 1) sharing adjacent lines only, and 2) sharing both adjacent lines and corners. Therefore, we generated two types of adjacency lists based on the Neumann neighborhood adjacency structures and Moore neighborhood adjacency structures using ArcGIS (ESRI, Redlands, CA, USA).

For the case study, we assumed that a land manager or planner would like to develop corridors that connect separated protection forests with a minimum number of polygons for each possible forest “island”. Furthermore, we assumed that not only forest polygons (either “production” or “special use”)
but also polygons classified as “non-forest” are available for corridors because most “non-forest” polygons are small agricultural areas or contain woody vegetation, regardless of their classification.

4. Results

Figure 5a shows the existing reserved habitats represented by red polygons. These habitats correspond to the areas classified as protection forest in Fig.4. Figure 5b shows the resultant three contiguous clusters derived from the proposed clustering model. The forest landscape is revealed to be imperfect. The 1st cluster contains 1921 forest units with 544 habitat units, while the 2nd has 953 units with 216 habitats and the last, has 281 units with 122 habitats (see Table 3). The 1st and 2nd clusters cover the southern and northern parts of the landscape, while the 3rd cluster covers the western region of the landscape. Region 3 of the landscape is the smallest.

Table 3. Resultant clusters.

| Cluster     | Units | Habitats |
|-------------|-------|----------|
| 1st Cluster | 1921  | 544      |
| 2nd Cluster | 953   | 216      |
| 3rd Cluster | 281   | 122      |

We sought an optimal corridor network for each cluster, separately. Figure 6 shows an optimal corridor network derived for all clusters. Since all habitats are connected in the 3rd cluster, no
other unit was added to part of the corridor. The derived optimal corridor included 4 additional non-habitat units in the corridor network for the 2nd cluster. The 1st cluster added 37 non-habitat units in the corridor network. Because of the small size of these units, the derived corridor seems long, distance-wise.

We, then modified the objective function to minimize the total length of arcs connected to habitat units from non-habitat units. In other words, let us introduce the distance coefficients for each arc, \( l_{ij} \), which is the distance between centroids of two adjacent polygons assigned to \( i \)-th and \( j \)-th nodes. The resultant objective function becomes:

\[
\min \{ y_{ij} \} \sum_{i \in S} \sum_{j \in NB_i} l_{ij} \cdot y_{ij}
\]

In this way, we can seek an optimal solution with the shortest corridor connection.

Table 4. Optimal corridor connection with different objective functions.

| Cluster   | Units | Habitats | Connect | CPU(sec) | GAP (%) | OBJ (ha) | Binary | Const |
|-----------|-------|----------|---------|----------|---------|----------|--------|-------|
| 1st Cluster | 1921  | 544      | 37      | 277.55   | 0       | 361.74   | 11083  | 19508 |
| 2nd Cluster | 953   | 216      | 4       | 38.20    | 0       | 7.53     | 5587   | 9812  |
| 3rd Cluster | 281   | 122      | 0       | 0.22     | 0       | 0        | 1613   | 2843  |
| min       | 1st Cluster | 1921  | 544      | 24      | 76.30   | 0        | 18126.04 | 11083 | 19508 |
| unit      | 2nd Cluster | 953   | 216      | 4       | 65.35   | 0        | 2777.63  | 5587  | 9812  |
| area      | 3rd Cluster | 281   | 122      | 0       | 0.14    | 0        | 0       | 1613  | 2843  |

Figure 7 shows the optimal solution with the objective function of Eq.[17]. While the optimal corridor connection for the 2nd and 3rd clusters did not change, the 1st cluster showed the shorter arc connection with 13 less non-habitat units for corridor than that of Fig.6. The detailed difference of corridor connection for the 1st cluster in Fig.6 and Fig.7 was revealed in Fig.8. Figure 8a had smaller unit area for corridor connection, while the shortest corridor connection was shown in Fig.8b. Table 4 shows the resultant solutions with each model statistics.

5. Discussion and Conclusions

Designing corridor connection patterns, which achieve structural connectivity, for biodiversity conservation can be addressed within the land-use allocation problem. This is because it is basically the problem of allocating land-uses considering geographic and vegetation conditions of nearby areas of
the reserved habitats as well as their spatial distributions. Various spatial optimization models have been developed to explore an optimal corridor connection for reserved area networks within forest landscape.

By its nature, the optimization process can fail and unable to find an optimal corridor connection when there are no possible ways to physically connect isolated habitat units for reserved habitats. For example, when we formulate a corridor network optimization model to explore the optimal connectivity between two isolated habitat unit for reserved habitats, without noticing that they are located in landscapes which are physically separated from each other, the model fails to generate a feasible solution. In order to avoid such failure, first, we need to identify the physical boundaries of clusters in the landscape, and then prepare a dataset for each separated cluster in the landscape. After identifying separated clusters, we need to seek an optimal connection among reserved habitat units in each separated cluster. For each cluster, our second model can search for an optimal corridor connection among these habitat units.

Despite the little attention given to cases with one contiguous forest landscape which possibly consist of smaller separated forest “islands”, infeasible model settings due to non-contiguous landscape can stem from various reasons, especially when we apply a corridor network optimization model to a large forest landscape. For example, potential boundaries may be overlooked from the analysis, simply due to the lack of knowledge of how artificial structures, agricultural clearing, or a mixture of these, have fragmented the entire large forest landscape covering multiple landowners and management jurisdictions (Kennedy et al. 2009). Sometimes the potential physical boundaries

Figure 7. Corridor network for three regions with minimum length of arcs through non-habitat units for corridor.

Figure 8. Corridor connection in the 1st cluster.
such as road networks are too narrow to identify without zooming in and focusing on the details of a map. However, focusing on details makes it difficult to capture boundaries at a larger scale, especially when boundaries are created by, for example, a narrow road network. In such a case, potential boundaries are overlooked from the analysis of the entire landscape (Harrower and Sheesley 2005; Florence et al. 1996) and separated landscapes are mistakenly treated as one contiguous landscape. The shortage of skilled labour may also result in the only map available for the analysis containing imperfectly delineated boundaries (Li-juan et al. 2005). For example, although two adjacent polygons must have a common boundary between them, unskilled personnel may draw a common boundary with gaps or overlaps. These errors may generate a map of one contiguous forest landscape, which is accidentally separated into several fragmented forest areas.

Without a systematic approach, it is time-consuming and labor-intensive to detect errors (such as gaps and overlaps) that cause the landscape to be unintentionally divided into smaller parts, especially in a large forest landscape. Then, the planner and practitioners have to spend a great deal of time to extract a contiguous forest area from an entire landscape to prepare separate data sets for the analysis.

We developed a spatial optimization model for developing a corridor plan for forest landscape where not only suitable forest area are fragmented, but are permanently divided into smaller portions by abiotic disturbances such as road networks building and conversion to non-forest land-uses. Our first model identifies the minimum number of clusters of forest units by formulating the problem as a maximum flow problem. Then, our second model explores the optimal corridor allocation pattern with a maximum flow algorithm for each cluster. Our proposed approach allows us to solve such practical problems by applying an optimization model to a real-life large-scale landscape problem in a systematic way. Our approach is also useful for various cases of non-contiguous forest landscape because it allows us to evaluate if the landscape is non-contiguous or not prior to optimizing a corridor connection pattern.

Our study also sheds light on the importance of precisely and completely delineating, mapping, and identifying boundaries of land-use types. GIS and remote sensing technologies have been increasingly used and have become a crucial component for forest landscape management planning (Wing and Bettinger 2003; Shao et al. 2006; Kascaemsuppakorn et al. 2010). Delineating and mapping boundaries of land-use types are essential and important for GIS-based land-use planning especially, when the plan requires us to generate adjacency relationships based on a GIS map in order to evaluate spatial configurations such as connectivity. However, it is very common to hire unskilled workers for preparing GIS base maps in a developing country such as Vietnam. When skilled personnel are not easily available, precise delineation and complete identification of polygon boundaries becomes a challenging task and results in a “low quality” map (Bishop et al. 2000). As previously discussed, “low quality” GIS map may result in generating a misleading optimal corridor plan or fail to generate a feasible solution. Therefore, the “quality” of GIS-based land-use planning depends on the “quality” of the map, and an imprecise map representation causes incorrect and error-prone analyses and decisions (Campbell and Shin 2012).

Finally, our study contributes to the existing body of literature on corridor network in Vietnam. Hoang et al. (2013) applied GIS to identify the spatial distribution of various forest conditions in Thừa Thiên Huế Province, Vietnam and proposed a corridor development plan which connects suitable forest habitats. Raedig et al. (2017) identified areas for biodiversity conservation based on tree species distribution and considered potential corridor which connects these areas. However, no optimization model has been developed and applied to explore corridor network in Vietnam (Nghiem 2011). This study provides a basis for developing a systematic approach for exploring an efficient and effective corridor plan which is economically feasible, ecologically sound, and sustainable in Vietnam.

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