IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received February 16, 2019, accepted March 1, 2019, date of publication March 12, 2019, date of current version April 1, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2904552

Dual-Flow Structure to Design a Continuous and Compact Nature Reserve

CHIH-WEI LIN[1,2,3], WEI-HAO TU[3], AND JIN-FU LIU[3,4]
[1]College of Forestry, Fujian Agriculture and Forestry University, Fuzhou 350002, China
[2]Forestry Post-Doctoral Station, Fujian Agriculture and Forestry University, Fuzhou 350002, China
[3]College of Computer and Information Sciences, Fujian Agriculture and Forestry University, Fuzhou 350002, China
[4]Strait Nature Reserve Research Center, Fujian Agriculture and Forestry University, Fuzhou 350002, China

Corresponding author: Chih-Wei Lin (cwlin@fafu.edu.cn)

This work was supported in part by the Natural Science Foundation of Fujian Province of China under Grant 2016J01718, in part by the China Postdoctoral Science Foundation under Grant 2018M632565, and in part by the Channel Post-Doctoral Exchange Funding Scheme.

ABSTRACT Establishing the conservation reserves is an efficient approach to protect various species, in which maintaining the spatial characteristics of the habit is an important issue. A continuous and compact reserve is vital for long-term survival and reproduction of various species. However, the existing methods for nature reserve design have the problem of the selected sites which are sparse in space. The sparseness refers to the isolated regions which are the unselected (selected) sites and surrounded by the selected (unselected) sites in the designed nature reserve and thus making the management of protected areas and exchange of information between species difficult. In this paper, we propose the concept of a dual-flow mechanism which is called the dual-flow structure (*DFS*) to address the problem of sparseness in sites selected for the reserve network design. The DFS constructs two consecutive arcs: one is for selected sites and the other is for unselected sites, simultaneously. Those two arcs ensure that each site has at least one adjacent site which has the same status (selected/unselected) with the competitive mechanism. The concept of two consecutive arcs can solve the problem of sparseness and achieve spatial continuity. The DFS further utilizes the perimeter in dual-flow structure to achieve the spatial characteristic of compactness. The main contributions of this study are: (1) we design a novel mathematical model which solves the problem of sparseness in the space, including selected and un-selected sites; and (2) the DFS generates the connectivity and compactness of the reserve network with the scientific and reasonable techniques. In the experiments, we take the Daiyun Mountains as a study area to demonstrate the feasibility and effectiveness of the proposed model.

INDEX TERMS Continuous, compact, dual-flow structure, nature reserve, Daiyun mountains.

I. INTRODUCTION

Recently, due to the rising of the conception of protecting the natural ecosystems, there has been much interest in constructing the natural conservation reserve [1], [2]. Establishing reserve is an efficient approach to protect species and to achieve the goal of maintaining the biodiversity [3], [4]. It is constructed with minimum area or minimum economic cost because of the requirement of economic development and the constraints of land resources. To maximize the performance of biodiversity in the reserve area, an efficient methodology of the site selection is needed.

This task is complex and many methods have been proposed over the last two decades. Among these methods, prioritization-based according to the protection value of each sites [5]–[7]. The protection value is evaluated by using qualitative [8], quantitative [9], [10] or comprehensive evaluation methods and various criteria are considered [11], [12]. The sites with high scores are selected to generate the conservation reserve to protect species and environments. The characteristics of these methods are simple, intuitive, and intelligible. However, most of those methods are depended on the subjective analysis and require numerous of sites. For example, Wright DF [13] assesses the potential nature reserves by using the quantitative and qualitative evaluation schemes, and Moffett *et al.* [14] summarizes the multicriteria decision-making methods for the reserve planning and design, both of those need the experience of experts in decision.

The associate editor coordinating the review of this manuscript and approving it for publication was Amjad Mehmood.

The heuristic-based algorithms overcome the problems of the prioritization-based approaches by applying mathematical model and include Greedy, Genetic, Simulated annealing and Tabu search algorithms. Greedy algorithm provides the global optimal solution by working out a series of the local optimal solutions [15]–[18]. Genetic algorithm utilizes the natural evolutionary process to achieve the optimal solution [19], [20]. Tabu search algorithm records the information of movements to avoid falling into the local search by using the short-term memory structure. The short-term memory structure is also called the Tabu List, the longer the Tabu List is, the better the search result is [21]–[23]. To organize the reserve network, those algorithms are associated with various biological information, such as the species richness of each sites, the species distribution, and the habitat coverage. The heuristic-based algorithms can quickly search the feasible solution, but can only get the sub-optimal solution or approximate optimal solution [24].

The optimization-based algorithms construct a mathematical model with optimal solver to solve the problem of optimization. The main concept of the optimization-based algorithms is to maximize the covering area with restrictions on fixed resources or to minimize the resource with the condition of the fixed covering area. Set Covering Problem (SCP) and Maximal Covering Problem (MCP) [25]–[27] are both the famous optimization-based algorithms which attempt to maximize the biodiversity with minimum area. SCP satisfies the requirement of protecting species with minimum cost and MCP maximizes the species with the fixed resource. Although those methods can effectively increase the utilization rate of resource, the spatial characteristics are missing. The spatial properties, which affect the biodiversity, are related to habit fragmentation. The spatial information in the reserve are regarding to the relative position between selected sites including the size of reserve, the shape of reserve, the number of reserve, the interval between reserves and the continuity of reserve [28]. Graphic theory in operations research utilizes the vertices and edges to construct the graphic structure. The combinations of the vertices and edges can provide the spatial characteristics and solve the problems of spatial relationships in various areas. The integer linear programing is part of graphic theory which solves the problems by minimizing or maximizing the objective function. Numerous methods, which combine the integer linear programing with graphic theory, have been proposed to solve the spatial problem. Önal and Briers [29] minimizes the distance between sites and shortens the boundary of the selected site to construct the compact reserve. Williams*et al.,williams2008optimal* minimizes the distance between reserves by considering the distance requirements. Jafari*et al.,jafari2013new* improves the mathematical model of continuity and compactness by minimizing the perimeter of the boundary, the boundary constraint can be applying to various mathematical models. Although the optimization-based algorithms can provide the characteristic of spatial continuity in the selected sites by associating spatial relationships with mathematical models, the spatial distribution of the selected site is sparse. The sparseness makes empty phenomenon appear inside of the selected sites which means the un-selected (selected) sites are surrounded by the selected (un-selected) sites. The phenomenon of sparseness breaks the completeness of habitat and causes the non–continuity of habitat. Some studies associate the spatial characteristic of the compactness in the local region to overcome the issue of sparseness [30], [31]. Although, the characteristic of compactness can eliminate the sparseness, there are two problems when achieving the compactness: (1) numerous of sites are required, (2) the sites which are located in the marginal area are ignored.

When choosing a series of sites, the most important consideration is to maintain the integrity of habitat. The spatial characteristics, such as continuity and compactness, are provided for animal migration and useful for species propagation. In this paper, we propose a novel mathematical model called *Dual-Flow Structure (DFS)* by considering the spatial characteristics for reserve sites selection. DFS selects the sites by considering a bi-directional flow, one is selected and the other is un-selected, to construct the spatial continuity. In addition, DFS further utilizes the spatial characteristics of the perimeter of reserve network to perform the spatial compactness. DFS designs the competition mechanism of two arcs, which achieves spatial characteristics and addresses the problem of spatial sparseness.

The rest of this paper is organized as follows. First, we introduce the problem when selecting site with linear integer programming in Section II. After that, we describe the proposed mathematical model, Dual-Flow Structure in Section III. Then, we describe the study area and evaluate the ecological information to design reserve in Section IV. Next, we demonstrate the experimental results and discussion in Section V. Finally, we give the conclusions in Section VI.

II. THE PROBLEM

To design a conservation, a set of sites are considered [8], [9] in which the shape of each site can be regular or irregular. The site is also called the decision unit, it has two states: selected and unselected, and the sites with selected status compose the reserve network. To simplify, we take the sites with regular shapes as the decision units in this study. The concept of continuity in graph theory can be simulated as the tree graph, each vertice can reach to any other vertices with a path, as shown in Fig. 1. In other words, a designed reserve is continuous when the tree is composing of a series of vertices and edges. The tree in graph theory is an undirected graph. To consider the spatial characteristic of continuity in the linear integer program, the concept of directed graph is concerned. If two sites have a common edge, those two sites are regarded as the adjacent sites and each adjacent site is linked with a directional arc. The selected sites have the spatial characteristic of continuity if the arcs connect any two sites to form a connected path and that makes the selected sites to be connected. Although the directional arc

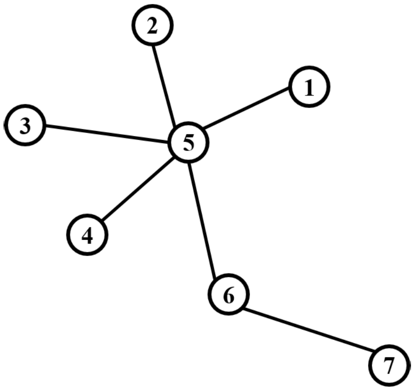

FIGURE 1. Example of tree in graph theory.

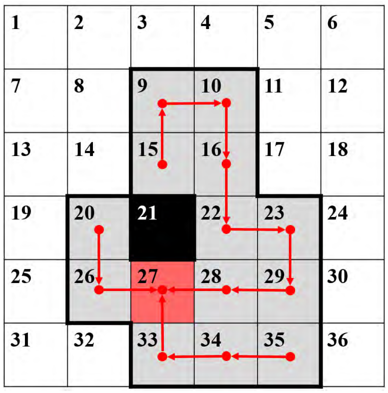

FIGURE 2. Examples of sparseness phenomenon in selected sites.

with connected path can achieve the continuity of the reserve, the isolate sites still exist, as the black block shown in Fig. 2.

Fig. 2 is an example of the sparseness with 6×6 grids. In Fig. 2, each grid is taken as the decision unit, and its index is numbered at the left-top corner. $S = \{X_i, i = 1, 2, \ldots n\}$ presents the set of the study area, in which X_i is the decision unit. X_{27} is the center site of the reserve, which is also called the sink point of the reserve. The selected sites are indicated by the red points, and the connected arcs are indicated by red line with arrows showing the directions. Although the selected sites are connected, the spatial distribution is sparse, which means that the isolate sites still exist in the designed reserve. In Fig. 2, X_{21} is the unselected site which is located in the reserve. Its neighbors, $X_{15}, X_{20}, X_{22}, X_{27}$, are all selected sites. X_{21} is an isolated site which can neither be protected nor be used for the development of human living in the practice, which is a waste of resources and is the barrier of species exchange.

In this paper, we proposed a novel mathematical model, dual-flow structure (DFS), which considers the continuity in both selected and unselected sites and associates with spatial characteristic of compactness, to solve the problem of sparseness. The proposed model can ensure that there exists at least a neighbor with the same status, such as selected or unselected, for each site.

III. DUAL-FLOW STRUCTURE

The most important issue in the nature reserve design is the site selection, in which the mathematical technique is a useful approach. In this study, we propose the dual-flow structure (DFS), which can be applied to any types of mathematical models of integer linear program, to select the protected sites.

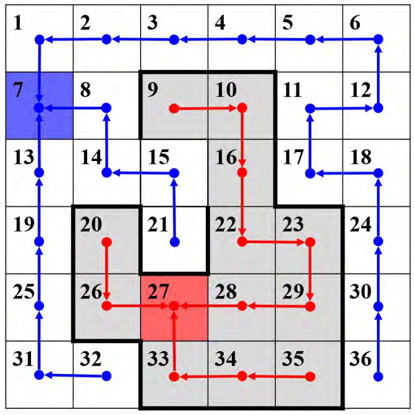

FIGURE 3. An illustration of dual-flow structure.

Fig. 3 illustrates the concept of the dual-flow structure. The site X_7 with blue color is the center of the non-reserve area which is the unselected unit (the sink point of the unselected sites). All unselected sites flow into X_7 and are connected with the blue directed arcs. To compare with the existing approaches with spatial continuity and to maintain the continuity of consistency of unselected units, as shown in Fig. 3, the status of X_{15} which is the neighbor of X_{21} is switched from selected to unselected unit. DFS not only changes the selected units into unselected state, but also changes the unselected units into selected status. DFS performs the optimal solution for the defined objective function which addresses the problem of the isolated sites.

The goal of reserve design is to maximize the protection benefits with an appropriate number of sites. In DFS, we design the objective function which associated the ecological information with site selection. The goal of objective function is to maximize ecological information with an appropriate number of sites, and the equation is written as follows,

$$\min\ c = \sum_{i} U_i(1 - e_i), \tag{1}$$

where c is the cost of the objective function and U_i is a binary variable $\{0, 1\}$. U_i is set to 1 if the site i in reserve is selected, otherwise, is set to 0. e_i is the ecological value of site (grid) i which is evaluated in Section IV-B. $\sum_i U_i$ is to minimize the area of selected sites. $1 - e_i$ is an inverse indicator, the higher the ecological value is, the lower value of an inverse indicator is.

To achieve the goal of the objective function Eq. 1, we further consider the constraint for the protection of various species in reserve design, the mathematical form is expressed as,

$$\sum_i \delta_{s_i} U_i \geq k_s, \quad \forall s \in S, \tag{2}$$

where s is the target species and S is the set of the target species. δ_{s_i} is the percentage of species s at site i in the study area. k_s is a parameter to determine the percentage of each protecting species in reserve design. Eq. 2 presents that the sum of the percentage of species s at the selected sites must be larger than the percentage of protecting species k_s in the study area. According to the investigation, we take the part of the zonal vegetation and protected species as the target species including *Pinus taiwanensis*, *Sassafras tzumu*, *Liquidambar formosana*, *Fokienia hodginsii*, *Cryptomeria japonica*, *Pinus massoniana*, *Schima superba*, *Paulownia fortunei*, *Cunninghamia lanceolata*, *Taiwania cryptomerioides*, *Cinnamomum bodinieri*, and *Tsuga longibracteata*. *Pinus taiwanensis*, *Sassafras tzumu*, *Liquidambar formosana*, *Pinus massoniana*, *Schima superba*, *Paulownia fortunei*, and *Cunninghamia lanceolata* are the zonal vegetations; *Fokienia hodginsii*, *Taiwania cryptomerioides* and *Cinnamomum bodinieri* are the 2^{nd} class national protected species; *Cryptomeria japonica*, and *Tsuga longibracteata* are the Fujian provincial protected species.

Species exchange is the key for the long-term survival of species, in which the spatial continuity of nature reserve is an efficient form. To ensure the spatial continuity, we have to consider the adjacent and the directional relationships in the process of site selection. The adjacent and directional relationship between two selected sites are described in the following equations,

$$U_i + V_i = 1, \quad \forall i = 1, 2, \ldots, n \tag{3}$$

$$f^d_{j,i} - f^d_{i,k} \geq U^d_i g_i, \quad j,\ k \in N_i,\ j \neq k,\ \forall i = 1, 2, \ldots, n \tag{4}$$

$$M^d_{j,i} \leq B, \quad j \in N_i,\ \forall i = 1, 2, \ldots, n \tag{5}$$

$$\sum_i T^d_i \leq C, \quad \forall i = 1, 2, \ldots, n \tag{6}$$

where n is the number of sites; U_i and V_i are statuses of a site i, and be presented as selected and unselected, respectively. V_i is a binary variable {0, 1}; V_i is set to 1 if a site i is unselected in reserve, otherwise, is set to 0. $f_{i,j}$ is the outflow of site i and $f_{j,i}$ is the inflow of site i; i is the selected site; N_i is the set of adjacent sites of the selected site i; j and k are the neighbors of site i which belong to N_i and $j \neq k$; d is a binary variable {0, 1}; g_i is the property of site i. The difference between inflow and outflow should be greater than or equal to $U_i g_i$. Inflow presents the flow which goes from site j to site i, and outflow is the reverse flow of inflow which goes from site i to site k. In both selected and unselected directions, they all have inflow and outflow statuses. d is set to 0, if it is the process of selecting sites; otherwise, is set to 1. $M^d_{j,i}$ is the number of inflow which flows from the neighbor j to the selected site i. T_i is a sink point and is a binary variable {0, 1}; if $T_i = 1$ presents that the site i is selected to be a sink point of nature reserve. B and C are the restricted parameters.

Eq. 3 is the competitive mechanism of dual-flow structure, which restricts the status of a site i and has to be selected or unselected. Eq. 4 achieves the connectivity by using the relationship between inflow and outflow. To avoid a site be selected repeatedly, Eq. 5 restricts the inflow number of selected site i. In reserve design, it can have more than one sink point. The sink points attract flows and form the reserve network. Eq. 6 restricts the number of the sink points of the nature reserve which should be smaller than parameter C.

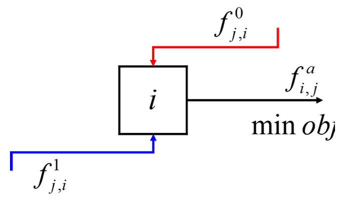

FIGURE 4. An illustration of competitive mechanism.

Fig. 4 illustrates the competition of the dual-flow structure, and the inflow of selection $f^0_{j,i}$ and that of unselection $f^1_{j,i}$ are indicated as red and blue lines, respectively. In Fig. 4, $f^0_{j,i}$ and $f^1_{j,i}$ reach the site i and compete with flow to achieve the goal of minimizing the objective function Eq. 1. If $f^0_{j,i}$ is the winner in the competition, the site i is selected and the outflow is $f^0_{i,j}$. Otherwise, site i is unselected and the outflow is $f^1_{j,i}$. We utilize the characteristics of the change of flow to achieve the continuity in design reserve, and the competition of the dual flow to minimize the objective function.

In general, flow can be defined as the total land price of the selected sites or the total number of selected sites. Taking the price of site as an example, the site property g_i is the price of each site, and inflow and outflow ($f_{j,i}$ and $f_{i,j}$) are the total cost before and after the selection of site i. In this study, we take the total number of sites as the flow, and the site property g_i is set to be 1. If $d = 0, f^d$ is marked as the arc of the selected sites; if $d = 1, f^d$ is marked as the arc of the unselected sites. In our study, we set parameter of C to be 1 to find the best sink point through an iterative process of optimization and to demonstrate the capability of the continuity of the proposed mathematical model in the study area.

Although considering the spatial continuity in designing reserve can solve the problem of sparseness, the shape of the reserve is too narrow which is infaust to the information exchange between species. We further consider the spatial characteristic of compactness [32] in reserve design and that is associated with the concept of the dual-flow structure. The equation of spatial compactness is expressed as following,

$$\min P^d, \tag{7}$$

$$P = \sum_i R_i - \sum_i Z_{i,j} D_{i,j}. \tag{8}$$

where P is the perimeter of sites; if $d = 0$, $P^{d=0}$ is the total perimeter of selected sites; otherwise, $P^{d=1}$ is the total

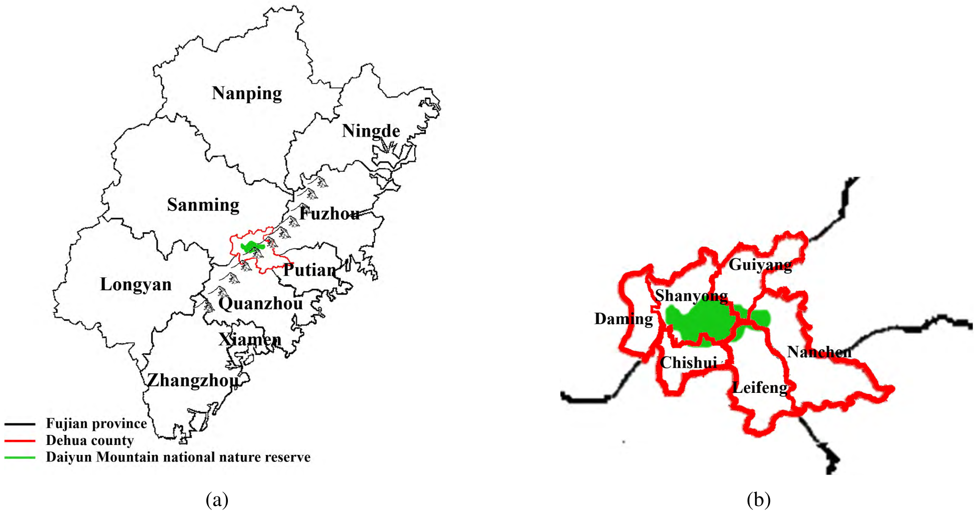

FIGURE 5. Study area – Daiyun Mountains district. (a) Daiyun Mountains nature reserve in Fujian. (b) Daiyun Mountains nature reserve covers 6 villages.

perimeter of unselected sites. R_i is the perimeter of site i. $Z_{i,j}$ is a binary variable {0, 1} which presents the status of site i and its neighbor site j, $Z_{i,j}$ is set to 1, if both of site i and its neighbor site j are selected, otherwise, $Z_{i,j}$ is set to be 0. $D_{i,j}$ is the length of the common edge between site i and site j.

Eq. 7 calculates the perimeter of the reserve which is suitable for regular unit. The perimeter is calculated by adding four edges of the selected sites and subtracting the common edges. The goal is to minimize the perimeter of the reserve with spatial compactness. Therefore, we associate Eq. 1 with Eq. 7 to form a new objective function, as shown in the following,

$$\min\ c = w \cdot \sum_{i} U_i(1 - e_i) + (1 - w) \cdot P^d, \tag{9}$$

where w is the weight of ecological value of the selected sites and $1 - w$ is the weight of the perimeter of the reserve. The new objective function Eq. 9 achieves the goal which maximizes the ecological value and minimizes the perimeter of the designed reserve. In this study, we take the branch and bound algorithm into the proposed model to obtain the optimal solution. The branch and bound algorithm gets optimal solution between the upper and lower bounds of the model by iteration, in which the lower and upper bounds are from the slack and feasible solutions of the model, respectively.

IV. MATERIALS

In this section, we first introduce the study area, Daiyun Mountains, China. Next, we present the evaluation of the ecology of the study area.

A. STUDY AREA: DAIYUN MOUNTAINS, CHINA

Daiyun Mountains is one of the two mountain chains of Fujian province of China, in which the Daiyun Mountains nature reserve is located in Dehua County (Figure 5(a)). The Daiyun Mountains nature reserve is one of the earliest established nature reserves in Fujian Province that is built in 1985 and is upgraded to the national nature reserve in 2005. It covers 6 villages and towns with 18,768 sublots and has an area of 13472.4 hm^2 ((Figure 5(b)). Daiyun Mountains has the largest area covered by native *Pinus taiwanensis* Hayata in the southeast coast of China. It is a typical forest ecosystem of mountain. The distinctive geology, geomorphology, and climate produce a lot of species which have abundant biodiversity and several rare tree species. The Daiyun Mountains nature reserve has 2066 species of the higher plants, including 149 species of bryophytes, 183 species of ferns, 20 species of gymnosperms, and 1714 species of angiosperms; 420 species of vertebrates, including 68 species of fish, 30 species of amphibians, 70 species of reptiles, 194 species of birds and 58 species of mammals; 1645 species of insects, 136 species of large-scale fungi and 56 species of soil microorganisms [33].

To design a reserve, there is some information that should be considered, such as the information of animals, plants, microorganisms and abiotic environmental factors. However, it is difficult to collect the complete real data by forest resource investigation for various species. Therefore, we use plants information to present the condition of reserve. The higher level the health of plants is, the better the ecological environment is. For plants information, we consider the information of plants with zones, province and nationally protected species, which are the second category investigation of forest resource to generate the ecological information.

In this study, we select species according to the plants of zonality and protection of Daiyun Mountains for reserve design. Its zonal vegetation is the montane broadleaved and coniferous forests (Figures 6(a) and 6(b)). We select the *Pinus taiwanensis* Hayata, *Liquidambar formosana*, *Pinus massoniana*, *Cunninghamia lanceolata*, *Schima superba*, and other

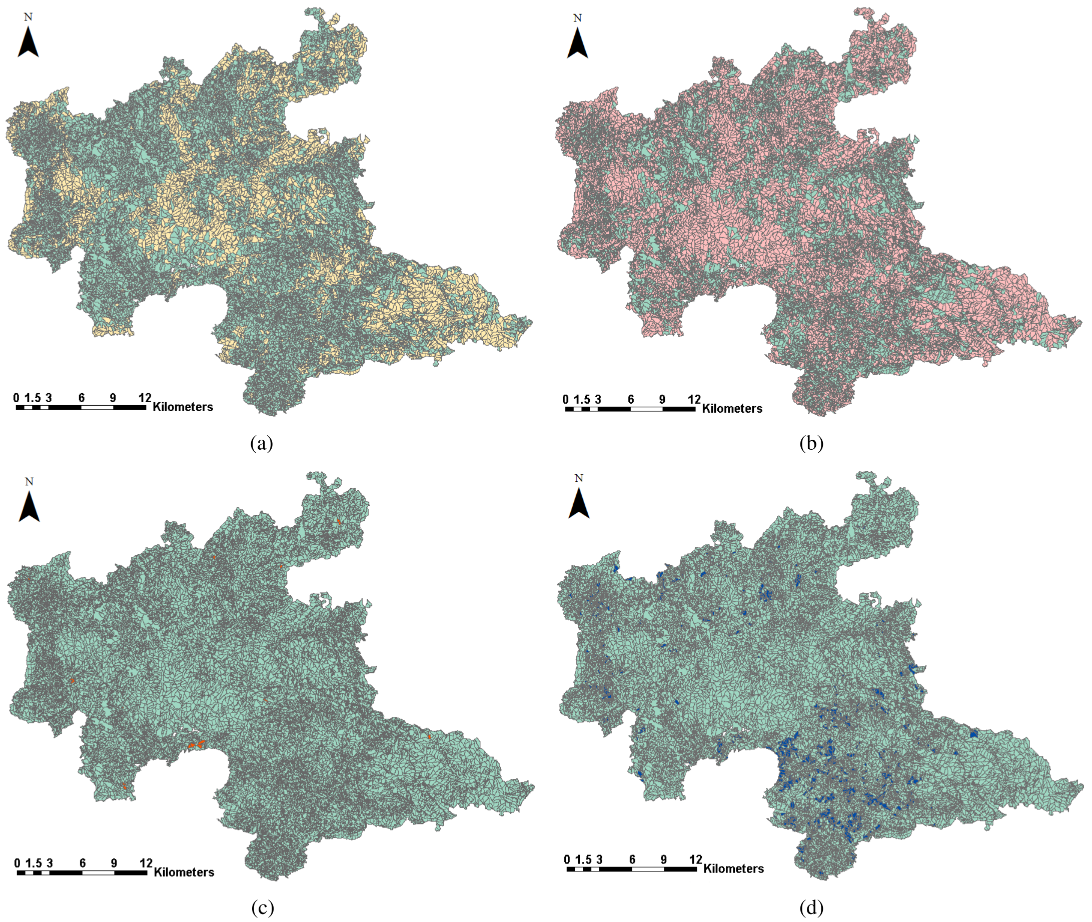

FIGURE 6. The distribution of species and vegetation. (a) zonal vegetation - montane broadleaved forests, (b) zonal vegetation - coniferous forests, (c) The protected species, and (d) alien species. The zonal vegetation of montane broadleaved forests are indicated as yellow color and the zonal vegetation of coniferous forests are indicated as red color. The protected species are indicated as orange color. The alien species are indicated as blue color.

TABLE 1. Grading standard of ecological score.

Score	L_C	VoT	S_C	H_{avg}/m	D_m/cm
10	*stand*	*obv. & dom.*	0.8 over	16 over	20 over
8	*c & b*	*dom.*	$0.7 \sim 0.8$	$10 \sim 16$	$14 \sim 20$
6	*o & s*	*single dom.*	$0.6 \sim 0.7$	$7 \sim 10$	$10 \sim 14$
4	*s & u*	*no dom.*	$0.4 \sim 0.6$	$4 \sim 7$	$8 \sim 10$
2	*u & n*	*single*	$0 \sim 0.4$	$0 \sim 4$	$0 \sim 8$
0	*non-forest*	*no species*	0	0	0
Score	C_{age}	S_Q	S_R	Z_{VT}	
10	C_{age}^{Mid}	Most fertile	*G & E*	$M^B \& M_B^C$	
8	C_{mat}^{Near}	More fertile	*LI & LII*	$M^C \& R_P^C \& R_P^B \& B$	
6	C_{Mat}	fertile	*LIII*	$C_P \& B_P$	
4	C_{mat}^{Over}	Infertile	*R & E*	–	
2	C_{age}^{Young}	–	–	–	
0	–	–	–	–	

hardwood species to represent the zonal vegetation of Daiyun Mountains. We also consider the 2^{nd} class national protected species, *Fokienia hodginsii*, *Taiwania cryptomerioides* and *Cinnamomum bodinieri*, and the Fujian provincial protected species, *Cryptomeria japonica* and *Tsuga longibracteata*, in our study (Figure 6(c)). To maintain the diversity and to evaluate the quality of ecological environment, we further consider the alien species, *Eucalyptus robusta* and *Pinus taeda* (Figure 6(d)).

B. ECOLOGICAL INFORMATION

We consider the ecological information to evaluate the significance of each sublot for protecting and maintaining biodiversity. In our study, we adopt the land class (L_C), the varieties of trees (VoT), the stand closure (S_C), the average height of trees (H_{avg}), the mean diameter of trees (D_m), the age composition of trees (C_{age}), the site quality (S_Q), the species rareness (S_R), and the zonal vegetation type (Z_{VT}) to be the ecological information. The land class (L_C) is to describe the coverage of the tree species and the utilization. The varieties of trees (VoT) presents the competition between tree species. In an ecological system, the dominant tree species is the key to assess the resilience and the vulnerability of the forest [34], [35]. It affects the stability of the communities and is the factor for species survival [36]. The stand closure (S_C) is the ratio of the vertical projection area of canopy to the area of forest, it presents the utilization between different trees. The structure of forest stand shows the quality of forest resources including VoT, H_{avg}, D_m, and C_{age}. The growth of plant is related to S_Q, the higher the fertility is, the better the plant grows. S_R and Z_{VT} present the number of rare species and condition of vegetation type. We transform the ecological information into ecological score e for each sublot according to Table 1.

To enhance the readability, the items of L_C are abbreviated as: *c & b* is the commercial and the bamboo forests; *o & s* is the open woodland and the shrub land; *s & u* is the suitable and the unplanned lands; *u & n* is the unutilized wasteland and the non-forest land. The items of VoT are abbreviated as: *obv. & dom.* is the obvious dominating species with multiple accompanying species; *dom.* is the dominating species with multiple accompanying species; *single dom.* is the single dominating species with single accompanying species; *no dom.* is no dominating species; *single* is the single species. The items of C_{age} are abbreviated as: C_{age}^{Mid} is the middle-aged stand; C_{mat}^{Near} is the near-mature forest; C^{Mat} is the mature forest; C_{mat}^{Over} is the over-mature forest; and C_{age}^{Young} is the young-aged stand. The items of S_R are abbreviated as: *G & E* is the global rare and the endangered species; *LI & LII* is the grade national main protective plants of level I and II; *LIII* is III grade national main protective plants; *R & E* is the regional rare and the endangered species. The items of Z_{VT} are abbreviated as: $M^B\&M_B^C$ are the broadleaved mixed forest, and the coniferous and broadleaved mixed forest; M^C, R_P^C, $R_P^B\&B$ are the coniferous mixed forest, the relatively coniferous pure forest, the relatively broadleaved pure forest and the bamboo forest. $C_P\&B_P$ are the coniferous pure forest and the broadleaved pure forest.

The ecological score of each sublot is calculated by accumulating the score of each item, as shown in Table 1. For example, one of the sublots i has the properties includes *stand*, *dom.*, S_C is $0.7 \sim 0.8$, H_{avg} is $7 \sim 10$, D_m is $8 \sim 10$, C_{age} is C_{Mat}, S_Q is fertile, S_R is *R & E*, and Z_{VT} is $C_P\&B_P$. The scores of each item are 10, 8, 8, 6, 4, 6, 6, 4, 6 and the total score of ecology of that sublot i is $e_i = 10 + 8 + 8 + 6 + 4 + 6 + 6 + 4 + 6 = 58$.

Due to the difficulties of field investigation and the limitation of human and material resources, the sampling points cannot cover each sublot, as shown in Figure 7.

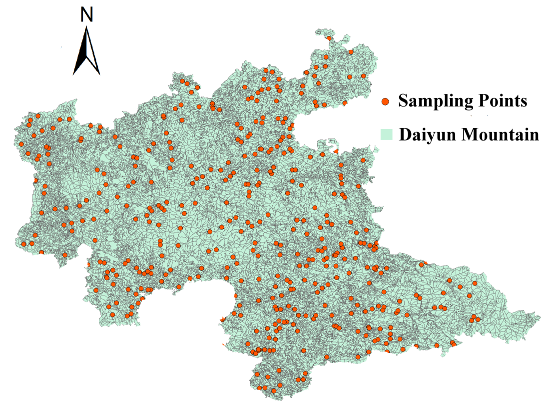

FIGURE 7. Sampling point in the study area.

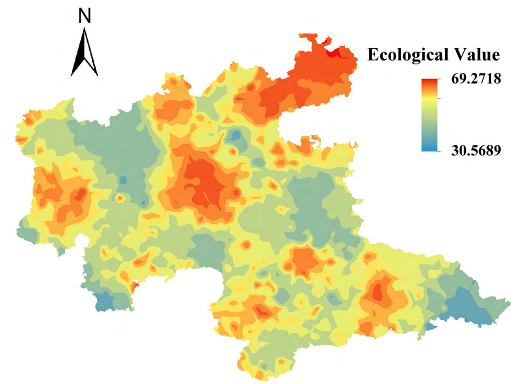

FIGURE 8. Simulation result of the distribution of Daiyun Mountains.

Figure 7 presents the distribution of the sampling points of the second category investigation of forest resource which are indicated as orange points. Although there are a lot of sampling points in our study area, the coverage area is incomplete. To solve this problem, we use statistical technique to estimate the ecological value to present the species distribution. In this study, we use the universal Kriging interpolation method to estimate the distribution of ecological value of Daiyun Mountains. The Kriging interpolation method considers the linear unbiased optimal properties to estimate the estimated points which can provide higher accuracy compared with other interpolation methods. The interpolation result of ecological value of Daiyun Mountains is shown in Figure 8. Figure 8 demonstrates that the distribution of ecological value is obviously different in Daiyun Mountains. Some regions, such as the northeast, part of southeastern, part of southern, part of the western, part of northern, and part of the central, have higher ecological values compared with the rest regions. The indexes of these regions are better than the average, which is consistent with the second category investigation of the forest resource.

The sublot, which has an irregular shape, is the basic unit for the evaluation of the ecological score. Figure 9 is an example of sublot of Shanyong in Daiyun Mountains district,

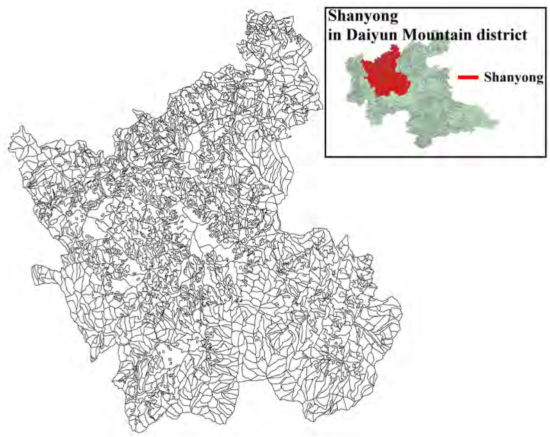

FIGURE 9. Example of sublot of Daiyun Mountains district.

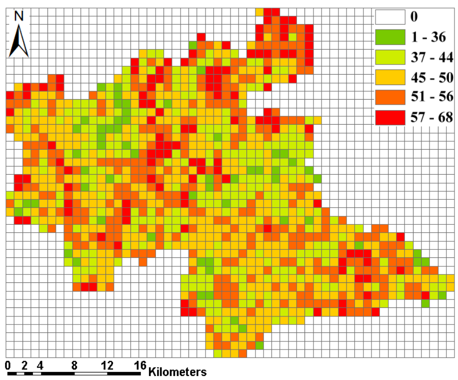

FIGURE 10. The ecological score of each grid in Daiyun Mountains district.

and it has a numerous of sublots. There are 18,768 sublots in our study area, and that consumes a lot of computational cost including the resource of CPU and memory when selecting sites. Therefore, we separate the study area into $n \times n$ grids with regular shape to reduce the computational cost. The number of grids with grid size of $0.25 \times 0.25\ km^2$, $0.5 \times 0.5\ km^2$, $1 \times 1\ km^2$, $2 \times 2\ km^2$, and $3 \times 3\ km^2$ are 36,288, 9,072, 2,268, 567, and 252, respectively. To consider experimental resource and to prove the feasibility of the proposed mathematical model, we select the parameter with $n = 1$, in our study. Then, we re-calculate the ecological score for each grid based on the ecological score of each sublot. We utilized the ecological score and center of gravity of each sublot to evaluate the ecological score of each grid. If the center of gravity of the sublot j is located at the grid i, the ecological value of the sublot j belongs to the grid i. The formula can be formally defined as follow,

$$e_i = \frac{1}{n} \sum_{j}^{n} \varepsilon_j, \tag{10}$$

where e_i is the ecological score of each grid, and ε_j is the ecological score of the sublot j. To eliminate the influence of value, we use normalization method to correct the evaluated ecological value, as shown in the following equation,

$$e_i = \frac{e_i - \min(e_i)}{\max(e_i) - \min(e_i)}, \tag{11}$$

where e_i is the normalized ecological score of grid i. Fig. 10 shows the distribution of ecological score of each grid in Daiyun Mountains district. Fig. 10 indicates that the high ecological value is mainly concentrated in the center of Daiyun Mountains and extend to northeast and southwest part of Daiyun Mountains.

V. EXPERIMENTAL RESULTS AND DISCUSSION

We take Daiyun Mountains in China as the study area, and apply the proposed model, which is described in Section III, to design the conservation.

To demonstrate the feasibility of the proposed model, we compare the proposed method with three popular site selection models: (1) the species set covering problem (SSCP); (2) the network flow problem (NFP); (3) simulated annealing (SA). SSCP and NFP belong to the optimization-based algorithms but have different properties. SSCP is the classic model in optimization problem which satisfies the requirement of the species protection with minimum costs; NFP is the famous integer linear programming which considers the characteristic of spatial continuity in site selection. Simulated annealing is one of the popular heuristic-based algorithms which quickly searches the feasible solution.

In Figs. 11 and 12, the sites marked as black are indicated as the selected sites. The sparseness is the isolated region and has two types in the designed nature reserve. Type A is the unselected sites which surrounded by the selected sites, and Type B is the selected sites which surrounded by the unselected sites. In Figs. 11 and 12, the sparseness of type A is indicated as red rectangles and the sparseness of type B is indicated as blue rectangles. In Figs. 11 and 12, the selected sites which is continuous and narrow is indicated as green rectangle.

Figs. 11 demonstrates the results of each mathematical model with $k_s = 0.3$. Figs.11 (a), (b), and (c) are the results of species set covering problem (SSCP), network flow problem (NFP), and simulated annealing (SA), respectively. Although SSCP selects sites with high ecological value, the spatial distribution of the selected sites is sparse which loses the spatial characteristics of continuity and compactness, and be indicated as blue rectangles in Fig. 11 (a). In Fig. 11 (a), there are a lot of isolated sites, which are the selected sites and surrounded by the unselected sites, and show the discontinuous phenomenon in space. NFP overcomes the problem of spatial continuity of SSCP, but still has two problems, one is the phenomenon of sparseness and the other is the problem of the selected sites which is narrow in space. The sparseness of NFP is type A, which is indicated as red rectangles in Fig. 11 (b). Moreover, NFP only considers the spatial continuity and that makes the shape of the selected sites continuous but narrow. Comparing with SSCP and NFP,

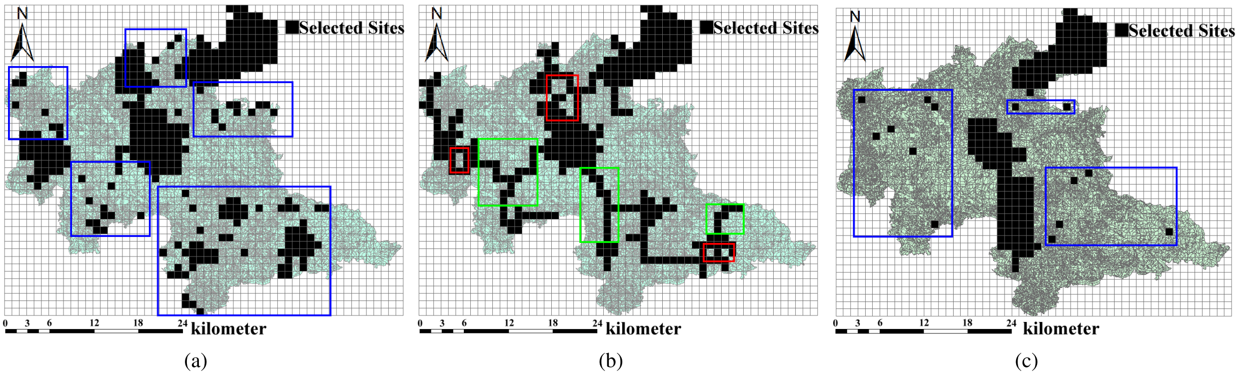

FIGURE 11. **The results of site selection with the percentage of protecting species $k_s = 0.3$. (a) Species set covering problem (SSCP), (b) network flow problem (NFP), and (c) simulated annealing (SA).**

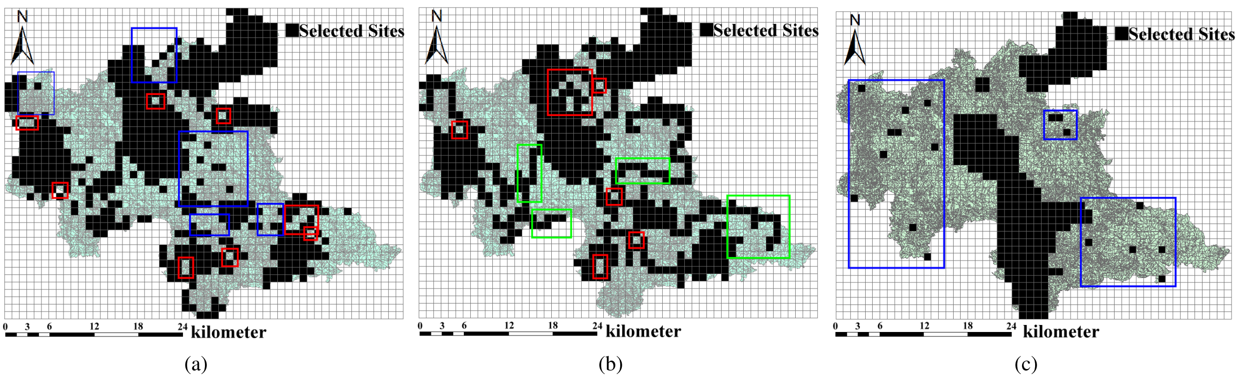

FIGURE 12. **The results of site selection with the percentage of protecting species $k_s = 0.5$. (a) Species set covering problem (SSCP), (b) network flow problem (NFP), and (c) simulated annealing (SA).**

although SA does not have the narrow phenomenon in space, it still has the isolate sites in the designed reserve, the spatial characteristics are lost.

The number of selected sites of those mathematical models is increased when the percentage of protected species (k_s) is increased, the problem of spatial distribution still exists in the designed reserve. Fig. 12 demonstrates the problem of spatial distribution of various mathematical models with $k_s = 0.5$. Figs. 12 (a), (b) and (c) are the results of SSCP, NFP, and SA, respectively. To compare Fig. 12 with Fig. 11, the number of selected sites is increased and still has the problem of spatial distribution. In Figs. 12 (a) and (b), the number of isolate sites (Type *A* and Type *B*) obviously increases in the designed reserve compared with Figs. 11 (a) and (b). Comparing Fig. 11 (c) with Fig. 12 (c), although some selected regions become more compact, the number of the scattered points increases.

Fig.13 demonstrates the results of the proposed mathematical model(Dual-Flow Structure, DFS). Figs. 13 (a) and (b) are the results of DFS with $k_s = 0.3$ and $k_s = 0.5$, respectively. Sites with high ecological values are considered and the problem of spatial distribution is solved. In Fig. 13, the selected sites which are indicated as black are connected and that provides the spatial continuity for the species exchange. The adjacent sites of the selected sites are close, which forms the compact shape to present the spatial compactness. DFS performs the spatial continuity on both processes of selected and unselected decisions which overcomes the problem of the isolate sites (Type *A* and Type *B*) in reserve design. In the procedure of solving the sparseness problem, DFS minimizes the objective function and maximizes the ecological value of reserve to design a reasonable area without sacrificing the spatial continuity and compactness.

The quantitative comparison results are summarized in Table 2. The total ecological value and total number of sites in the study area are 900.22 and 1137, respectively. In the process of analyzing the qualitative and quantitative results, although SA selects sites with least number of sites, it has the lowest ecological value and the spatial distribution of the selected sites is sparse as shown in Figs 11 (c) and 12 (c). The results of SA cannot achieve the goal of reserve protection for it is not conducive to species exchange. DFS has the approximate quantitative results compared with SSCP and NFP in both ecological value and number of sites, and it also solve the problem of spatial sparseness and achieves spatial characteristics such as continuity and compactness in reserve design.

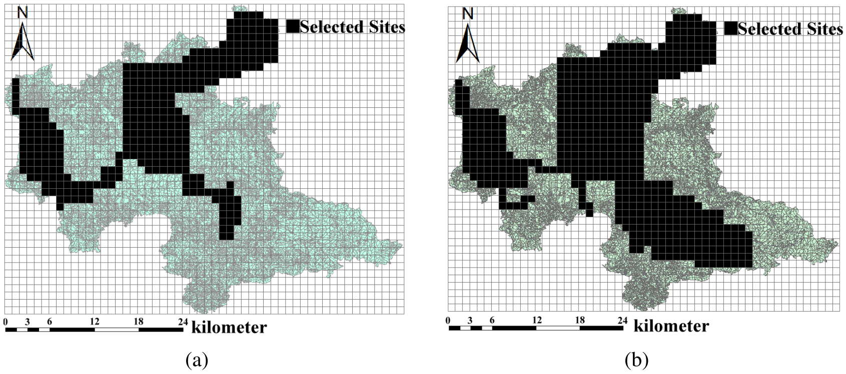

FIGURE 13. The results of the proposed mathematical model (Dual-Flow Structure, DFS). (a) $k_s = 0.3$. (b) $k_s = 0.5$.

TABLE 2. Quantitative comparison results on popular models.

Models	$k_s = 30\%$		$k_s = 50\%$	
	Eco. Value	No. sites	Eco. Value	No. sites
SSCP	282.76	327	457.52	544
NFP	280.24	327	455.61	546
SA	157.75	187	105.62	169
DFS	276.91	328	452.01	549

VI. CONCLUSION

In this study, we proposed a novel mathematical model, Dual-Flow Structure (DFS), to solve the problem of spatial distribution in reserve design. DFS provides a reasonable proposal with a scientific theory to design the reserve, which forms the dual-flow structure in design by considering the flows of selection and unselection simultaneously and achieves the minimization of objective function by the dual-flow competition. DFS considers the spatial constraints between adjacent sites in both flows and achieves the spatial continuity and compactness in the selected and unselected sites. The dual-flow competition eliminates the isolate sites and overcomes the spatial sparseness in the designed reserve.

To prove the feasibility of the proposed model, we take the Daiyun Mountains as the study area. The proposed model is compared with three famous mathematical models, species set covering problem (SSCP), network flow problem (NFP), and simulated annealing (SA), which have been used in site selection. SSCP only considers the sites with high ecological value, the spatial distribution of the selected sites is sparse. Although NFP selects sites by considering the spatial continuity, the spatial distribution of selected sites still has the phenomenon of spatial sparse and isolate sites in the designed reserve. SSCP and NFP are popular mathematical models in linear integer programming whereas they still have the drawbacks of spatial distribution. We further analyze the heuristic algorithm by using simulated annealing. SA is one of the famous algorithms in heuristic algorithm which quickly searches the local optimal solution. Although SA can quickly provide the solution for site selection, the spatial characteristics of selected sites are lost. DFS utilizes the dual-flow mechanism to eliminate the problem of isolate sites in the designed reserve and to maintain the spatial continuity and compactness.

REFERENCES

[1] E. Wikramanayake, M. McKnight, E. Dinerstein, A. Joshi, B. Gurung, and D. Smith, "Designing a conservation landscape for tigers in human-dominated environments," *Conservation Biol.*, vol. 18, no. 3, pp. 839–844, Jun. 2004.
[2] E. McLeod, R. Salm, A. Green, and J. Almany, "Designing marine protected area networks to address the impacts of climate change," *Frontiers Ecology Environ.*, vol. 7, no. 7, pp. 362–370, Sep. 2009.
[3] P. R. Ehrlich, "Population biology of checkerspot butterflies and the preservation of global biodiversity," *Oikos*, vol. 63, no. 1, pp. 6–12, Feb. 1992.
[4] R. L. Church, D. M. Stoms, and F. W. Davis, "Reserve selection as a maximal covering location problem," *Biol. Conservation*, vol. 76, no. 2, pp. 105–112, 1996.
[5] F. R. Gehlbach, "Investigation, evaluation, and priority ranking of natural areas," *Biol. Conservation*, vol. 8, no. 2, pp. 79–88, Sep. 1975.
[6] S. C. Newbold and J. Siikamäki, "Prioritizing conservation activities using reserve site selection methods and population viability analysis," *Ecolog. Appl.*, vol. 19, no. 7, pp. 1774–1790, Oct. 2009.
[7] A. Das *et al.*, "Prioritisation of conservation areas in the Western Ghats, India," *Biol. Conservation*, vol. 133, no. 1, pp. 16–31, Nov. 2006. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0006320706002096
[8] D. R. Helliwell, "Valuation of wildlife resources," *Regional Stud.*, vol. 3, no. 1, pp. 41–47, Aug. 1968.
[9] H. J. Harris, M. S. Milligan, and G. A. Fewless, "Diversity: Quantification and ecological evaluation in freshwater marshes," *Biol. Conservation*, vol. 27, no. 2, pp. 99–110, 1983.
[10] F. Goötmark, M. Åhlund, and M. O. G. Eriksson, "Are indices reliable for assessing conservation value of natural areas? An avian case study," *Biol. Conservation*, vol. 38, no. 1, pp. 55–73, 1986.
[11] R. L. Pressey and A. O. Nicholls, "Efficiency in conservation evaluation: Scoring versus iterative approaches," *Biol. Conservation*, vol. 50, nos. 1–4, pp. 199–218, 1989.
[12] J. Ananda and G. Herath, "A critical review of multi-criteria decision making methods with special reference to forest management and planning," *Ecolog. Econ.*, vol. 68, no. 10, pp. 2535–2548,Aug. 2009.

[13] D. F. Wright, "A site evaluation scheme for use in the assessment of potential nature reserves," *Biol. Conservation*, vol. 11, no. 4, pp. 293–305, Jun. 1977.
[14] A. Moffett and S. Sarkar, "Incorporating multiple criteria into the design of conservation area networks: A minireview with recommendations," *Diversity Distributions*, vol. 12, no. 2, pp. 125–137, Mar. 2006.
[15] J. B. Kirkpatrick, "An iterative method for establishing priorities for the selection of nature reserves: An example from tasmania," *Biol. Conservation*, vol. 25, no. 2, pp. 127–134, Feb. 1983.
[16] C. R. Margules, A. O. Nicholls, and R. L. Pressey, "Selecting networks of reserves to maximise biological diversity," *Biol. Conservation*, vol. 43, no. 1, pp. 63–76, 1988.
[17] B. Csuti *et al.*, "A comparison of reserve selection algorithms using data on terrestrial vertebrates in oregon," *Biol. Conservation*, vol. 80, no. 1, pp. 83–97, Apr. 1997.
[18] S. Polasky, J. D. Camm, A. R. Solow, B. Csuti, D. White, and R. Ding, "Choosing reserve networks with incomplete species information," *Biol. Conservation*, vol. 94, no. 1, pp. 1–10, Jun. 2000.
[19] A. J. A. van Teeffelen, M. Cabeza, and A. Moilanen, "Connectivity, probabilities and persistence: Comparing reserve selection strategies," *Biodiversity Conservation*, vol. 15, no. 3, pp. 899–919, Mar. 2006.
[20] J. O. Cerdeira, L. S. Pinto, M. Cabeza, and K. J. Gaston, "Species specific connectivity in reserve-network design using graphs," *Biol. Conservation*, vol. 143, no. 2, pp. 408–415, Feb. 2010.
[21] R. K. Kincaid, C. Easterling, and M. Jeske, "Computational experiments with heuristics for two nature reserve site selection problems," *Comput. Oper. Res.*, vol. 35, no. 2, pp. 499–512, 2008.
[22] M. Ciarleglio, J. Wesley Barnes, and S. Sarkar, "ConsNet: New software for the selection of conservation area networks with spatial and multi-criteria analyses," *Ecography*, vol. 32, no. 2, pp. 205–209, Apr. 2009.
[23] M. Ciarleglio, J. W. Barnes, and S. Sarkar, "ConsNet—A tabu search approach to the spatially coherent conservation area network design problem," *J. Heuristics*, vol. 16, no. 4, pp. 537–557, Aug. 2010.
[24] H. Possingham, I. Ball, and S. Andelman, "Mathematical methods for identifying representative reserve networks," in *Quantitative Methods for Conservation Biology*. New York, NY, USA: Springer, 2000, pp. 291–306.
[25] L. G. Underhill, "Optimal and suboptimal reserve selection algorithms," *Biol. Conservation*, vol. 70, no. 1, pp. 85–87, 1994.
[26] J. D. Camm, S. Polasky, A. Solow, and B. Csuti, "A note on optimal algorithms for reserve site selection," *Biol. Conservation*, vol. 78, no. 3, pp. 353–355, Dec. 1996.
[27] K. Gaston, R. Pressey, and C. R. Margules, "Persistence and vulnerability: Retaining biodiversity in the landscape and in protected areas," *J. Biosci.*, vol. 27, no. 4, pp. 361–384, Jul. 2002.
[28] J. M. Diamond, "The island dilemma: Lessons of modern biogeographic studies for the design of natural reserves," *Biol. Conservation*, vol. 7, no. 2, pp. 129–146, Feb. 1975.
[29] H. Önal and R. A. Briers, "Selection of a minimum-boundary reserve network using integer programming," *Proc. Roy. Soc. London B, Biol. Sci.*, vol. 270, no. 1523, pp. 1487–1491, Jul. 2003.
[30] J. C. Williams, "Optimal reserve site selection with distance requirements," *Comput. Oper. Res.*, vol. 35, no. 2, pp. 488–498, Feb. 2008.
[31] N. Jafari and J. Hearne, "A new method to solve the fully connected reserve network design problem," *Eur. J. Oper. Res.*, vol. 231, no. 1, pp. 202–209, Nov. 2013.
[32] D. T. Fischer and R. L. Church, "Clustering and compactness in reserve site selection: An extension of the biodiversity management area selection model," *Forest Sci.*, vol. 49, no. 4, pp. 555–565, Aug. 2003.
[33] P. Lin, *The Comprehensive Scientific Investigation Report of the Daiyun Mountains Nature Reserve*. Xiamen, China: Xiamen Univ. Press, 2003.
[34] T. G. Whitham *et al.*, "Community and ecosystem genetics: A consequence of the extended phenotype," *Ecology*, vol. 84, no. 3, pp. 559–573, Mar. 2003.
[35] M. T. Johnson and J. R. Stinchcombe, "An emerging synthesis between community ecology and evolutionary biology," *Trends Ecology Evol.*, vol. 22, no. 5, pp. 250–257, May 2007.
[36] A. Abdollahnejad, D. Panagiotidis, S. S. Joybari, and P. Surový, "Prediction of dominant forest tree species using quickbird and environmental data," *Forests*, vol. 8, no. 2, p. 42, Feb. 2017.

CHIH-WEI LIN was born in Taipei, Taiwan, in 1981. He received the B.S. degree in civil engineering, and the B.E. degree in computer science and information engineering from Tamkang University, Taipei, Taiwan, in 2004, the M.S. degrees in civil engineering and in computer science and information engineering from National Central University, Taoyuan, Taiwan, in 2007, and the Ph.D. degree in computer science and information engineering from National Taiwan University, Taipei, in 2015.

He joined the College of Computer and Information Sciences, Fujian Agriculture and Forestry University, Fuzhou, China, since 2015. His research interests include image analysis, biometric verification, and video surveillance, machine learning, and nature reserves.

Dr. Lin was a Program Committee Member of the ISPDC'16, the ISPDC'17, the ISPDC'18, the IMMM'18, and the CSE'18, and was the Publicity Committee Member of the IFSA-SCIS'17. He is currently the Program Committee Member of the ISPDC'19.

WEI-HAO TU received the B.S. degree in statistics from Fujian Agriculture and Forestry University, Fuzhou, in 2016, where he is currently pursuing the master's degree. His research interests include image recognition, data mining, artificial intelligence, and resource statistics.

JIN-FU LIU received the B.S. degree in mathematics from Fujian Normal University, China, in 1990, the M.S. degree in resources and environment from Fujian Agriculture and Forestry University, China, in 1997, and the Ph.D. degree in resources and environment from Northeast Forestry University, China, in 2004. In 1990, he joined the Department of Forestry Industry, Fujian Agriculture and Forestry University, China, where he is currently a Professor with the College of Computer and Information Sciences. His research interests are in the area of forest management, ecology, and wildlife conservation and utilization.