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A GIS-based multi-criteria decision making approach to forest conservation planning at a landscape scale: a case study in the Kinabalu Area, Sabah, Malaysia

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Abstract

This paper presents a geographic information system (GIS)-based multi-criteria decision making approach for forest conservation planning at a landscape scale. This approach enables decision makers to evaluate the relative priorities of conserving forest areas based on a set of preferences, criteria and indicators for the area. Compromise programming techniques are used to integrate the forest conservation priority maps of decision groups where a separation distance is calculated. A clustering analysis was applied to identify potential conservation areas as the basis of delineating potential new protected areas. The study was conducted in the Kinabalu area, Sabah, Malaysia where two polygons neighboring the Kinabalu Park were delineated. A group of 11 polygons totaling 2050 ha has also been detected in the western part of Kinabalu Park. The study recommends the inclusion of a forest polygon (359 ha) neighboring Kinabalu Park and another (4361 ha) to the west of the park as new protected areas. A green corridor linking the potential new protected areas and Kinabalu Park should also be constructed to facilitate animal movement and interaction. This study reveals that riparian vegetation is an important aspect to forest conservation and the legislation to protect riparian zones should be strengthened.
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Keywords: Forest conservation planning; GIS; Multi-criteria decision making; Kinabalu

1. Introduction

An important aspect of conservation planning is the evaluation and selection of conservation areas using a set of criteria termed criteria-based evaluation (Bibby, 1998). If the conservation target is forest, then forest conservation planning can be defined as activities to evaluate the forest with appropriate criteria and techniques at a landscape scale, and to prioritize the forest so that potential forest areas for conservation can be selected. The planning process does not deny the conservation value of other forest areas but rather that in relation to the agreed goals, conservation actions may not be as urgent (Williams, 1998).

Conservationists often focus on a particular species and usually it is "charismatic megavertebrates" that attract public attention, have symbolic value, and play key roles in ecotourism (Primack, 1993). This

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single-species approach is a very expensive and inefficient approach because all organisms per se cannot be conserved (Barnes et al., 1998). There has been a gradual shift from a single-species approach to a multi-species approach, and ecosystems should be the target for conservation efforts (Franklin, 1993; Vuilleumier and Prelaz-Droux, 2002). Ecosystem conservation may conserve more species in a self-maintaining unit.

Habitat fragmentation has been widely recognized as a major threat for biodiversity and ecosystem conservation (e.g. Spies et al., 1994; Lathrop and Bognar, 1998). Land use activities such as forest clearing and other management activities for commercial timber production can fragment populations of forest dependent wildlife (Lamberson et al., 1994). Impacts of land use activities on ecosystems have been identified by using activity-environmental impact matrices (e.g. Cook and Van Lier, 1994; Senes and Toccolini, 1998). Modeling of ecologic networks in fragmented landscapes provides an understanding of the impacts of human activities on wildlife dispersal and it can assist forest ecosystem conservation planning (Vuilleumier and Prelaz-Droux, 2002). Gaps of conservation areas have been analyzed at a landscape scale to improve conservation area networks (Scott et al., 1993). Landscape indices may also be useful to forest ecosystem conservation planning because the indices can be used to characterize forest fragmentation (e.g. Hulshoff, 1995; Lindenmayer et al., 1999). The relationships between species number and landscape indices have been investigated (e.g. Collinge, 1996; Drechsler and Wissel, 1998). To address conservation issues in managed forests, ecosystem models have been used in optimization of forest landscapes for use and conservation (e.g. Boyce, 1995) and landscape ecological aspects have been considered in forest planning (e.g. Kangas et al., 2000).

1.1. Conservation planning and GIS-based evaluation

The capability of geographic information systems (GIS) in handling spatial aspects of conservation has boosted its use in the criteria-based evaluation for prioritization and selection of potential conservation areas. This is because most of the criteria for conservation planning are spatial data. For example, GIS techniques have been used for predicting the distribution of the wild relatives of bean by analyzing climate conditions that favor bean's growth (Jones et al., 1997), and for planning potential conservation areas by using relationships between environmental factors and the distribution of birds (Mariuki et al., 1997). GIS techniques were found invaluable as a rapid tool for wildlife species habitat modeling under situations of incomplete data (Rubino and Hess, 2003). Smallwood et al. (1998) employed an indicators assessment approach using GIS techniques for evaluating habitat of several species. Gap analysis developed for detecting unprotected high-conservation-value areas at a landscape scale was also based on GIS techniques (Scott et al., 1993). The selection of conservation areas in most of these studies is based solely on scientific results where a rational decision making process is assumed.

1.2. Multi-criteria decision making and GIS

Multi-criteria decision making implies a process of assigning values to alternatives that are evaluated along multi-criteria. Multi-criteria decision making can be divided into two broad classes of multi-attribute decision making and multi-objective decision making. If the problem is to evaluate a finite feasible set of alternatives and to select the best one based on the scores of a set of attributes, it is a multi-attribute decision making problem. The multi-objective decision making deals with the selection of the best alternative based on a series of conflicting objectives (Massam, 1988). Both multi-attribute decision making and multi-objective decision making problems can be single-decision-maker problems or group decision problems. There are many classifications in place for the extensive formal methods and procedures for handling multi-criteria decision making (see Hwang and Masud, 1981; Massam, 1988). Conventionally, multi-criteria decision making techniques have largely been aspatial, i.e. assumption of homogeneity within a study area. In reality, the criteria vary across space in many decision making problems (Tkach and Simonovic, 1997; Malczewski, 1999).

Despite its potential to be integrated into solving planning problems related to spatial entities, multi-criteria decision making approach remained in operational research and management fields for a substantial period of time (Eastman et al., 1993). From the 1990s, integration of the multi-criteria decision making approach with GIS for solving spatial planning problems has received considerable attentions among urban planners. The ability of GIS to integrate with the multi-criteria decision making approach has been shown in studies related to site determination for a nuclear waste facility (Carver, 1991) and for a noxious waste facility (Malczewski, 1996). And the GIS-based multi-criteria decision making approach has also extended to solving planning problems that involve conflicting multi-objectives such as land use allocation problems (e.g. Janssen and Rietveld, 1990; Eastman et al., 1995; Yeh and Li, 1998). Relatively few studies related to forest conservation have employed multi-criteria decision making approach with GIS techniques. A GIS-based multi-objective evaluation was experimented with for management optimization of urban green parks in Italy (Villa et al., 1996). The GIS-based multi-criteria decision making approach was also used in solving forest conservation as single-decision-maker problems (e.g. Pereira and Duckstein, 1993; Keisler and Sundell, 1997).

As pointed out by Hwang and Lin (1987) and Massam (1988), spatial problem decisions are often made under a multi-decision maker context. Likewise, forest conservation concerns many stakeholders and it must also be considered as a group decision problem. Forest conservation is an important aspect of public forestry where the decision making process has to consider the existence of a great number of different stakeholders and a broad variety of conflicting goals and objectives (Kangas et al., 1996). Forest conservation typically involves selection of potential areas from many alternative areas based on some conflicting criteria. In the case of Sabah, Malaysia, forest conservation decisions are decided in a consensus among different sectors such as forestry, water resources and conservation parks. They are often characterized by unique preferences with respect to the relative importance of evaluation criteria. Public participation in forest resource use and conservation can promote communication between the interest groups and gather information about the values, attitudes and beliefs of the groups (Pykalainen et al., 1999). In relation to multi-criteria evaluation, existence of multi-decision makers has been considered by deriving weights for evaluation criteria through participation of relevant officials in workshops (Sierra et al., 2002).

Multi-criteria decision making approach can provide a framework to represent the decision groups into a single model. They can be considered as a coalition (Malczewski, 1999), who can agree only on the problem structure (set of alternatives and evaluation criteria) but disagree on the relative importance of the criteria. The multi-criteria group decision making approach has been used in some non-GIS planning applications (e.g. Van Huylenbroeck and Coppens, 1995; Kangas et al., 1996; Malczewski et al., 1997). In the noxious waste facility study of Malczewski (1996), use of the multi-criteria decision making approach with GIS techniques under a group decision making context was investigated.

In this paper, forest conservation is considered as multi-attribute decision making with the existence of decision groups. It is termed multi-criteria group decision making (Malczewski et al., 1997). We outline the use of multi-criteria group decision making with GIS techniques for forest conservation planning in the Kinabalu area, Sabah, Malaysia. We show how preferences of conservation groups can be derived and incorporated in prioritizing forest areas for conservation. We derived indicators at a landscape scale for the criteria covering the interests of the conservation groups. The preferences and indicators are combined to generate potential conservation areas. The potential conservation areas serve as the basis for delineation of potential new protected area.

2. The GIS-based multi-criteria decision making approach to forest conservation planning

The GIS-based multi-criteria decision making approach for the forest conservation planning is shown in Fig. 1. Firstly, forest conservation planning, as a multi-criteria decision making problem is formulated using the Analytical Hierarchy Process technique (Saaty, 1980). Criteria and indicators are evaluated using GIS, remote sensing techniques, coupled with field data and literature. All the scores are standardized because they are not non-commensurate. Preferences on the criteria and indicators are expressed as weights that are assigned by decision makers. Combining the weights and the indicator maps generates

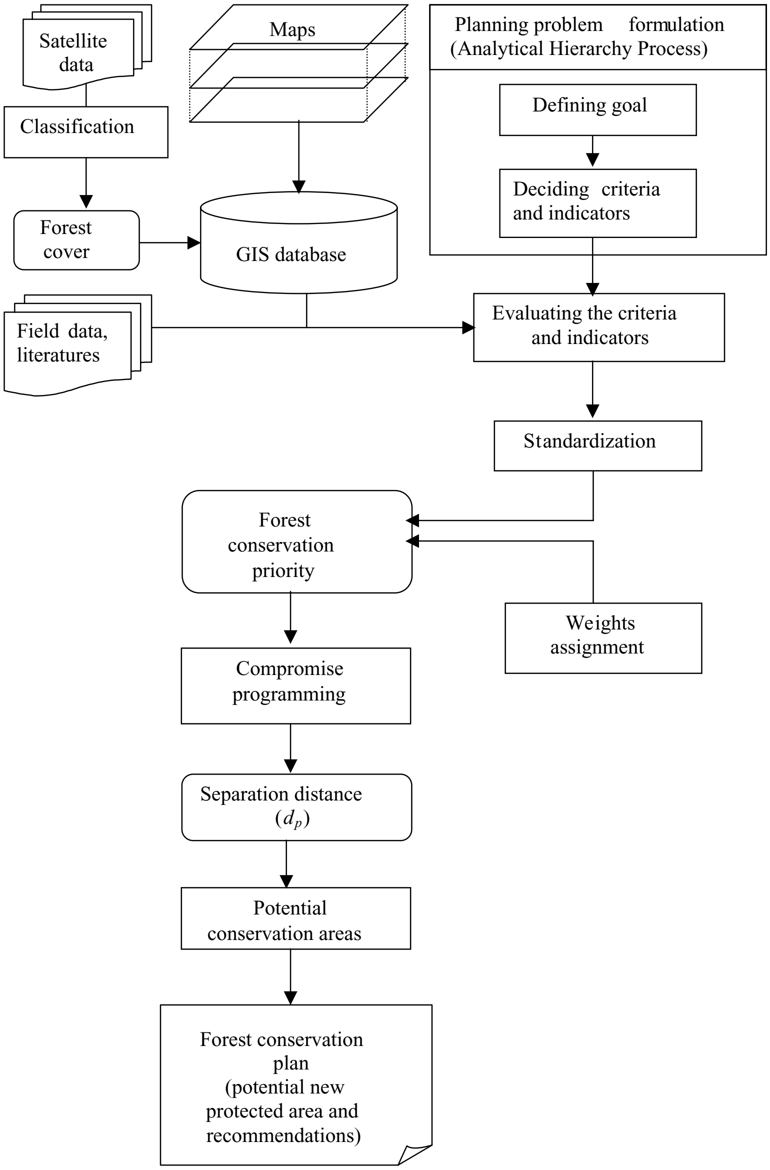

Fig. 1. The GIS-based multi-criteria decision making approach to the forest conservation planning.

forest conservation priority maps of the decision makers. They are then integrated using compromise programming techniques where a separation distance is calculated. Potential conservation areas are generated using thresholds on the separation distance image for delineating potential new protected areas. Based on the potential conservation areas, the forest conservation plan, containing the potential new protected areas and the recommended conservation actions, is generated.

2.1. Hierarchy structure of forest conservation priority evaluation

Forest conservation planning is structured as a hierarchy that consists of a goal at the top level, and criteria and indicators at subsequent levels. The Analytic Hierarchy Process technique allows preferences of decision groups to be incorporated into a planning problem. It actually provides a framework for structuring the problem as a hierarchy where preferences of decision groups can be elicited as weights by pairwise comparisons. The analytical hierarchy process procedure (see Saaty, 1980 for details of the technique) involves: establishing a graphic representation of the problem as a hierarchy; weighting the elements at each level of the hierarchy; calculating the weights; and estimating the consistency ratio.

No weights were given to the decision groups in this study. In the situation where there is a superior decision maker then weights can be given to the decision groups to differentiate their roles in the outcomes (e.g. Kangas et al., 1996; Malczewski et al., 1997). The goal among the decision groups is the same; to evaluate forest conservation priority in the study area. Given the hierarchy, for each level, a pairwise comparison matrix is constructed to rate the relative importance of each element according to their impacts on the level above and weights (w_i) are subsequently computed using the Analytic Hierarchy Process technique. Example of the hierarchy structure of a decision group is shown in Fig. 2 where weights are assigned by a conservationist who is a key figure in Sabah Parks, the enacted body that governs all the parks in the state. To demonstrate the planning under the multi-decision groups circumstance, an additional two weight patterns were arbitrarily generated. One represents neutral decision makers where even weights were given to all the criteria and indicators whereas the other one follows the same weights for the criterion of potential

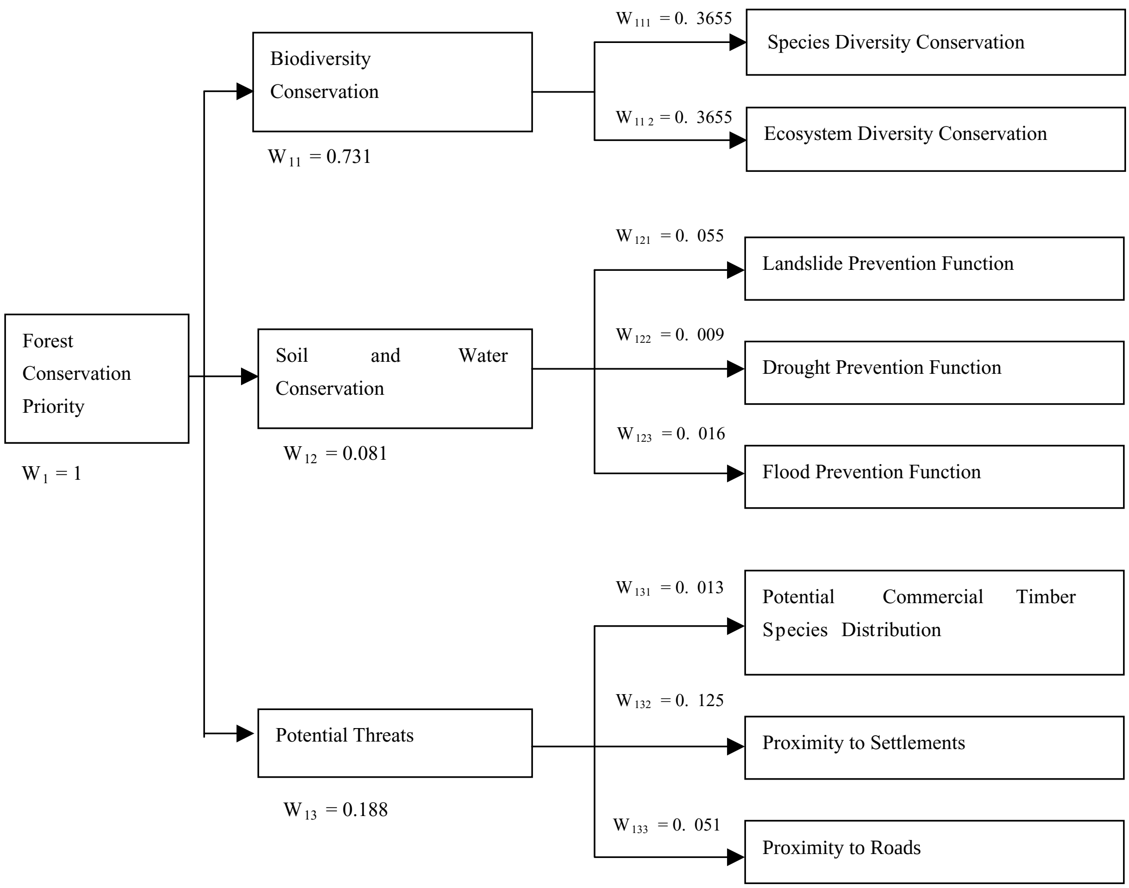

Fig. 2. Hierarchy of the forest conservation planning in Kinabalu Area, Sabah, Malaysia, and weights of the conservationist.

Table 1
Weights setting for the forest conservation planning

	Biodiversity conservation	Soil and water conservation	Potential threats
DM1 (all = equal weights)	0.333	0.333	0.333
DM2 (biodiversity and soil and water = equal weights)	0.406	0.406	0.188
DM3 biodiversity-oriented (biodiversity = preference)	0.731	0.081	0.188

DM: decision maker.

threats as the conservationist but have equal weights for the remaining two criteria (Table 1).

2.2. Forest conservation priority evaluation

In a GIS-based multi-criteria decision making approach, all the pixels in an indicator map or layer can be represented as

$$X = \{x^1, x^2, \dots, x^K\} \tag{1}$$

A multi-criteria pixel refers to a pixel which is a vector containing i attributes or indicators, corresponding to the indicators forming the database. Individual x_i^k designates the score of an attribute i (indicator map) attained by pixel k, as below:

$$x^k = (x_1^k, x_2^k, \dots, x_I^k) \tag{2}$$

where $k = 1, 2, \dots, K$; $i = 1, 2, \dots, I$.

Based on the hierarchy structure, the forest conservation priority can be evaluated by the following equation:

$$C^k = \sum_{i=1}^{I} w_i x_i^k \tag{3}$$

The C^k designates the forest conservation priority attained by kth alternative. x^k is the kth alternative, a pixel containing i indicators with standardized scores which are GIS layers. The w_i of the indicators is calculated by using pairwise comparison in the Analytic Hierarchy Process technique. This is the case where the decision making process involves only one decision maker. In the case of multiple decision makers, C^k becomes

$$C_m^k = (C_1^k, C_2^k, \dots, C_M^k) \tag{4}$$

where m is the decision maker, $m = 1, \dots, M$.

As the indicators are non-commensurate by their nature, standardization is needed. There are many ways to standardize the raw scores, which are measured in different units and in different scales such as nominal, ordinal, interval and ratio scales. This study adopts the most frequently used procedure that uses the minimum and maximum scores as scaling points (e.g. Carver, 1991; Malczewski, 1996). For an indicator where a higher score indicates increasing importance, it is standardized using Eq. (5). Otherwise, it is standardized with Eq. (6):

$$x_i^k = \frac{s_i^k - s_i^{\min}}{s_i^{\max} - s_i^{\min}} \tag{5}$$

$$x_i^k = \frac{s_i^{\max} - s_i^k}{s_i^{\max} - s_i^{\min}} \tag{6}$$

where $s^{\min}$ is the minimum score and $s^{\max}$ is the maximum score

2.3. Integration of forest conservation priority of decision groups using compromise programming techniques

The forest conservation priority of the multi-decision makers can be integrated by using a compromise programming technique. The compromise programming technique identifies the alternatives, which are closest to the ideal point by using a measure of distance. The ideal point is usually an alternative with an unattainable level. It is defined as 1 for each forest conservation priority map. The distance metric in Zeleny (1982), dependent on the exponent p, can be written as d_p (separation distance measure):

$$d_p = \left[\sum_{m=1}^{M} (C_m^* - C_m^k)^p\right]^{1/p} \tag{7}$$

where

$$C^* = (C_1^*, C_2^*, \dots, C_M^*) \quad (8)$$

Euclidean distance ($p = 2$) is normally used. The smaller the d_p, the closer is the alternative to the ideal point and thus to being selected. This alternative is called the "compromise solution."

3. Forest conservation planning in the Kinabalu Area, Sabah, Malaysia

3.1. Study area

Conservationists often have contradictory views on which forest to conserve where. While some stress the importance of forests in remote areas because of their pristine ecological integrity, others emphasize forest adjacent to human settlements because of various form of threats that may reduce the forest. Many studies have been emphasizing the need to prioritize conservation based on degradation and destruction risks (e.g. Olson and Dinerstein, 1998; Myers et al., 2000). The degradation and destruction risks have been closely associated with human activities (Vuilleumier and Prelaz-Droux, 2002; Sierra et al., 2002). If the forest conservation priority is interpreted as relative urgency of conservation actions then forest adjacent to human settlements must be emphasized. The Kinabalu area is located at the northeastern part of Kota Kinabalu, the capital of the state of Sabah, Malaysia (Fig. 3). This area consists of low-lying flood plains at coastal areas to a rocky mountain at 4095 m (Mount Kinabalu). This is the highest peak between the Himalayas and Mount Whelm in Irian Jaya, and is located within the Kinabalu Park (753.7 km^2), which was gazetted in 1964. Forest ecosystems in this region are very diversified, from mangroves at the coastal area to lowland rain forest, montane rain forest and subalpine forest. Ultrabasic forest, originating from special geological substrates is also found (Phua and Tsuyuki, in press). Mean air temperature decreases from over 30 °C at lowland areas to about 10 °C at 3700 m. Average, minimum and maximum rainfall of the study area are 3274, 2451 and 5487 mm, respectively.

3.2. Criteria and indicators for forest conservation planning

There is no definition for "appropriateness" of criteria used but they should be explicit and quantifiable (Bibby, 1998). The criteria and indicators for sustainable forest management have been developed (e.g. Montreal Process and Helsinki Process) after the Earth Summit in 1992 as a result of increasing recognition of the importance of sustainable forest management. Use of the criteria and indicators for sustainable forest management for forest conservation at a local forest management unit has been examined (e.g. Mrosek, 2001). We examined the criteria and indicators of three initiatives; the International Tropical Timber Organization's criteria and indicators, Montreal Process and Helsinki Process, for quantifiable criteria. Table 2 lists the criteria common in the three initiatives. Only one criterion related to global carbon cycling was not shared by the three initiatives. All of the criteria may be evaluated using GIS and remote sensing techniques except for the criteria related to cultural and socio-economic benefits, and

Table 2
Comparison of the criteria and indicators for sustainable forest management (Hiroshima, 1997)

	Criterion related to		
	Montreal process	Helsinki process	ITTO
Biodiversity conservation	Criterion 1	Criterion 4	Criterion 5
Maintenance of forest productivity	Criterion 2	Criterion 3	Criterion 4
Forest health and vitality	Criterion 3	Criterion 2	Criterion 3
Soil and water resources	Criterion 4	Criterion 5	Criterion 6
Global carbon cycle	Criterion 5	Criterion 1	–
Cultural and socio-economic benefits	Criterion 6	Criterion 6	Criterion 7
Legal, economic and institutional frameworks	Criterion 7	In consideration	Criterion 1

ITTO: International Tropical Timber Organization.

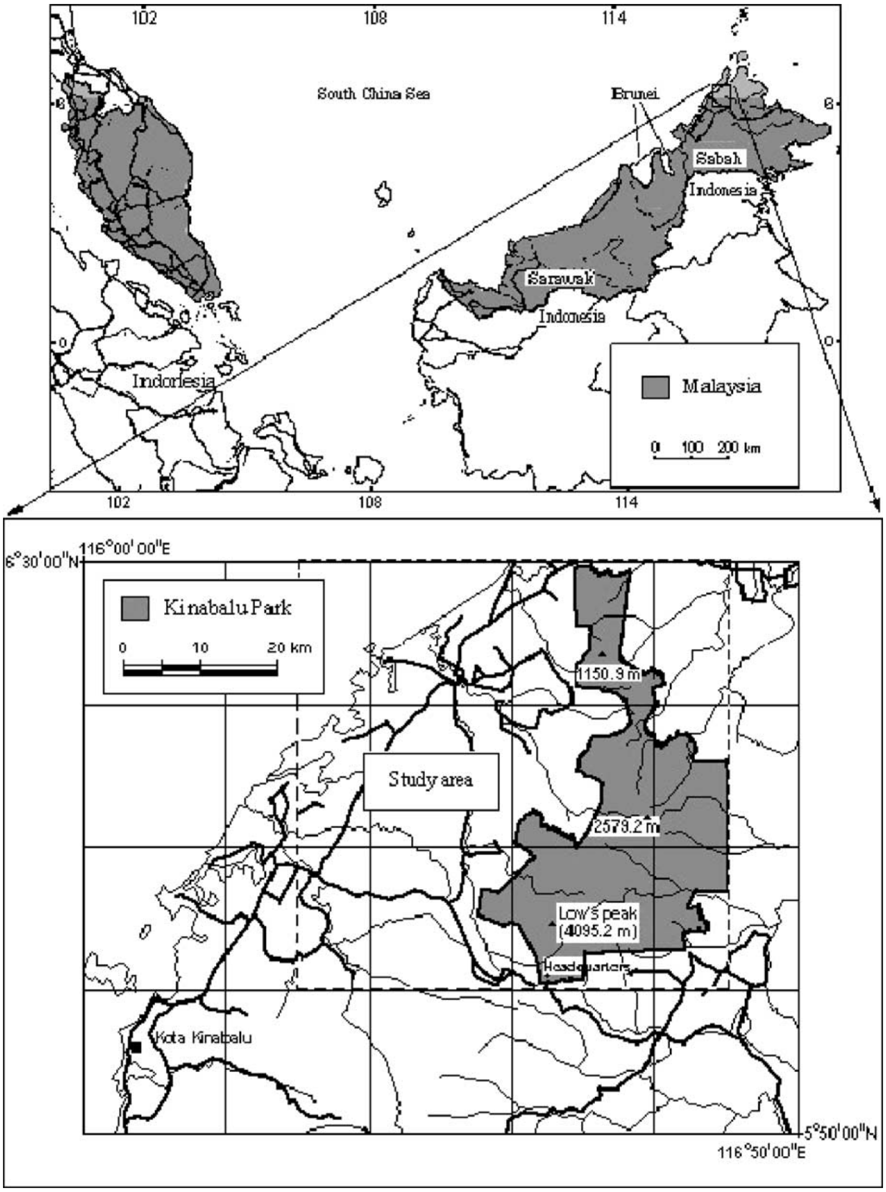

Fig. 3. Location of study area.

legislation. To demonstrate how forest conservation planning can be implemented with the GIS-based multi-criteria decision making approach, we adopted the criteria of biodiversity conservation and soil and water conservation functions. Spatially quantifiable indicators were developed for each of the criteria, i.e. species and landscape diversity conservation functions for the criterion of biodiversity conservation, and landslide, flood and drought prevention functions for the criterion of soil and water conservation. A criterion of potential threats, comprising indicators of proximity to settlements as well as to roads, and distribution of number of commercial species was also developed.

3.3. Evaluation of the criteria and indicators for forest conservation planning

The procedures of the evaluation of the indicators are briefly described below but details may be found in Phua and Minowa (2000).

3.3.1. Biodiversity conservation function

3.3.1.1. Species diversity. In Mount Kinabalu area, species richness and Fisher's alpha index decreased with increasing altitude (Kitayama, 1992, 1993, 1996). Aiba and Kitayama (1999) further reported that geological substrates could influence the altitudinal pattern of biodiversity. In this study, Fisher's alpha diversity index data from Kitayama (1993) and Aiba and Kitayama (1999) are used for regression analyses between the index and the altitude by ultrabasic and non-ultrabasic substrates. The species diversity conservation function maps for the non-ultrabasic and ultrabasic substrates are derived using the empirical relationships (adjusted $R^2 > 0.94$ for both regression models) with a digital elevation model and geologic vector layer.

An exception was made for mangrove forest where it was treated as a homogeneous vegetation cover because it only occurs in coastal lowlands. Field data on mangrove forest in the Palawan Island of the Philippines were acquired from the Japan Oversea Forestry Consultants Association (1999) for calculating Fisher's alpha index. As the Palawan Island is neighboring the Malaysian state of Sabah to the north, the mangrove species composition and structure were assumed to be similar in the two locations. In fact, mangroves in Sabah and other parts of Borneo, together with the Philippines, Papua New Guinea, the Malay Peninsular, Singapore, Java, Sumatra, Sulawesi, Halmahera, Bali, Lombok and Timor are classified as the *Rhizophora mucronata* area" of the Southeast Asia and Pacific region (Nakamura, 1992).

3.3.1.2. Ecosystem diversity. Ecosystem diversity can be considered using the conventional alpha or beta diversity indices (Barnes et al., 1998). In this study, ecosystem diversity is defined by an ecosystem diversity index (EDI) which consists of measures of the diversity of richness of forest ecosystem types, the complexity of shape and ecosystem size. The index is calculated using Eq. (9):

$$\mathrm{EDI}_j = \mathrm{FI}_j \mathrm{SI}_j \mathrm{AI}_j \tag{9}$$

where FI is the Fisher's alpha diversity index; SI the Shape index, $\mathrm{SI} = \lambda - (\lambda - 1)\sqrt[4]{a_j}/g_j$ Yoshida and Tanaka (2001), $\lambda = 2$, square replaces circle as the simplest shape; g_j the perimeter of forest type *j*, a_j the area of forest type *j*; AI the ratio of area of forest type *j* to the total forest area; *j* is the forest type (1, 2, ..., *J*).

The diversity of richness at a higher organization level (FI) is represented by the mean of Fisher's alpha diversity index of a forest type. The shape index (SI) indicates the complexity of an ecosystem as the degree of deviation from the "simplest" shape of a forest ecosystem. A square is considered the "simplest" shape instead of a circle in Yoshida and Tanaka (2001). AI represents the ratio of the area of a forest type to the total forest area, and it implies that a bigger area constitutes a higher level of ecosystem processes than a smaller area.

3.3.2. Soil and water conservation functions

The soil and water conservation functions refer to landslide prevention, flood prevention and drought prevention functions. The landslide prevention functions of forests are considered in terms of landslide hazard. The more hazardous an area is, the more important is to keep the forest in place. Forest is known to have an important role in preventing landslides as the root systems help to bind soil (Japanese Forestry Agency, 1989, 1991, 1998; Stredansky, 1994). The drought and flood prevention functions of forest address the water retention capability of the forest. Forest plays an important role in recharging ground water by increasing the rate at which rainwater infiltrates into the soil and releases the water slowly (Japanese Forestry Agency, 1989, 1991, 1998).

Weighted linear combinations of GIS layers that have been widely used in GIS-based studies (e.g. Kato et al., 1997) were used to evaluate the soil and water conservation functions. More details can be found in Phua and Minowa (2000). Based on an extensive review of related literature, slope, rainfall, soil depth, geology and topography were adopted as the factors of the soil and water conservation functions. Each factor was scored according to its importance to the function and generated as a GIS layer. The score and the weights that describe the relative importance of each factor towards the function were referred to the literature and examined by experts. The linear combination of the weights and factors for the evaluation of the soil and water conservation functions are as follows:

$$\text{landslide prevention function} = 0.3\text{slope} + 0.2\text{annual rainfall} + 0.2\text{soil depth} + 0.15\text{geology} + 0.15\text{topography}$$

$$\text{flood prevention function} = 0.2\text{slope} + 0.2\text{annual rainfall} + 0.25\text{soil depth} + 0.15\text{geology} + 0.2\text{topography}$$

$$\text{drought prevention function} = 0.1\text{slope} + 0.25\text{annual rainfall} + 0.3\text{soil depth} + 0.15\text{geology} + 0.2\text{topography}$$

3.3.3. Potential threats

The forest in this suburban region has been exposed to various forms of threats that are induced by human presence. These threats are deforestation through shifting cultivation, logging and land alienation. The threats can be measured in terms of proximity to settlements and roads that provide access to deforestation activities. On the forest side, timber resource availability potentially attracts logging activities. The potential distribution of commercial species can thus measure threats of logging activity. Distribution of number of commercial species (Sabah Forestry Department, 1989) is empirically derived based on its relationship

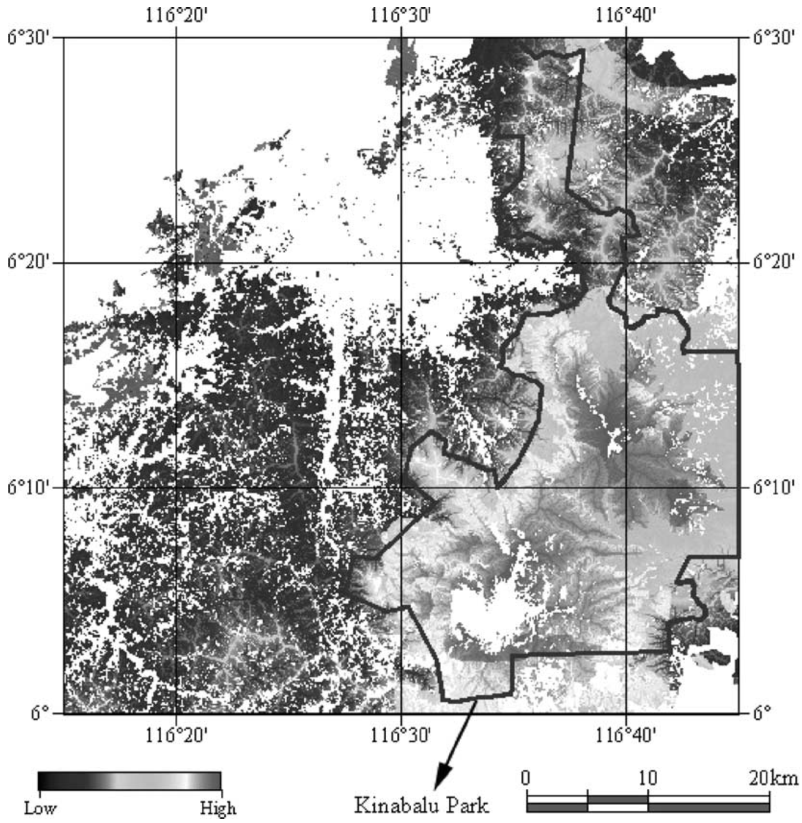

Fig. 4. Distribution of the separation distance. Darker color areas indicate better alternatives of conservation based on mutual agreement and priority. Note that a significant part of forest in Kinabalu Park is not highly prioritized with the preference setting in this study.

with altitude. At least 40 species are found in the area and they can be found up to an altitude of 2000 m.

3.4. Results

The forest conservation priorities of the three decision makers are calculated by using Eq. (3). Combining the three priority images with Eq. (7) produces the separation measure (d_p). The d_p image represents the compromised solution of the three decision makers (Fig. 4). Relatively small d_p values indicate smaller disparity in terms of conservation priority among the three decision makers. In other words, forest areas of smaller d_p values are more important in terms of forest conservation. The d_p image is used to generate potential conservation areas for deriving forest conservation plans by using some thresholds. The thresholds are generated by clustering analysis on the forest conservation priority images of the decision makers. The smallest mean can be considered as the best thresholds (in terms of mutual agreement and priority) for generating the potential conservation areas for delineating potential new protected areas.

Kinabalu Park is excluded for further analysis because it is an existing protected area. Using the means of the clusters as thresholds, site selection is carried out in the unprotected area for producing potential conservation areas. The percentage of area selected by using the means of the clusters is shown in Fig. 5. The smallest and second smallest means select 14 and 56% of the unprotected forest areas as potential conservation areas, respectively.

Feasibility of drawing up potential new protected areas was analyzed by vector line tracing on the potential conservation areas delineated by the smallest d_p, which resulted in 3566 polygons. They are scattered and are found in various sizes, from 1 ha to more than 200 ha. There is no general agreement on the size of a protected area except the general intuition that bigger is better (Primack, 1993). This is to ensure integrity of the forest ecosystem. In the study area, small mammals are commonly found in the lowlands and hills, and extend up the slopes of Mount Kinabalu. At least 90 species have been recorded within and around Kinabalu Park and 21 of them are bats (Payne, 1996). Minimal size of 100 ha is suggested for conserving 1000 individuals of small herbivores

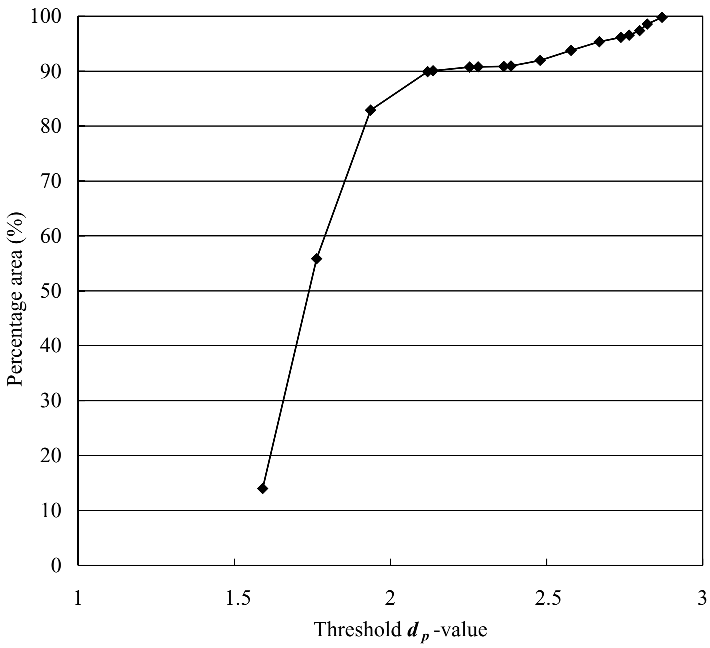

Fig. 5. Percentage areas selected using various thresholds.

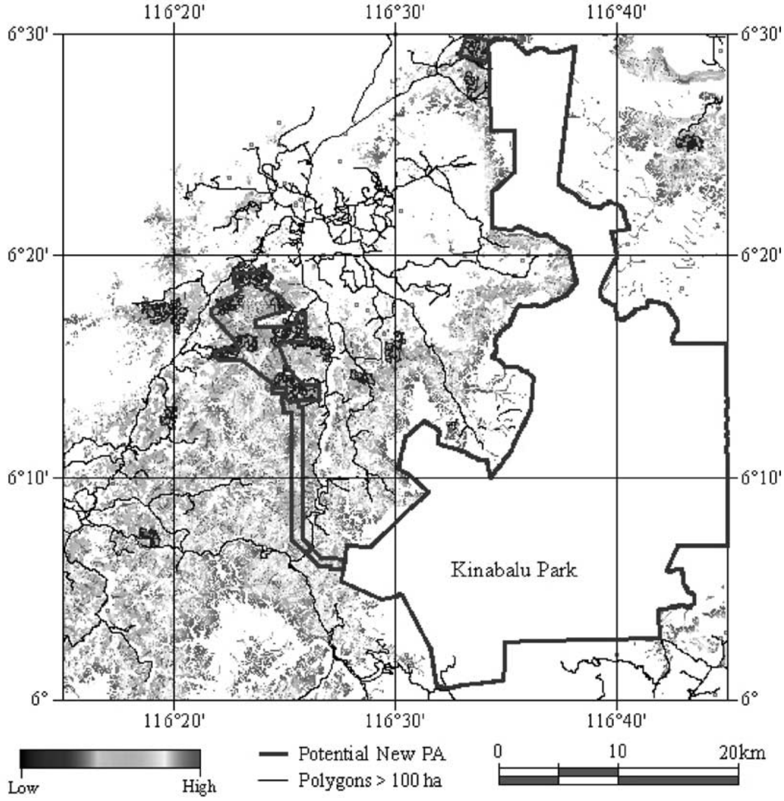

Fig. 6. Overlay of potential new protected areas on the potential conservation areas delineated by the second smallest mean d_p threshold. Note that the potential conservation areas constitute largely riparian forest scattered through out the area. The potential new protected area adjacent to the northern part of Kinabalu Park is recommended to be included to the park. The corridor must cross at least one road to connect the potential new protected area at the western part to Kinabalu Park.

(Schonewald-Cox, 1983). Using the minimum habitat size criterion for small mammals, we produced 22 forest polygons for delineating potential new protected areas (Fig. 6). Two of the polygons, adjacent to Kinabalu Park at the northwestern part, can be combined to form a single polygon of 359 ha (Fig. 6). Inclusion of the polygon into the existing park is conceived as feasible since it is directly connected to the existing park.

Eleven of the polygons totaling 2050 ha are found in the western part of the study area, between two roads running in north–southwest and north–south directions (Fig. 6). These 11 polygons are adjacent to each other forming a potential new protected area. A good reserve design should avoid small and isolated protected areas (Primack, 1993).

Overlay analysis between the 11 polygons and the potential conservation areas generated from the threshold of the second smallest d_p revealed that it is possible to draw a single polygon with a size of 4361 ha. The settlements and non-forest areas are avoided. However, it will be necessary to provide a corridor to connect this polygon to Kinabalu Park to enable interaction and movement of animals. For this, the road network and settlement vector layers are overlain and analyzed. The Kota Kinabalu–Ranau road running north–south remains as the main obstacle for the polygon to be connected to the park. Although a corridor can be drawn to connect to the southwest part of the park, it still has to cross at least one road in order to connect to Kinabalu Park (Fig. 6).

Riparian forest is important for conservation because it was selected in both analyses using thresholds. The riparian forest generally occurs on at slightly higher elevations than the flood plains, along the margins of water bodies. The riparian forest is in fact a favored habitat for animals including birds, because it provides cover, food and access to water (Jeffries and Mills, 1990). It is also very important to ensure vegetation cover permanently along the riverbanks to reduce soil erosion into the river. Since riparian vegetation is scattered in the study area, strengthened legislation is recommended for conserving forest and vegetation along river networks and this is relevant at the state and national levels. Although there are recommendations for reserving land along the riverbanks as well as to encourage landowners to plant stabilizing vegetation along the water courses, no scientific studies have been carried out. The findings in this study have explicitly evaluated and concluded that such actions are vital in a number of ways.

The results of our study suggest implementation of following forest conservation actions:

(i) inclusion of the forest polygon (359 ha) neighboring Kinabalu Park at the northwest part into the park and effective enlargement of the park;
(ii) establishing a new protected area (4361 ha) to the west of the park where movement and animal interaction should be facilitated by constructing a corridor to the western boundary of the park;
(iii) strengthening legislation to conserve the riparian forest at the state and national levels.

4. Discussion and conclusion

Selection of sites based on certain appropriate criteria is necessary in forest conservation planning. The criteria and indicators for sustainable forest management can be considered as the common standards for forest conservation among global community because the criteria and indicators target the achievement of forest protection as well as human oriented forest functions such as timber use and recreational use in a sustainable way (Mrosek, 2001). Biodiversity is a widely used biological criterion for species conservation planning (Smith and Theberge, 1986). It is also found in the criteria and indicators for sustainable forest management (see Table 2). A biodiversity index is a straightforward measure of the number of species and their arrangements in a spatial unit. The biological criterion used in this study includes species richness but also employed a more sophisticated biodiversity index. Rarity is another frequently used criterion in the species-based conservation planning (Smith and Theberge, 1986). Rarity may be an evolved property as a result of habitat specificity and small natural range or density (Bibby, 1998). Its use in the conservation planning presumes reliable data on the range or the numbers of individual species, which is sometimes impractical. In developing tropical countries, lack of reliable data and financial capacity to obtain such data are among the practical difficulties preventing the use of rarity as one of the conservation planning criteria. At a narrower sense, endemism due to habitat specificity may be included at the ecosystem level. In the study area, only the ultrabasic forest is an endemic forest type. A binary indicator layer can be easily incorporated if the forest type with high endemism is considered of absolute importance. However, it is necessary to bear in mind that the criteria and indicators for sustainable forest management are not specifically developed for conservation planning purposes. Criteria other than those in the criteria and indicators for sustainable forest management should be added wherever relevant. The GIS-based multi-criteria decision making approach is so simple and flexible that any number of criteria and indicators can be employed. However, the decision makers or those involved in the weight assignment may face difficulty in giving weights on a pairwise basis.

As well as the spatial aspect involved, this study has shown how forest conservation planning can be tackled as a decision making process. For preferences to be quantitatively expressed, the GIS-based multi-criteria decision making approach allows incorporation of decision makers, experts or other stakeholders into the forest conservation planning. With the compromised programming technique, the stakeholders from different sectors such as wildlife and water resources can be integrated. This may help in preventing and reducing conflicts between the sectors because the potential protected areas are based on mutual agreements and compromises. Maikhuri et al. (2000) suggest that local communities should be involved in decision making for resolving conflicts between people and protected areas.

The GIS-based multi-criteria decision making approach allows the planner to draw up potential new protected areas based on the forest polygons delineated with a minimum size criterion. Field experts can then conduct more detail studies on the actual areas needed for conservation. As such, the GIS-based multi-criteria decision making approach may reduce costs and time involved in the early planning stage of identifying potential new protected areas at a landscape scale. The savings in actual costs and time should be investigated in future studies.

This study presents an approach to integrate decision groups in forest conservation planning. However, more actions are needed to realize the forest conservation plan. The potential protected area (4361 ha) can be designated as one of the IUCN's protected area categories (IUCN, 1994). In this regard, the biosphere reserve model (Well and Brandon, 1993) may be appropriate for the potential protected area where a buffer zone is established in the surroundings of the potential protected area. However, this must be done within the framework of stakeholders' consultation as there is a potential risk of failing to recognize local people needs. Lack of legal authority of the protected area agencies over the zone must also be addressed (Sanjay and Weber, 1994). Initiatives to influence the land use decisions in the surrounding areas of the protected area have to be taken. This can be achieved by introducing incentive schemes to compensate the owners for not converting the forest to agricultural land or adopting destructive uses. The incentive scheme can be a powerful management tool to divert crop cultivation to species that are more compatible with conservation objective and also lesser risks of damage by wildlife (Maikhuri et al., 2000). Again, legislation may be needed to put it into practice. The value of biodiversity conservation may be of little interest if the individual landowners making land use decisions are unable to capture the economic benefits (Pearce et al., 1993).

On the other hand, the potential protected area can also be considered as a multiple use area, i.e. the sixth category of the IUCN's protected area classification (IUCN, 1994). A closely monitored multiple use conservation area can provide certain degrees of protection. Conservation optimization techniques (e.g. Ive et al., 1989; Boyce, 1995; Kangas et al., 2000) can be used to produce the best management plan to balance conservation and economic activities on the multiple use area.

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