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生物多样性管理最小有效面积选取模型与 GIS 的耦合

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摘要：人口的增长和自然资源的有限性决定了很难把更多的土地用于生物多样性的保护。通过 BMAS(生物多样性管理面积选取)模型与 GIS(地理信息系统)的结合，可以用尽可能少的土地资源实现一定水平的生物多样性的保护。该方法初步在西双版纳的勐拉县进行了应用。与现实自然保护区面积的对比，用模型选区自然保护区有显著效果。该方法在保护与发展矛盾尖锐的发展中国家非常适用。

关键词：GIS；管理面积；生物多样性

An integration of GIS and modeling in selecting minimum areas for target biodiversity conservation

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Abstract: The conflict between limited natural resources and growing population makes it extremely difficult to apply a conservation strategy that requires the largest land area for biodiversity conservation. By integrating the BMAS (Biodiversity Management Areas Selection) model with GIS, one can streamline the strategy to determine the minimum area for a given level of biodiversity conservation within a region. This methodology was applied in Mengla County of Xishuangbanna Prefecture, China. The comparison of the model-selected areas with the existing nature reserve areas shows BMAS model's application is effective in conservation zoning and evaluations. This methodology is particularly useful in developing countries whose conservation and development have major conflicts.

Key words: GIS; minimum areas; biodiversity

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Introduction

Human is causing changes in environments and declines in Earth's biodiversity through the alteration and destruction of critical habitats, including the draining of wetlands, clearing woodland for agriculture, felling of forests for timber, and pollution of the environment[1]. The conservation of the environment and natural resources has become a common theme around the world.

Biodiversity conservation is also one of the most popular topics for discussion both as scientific and political issues and at national, regional and global levels. The main theme of the discussion is the contribution of biological diversity to social and economic development; losses of biological diversity and their causes; how to manage the remaining biological diversity for sustainable utilization; the measurement for conservation of biological diversity and techniques for measuring and monitoring of biological diversity[2,3].

Researchers have discussed a variety of methods to protect habitats and biodiversity within a region, such as developing reserves and corridors, changing land use patterns, managing the landscape within limits to protect biodiversity, and managing captive breeding and release programs[4,5]. Within a region, practically all of these techniques might be used to protect the natural environment and its diversity. To address regional biodiversity and plan for its protection, it is necessary to maintain up-to-date and accurate data on a wide variety of data coverage. Because of the detail and amount of such data as well as the importance of the spatial relationships inherent in location and proximity, it is natural to take advantage of Geographic Information Systems (GIS)[6]. The use of GIS is viewed as not only valuable, but for all intents and purposes, indispensable[7].

In addition, quantitative analysis methods in landscape scale, including computer aided modeling, have been developed to help implant conservation planning[8]. Such models, when integrated with GIS databases, could become very strong tools for assisting decision making in this field. The Biodiversity Management Area Selection (BMAS) model is just such an example and represents a significant advance in this direction[9].

The major objective of the research is to test the application of BMAS model and to examine the significance of its application by comparing the optimized protected areas with the existing nature reserves in the region. Recommendations will be made on the broad applications of the methodology.

1 Study Site and Its Conservation Problems

Mengla County is situated at the most south point of southwest China, bordering Laos on the east, south and southwest, and Myanmar on the west. Mengla County belongs to Xishuangbanna prefecture, one of the richest biodiversity areas in China. Since 1990s, many efforts have been made to protect this area's biodiversity[10]. Nature reserves have been designated to contribute to regional maintenance of native genetic pool, species and community levels of biodiversity, and the processes that maintain biodiversity[11]. Two major nature reserves are located in the west and south of the region. They cover areas of 200 and 600 km^2, respectively. The protected areas provide habitat for several forest vegetation types and numerous plants/animal species[12]. People who resided inside the protected areas had largely moved to the outside. However, the conservation and its management efforts cannot be completely ensured because human population is increasingly inducing environmental and land use changes in the surrounding areas.

Located within the upstream Mekong region, which is viewed as having the biggest development potential in southeast Asia, Mengla has undergone great changes economically, particularly after China opened up. These changes generated more and more pressure on land use change. Apparently, the social-economic changes have made the biodiversity conservation a more delicate task as a very complicated scenario is presented to the conservationist, with unprecedented urgency. Three main problems have been identified in this study:

(1) The conflict between development and protection. Even though it's desirable to set aside large areas for conservation purposes, guaranteeing a satisfactory protection of biological resources, it is also realized that a balance between development and conservation must be struck, bearing in mind that a huge financial burden may be incurred by large conservation areas, especially when human population pressure is huge.

(2) As the areas of land that can be designed for conservation is constrained, the number of species in such conservation areas would probably be lower. For more efficient biodiversity conservation, sites of sufficient size have to be carefully chosen to assure the coverage of as many species as possible.

(3) The proximity of conservation areas to dense human settlements or heavy traffic makes biodiversity conservation more difficult. For example, if an area already has a dense human population or is exposed to extensive road traffic, the higher accessibility of human activities would make it not very suitable for biodiversity preservation purpose.

The problems raised above are not exhaustive, but they make it clear enough that even in rather isolated areas, biodiversity conservation or biodiversity management become complicated.

2 Methods, Procedures, and Results

Among its various elements, vegetation diversity is by far the most important one of biodersity conservation, as it's the basis for plant, animal species diversity[13]. As remote sensing techniques and GIS are successful in mapping and monitoring vegetation and would be an integrated part in this research. Besides, the fact that conservation zoning is based on geographical location and concerns much about spatial relationship also makes it a suitable case for GIS application[14].

BMAS is an optimization model with a purpose of helping guide in the selection of areas suitable for the core of biodiversity management areas[7]. This approach identifies areas that are both appropriate for the protection and enhancement of biodiversity, and large enough to represent at least a minimum amount of a given element's distribution to alleviate the conflicts between the conservation and land use pressure[15]. Technically, BMAS model involves the solving of a multi-dimensional knapsack problem. This task can be accomplished by an computerized optimization software LINDO (Linear, Interactive, and Discrete Optimizer) (http://www.lindo.com/).

BMAS model considers parameters both in social and economic field (human density, road network, private and public land, etc.) and biological category with concerns about the vulnerable elements and their distributions. All the parameters concerned in BMAS are the attributes of location and area data in space and time. The values of the parameters can be derived from GIS database and spatial analysis.

GIS data layers include watershed, vegetation, nature reserve, road density, and human density in the study area. Spatial analysis functions, such as overlay analysis, are used to produce secondary data layers. Both the primary and secondary data layers are then translated into input data for running BMAS model. The optimizing processes can help allocate the most suitable and most compatible planning units that overlap with all forest vegetation types in the region. The objective involves minimizing the total area selected as well as optimizing the suitability of those areas selected by minimizing any such incompatibility (Fig. 1). The entire procedure includes the following steps:

Step 1 Creating GIS Data Layers

The vegetation layer was derived from visual interpretations of 1∶20 000-scale black-white aerial photographs acquired in the March of 1989 and Landsat TM data acquired on Feb. 2, 1988 and May 28 of

1992. The boundaries of vegetation types were registered to match topography map. The scale of the resulting paper map was 1∶200 000.

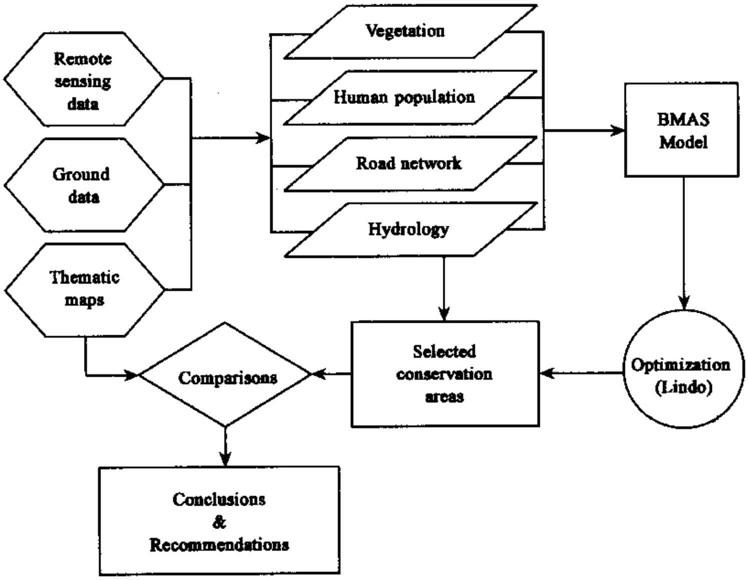

Fig. 1 A flow chart of the methodology of this study

The test area of 4,355 km^2 was located in northern Mengla County. Based on the topography map, the test area consisted of 42 watersheds. These watersheds were used as the conservation zoning units.

In addition to vegetation layer, road network layer, village and town position layer, watersheds distribution layer, location of national parks layer were also digitized. +Step 2 Defining Protection Targets

Over 800 km^2 of natural reserves were included in the test area. They protects tropical northern rainforest, seasonal rain forest, tropical mountain rain forest, limestone hill monsoon forest, mountain mossy evergreen broad-leaved forest, monsoon evergreen broad-leaved forest, tropical bamboo forest, and many rare plant and animal species. These forest types have uneven areas inside and outside protected areas (Table 1). All the 6 types of forest are considered endangered ecosystems in China[16,12,17].

Table 1 The New Target Level settled for representing forest types in BMAS model

Vegetation type	Total area (km^2)	Existing cover (km^2)	Existing cover (%)	Minimum target (Min_k) (%)	Minimum target (Min_k) (km^2)
1. Season rain forest	136.5	50.4	37	37	50.4
2. Mountain rain forest	15.7	4.3	27	27	4.3
4. Deciduous monsoon forest	30.3	0	0	30	9.1
5. Limestone hill monsoon forest	127.1	35.7	28	28	35.7
6. Monsoon evergreen broad-leaved forest	1581.3	513.9	32	32	513.9
7. Mossy evergreen broad-leaved forest	7.4	7.4	100	50	3.7
10. Tropical bamboo forest	114.1	1.6	1	20	22.8
Total/Weighted Average	2,012.4	613.3	30.0	31.4	639.9

Table 1 indicates that the existing nature reserves are protecting most of forest vegetation types that occur in the test area but not all. All the Mossy Evergreen Broad-leaf Forest is included in the protected areas. Over 30% of Seasonal Rain Forest and Monsoon Evergreen Broad-leaf Forest and over 20% of Mountain Rain Forest and Limestone Hill

Monsoon Forest area distributed in the present the protect areas. Deciduous Monsoon Forest and Tropical Bamboo Forest had not been protected, which account for 0% and 1% of total protected areas, respectively.

Based on the proportions of forest vegetation in the region, the minimum targets (Min_k) of these vegetation types within the study area were determined (Table 1). These target levels are considered as subjective compromises between protected forest vegetation in nature reserves and total vegetation in the region.

Step 3 Quantifying Biological and Socio-Economic Attributes

This step is to generate the biological and socio-economic values associated with each planning unit. These values should be formatted suitable for sunning BMAS model.

The area of every forest type in each watershed was calculated by overlaying the watershed boundaries with forest map.

The socio-economic data include population density (H) and road impacting (r). Other suitability factors, considered in original BMAS model, such as percentage of the area of each unit that is held in private ownership and the density of public-private land interface, were been considered as necessary suitability factors due to the throughout public land ownership system in China. Here, H and r are the only measures of the suitability and potential effectiveness of conservation management. For example, a high value reflects low compatibility or potential as a conservation zone and a low value is indicative of being very suitable and compatible for targeting as a conservation zone.

The number of resident points within each watershed defined as the human density class, the higher class, the lower suitability; similarly, the road density will represent the road impact class, the higher class, the low suitability.

The final road and human impact class are defined as impact class that is produced by linear transformation of the road density range and resident points range to 0 to 100% (no road and residential point means impact class equal to 0; road density or residential points are maximum in above table means the respective impact class equal to 100), for the purpose of matching the value range of the bio-ecological parameter (here is the watershed area which with an average of 104 km^2).

Step 4 Modifying BMAS Model and Arranging Input Data

The original BMAS model is formulated as follows[7]:

$$Minimize\ Z = \sum_j (w_1 a_j + w_2 Hd_j + w_3 r_j + w_4 Pla_j + w_5 PPl_j) X_j \tag{1}$$

Subject to the following conditions:

(1) Element k is sufficiently represented in BMAS according to the target level, that is,

$$\sum_j a_{jk} X \geqslant Min_k \ for\ each\ k \ \varepsilon\ K \tag{2}$$

(2) Integer requirements $X_j = 0$ or 1 for each $j \ \varepsilon\ J$

where, w is weighting factor, a_j is the area of planning unit, Hd_j is human density measurement for planning unit, r_j is the percent of the area of unit j that is impacted by roads, Pla_j is the percent of the area of unit j that is held in private ownership, and PPl_j is the density of public-private land interface.

All the factors were processed with the same rule: the higher the value, the more development/access and the lower the suitability for using as a biodiversity management area. Hence, minimizing the input values means to optimize conservation. One of the advantages of BMAS model is that there is no restriction on the number or kinds of factors in BMAS.

In this study, we selectively used the area of planning unit a_j, human population density H_j (the residential point density), and road density r_j. To simplify the simulation, w_i was not considered.

The input data sets were processed from GIS database and spatial analysis function of ARC/INFO. The constrains of the BMAS formulation of each watershed were derived from the area of each forest type found in each watershed.

Step 5 Running the Model to Select Watersheds by LINDO

This research used LINDO, commercial optimization software, to solve the BMAS model problem that could be categorized into integer programming in operation research.

Two options were tested in the study. In the first option, the input data set of objective function was just bio-ecological data (the area of watershed). Second, the input data sets were the area of watershed, human density impact, and road density impact. Under each option, a set of watersheds were derived (Tables 2 and 3).

Table 2 The selected watersheds and total reserved area

The first option		The second option	
Selected watershed No.	Reserved area	Selected watershed	Reserved area
15	104.9	15	104.9
16	66.8	19	86.0
21	50.3	24	175.8
26	74.8	25	83.1
27	107.9	26	74.8
28	81.7	27	107.9
29	175.1	30	97.2
30	97.2	37	38.6
37	38.6	40	73.4
38	62.6	42	135.1
40	73.4	Total	976.8
Total	933.32		

Table 3 The comparison of target level and actual reserved level under the first option and second option

Vegetation type	Total area (km^2)	Target level (%)	Target area (km^2)	First option		Second option	
				(%)	km^2)	(%)	(km^2)
1. Season rain forest	136.5	37	50.4	41	55.8	37	51.0
2. Mountain rain forest	15.7	27	4.3	27	4.3	27	4.3
4. Deciduous monsoon forest	30.3	30	9.1	53	16.1	35	10.5
5. Limestone hill monsoon forest	127.1	28	35.7	28	35.3	30	38.6
6. Monsoon evergreen broad-leaved forest	1581.3	32	513.9	33	522.5	33	521.7
7. Mossy evergreen broad-leaved forest	7.4	50	3.7	70	5.1	51	3.8
10. Tropical bamboo forest	114.1	20	22.8	30	34.6	58	66.4
Total/Weighted aervage	2,012.4	31.4	639.9	33.4	673.7	34.5	696.3

The two runs of the model gave out a satisfactory optimal result that reaches or overreaches the target goals as well as minimizes the total land area for conservation. In the first option, for example, the selected total reserve area is 933.31 km^2, occupying 21% of all the study area, and, at the same time, the reserved level of all vegetation types within the selected area are much more than 25%.

3 Discussion

3.1 Watershed Selection

In the first option, suitability parameters only focused on bio-ecological factors such as vegetation and watershed distribution. The model selected 11 out of 42 watersheds as a new suitable conservation area. With a total area of 933.3 km^2 and accounting for 21% of the total study area, the newly selected conservation area contains on average 33.4% of forest vegetation in area (Table 3).

In the second option, parameters also included human density and road impact factors. The model identified 10 out of 42 watersheds as a new conservation area. The total area of the new conservation area was 976.8 km^2, occupying 22% of the total study area. The newly selected conservation area contains on average 34.5% of forest vegetation in area (Table 3).

From this point of view, both simulations resulted in similar results. One important limitation is that BMAS model does not consider the spatial patterns of selected conservation units. Therefore, the similarity in numbers between the two runs does not mean similarities in patterns (Fig. 2). It is noticed that there is a moderate level of natural clustering of several watersheds selected by the model. It seems that the appearance is caused by underlying spatial correlation of both the distributions of forest vegetation types and of the suitability factors.

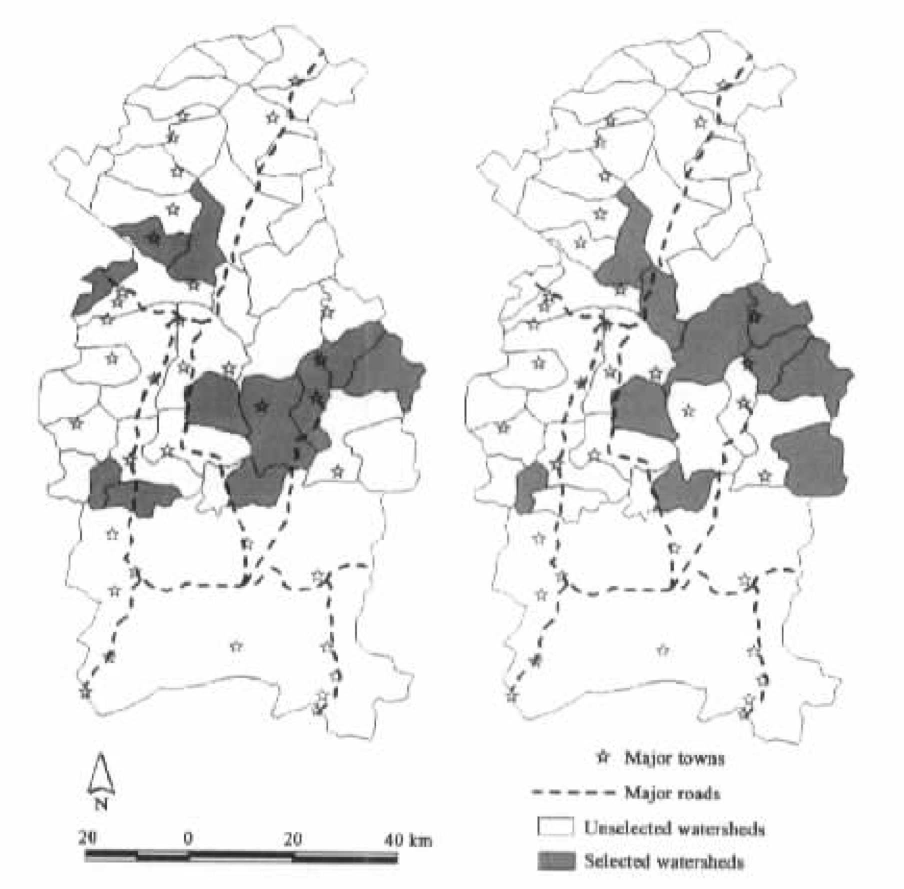

Fig. 2 A visual comparison of selected watersheds between option 1 (left) and 2 (right)

The southern part of Mengla County was not simulated due to the lack of data

3.2 Comparisons of the Newly Selected and Existing Conservation Areas

Although the existing nature reserve protect similar amount of total forest vegetation with newly selected conservation areas, there are major differences in location between the existing nature reserves and BMAS simulation results, as well as between the two options of BMAS runs (Table 4 and Figure 3). These differences indicate that if the tasks of the nature reserves do not meet the requirement of BMAS in this case study. In other words, the existing nature reserves are not the most optimal selection in the study area. The locational differences between the two BMAS options resulted from different suitability parameters considered. The combination of bio-ecological and socio-economic data is supposed to be more convincing than bio-ecological data alone for running BMAS. At the mean while, the big differences also indicate that the human activities have significant influence on biodiversity conservation in the study area. Therefore, BMAS model demonstrates the strong ability to take into account a variety of constraints that affect the performance of biodiversity conservation theme, and biodiversity conservation itself is a multi-dimensional task.

Despite of the major differences, the overlap area between the existing nature reserves and newly selected areas exceeds 40%. This indicates that the existing nature reserves are partially acceptable for the optimal biodiversity management.

Table 4 The overlap of the existing protected area and newly selected area for conservation

	Existing protected area (km^2)	New selected area (km^2)	Overlap area	% of Overlapped
Option 1	836.9	933.3	440.1	47
Option 2	836.9	976.8	396.8	41

In addition, the actual protected level of each vegetation types in the new selected area exceeding the target levels, which, in turn, is the same or larger than the protected level in the existing nature reserves. This indicates that the new system is somewhat more efficient than the old one.

3.3 The Importance of GIS Database

To guarantee the quality, suitability and alternative of the optimal results produced by BMAS, the accuracy, integrity and flexibility of GIS database is the key. For example, if the scale of the vegetation map used was larger than 1∶20 000, the accuracy of the model result would be more precise. If higher resolution satellite image data or air photography was available to produce detailed maps like the distribution of plant communities, species, endemic plants or old-growth stand, etc., other alternative results with target levels for different protection elements would be solved out by BMAS model.

The spatial analysis functions provide the possibility for the processing of various data sets needed by BMAS model. Any socio-economic, land use, and biological data considered in biodiversity planning that would be measured can be defined as suitability factors, and then be arranged as one set of input data of BMAS model. At the mean time, remote sensing technique can help update the various data needed.

3.4 The Operation of LINDO Software

The LINDO software proved efficient to enable BMAS model to generate the optimal result of the research. Because the biodiversity conservation strategy is to allow successful integer programming, the input parameters produced from the GIS database could be input to optimization software directly. In our case, the computing time for the medium scale of data amount is within 5 minutes which is much less than the time used for data input. Hence, the larger scale planning issue or larger amount data computing is obviously possible. Anyway, understanding the strategy and algorithms of BMAS model as well as finding suitable software or developing a computing program for individual cases are a necessary component of entire research.

3.5 Others

Although an optimal result had been produced for the research is a set of watersheds for biodiversity management goal in the study area, the obvious limitations must be mentioned to ensure the application scope of the BMAS model.

Some factors influencing conservation zoning have not been taken into account according to BMAS strategy and modeling operation. For example, the contiguity of the selected watersheds, the ecosystem processing within and outside the selected areas, etc.. Therefore, BMAS is not a comprehensive reserve design model. Instead, it is a component of an overall biodiversity conservation strategy at a regional scale.

4 Conclusions

(1) The exercise of selecting potential biodiversity conservation area with BMAS model in Mengla County suggested that the whole technique was powerful and meaningful. The selected area is superior to

the existing nature reserves because it exceeds the current protection level and is less influenced by human activities. The comparisons of the newly selected conservation areas and the existing nature reserves in Mengla County provide heuristic information about how to improve biodiversity management in the region.

(2) Comprehensive analysis of biodiversity conservation planning can be well accomplished with the aid of GIS, Remote Sensing and computer models. BMAS model is useful to include establishing quantitative targets and definite constraint values, processing operation research like heuristics, and calculating out the optimal results by certain algorithms. If values of any elements within the model change, the established model can solve the alternative problem quickly and conveniently. This will benefit decision makers in the changing world for saving time in decision making processes. For example, the target levels and suitability parameters and the attributes of each watershed could change with time.

(3) BMAS model, which is formulated into a standard and comprehensive integer programming question, allows large amount data input and can combine bio-ecological data with socio-economic data in conservation zoning considerations. This avoids analysis that separates nature from human influences. In this study, human population density and road accessibility were effective to be taken into account.

(4) GIS is an effective technique for providing and analyzing information used in planning biodiversity conservation. GIS especially has the following advantages:

(a) Providing complete and accurate data set. GIS database can store a many data layers that contain all sorts of spatial information and their attribution.

(b) Providing spatial analysis functions. GIS provides the possibility to process out data that meet various requirements except providing the primitive information from the original layers. In this study, it provided needed attributes data for each watershed quickly and clearly in the research.

(c) Displaying and printing simulation results with maps. Maps are convenient for visual analysis.

(5) The conservation zoning area selected by BMAS is a convincing reference for the processes of making final decisions on biodiversity planning. At least, they could be selected as preferred planning areas because they satisfy the target of safely protection the forest vegetation types, which provide primary biodiversity factors in the region and give out the most efficient solutions in terms of requiring the least area.

(6) Remote Sensing technology provides up to date and accurate data and makes the simulations of BMAS much more valuable and practical. The integration of BMAS model with GIS proved successful in conservation zoning in Mengla County. This study demonstrated the usefulness and flexibilities of BMAS model in its broader applications.

5 Recommendations

(1) In terms of the conservation zoning in the study area, this research was conducted to identify the most suitable and compatible area with the representing average 32% of each forest vegetation distribution to be the biodiversity management areas by BMAS model. BMAS model is just one component of an overall biodiversity management strategy of a region, the researches on other aspect of biodiversity management should be processed to make out a more comprehensive and efficient reserve system than the existing one due to the land use change and other problems in the region.

(2) Regarding the data source, more detail and high resolution remote sensing will be a great help in conservation zoning in the study area. Due to complicated topography producing a landlocked phenomena in whole Yunnan Province including Mengla County, remote sensing should be a main source of spatial data, and the clear sky with little cloud makes all remote sensing technique and low altitude air photography available and efficient to identify species diversity in this region for the purpose of providing

large scale and accurate data for GIS databases.

(3)Concerning about the BMAS model itself, if possible, the factors regarding conservation biology like contiguity should be taken into account, to produce more reasonable result not only in terms of requiring the least area, but also considering other bio-ecological factors that influence the maintenance of biodiversity. Nonlinear integer programming can be used for more comprehensive design and evaluations of nature reserves[18].

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