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Design of nature reserve system for Red-Crowned Crane in China

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Abstract. A system of nature reserves is a necessary component of an integrated conservation strategy. The basic problem in the design of a nature reserve system is to select the smallest number of sites from a region for some conservation objectives. There are 33 nature reserves intended for the conservation of Red-Crowned Crane (*Grus japonensis*), totalling 3.1 million ha. Other habitats of Red-Crowned Crane are facing severe problems due to economic development and other human activities. GIS, iterative methods and the integer programming approach were employed to design the nature reserve system for Red-Crowned Crane, with conservation goals to protect 70 and 60% areas of highly and moderately suitable wetlands, respectively. The results indicated the need to designate six new nature reserves in Wulagai marsh, Duluhe River, Tumen River, Rizhao, Gaoyou Lake and Hongze Lake, and showed a protection zone in Songnen Plain (between Heilongjiang Province and Jilin Province) and three clusters of nature reserves in Sanjing Plain, which, will be used as reference for the designation of new nature reserves, or enlargement and adjustment of existing nature reserves. The iterative method and integer programming approaches were feasible for design of nature reserve system.

Introduction

While the conservation of species requires complex management strategies, establishment of a system of nature reserves for species protection is a necessary component of an integrated strategy. Resources need to be allocated to the selection of sites that collectively provide sufficient high-quality habitat to maintain viable populations of all native species (Church et al. 1996). The basic problem is 'to select the smallest number of sites from some biological domain which represents all, or as many as possible, of the species in that domain' (Margules et al. 1988).

Article 8(b) of the Convention on Biological Diversity stipulates that each Contracting Party shall, as far as possible and as appropriate, develop, where necessary, guidelines for the selection, establishment and management, of protected areas or areas where special measures need to be taken to conserve biological diversity.

Landscape heterogeneity promotes the persistence of species and the stability of ecosystems. For instance, young and adults need different habitats. Also, many species need different types of habitats with changing seasons or activities. The persistence of species and overall conservation of ecosystems needs a network of reserves. Conservation based on single isolated nature reserves is not enough. Different levels or nodes in hierarchical biological system should be treated as conservation objects, and connected as a network, to increase connectivity. For migratory birds, more attention should be paid to the protection of breeding and wintering areas. Maintaining the regional and ecological integrity of ecosystems is the basic principle of design of nature reserve system.

The Red-Crowned Crane (*Grus japonensis*) is one of the most endangered migratory birds in the world (Collar et al. 1994; Species Survival Commission/International Union for Conservation of Nature and Natural Resources 1994; Ma et al. 1998, 1999). Due to its rarity, the species was included in the Red List of Threatened Species and was classified as vulnerable (World Conservation Monitoring Centre 1994). The species was also classified as national first-grade protected animal in China.

Although considerable attention has been paid to the conservation of Red-Crowned Crane in China, it still faces a series of problems of habitat security. These include: (1) loss of habitats due to reclamation of wetlands for agriculture; (2) loss of water resources for wetlands due to water control and diversion projects; (3) destruction of habitats caused by environrnental pollution; (4) negative impacts of human activities on habitats of the species; (5) lack of systemic planning for nature reserves with unreasonable allocation of nature reserves. It is necessary to optimize the network of nature reserves for red-crowned crane with systemic approaches (Margules and Pressey 2000).

China has promulgated the National Programme for Nature Reserves and the Regulation on Nature Reserves, with principles to select nature reserves. This study attempts to employ GIS, iterative method and integer programming approach to design a nature reserve system for Red-Crowned Crane.

The earliest objective method ranked sites based on their intrinsic values, picked the best or richest site first, recalculated the value of remaining sites based on the current state of the network, and continuing until a stopping rule was reached (Kirkpatrick 1983). This method quickly identifies indicative minimum reserve requirements, but does not easily explore alternative configurations for reserve networks (Pressey et al. 1997). Integer programming approaches were used to select small wood in Norway, based on breeding species and vascular plants (Saetersdal et al. 1993), or native vegetation in Australia (Cocks and Baird 1989). The integer programming approach is the optimal solution for reserve selection, but cannot indicate the relative importance of potential reserves, involves a large amount of calculation and sometimes no solution exists. Iterative methods and integer programming algorithms should be complementary, rather than competing approaches (Pressey et al. 1996).

Methods

The location and study sites include Inner Mongolia Autonomous Region and Heilongjiang Province which are 50°N southward and 116°E eastward, Jilin Province, Liaoning Province, Hebei Province 11.6°E eastward, Tianjing City, Shandong Province, Jiangsu Province, and part of Xinxiang City of Henan Province (Figure 1).

The definition of wetlands by Lu (1990) was adopted, but paddyfields and irrigated farmlands were not included because of intense human disturbance. Wetland area had a threshold of over 2000 ha, because small wetlands do not protect cranes. However, the existing wetland reserves were included.

The Red-Crowned Crane is a wading bird, found usually in wetlands. The suitability of wetlands for the species was assessed according to the distribution and ecological characteristics of the species and the environmental quality of wetlands. Wetlands were classified as highly, moderately and low suitability. Fifty individuals was the minimum viable population used (Soule 1987). Wetlands with fifty or more cranes were defined highly suitable wetlands;

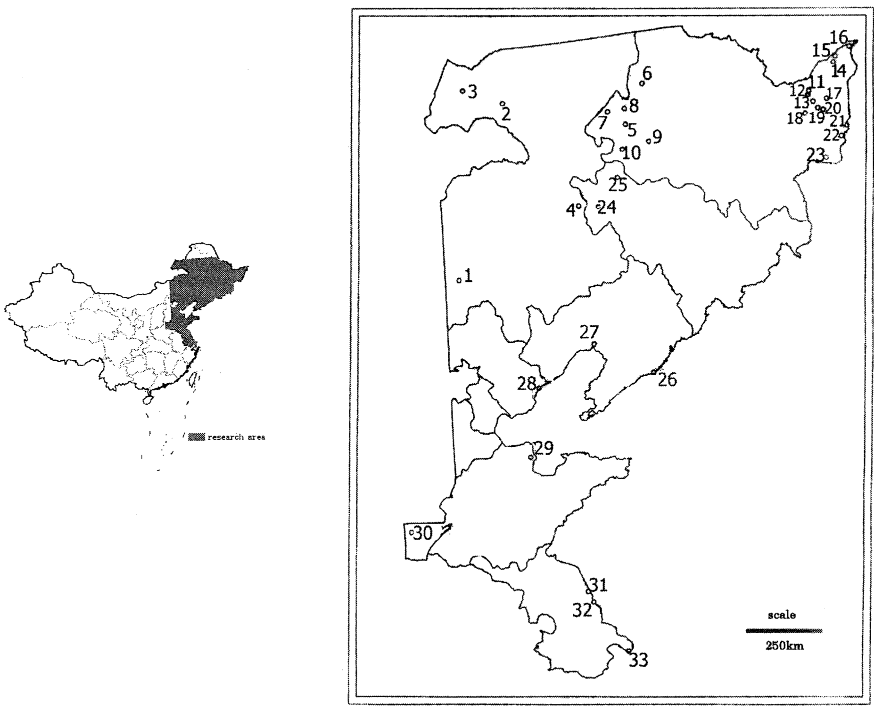

Figure 1. Geographic range of study sites and existing nature reserves intended for the conservation of Red-Crowned Crane in China (numbers in the diagram refer to number of reserves in Table 2).

wetlands with cranes between 1 and 49 were defined moderately suitable wetlands; and low suitable wetlands have no cranes.

The entire area, was divided as grids with 25 km long and 25 km wide. The units (grids) with highly or moderately suitable wetlands were numbered in the order northeast Inner Mongolia, Songnen Plain, Sanjiang Plain, Bohai Bay, Yellow Sea and Yancheng. There were 63 units of highly suitable wetlands, including 19 units of existing nature reserves; and 49 units of moderately suitable wetlands, including 14 units of existing nature reserves (Figure 2). There were totally 79 units of wetlands from which new reserves can be selected.

The main methods of design for nature reserve system are GAP, scoring, iterative method and integer programming. The iterative method and integer

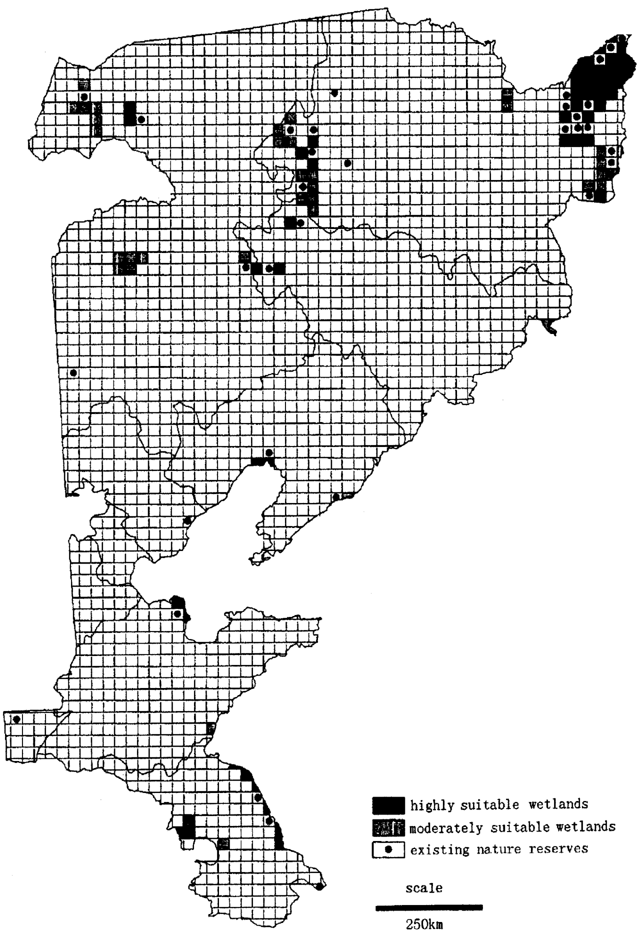

Figure 2. Grids of wetlands in the research area.

programming are more effective (Xu 2000). The network design only considered highly suitable and the moderately suitable wetlands, because they are the main habitats of the crane. The conservation objectives of the design are to protect 70% of highly suitable wetlands and 60% of moderately suitable wetlands, respectively (Table 1). The number of cranes in wetlands was collected from literatures in Table 2 published between 1990 and 1999.

From 63 units of highly suitable wetlands, 44.1 reserves need to be selected to protect 70% of highly suitable wetlands. Because there were already 19 units of highly suitable wetlands in nature reserves, at least 26 units need to be selected to meet the restriction (2) of integer programming approach. From 49 units of moderately suitable wetlands, 29.4 reserves need to be selected to protect 60% of moderately suitable wetlands. Because there were already 14 units of moderately suitable wetlands in nature reserves, at least 16 units need to be selected to meet the restriction (3) of integer programming approach. In both iterative and integer programming approaches, reserves need to be selected from 79 units of wetlands, therefore $i = 1,2,3,\ldots,79$.

Results

Data of wetlands were from China's Wetlands (Lu 1990), China's Wetland Vegetation (Lang 1999), Wetland and Waterfowl Conservation – Proceedings of Northeast Asia International Workshop on Wetland and Waterfowl Conservation (Chen and Zhang 1998), and Conservation and Sustainable Use of Wetlands – Workshop of Wetland Conservation in China (Department of Wildlife and Forestry Plant Conservation Ministry of Forestry 1996).

The bird is distributed in Hokkaido, Japan, North Korea, South Korea, eastern Russia, Mongolia, and the northeast and the eastern coasts of China. There exist breeding and wintering areas in China. Its breeding areas are mainly distributed in Heilongjiang Province, Jilin Province, Liaoning Province, and Inner Mongolia Autonomous Region. Its wintering areas are located in wetlands along low reaches of Yangtze River (Table 2). The cranes breeding in Sanjiang Plain and Xinkai watershed migrate south, along Wusuli River through Tumen River and eastern coast of North Korean peninsula, and winter in Demilitarized Zone (DMZ) between North Korea and South Korea. The cranes breeding in Zhalong and Xianghai areas migrate south, along western coast of Bohai Sea through Panjin (in Liaoning Province) and Yellow River Delta, and winter in costal wetlands of Yancheng (in Jiangsu Province), Figure 1 represents the geographic range of study sites and the distribution of existing nature reserves intended for the conservation of Red-Crowned crane. By the end of 1999, 33 nature reserves were set up to protect the Red-Crowned Crane and its habitats, totalling 3.1 million ha (Table 2).

In the iterative method, units in existing nature reserves or a unit of wetlands without nature reserve were first selected, and the second unit nearest to the

Table 1. Analytical methods used to select reserves.

Iterative method	
Objectives	Protect 70% of highly suitable wetlands and 60% of moderately suitable wetlands, respectively
Steps	(1) Select units with existing nature reserve
	(2) Select one unit from a wetland that is not a nature reserve*
	(3) For highly suitable wetlands, select one unit nearest to the unit that already exists in a nature reserve*
	(4) For moderately suitable wetlands, select one unit nearest to the unit that already exists in a nature reserve*
	(5) If the highly suitable wetlands are not protected, select the second unit nearest to the unit that already exists in a nature reserve from highly suitable wetlands. If the conservation objective is realized, the selection of units from highly suitable wetlands stops
	(6) If moderately suitable wetlands are not protected, select the second unit nearest to the unit that already exists in a nature reserve from, moderately suitable wetlands. If the conservation objective is realized, the selection of units from moderately suitable wetlands stops
Integer programming	
Objectives	Protect 70% of highly suitable wetlands and 60% of moderately suitable wetlands, respectively
Model	Minimize $Y = \sum x_i$
	Subject to:
	(1) Wetlands where no nature reserve is distributed should be protected
	$x_9 + x_{10} + x_{11} + x_{12} + x_{13} \geq 1$
	$x_{31} + x_{32} \geq 1$
	$x_{65} + x_{66} \geq 1$
	$x_{77} \geq 1$
	$x_{78} + x_{79} \geq 1$
	(2) 70% highly suitable wetlands should be protected
	$x_7 + x_8 + x_{18} + x_{19} + x_{20} + x_{27} + x_{29} + x_{30} + x_{33} + x_{34} + x_{35} + x_{36} + x_{37} + x_{38} + x_{39} + x_{40} + x_{41} + x_{42} + x_{43} + x_{44} + x_{45} + x_{46} + x_{47} + x_{48} + x_{49} + x_{50} + x_{51} + x_{52} + x_{53} + x_{54} + x_{55} + x_{56} + x_{57} + x_{64} + x_{68} + x_{69} + x_{70} + x_{72} + x_{73} + x_{74} + x_{75} + x_{76} + x_{78} + x_{79} \geq 26$
	(3) 60% moderately suitable wetlands should be protected
	$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} + x_{15} + x_{16} + x_{17} + x_{21} + x_{22} + x_{23} + x_{24} + x_{25} + x_{26} + x_{28} + x_{31} + x_{32} + x_{58} + x_{59} + x_{60} + x_{61} + x_{62} + x_{63} + x_{65} + x_{66} + x_{67} + x_{71} + x_{77} \geq 16$
	(4) Variables should be integers
	$x_i = 0$ or 1, $i = 1,2,3,\ldots,79$

* If there are several units to the wetland, select the first one.

unit that already exists in a nature reserve was selected, until the conservation objectives were met. As there were already 19 units in existing nature reserves, 26 units need to be selected from 44 additional units of highly suitable wetlands (total number of units of highly suitable wetlands was 63), to protect 70% of highly suitable wetlands. Also there were already 14 units in existing nature reserves, 16 units need to be selected from 35 additional units of moderately suitable wetlands (total number of units of moderately suitable wetlands was 49), to protect 60% of moderately suitable wetlands. According to the steps of the iterative method, 26 units from highly suitable wetlands and 16 units from moderately suitable wetlands were selected (Figure 3). Most candidate units were proximate to existing nature reserves, and six candidate units indicated the need to designate new nature reserves. This illustrated the blueprints for the designation of new nature reserves or enlargement and adjustment of existing nature reserves.

There were 79 additional units (variables) which can be selected from highly and moderately suitable wetlands in the integer programming. As there were only four restrictions in the integer programming, its equation has solutions, but solutions are not unique. The scenario of optimal solutions were various. A more realistic set of potential sites for nature reserves was selected, based on the consideration that a unit of wetlands without nature reserve should be selected and nature reserves should be in proximity to protect more effectively the crane (Figure 4). Most potential sites were near to existing nature reserves, and six candidate units need to be designated as new nature reserves.

Discussion

The iterative method and integer programming approach illustrated two sets of potential sites for nature reserves. These two sets of potential sites indicated the need of designation of six new nature reserves in Wulagai marsh, Duluhe River, Tumen River, Rizhao, Gaoyou Lake and Hongze Lake, and showed a protection zone in Songnen Plain (between Heilongjiang Province and Jilin Province) and three apparent clusters of nature reserves in Sanjing Plain. The set of potential sites produced by iterative method was more centralized to existing nature reserves, due to its algorithm, especially in Sanjing Plain, while the set of potential sites produced by integer programming approach had more connectivity between nature reserves, especially between Sanjing Plain and Xingkai Lake. These analyses for the design of nature reserve system produced blueprints for the conservation of Red-Crowned Crane, and founded scientific basis for the designation of new nature reserves or enlargement and boundary adjustment of existing nature reserves.

Due to extensive areas and difficulty in collecting data, this design of nature reserve system was at a large spatial scale. The assessment of the suitability of wetlands is relatively simple and more sophisticated indicators should be used to assess the wetland value. To improve assessment, remote sensing data could be used.

If a particular highly suitable wetland has only one unit, this unit is certainly included in the set of potential sites. If a particular highly suitable wetland has more than one unit, such as 2 or 3 units, one unit is certainly included if there is no existing nature reserves; and one additional unit should be incorporated if

Table 2. Location, number of Red-Crowned Crane and use of location (B–breeding, S–stopover, W–wintering) in China and Nature Reserves and their conservation category (W–wildlife, H–inland wetland, M–marine and coast).

Province/Location	Cranes	Use	References	Nature Reserves (ha)	Conservation category
Inner Mongolia					
Daliruoer	3	B	Ma (1990), Management Committee of Daliruoer Nature Reserve (1996)	1. Dalinuoer (119,413)	W
Wulagai marsh	Occasional	B	Lu (1990)		
Hulun Lake	Occasional	B	Lu (1990)	2. Dalaihu (740,000)	H
Huihe River	50–350	B	Ma (1990), Liu (1998a)	3. Huihe River (120,000)	H
Keerqin marsh	40	B	Institute of Environmental Protection of Inner Mongolia (1988)	4. Keerqin (126,987)	W
Heilongjiang					
Wuyuerhe River watershed and Zhalong	180–243	B	Lu (1990), Ma (1990), Zhao and Wu (1990), Ministry of Forestry (1997)	5. Zhalong (210,000)	W
Lianhuanpao	Occasional	B	Wang and Du (1998)	6. Maoshan (26,641)	W
				7. Changjigang (5321)	W
				8. Fuyu (2880)	W
				9. Lianhuanhu (43,000)	W
Heiyupao	Occasional	B	Ma (1990)	10. Heiyupao (14,400)	W
Northeast Sanjing Plain and Honghe River Nature Reserve	Over 100	B	Lu (1990), Ma (1990), Environmental Protection Bureau of Heilongjiang Province (1995), Cui and Pu (1999), Xing (1999);	11. Fujin (3333)	H
				12. Lianshanpao (2000)	W
				13. Xinglong (4800)	H
				14. Honghe (21,836)	H
				15. Bacha (20,000)	H
				16. Sanjiang (198,089)	H
Qixinghe River, Raolihe River and Xinlong Nature Reserve	Over 170	B	Lu (1990), Ma (1990)	17. Raolihe (58,922)	H
				18. Qixinghe (20,000)	H
				19. Yanwo (11,898)	H
				20. Changlin (10,000)	H
Lower reaches of Duluhe River	23	B	Lu (1990), Ma (1990)	21. Baofeng (30,000)	H

Yinchun marsh	Occasional	B	Lu (1990)	22. Hukou (15,000)	H
Xiaoxingkai Lake	13	B	Zhao and Wu (1990), Pu and Li (1990)		
Xingkai Lake	45–73	B	Lu (1990), Ma (1990), Pu and Li (1990, 1998), Luan and Li (1999)	23. Xingkai Lake (222,488)	W
Changjigang wetland	Occasional	B	Lu (1990)		
Jilin					
Xianghai Nature Reserve	50	B	Ma (1990), He and Li (1999)	24. Xianghai (105,467)	H
Momoge nature reserve	100	B	Lu (1990), Management Office of Momoge Nature Reserve (1996)	25. Mornoge (144,000)	W
Tumen River area	20–30	S	Zhao and Wu (1990)		
Liaoning					
Estuary of Yalujiang River	Occasional	S	Lu (1990), Dong and Wei (1998)	26. Yalujiang (108,100)	M
Wetland of Liaohe River Delta	30–50 breeders; 300–500 migrators	B/S	Lu (1990), Ma (1990), Qiu (1998), Xiao and Hu (1996)	27. Shuangtaihekou (80,000)	W
Hebei					
Beidaihe area	501	S	Department of Forestry Heilongjiang Province (1990)	28. Beidaihe (150)	W
Shandong					
Delta of Yellow River	800 migrators	S/W	Lv and Zhao (1998), Zhao and Song (1995)	29. Yellow River Delta (153,000)	M
Changshan archipelago	10	S	Ji and Yu (1990a, b)		
Coastal wetlands of Rizhao County	4	W	Ji and Yu (1990a, b)		
Henan					
Wetlands along ancient Yellow River watercourse in northern Henan	6–12	S	Lu (1990), Xu and Liu (1990, 1996)	30. Yubei Yellow River Ancient Watercourse (24,780)	W
Anhui					
Shijiu Lake	4–12	W	Lu (1990)		

Table 2. Continued.

Province/Location	Cranes	Use	References	Nature Reserves (ha)	Conservation category
Jiangsu					
Costal wetland of Yancheng	1020	W	Liu (1998b), Liu and Wang (1999)	31. Yancheng (453,00)	W
				32. Dafeng (2667)	W
Hongze Lake	78	W	Lu (1990)		
Gaoyou Lake	Occasional	W	Lu (1990)		
Shaobo Lake	22	W	Lu (1990)		
Xinlongsha, Qidong City	Over 50	W	Environmental Protection Bureau of Qidong City (1991)	33. Xinglongsha (1000)	W

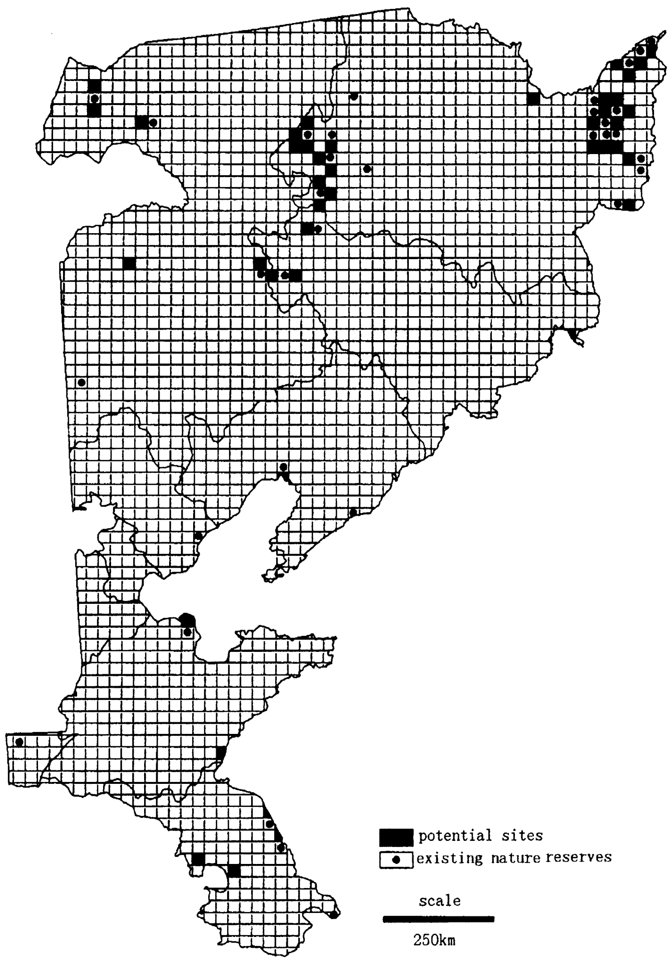

Figure 3. Potential sites for nature reserves selected by the iterative method.

there is existing nature reserves and the protection objectives have not been met. However, the entire wetland may not be incorporated into the set of potential sites because the protection objectives may have been met. If the entire wetland needs to be incorporated into the set of potential sites, the protection objectives have to be increased to ensure the inclusion of this wetland.

Alternative sets of potential sites can be compared, considering economy, land use and biodiversity conservation, to decide designation of new nature reserve or enlargement and adjustment of existing nature reserves. Coordination of conservation costs and objectives needs further discussion. If the area of each unit is of the same, the budget restriction of reserves can be understood as the number of selected units. The integer programming model expresses this. If

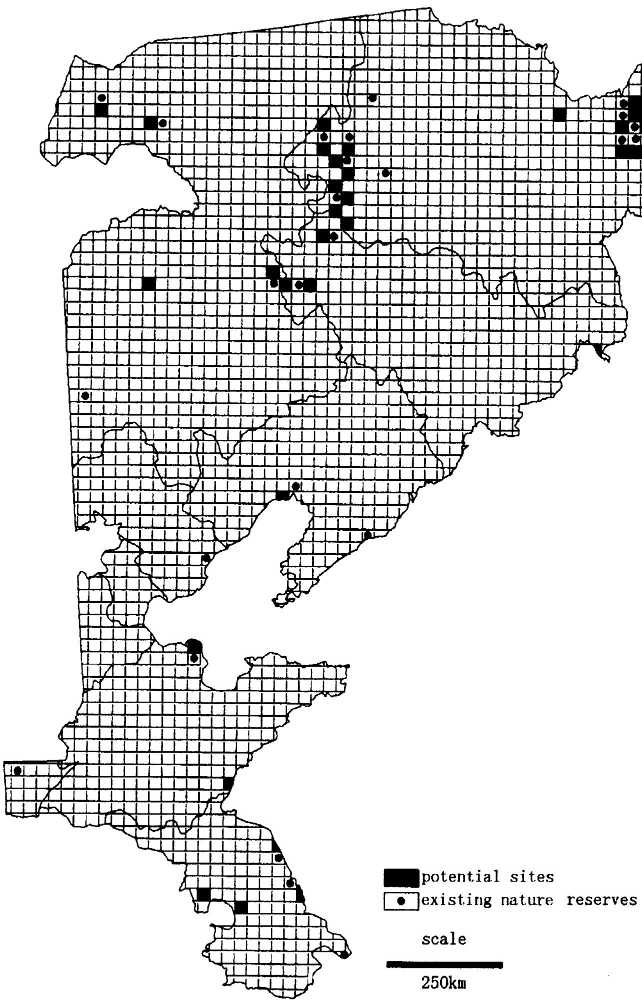

Figure 4. Potential sites for nature reserves selected by the integer programming approach.

the area or cost of units is variable, the model may restructured:

$$\sum_{j=1}^{m} c_j X_j \leq B,$$

where c_j is the cost of unit j and B is the given budget.

More variables can be included in this integer programming approach. For example, the number of residents in nature reserves can be a restriction. The effectiveness of methods of network design should be further tested. Computer software package can also be designed to facilitate the calculation of these approaches. The design of nature reserve system for Red-Crowned Crane indicated that iterative method and integer programming approach are feasible. These two algorithms could be applied into the design of nature reserve system for all protected wildlife. However, species of all protected wildlife should be included in the indicator system.

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