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Response of oriental white storks *Ciconia boyciana* to the accumulative impact of anthropogenic habitat destruction and possible Allee effect

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Abstract

The Oriental White Stork *Ciconia boyciana* is threatened with extinction due to anthropogenic habitat destruction. The scaling of its environmental capacity (K) with number of patches (P) has been studied and its response to the cumulative impact of anthropogenic habitat destruction has been simulated by a non-autonomous population model for single species. The results are: 1) The scaling index of environmental capacity of the Oriental White Stork to number of patches is 0.9768, i.e., $K \propto P^{0.9768}$. 2) By designing different scenarios to improve habitat quality, we find that it is more beneficial for the long-term persistence of the Oriental White Stork to increase average patch size than to increase the number of patches, if the total area of habitat remains the same. 3) If the Allee effect is significant, the Oriental White Stork is a 'living dead' species – one which is doomed to local extinction. To avoid extinction, habitat quality must be considerably improved.

Keywords: Oriental White Stork; habitat destruction; accumulative impact; Allee effect; scaling relation

Introduction

The Oriental White Stork *Ciconia boyciana* is a threatened wetland-obligate species. It nests on tall trees and artificial structures such as electricity pylons and feeds on fish and small animals in open, usually fresh water wetlands, and occasionally coastal tidal flats. The breeding population mainly inhabits the Heilong River and Wusuli River basins along the border between Russia and China (Smirenski 1991). In September, following breeding, most of the storks migrate to areas around the lakes along the middle reaches of the Yangtze River in eastern China and return in the following March (Wang 1991). Due to habitat destruction and overhunting, the Oriental Stork is classified as 'Endangered' on the IUCN Red List of Threatened Species (Birdlife International 2001) and is a national first-category wildlife species on China's List of Wildlife Under State Important Protection (Zheng and Wang 1998). Its population in the wild is estimated at $<$ 2,500 (Wang and Yang 1995).

The Oriental White Stork was more widely distributed in the 1960s but it has since undergone a rapid population decline due to deforestation, wetland reclamation for agriculture, over-fishing, and disturbance. The Oriental White Stork could be a 'living dead' species, as defined by Hanski (1997) – a species whose threshold conditions for survival may no longer be met following habitat loss, but has not yet died out due to the time delay in response to

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environmental change. If so, what can be done to improve habitat quality to ensure its long-term persistence? Direct observations and experiments cannot fully explain all the long-term and large-scale biological consequences of habitat loss and fragmentation. Simulation provides an effective tool for studying population dynamics but previous models have ignored the cumulative impact of anthropogenic habitat destruction, which may continue to have an impact even after destruction ceases. Therefore, a non-autonomous dynamic model is considered to be most suitable for studying population dynamics under the cumulative impact of habitat destruction (Lin and Liu, 2006).

Scaling laws express a systematic and universal simplicity among complex systems in nature (Homes *et al.* 2004). In this paper, we first identify the scaling relation between the environmental capacity of the Oriental White Stork and the number of patches by a scaling power law. Secondly, we forecast the storks' population dynamics by a non-autonomous population dynamics model. We set out to identify the mechanism of the storks' response to the cumulative impact of anthropogenic habitat destruction and to resolve whether it is a 'living dead' species by use of numerical simulations. Finally, we simulate different scenarios for improving habitat quality, which provide some implications for conservation of the Oriental White Stork.

Methods

Study site

The study was conducted in Naoli River Basin (45°43′–47°35′N, 131°31′2–134°10′E), the hinterland of Three Rivers Plain in Heilongjiang Province in northeast China. It borders the watershed of Wanda Mountain on the southeast, and adjoins Wusuli River to the east and has a total area of 24,167 km^2.

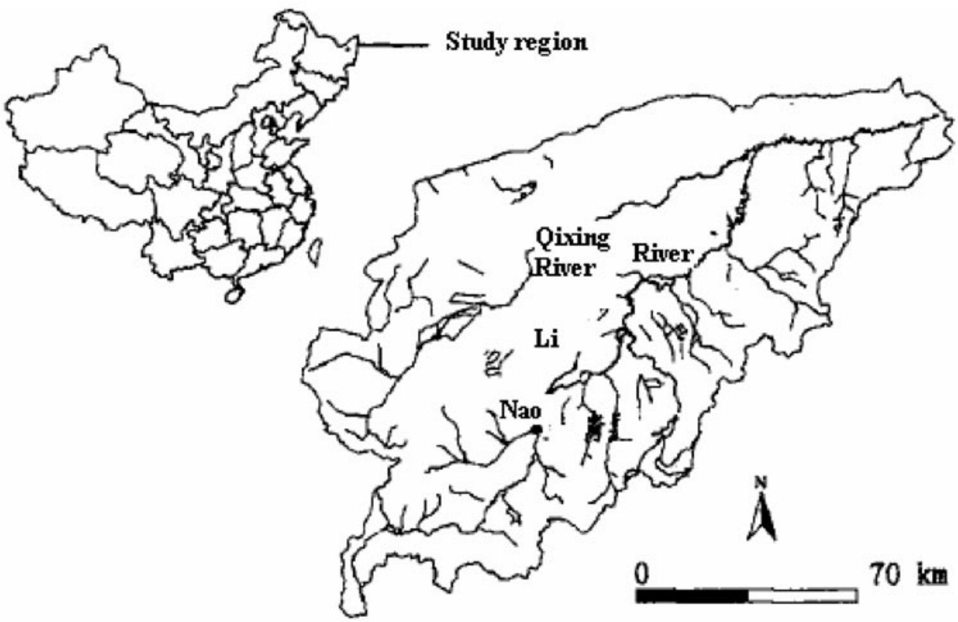

Figure 1 Location of Naoli River basin in China.

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This study area, one of the most important centres of production of commodity cereals in China, mainly consists of six counties and seven modern farms. The population is 1.25 million, of whom 65.6% are peasants. There are four wetland reserves in the Naoli River Basin which are very important for conserving biodiversity and maintaining ecosystem function. Wetland reclamation for agriculture has been intense since 1960 due to human population explosion and rapid economic growth, and wetlands have shrunk by 80% (Liu *et al.* 2002, Liu and Li 2006). The remaining wetlands now account for only 11% of the total area of Three Rivers Plain.

Data sources

Table 1 shows the numbers of Oriental White Storks, area of habitat and number of habitat patches in Naoli River Basin in the 1960s, 1970s, 1980s and 2000s (Liu *et al.* 2006, Lin 2005). Table 1 shows that the habitat has decreased rapidly and the extent of wetland has decreased and become highly fragmented.

Non-autonomous Population Dynamics Model for Single Species with Allee effect under accumulative impact of anthropogenic habitat destruction

$$\frac{dN}{dt} = rN(1 - N/K) \tag{1}$$

Equation 1 is the well known logistic growth model. Herein, r is the intrinsic growth rate, N is the population size, and K is the environmental capacity of the storks. In the logistic model, *per capita* growth rate increases as the population density decreases. Very small populations may be more susceptible to extinction due to the Allee effect (Allee 1931). Small population size may lead to low fecundity (McCarthy *et al.* 1997), increasing the risk of local extinction when population density falls below a threshold level. The Oriental White Stork has a small population size and is monogamous (Xu *et al.* 1993) and it can be difficult for birds to find mates in highly fragmented habitats.

The stork is social in the breeding season and social disruption to either foraging or anti-predator behaviour can also trigger an Allee effect in birds and has been documented for a variety of species (Sæther *et al.* 1996, Courchamp *et al.* 1999, Reed 1999, Stephens and Sutherland 1999).

In the Naoli River Basin, habitat destruction is expressed not only as rapid habitat loss, but also a rapid increase in inter-patch distance and number of patches (Liu *et al.* 2006, Lin 2004). Given the above, it is therefore essential to include the Allee effect into Model (1).

$$\frac{dN}{dt} = rN(1 - N/K)(N/K - A/K) \tag{2}$$

Where $N/K\text{-}A/K$ is Allee effect, A ($0 < A < K$) is the threshold population size below which dN/dt < due to Allee effects (Dennis 1989, Lewis and Kareiva 1993). The larger the A, the greater is the Allee effect. Obviously, the right-hand side of Eq. 2 is temporally explicit, and the model is an autonomous population dynamics model. Other models, such as the predator-prey

Table 1. Changes in habitat capacity of the Oriental White Stork, habitat area and number of habitat patches in Naoli River Basin.

Time	Area	Number of patches	Habitat capacity
1960s	7,228.9	479	1,326
1970s	6,831.7	568	1,158
1980s	4,976.1	336	814
2004	1,537.6	1,155	252

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model (Lotka 1925, Nicholson and Bailey 1935), and those of Levins (1969), Hanski (1997), Tilman *et al.* (1994) etc. are also temporally explicit. Therefore, they cannot be used to study the cumulative impact of anthropogenic habitat destruction. As the impact of anthropogenic habitat destruction on population dynamics may vary at different times (i.e., the effect is a function of time), a non-autonomous population dynamics model should be used to study the accumulative impact of anthropogenic habitat destruction over time. We introduce $f(t)$ to indicate the effects of anthropogenic habitat destruction on population dynamics.

$$f(t) = 1/t \tag{3}$$

where t is any time for population dynamics simulation after human activities stop. After the destruction stops, the effects of anthropogenic destruction on population fade away with time. Then the cumulative impact of anthropogenic destruction on environmental capacity can be expressed as:

$$F(t) = \sum_{i=1}^{i=t} 1/i \tag{4}$$

If T is the time when human activities stop, k_T represents the environmental capacity of the Oriental White Stork at that time, and $K(t)$ represents the environmental capacity considering the accumulative impact of anthropogenic habitat destruction. Then we derive the following equation:

$$K(t) = k_{\mathrm{T}}/F(t) = k_{\mathrm{T}}/\sum_{i=1}^{i=\mathrm{t}} 1/i \tag{5}$$

It is well known that the environmental capacity any species or population has a close relationship to mean patch size and number (Hanski 1998). If s and P denote average patch area and patch number respectively, then the relations between environmental capacity (K_T), mean patch size and patch number (denoting habitat fragmentation) can be expressed as:

$$K_T = a \times s_T \times P_T^n = a \times S_T \times P_T^{n-1} \tag{6}$$

Where a is constant, n is the scaling exponent, and S is the total area of habitat.

As we substitute Eqs. 5 and 6 for Eq. 2, a non-autonomous population dynamics model for single species under accumulative impact of anthropogenic habitat destruction can be expressed as:

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{a \times S_T \times (P_T)^{n-1} \Big/ \sum_{i=1}^{i=t} 1/i}\right)\left(\frac{N-A}{a \times S_T \times (P_T)^{n-1} \Big/ \sum_{i=1}^{i=t} 1/i}\right) \tag{7}$$

In contrast to the classical Logistic Model, the model we have proposed here involves not only time t, but also the cumulative impact of anthropogenic habitat destruction, and the landscape fragmentation factor, which imposes the most significant effects on population dynamics as well as the habitat area factor. Moreover, it also has the merits of the Logistic Model and sufficiently considers both environmental capacity and the Allee effect.

Results

Response of the Oriental White Stork to habitat destruction

Habitat destruction and fragmentation is by far the most significant cause of population and species extinction throughout the world (Hanski 1998). Both habitat loss and fragmentation in

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the Naoli River Basin decide the Oriental White Stork's capacity (Liu *et al.* 2006). Thus, we can improve habitat quality by increasing habitat area, i.e. increasing number of patches and patch size, and by decreasing fragmentation, i.e. decreasing patch number and increasing patch size. However, which is more significant, habitat loss or fragmentation? To answer this question we need to study the scaling of habitat area and the number of patches to environmental capacity, an aspect which is infrequently reported in the fields of landscape ecology and population dynamics.

To study the scaling relations of environmental capacity for the Oriental White Stork to patch number, we take the common logarithm of both sides as:

$$\log(K_T) - \log(S_T) = \log(a) + (n-1) \times \log(P) \tag{8}$$

Substituting the data from Table 1 into Eq.8 and then taking linear regression, we obtain the following:

$$a = 0.1968,\ n = 0.9768$$

That is, the scaling index of the storks' capacity to patch number is 0.9768 ($K_T \propto P_T^{0.9768}$). In the meantime, we obtain the scaling relations of the environmental capacity for the storks with patch number and habitat area:

$$K_T = 0.1968 \times s_T \times P_T^{0.9768} = 0.1968 \times S_T \times P_T^{-0.0232} \tag{9}$$

Eq. 9 shows that the number of patches has less effect on the environmental capacity of the Oriental White Stork than area of habitat, which in turn shows that the decline of the Oriental White Stork mainly results from habitat loss (Liu *et al.* 2006). Therefore, to avoid the storks' extinction, the most important measure is to increase the area of habitat. To do that, we can either increase patch area or number; however, which is more effective for the recovery of the population? To answer this question, we assumed that patch area remains unchanged and number of patches increases, or number of patches is unchanged and patch area increases, when the total area of habitat is increased by 50% and 100% respectively. Table 2 shows the environmental capacity for the storks in each of the four cases.

In case 1 (patch area is unchanged and number of patches increases by 50%) the capacity is 382, while in case 2 (number of patches is unchanged and patch area increases by 50%) the capacity is 385. In case 3 (number of patches increases by 100% with unchanged patch area) the capacity is 506, and in case 4 (patch area increases by 100% with unchanged number of patches) capacity is 514. Therefore, it is more beneficial for the Oriental White Stork to increase patch area than to increase the number of patches when the total habitat area remains the same.

Possible Allee effect and Oriental White Storks

As the Allee effect is likely to be very important for Oriental White Stork conservation, we simulated population dynamics on the assumption that that human habitat destruction ceased in

Table 2. The environmental capacity of the Oriental White Stork when habitat area increases.

Case 1	Case 2	Case 3	Case 4
Total area increases by 50%		Total area increases by 100%	
Patch area is unchanged and patch number increases	Patch area increases and patch number is unchanged	Patch area is unchanged and patch number increases	Patch area increases and patch number is unchanged
382	385	506	514

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2004. Figure 2 shows the storks' population dynamics when A = 20(a) and A= 30(b) with r = 0.065 (Xu *et al.* 1993). During the first decades, the population decreases sharply, but much more slowly later. When A = 20, the Oriental White Stork declines continuously, but reaches an equilibrium at low level rather than becoming extinct. When A = 30, the Oriental White Stork will become extinct (i.e. they will reach a threshold due to Allee effect) in 2216. Clearly, the population size of the Oriental White Stork declines quickly due to past habitat loss and fragmentation, and if the Allee effect is significant enough, they will go extinct. At the same time, we show that there is a long time-debt for the Oriental White Stork in which to respond to habitat destruction.

Figure 3 shows the impact of the Allee effect on extinction time. When $A \geqslant 30$, the Oriental White Stork will go extinct in its current habitat (original curve). However, only with $A \geqslant 46$ and $A \geqslant 62$, will they go extinct when habitat area increases by 50% and 100% respectively. With habitat area increasing, environmental capacity will increase, extinction will be delayed, and the threshold of Allee effect for species extinction will also rise.

Thus, if Allee effect is significant, the Oriental White Stork may be committed to extinction in their current environment with highly fragmented and reduced habitat, due to a delayed response to habitat destruction (Tilman *et al.* 1997). Liu *et al.* (2006) pointed out that the breeding population in Naoli River Basin is on the brink of extinction. But they also consider that there is some potential for the Oriental White Stork to recover if habitat quality improves. So, to protect Oriental White Storks, we must improve habitat quality sufficiently to prevent their extinction.

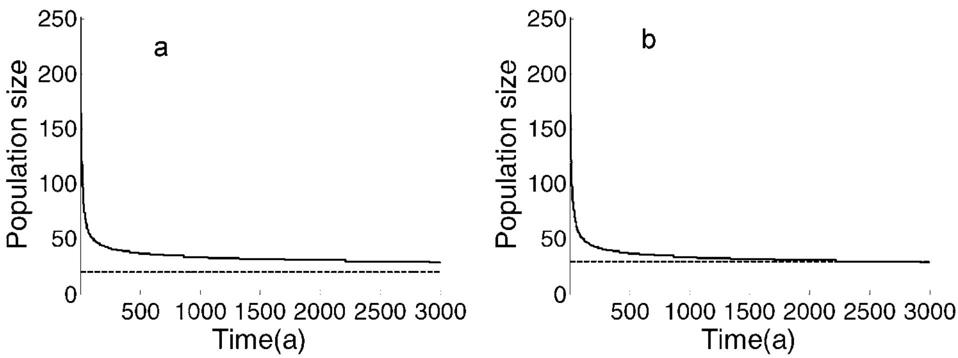

Figure 2. The population dynamic of the Oriental White Stork in the case of a = 10(a), a = 0.2(b), r = 0.065.

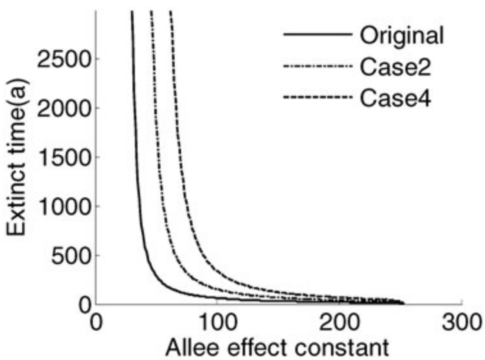

Figure 3. Impact of Allee effect on extinction time (Original represents present habitat, case 2 and case 3 correspond to Table 2).

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Discussion

From the above simulation, the following can be concluded:

1) Population decline mainly results from habitat loss.

2) The scaling exponent of patch number to environmental capacity is 0.9768. Moreover, on condition that increase in total habitat area is the same, the effect of the increase in mean patch size on extinction time is greater than the increase in patch number. Therefore, when restoring and improving habitat, we should give first priority to the enlargement of average patch size instead of increasing the number of patches, and to maintaining larger patches rather than smaller ones.

3) If habitat quality of Naoli River Basin is not improved and the Allee effect is significant enough, the Oriental White Stork will become extinct.

Liu *et al.* (2004a,b) found that linear corridors were the major factor leading to the fragmentation of the wetland landscape in Naoli River Basin, especially the construction of irrigation works. The number of field units increased from 1,234 to 13,546, which means that many large patches are divided into smaller ones. However, the Oriental White Stork requires very large areas for breeding (Su 1993) so loss of large patches makes the habitat less favourable for their survival. The Red-crowned Crane *Grus japonensis* in Naoli River Basin, listed as a national first-category wildlife species on China's List of Wildlife Under State Important Protection (Zheng and Wang 1998), also needs a large breeding area (Su 1993). This species is also threatened by extinction due to the loss of large patches in the core reserves (Zhang *et al.* 2006). In the meantime, by comparing different ways of improving habitat quality, we find that mean patch area has more influence on the species than the number of patches. Therefore, to preserve the Oriental White Stork, it is very important to reduce the number of field units in order to combine several smaller patches into larger ones. However, conservation efforts for the stork currently focus on artificial nest sites, artificial reproduction, and restricting cultivation and grazing (Zeng *et al.* 2003, Ma *et al.* 2006). So more efforts should be made to increase habitat area and improve habitat quality. As for reserve planning for the Oriental White Stork, the larger the reserve area is, the more beneficial it will be for species persistence. A large reserve is better than several smaller ones even when the total areas are equal (Diamond 1975).

5) There are many other factors, such as water quality, water level and vegetation that impact on habitat quality of the Oriental White Stork, but we only take habitat loss and fragmentation into consideration for simplicity. Environmental and demographic stochasticity, which are not considered in this model, can have a certain impact on estimates of extinction rate, and require further consideration. However, including these factors will make the model far more complex. Although nowadays many complex, spatially explicit metapopulation models have been developed to forecast population dynamics, they are too complicated to test with lots of parameters and the assumptions are difficult to estimate. The model we have put forward here is much easier to operate and to test. Like other models, there are numerous uncertainties in forecasting the extinction risk due to the variability of landscape structure, and environmental and demographic stochasticity. In short, the contribution of the model to conservation biology lies in the comparison between different landscape structures and different management cases (Hanski 1998, Lin and Xie 2005).

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