The Three Gorges Dam: an ecological perspective

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The Three Gorges Dam in China is the largest dam ever built. Its impacts on the biodiversity and ecological processes in the region are causing concern to ecologists worldwide. The dam and associated environmental alterations may result in a number of regional changes in terrestrial and aquatic biodiversity, as well as in ecosystem structure and functioning. The dam may also provide a rare opportunity for a grand-scale experiment in habitat fragmentation, allowing ecologists to develop and test a series of hypotheses concerning the dynamics of biodiversity and biotic communities and their responses to disturbances. Such research can help improve conservation practices, stimulate international collaborations, and promote public education on the environment.

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Dams have played an important role in human development throughout the world for thousands of years, providing water, controlling floods, irrigating crops, facilitating navigation, creating recreational opportunities, and generating motive power and electricity. By the end of the 20th century, about 45 000 large dams (>15 m in height) and an estimated 800 000 small dams had been built worldwide (WCD 2000), obstructing over 65% of fresh water flow to the oceans (McCully 1996; Nilsson and Berggren 2000). With more than 22 000 large dams (but only 22 before 1949), China is the largest dam-building country; by way of comparison, the country with the second-highest total, the US, has just 6390 (WCD 2000). Until recently, large dams were perceived as a symbol of progress in hydraulic engineering and economic development, but this image has waned steadily in the past several decades in the face of increased recognition of their failure to provide the expected economic benefits, along with heightened awareness of their detrimental effects on the environment (Milliman 1997). Dams have resulted in large-scale habitat fragmentation and ecosystem alterations that adversely affect both terrestrial and aquatic biodiversity (Dynesius and Nilsson 1994; Rosenberg *et al*. 2000; Terborgh *et al*. 2001; Wu *et al*. 2003a,b). Habitat fragmentation involves both a reduction or loss of habitat and a decrease in habitat connectivity.

In a nutshell:

- The Three Gorges Dam (TGD) is the largest dam in the world
- The total area which will be influenced by the TGD is approximately 58 000 km^2; about 1.13 million people will be displaced
- The Three Gorges Reservoir Region is an area of high biodiversity, including a number of rare and endemic species
- TGD will inundate large areas of agricultural, forest, and grassland ecosystems
- TGD may serve as a grand-scale experiment in habitat fragmentation

The debate over the world's largest dam, the Three Gorges Dam (TGD) (Figure 1), highlights many of the controversies relating to dam construction (see Edmonds 1991), but in this case the dam proponents prevailed, and the huge structure is now in place. Many ecologists and other scientists have expressed concern over the environmental consequences of the TGD. How is the TGD affecting the biodiversity and environmental conditions of the region? A thorough assessment of its effects requires adequate information on the composition and spatial distribution of biodiversity before and after dam construction, as well as long-term monitoring. Several field surveys have been published in Chinese since the 1980s (eg CASTGPC 1987; Chen *et al*. 1994; Yang 1997; Xiao *et al*. 2000). These studies provide critical, though incomplete, baseline information on the ecological conditions of the region before the dam was constructed and are of tremendous value in assessing the ecological effects of the TGD, now and in the future.

The purpose of this paper is not just to summarize the survey results from the Chinese literature; rather, we

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Figure 1. The Three Gorges Dam.

will synthesize some major findings in the literature, discuss the possible ecological effects of the TGD, and then make suggestions for future research in this region.

Environmental setting of the Three Gorges Reservoir Region

The Three Gorges Dam is built on the Yangtze River (Changjiang) in south-central China, the world's third longest river. The portion of the Yangtze River Basin between Chongqing and Yichang City (where the TGD is located), a distance of approximately 600 km, has become known as the Three Gorges Reservoir Region (TGRR; Figure 2). The total area of the TGRR (106˚–111˚50' E, 29˚16'–31˚25') is approximately 58 000 km^2, including the entire inundated area, or the Three Gorges Reservoir Inundated Area (TGRIA) and 19 administrative units (counties and cities) on both sides of the river. The TGD venture, projected to require 18 years to complete, was separated into three distinct phases (Wu 1995): Phase I – Planning activities (1992–1997); Phase II – Dam construction and partial implementation of hydroelectric power facilities (1998–2003); and Phase III – Full implementation of hydroelectric facilities (2003–2009).

TGRR has a humid subtropical monsoon climate, with a mean annual temperature of 15–19˚C, mean annual precipitation of 1250 mm, and relative humidity of 76%. The vegetation in the region is varied, with at least 144 distinct plant communities represented (Chen *et al*. 1994; Huang 2001; Shen and Zhang 2000). Studies have shown that the vertical vegetation zones and floristic composition are related to mountain climate and landform characteristics, as are the spatial distribution patterns of species diversity (Shen *et al*. 2001). As a result of long-term human activity (predominantly agriculture), much of the original TGRR forest vegetation below 1000 m has been destroyed, and the current land cover is dominated by secondary forests and agricultural fields.

The TGRR has a large number of terrestrial and aquatic species (see Table 1). The rich and unique biodiversity of the region can be attributed to its distinctive geographic location, complex topography, and climatology, and to many species having survived the Quaternary glaciations. One exceptional feature of the biodiversity in this region is the abundance of ancient, rare, endemic, and endangered species. There are, for example, at least 36 endemic plant species, as well as many ancient and rare species (Chen *et al*. 1994). The flora of the TGRR is composed of a rich mixture of species originating from the tropical, subtropical, and temperate zones, while the region's fauna is represented by a varied assemblage of both terrestrial and aquatic animals (Table 1).

Possible impacts of the TGD on biodiversity

Loss and isolation of terrestrial ecosystems

In 2009, when water levels are raised to 175 m, it is estimated that the total inundated area in the TGRR will be about 1080 km^2, with an average width of 1.1 km – about twice as wide as the river was before the dam was built. Consequently, more than 100 mountaintops and ridges will potentially become modern landbridge islands (that

Table 1. Biodiversity in the Three Gorges Reservoir Region (number of species by different taxonomic groups)

Higher plants	Insects	Terrestrial vertebrates	Fish	Aquatic plants, plankton, and benthic organisms
6388	3418 (including 368 species of butterflies)	500 (including 101 mammal, 319 bird, 35 reptile, and 32 amphibian species)	350	1085

Data are from Yang (1997), Liu *et al.* (2000), Xiao *et al.* (2000), and Huang (2001). Other scientists estimated that about 3500 species of higher plants are actually native to the region, and most of the rest are species introduced from outside the region for medical, economic, or other purposes (Weilie Chen pers comm) is, previously connected land areas isolated by flooding or rising sea levels). We used a digital elevation model (DEM) with 50-meter contour intervals and a Geographic Information System to estimate the number and spatial distribution of islands in the TGRA (Figure 3). When water levels were assumed to be 200 m, the estimated total number of landbridge islands was 102, with a total area of 80.67 km^2 and mean island size of 0.79 km^2 (SD=3.99); when water levels were assumed to be 150 m, the number of islands decreased to 47, with a total area of 58.70 km^2 and mean island size of 1.25 km^2 (SD=2.54). Based on these estimates, there is broad variation in island size, and most of the islands are smaller (Figure 4) than the average island size of about 30 km^2 (Table 2). Because our current DEM is too imprecise too allow us to examine the situation at a water level of 175 m (the target water level of the reservoir), and because there is no other direct information on the formation of islands at this time, these model predictions should be viewed with great caution. Nevertheless, it seems plausible to speculate that the number of islands at the reservoir water level of 175 m will be somewhere between 47 and 102.

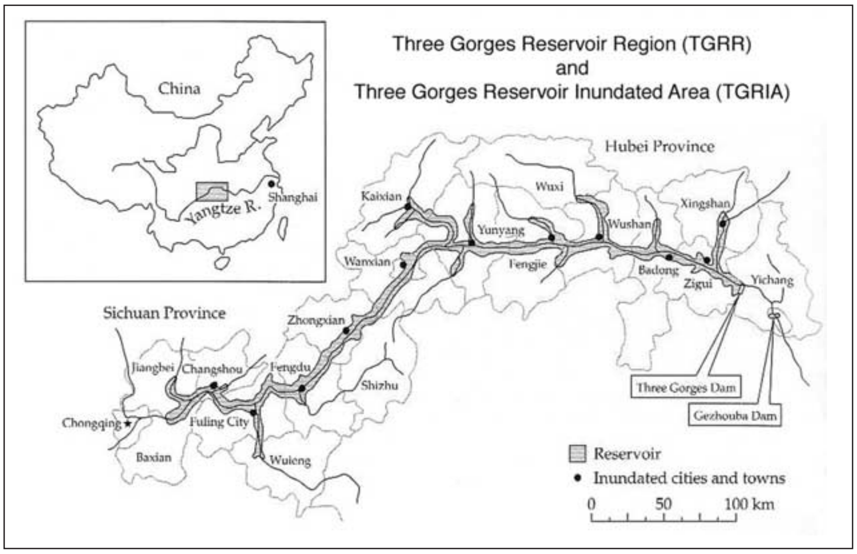

Figure 2. *The Yangtze River and the spatial extent of the Three Gorges Reservoir. The total area of the Three Gorges Reservoir Region (TGRR) is about 58 000 km^2, 1.4 times as large as the entire country of Switzerland. The Three Gorges Reservoir Inundated Area (TGRIA) is estimated to be 1080 km^2 when the water level is raised to 175 meters in 2009. (Adapted from Primack 2002.)*

Some plant and animal populations, and even some species, will potentially be completely or partially lost to inundation due to damming. However, the effects of the TGD on the biodiversity and ecological conditions of the TGRR will go far beyond merely reducing the total area of terrestrial habitats. In the following sections, we analyze some of the major possible ecological impacts that the TGD may have in the decades to come.

Effects of habitat fragmentation on terrestrial biodiversity

How will the TGD affect the terrestrial biodiversity and ecological processes of the region? This question cannot be answered in specific terms at the moment. However, several case studies of large-scale habitat fragmentation in different parts of the world can certainly help us understand the scope and magnitude of these effects.

When Lake Gatun was formed in the central part of the Panama Canal by damming the Chagres River in 1913, the inundation created a number of landbridge islands, including Barro Colorado Island. The first survey of the island's birdlife in the 1920s reported 208 breeding bird species, 45 of which had disappeared by 1970 (Terborgh 1974). In 1986, dam construction in Venezuela created the 4300-km^2 Lake Guri, turning hundreds of former hilltops into landbridge islands ranging from less than 0.1 ha to 150 ha in size (Terborgh *et al.* 2001). Field surveys in 1993 and 1994 revealed that small islands (0.25–0.9 ha) and medium islands (4–12 ha) had already lost more than 75% of the vertebrate species known to exist on the nearby mainland (Terborgh *et al.* 2001). Within 4 years, all of the islands had lost their top predators; populations of herbivores increased in the absence of predators which, in turn,

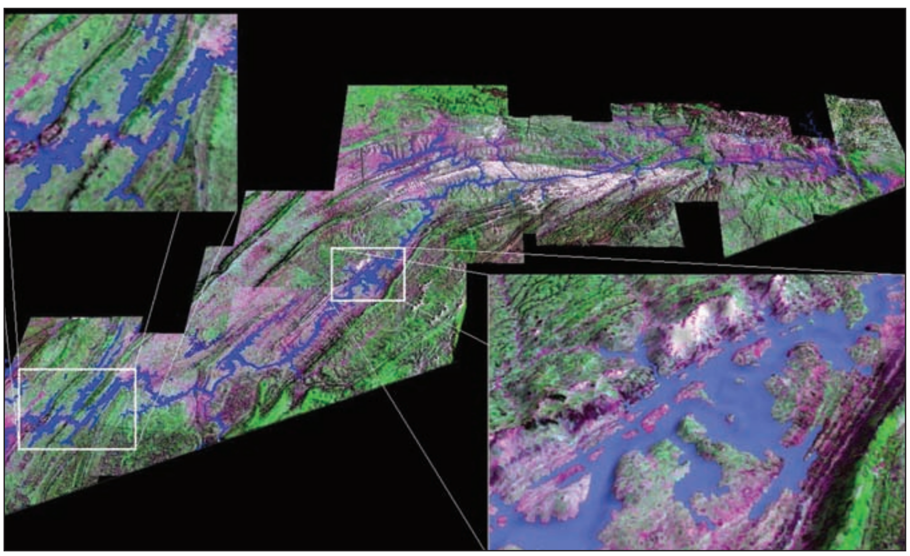

Figure 3. *Model-generated image of the Three Gorges Reservoir Inundated Area, showing the spatial distribution of new islands, assuming that the water level is raised to 200 meters. The DEM used has 50-meter contour intervals.*

Table 2. Number and size distribution of islands formed by damming in the Three Gorges Reservoir Region (estimated using a DEM)

Island statistics	Reservoir water level at 50 meters	Reservoir water level at 200 meters
Number of islands	47	102
Total island area (km^2)	58.70	80.67
Mean island area (km^2)	1.25	0.79
Island area standard deviation (km^2)	2.54	3.99
Largest island area (km^2)	10.96	39.15
Smallest island area (km^2)	0.0009	0.0018

resulted in a substantial reduction in the density of seedlings and saplings (Terborgh *et al*. 1997, 2001).

Another example comes from French Guiana, South America, where a hydroelectric reservoir, built in the 1980s by damming the Sinnamary River (the Petit Saut Dam), filled to a water level of 35 meters in June 1995, resulting in a 365-km^2 lake with several hundred landbridge islands (Cosson *et al*. 1999a,b; Fournier-Chambrillon *et al*. 2000). Within 4 years of inundation, vertebrate species diversity had decreased, regardless of dispersal ability over water, while other species became dominant on the islands (Cosson *et al*. 1999a). Most of the flooded trees died within 4 months, forming a zone of "ghost forests" around the islands (Terborgh *et al*. 1997), and physical conditions, forest structure, and species diversity exhibited marked changes towards the outer edges of the islands (Cosson *et al*. 1999a,b). A similar study in a tropical rainforest was reported by Lynam (1997), who investigated the rapid decline of small mammal diversity on 24 of about 100 landbridge islands created by the damming of the Saeng River to build a hydroelectric reservoir (165 km^2 in area) in southern Thailand in 1986. The Biological Dynamics of Forest Fragments Project in central Amazon, initiated in 1979, represents another large-scale experiment in habitat fragmentation. Research at this site, which covers a cleared area of 1000 km^2 divided into five 0.01-km^2 fragments, four 0.1-km^2 fragments, and two 1-km^2 fragments, demonstrates a wide range of fragmentation effects on biodiversity and biogeochemical processes (Bierregaard *et al*. 2001; Laurance *et al*. 2002).

From these and other studies of habitat fragmentation, it is probable that the TGD will have a number of impacts on the terrestrial biodiversity and ecological processes at multiple levels of biological organizations and over a range of spatial and temporal scales (Wu *et al*. 2003a; Figure 5). Some Chinese scientists have estimated that at least 34 local plant communities will be partly or completely flooded, including some vegetation types that are found only in the TGRR (Chen *et al*. 1994; Huang 2001). The loss of these habitats will most likely lead to the disappearance of animals that have difficulty migrating uphill or that are unique to these habitats. The terrestrial biodiversity and ecological processes of this area will be further affected by habitat fragmentation, modified local and regional climatic conditions, and changing land-use patterns in the TGRR due to the resettlement of more than 1 million people to higher elevations.

Effects on aquatic biodiversity

Habitat loss and associated environmental alterations caused by the TGD will not only affect terrestrial biodiversity, but also the aquatic biota in TGRR (Wu *et al*. 2003b; Xie 2003; Figure 5). Dams disrupt the natural seasonal flow patterns to which aquatic animals are adapted, block and destroy spawning grounds and migratory paths, and fragment aquatic populations (Dudgeon 2000; Pringle *et al*. 2000; Rosenberg *et al*. 2000). Certain rare aquatic species have reportedly already come under threat from the Gezhouba Dam (40 km downstream from the TGD) in the early 1980s, and TGD can only increase this threat. Xie (2003) argued that the aquatic habitat fragmentation caused by Gezhouba and the TGD on the Yangtze River is particularly detrimental to ancient endemic fish species, such as Chinese sturgeon (*Acipenser sinensis*), river sturgeon (Acipenser dabryanus), and Chinese paddlefish (*Psephurus gladius*). Many other migratory species may be also affected. Fu *et al*. (2003) estimates that more than 40 fish species, including 19 endemic to the river, will be adversely affected by the TGD, Gezhouba, and

Courtesy of F Yuan

Figure 4. *One of the many small islands possibly created by the rising waters in the Three Gorges Reservoir Inundated Area.*

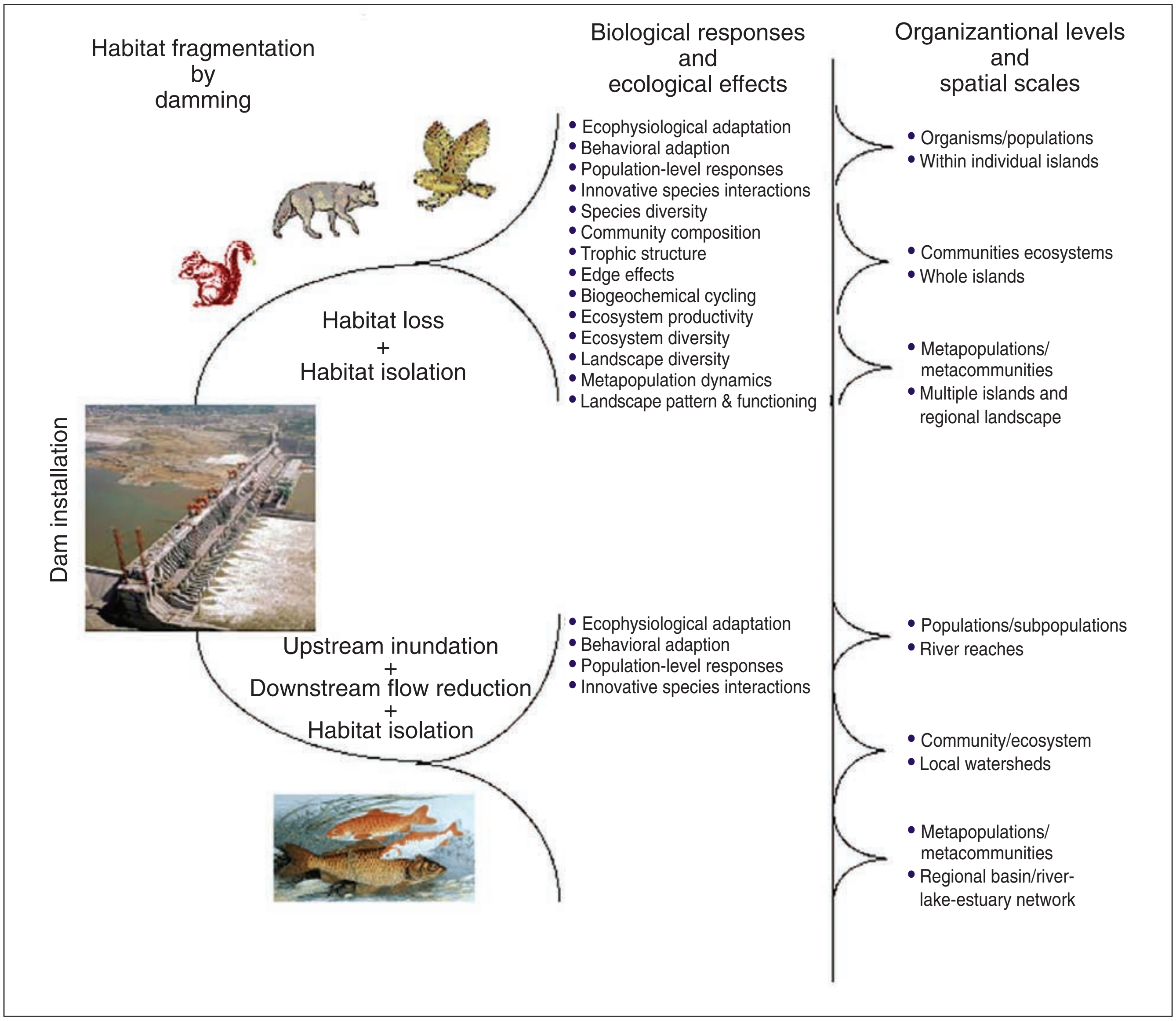

Figure 5. *Schematic representation of the possible effects of the Three Gorges Dam on biodiversity and a suite of ecological processes at multiple levels of biological organization through habitat fragmentation, upstream inundation, downstream flow reduction, and associated environmental alterations. While the reservoir water level has been raised to 135 meters since June 2003, rigorous research programs are yet to be established to address these problems.*

about 10 more dams that have been planned on the Yangtze. Some aquatic mammals (eg the Chinese river dolphin, *Lipotes vexillifer*) are even more vulnerable to the effects of dams than fish and freshwater invertebrates (McCully 1996; Fu *et al.* 2003). In addition, a suite of other factors may also affect the riverine biodiversity, including sedimentation, physical injuries, and noise disturbance due to increased navigation (Fu *et al.* 2003; Wu *et al.* 2003b).

Dams do much more than just stop the flow of water and fragment wildlife habitats in the affected river basin (McCully 1996; Rosenberg *et al.* 2000). A number of studies from different parts of the world have shown that they also reduce fishery productivity, release toxic substances into the water, cause eutrophication and the depletion of dissolved oxygen, contribute to sediment build-up, and result in downstream habitat changes, such as the deterioration and loss of floodplains, riparian wetlands, river deltas, and ocean estuaries (Dynesius and Nilsson 1994; Milliman 1997; Rosenberg *et al.* 2000). Most of these problems are likely to occur in the TGRR. Although detailed information is lacking, a general conclusion can already be drawn: going against the flow imperils native biodiversity and ecological complexity.

Research opportunities

As large-scale experiments are usually constrained by laws, ethical considerations, and logistical and scientific obstacles, such fortuitous natural experiments are extremely valuable (Diamond 2001). The TGD provides an extraordinary opportunity for large-scale experimentation in habitat fragmentation (Wu *et al.* 2003a). While all previous and ongoing studies of landbridge islands are in tropical forest areas, the TGD is located in a subtropical region, where the characteristics of biodiversity are different. In this section, we discuss some examples of research questions which focus on terrestrial biodiversity. For research opportunities concerning aquatic biodiversity, the reader is referred to Rosenberg *et al*. (2000), Pringle *et al*. (2000), Fu *et al*. (2003), and Wu *et al*. (2003b).

Species extinction and persistence

What species are most vulnerable and, conversely, more resilient to habitat fragmentation? What life history traits are responsible for the pattern of extinction and survival of species? How does this pattern compare with the patterns observed in other landbridge island studies?

Species loss as a result of isolated habitat fragments is not a random but rather a selective process. Species at higher trophic levels, large body size, high endemism, and limited dispersal ability tend to disappear first, while persistent species are usually generalists in terms of habitat and food requirements and/or have high abundance, long generation time, and inhabit a wide geographic range (Terborgh 1974; Laurance *et al*. 1997; Terborgh *et al*. 1997). Such broad patterns of extinction and survival have not been thoroughly tested (Terborgh *et al*. 1997), and there have been conflicting findings. For example, research by Terborgh *et al*. (1997, 2001) in Lake Guri showed that all landbridge islands lost their top predators within 4 years, while other studies have indicated that large-bodied top predators were among the first to go extinct. However, Cosson *et al*. (1999a) found that the largest members of animal groups were less sensitive to fragmentation.

Species-abundance and species-area relations

How do the species-abundance relation and the species-area relation on the islands change in time? Will there be a notable shift in the form of these relations?

The first level of ecological response of species to habitat fragmentation is often a change in the number of individuals. The collective representation of such changes can be described by the species-abundance relation (He and Legendre 2002). The temporal pattern of the species-abundance relation provides important information on: (1) how the pre-fragmented communities are assembled, (2) how the post-fragmented communities are reassembled, (3) how different species groups respond to the same fragmentation, and (4) how species richness changes with species abundance. The species–area relation for the landbridge islands may change dramatically before and after damming (Figure 6). It is an important way of summarizing biodiversity patterns across a broad range of spatial and temporal scales, and a useful tool for developing conservation plans in fragmented landscapes. The TGRR provides a unique opportunity to examine several aspects of the species-area relationship, including its mathematical form, variations with different species groups, and possible changes in time.

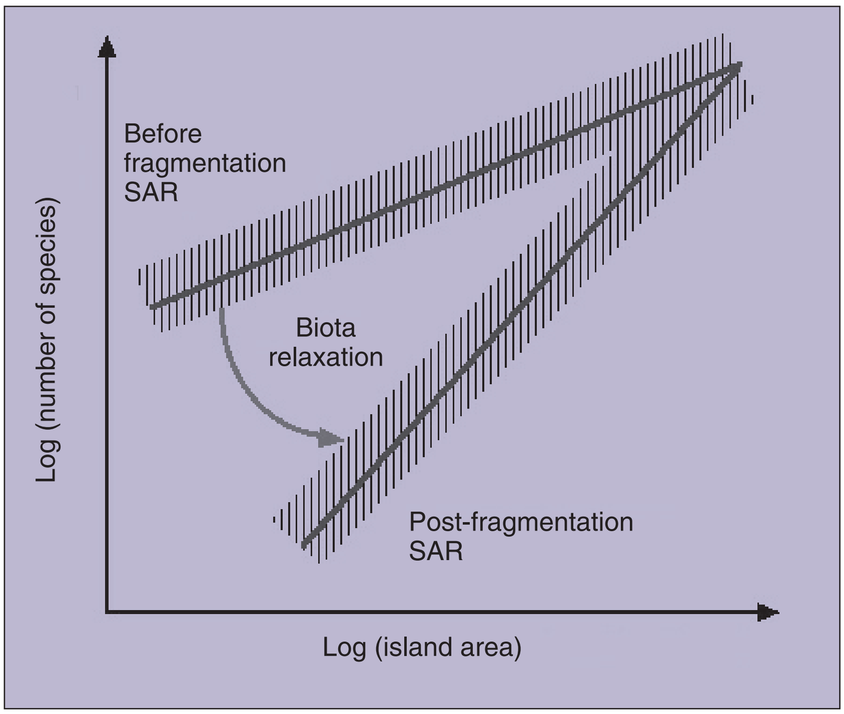

Figure 6. *The species–area relation (SAR) hypothesis: SAR may change considerably in time following dam construction. At the time of island formation, the number of species on islands may obey the commonly observed species-area relationship: SAR = cA^z. However, this relationship may change significantly later on because of differential and non-linear extinction rates for different species on islands of varying sizes. Eventually, a relatively stable species-area relation may be re-established, but its slope may be steeper because of the heavier loss of species on small islands.*

Land use change and biotic community dynamics

How do the biotic communities of landbridge islands with different human land use histories differ in their responses to the isolation resulting from damming? How do disturbed ecosystems restore their structure and functioning through the process of self-organization?

After habitat fragmentation, less disturbed islands may lose species due to isolation, whereas heavily modified islands may increase in species diversity due to progressive succession if agriculture on the islands is abandoned. Furthermore, less disturbed island communities may exhibit greater resistance to the invasion of exotic species. Most of the landbridge islands in the TGRR have been disturbed by human activities and covered by secondary forests, grasslands, and agricultural fields. This opens up new opportunities for addressing important questions of biotic community dynamics in relation to human disturbances. For example, the islands may be classified along a human disturbance gradient as slightly disturbed sites, moderately disturbed sites, and heavily disturbed sites. We may hypothesize that islands that had been little disturbed by human activities might be oversaturated with species at the time of damming, thus losing species afterwards due to habitat loss and isolation – a process referred to as biota relaxation. But species richness will likely increase on heavily disturbed islands (eg those dominated by monocultural crop fields or grasslands). Also, it is possible that less disturbed islands have higher resistance to species invasion than heavily disturbed islands. It is more difficult to speculate about how biodiversity will change on moderately disturbed islands at this time.

Changes in biodiversity and island vegetation patterns need to be monitored, with attention focused particularly on how different types of islands respond to possible species invasion and how biological communities on disturbed islands recover from past disturbances and re-organize themselves. Such studies will not only provide new tests on the effects of habitat fragmentation on biodiversity, but will also offer new insight into how biotic communities recover after major habitat alterations.

Discussion

The study of habitat fragmentation is of great scientific and practical importance (Harrison and Bruna 1999; Haila 2002; Wu and Hobbs 2002). Islands have served as fruitful natural experimental laboratories for studying a number of outstanding issues in evolution and ecology, including habitat fragmentation (Wu and Vankat 1995). There were over 45 000 large dams in more than 150 countries in 2000, and 160 to 320 new large dams are being built worldwide each year (WCD 2000). The rapidly increasing geographic extent and the rich biodiversity of these altered ecosystems warrant substantial research efforts. The TGD, and other dams, may offer rare opportunities for developing and testing our understanding of the effects of habitat fragmentation on biodiversity and improving conservation practices.

In habitat fragmentation experiments, it has often been difficult to separate the effects of habitat reduction and isolation from those of the landscape matrix in which the habitat patches lie. Landbridge islands provide rare opportunities in which matrix effects can be more readily controlled or quantified (Cosson *et al.* 1999a). One of the limitations with most existing large-scale natural experiments is the lack of baseline biological and land-use information prior to habitat fragmentation, and as a result such information has to be reconstructed retrospectively using (often incomplete) museum collections and historical records (da Fonseca *et al.* 2002). For example, detailed surveys of Barro Colorado Island were not conducted until nearly a decade after inundation; likewise, surveys were not carried out at Lake Guri until 4 years following inundation. For the TGD, considerable amounts of baseline data were already available at the time of damming from various Chinese sources, although the information was scattered and inconsistent.

If the TGD is not to be a lost opportunity, we believe that several activities must be undertaken. First, there must be a comprehensive and complete documentation of baseline information on the environmental settings and biodiversity before and after dam construction. Although several efforts have been made, additional studies are urgently needed in the next few years to ensure the adequacy of the baseline database in terms of coverage and details. Second, long-term monitoring and research programs need to be established, including projects that focus on terrestrial island ecosystems, aquatic ecosystems, and land–water ecotones. Most importantly, these should include permanent monitoring/research stations in these ecosystems. Third, research topics should focus on the impacts of habitat loss and changes on both terrestrial and aquatic biodiversity at multiple trophic levels and multiple spatial and temporal scales (Figure 6). Studies should focus on the effects of riverine habitat fragmentation caused by the dam, changes in water quality and biochemistry in the TGD reservoir on aquatic biodiversity, and habitat restoration and ecological succession at both the local ecosystem and regional landscape scales. These monitoring and research activities represent both great opportunities and challenges, and international collaborations will be crucial to meet the anticipated intellectual and financial demands.

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