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Research, part of a Special Feature on Telecoupling: A New Frontier for Global Sustainability

Complex effects of natural disasters on protected areas through altering telecouplings

Jindong Zhang [1,2], Thomas Connor [2], Hongbo Yang [2], Zhiyun Ouyang [3], Shuxin Li [2] and Jianguo Liu [2]

ABSTRACT. Increasingly, protected areas have been connected with the rest of the world through telecouplings (socioeconomic and environmental interactions over distances) that are essential for their structures and functions. Unfortunately, many of the Earth's protected areas are located in regions with frequent natural disasters that can profoundly affect telecouplings. Although there have been many studies evaluating socioeconomic or ecological effects of natural disasters separately, systematic evaluations of socioeconomic and ecological effects of natural disasters by altering multiple telecouplings have remained rare. With long-term data collected in China's Wolong Nature Reserve for giant pandas (Wolong), we applied the telecoupling framework to assess the effects of the 2008 Wenchuan earthquake on telecouplings that link Wolong with the rest of the world, as well as their subsequent effects on coupled human and natural systems in Wolong. Our results show that the earthquake altered all major components of multiple telecouplings and generated complex socioeconomic and ecological effects in Wolong. Based on these understood effects, we provide suggestions to enhance environmental sustainability and human well-being in Wolong and beyond.

Key Words: *ecological effects; natural disaster; protected areas; socioeconomic effects; telecouplings*

INTRODUCTION

As globalization continues, protected areas have been increasingly connected with the outside world through telecouplings (environmental and socioeconomic interaction over distances) such as nature-based tourism, trade of agricultural products, and rural-urban labor migration (Liu et al. 2015*a*, *b*). This trend has profoundly changed human-nature interactions in protected areas and generated complex socioeconomic and ecological effects (Kramer et al. 2009). Telecouplings have become essential for maintaining many protected areas' structures and functions by providing materials, capital, and information. For example, nature-based tourism has been widely promoted in many protected areas as an important mechanism to alleviate poverty and discourage local households from their traditional livelihood activities (e.g., farming and timber harvesting) that threaten the functioning of local ecosystems (Liu et al. 2012).

Unfortunately, many of the globe's protected areas are located in regions with frequent natural disasters such as earthquakes and hurricanes, which can dramatically change telecouplings (e.g., abruptly disrupt tourism) with cascading environmental and social effects (Dilley 2005, Hyndman and Hyndman 2014). The number and scale of natural disasters have been projected to increase in the future because of global environmental change and the increase of human disturbances in regions at risk of natural disasters (Dudley and Stolton 2010, Field 2012). Therefore, it is important to understand how natural disasters might change telecouplings that constitute critical linkages between protected areas and distant places (e.g., cities).

Previous studies estimating the effects of natural disasters have mainly focused on individual telecouplings separately while treating either socioeconomic (Blaikie et al. 2014, Yang et al. 2015, Wei et al. 2016) or ecological effects (Garwood et al. 1979, Zheng et al. 2012, Zhang et al. 2014) independently. Although these disparate research foci have generated useful insights into the effects of natural disasters, more comprehensive research is needed to integrate various aspects of natural disasters' influences into a systematic assessment of patterns, processes, simultaneous socioeconomic and environmental interactions, and implications for governance and policy across the world. For the management of protected areas, particularly those undergoing natural disasters, a systematic understanding of the interactive dynamics between local systems and the outside world, and the effects of these interactions on local human well-being and the environment is needed (McShane and Wells 2004, Liu et al. 2015*b*). Such knowledge can help to better manage the relationship between economic development and biodiversity conservation in protected areas (Dudley and Stolton 2010, United Nations 2016).

The telecoupling framework (Liu et al. 2013) provides a promising tool for integrating disparate research on natural disasters' impacts to obtain a comprehensive understanding of the interrelated ecological and socioeconomic effects on protected areas. In the telecoupling framework, each place is treated as a coupled human and natural system (CHANS), i.e., an integrated system in which human and natural components interact with each other (Liu et al. 2007). Different CHANS are connected with flows of materials, information, and energy. Depending on the direction of flows, systems can be classified as a sending system, receiving system, or a spillover system. In each of these CHANS, there are causes that strengthen or weaken telecouplings, agents that facilitate telecouplings, and effects that are generated by the telecouplings. The characteristics of the telecoupling framework, and the ways in which it differs from other frameworks, are discussed in greater detail in Liu et al. 2013. This framework has quickly gained popularity and has been successfully applied to a series of important issues, such as payment for ecosystem services programs (Liu and Yang 2013), flows of ecosystem services (Liu et al. 2016*a*), international land deals (Liu et al. 2014), energy

[1]Key Laboratory of Southwest China Wildlife Resources Conservation, China West Normal University, Ministry of Education, Nanchong, Sichuan Province, China, [2]Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, Michigan, USA, [3]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-environmental Sciences, Chinese Academy of Sciences, Beijing, China

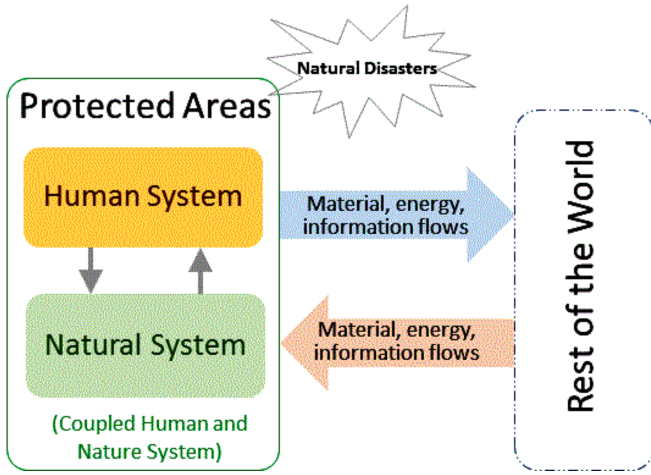
trade (Fang et al. 2016), urban water sustainability (Deines et al. 2016, Yang et al. 2016), species migration (Hulina et al. 2017), species invasion (Liu et al. 2013), conservation (Carter et al. 2014, Gasparri et al. 2016, Wang and Liu 2017, Yang et al. 2018), fisheries (Carlson et al. 2017), trade of sand (Torres et al. 2017), and trade of food and forest products (Liu et al. 2013, Liu 2014).

Natural disasters can affect local CHANS through dissolving, disrupting, or creating telecouplings. For example, primary material, energy, and information flows may be impeded because of natural hazards and loss of infrastructure (e.g., destruction of the road linking protected areas and outside world; Liu et al. 2013). On the other hand, some new flows, such as investments from government for postdisaster reconstruction, may emerge. These in turn affect socioeconomic and ecological conditions within a protected area (Fig.1). The effects of natural disasters on multiple telecouplings are also closely related to the resilience of local CHANS (Liu et al. 2013). After natural disasters, protecting or strengthening certain existing telecouplings enhances adaptability (Holling 1973, Folke et al. 2010, Liu et al. 2013), while the generation of new telecouplings relates to a CHANS' transformability (Walker et al. 2004). Applying the telecoupling framework thus allows researchers to more clearly understand the ecosystem and human system dynamics and the interactions among them, e.g., adaptive cycle and the panarchy (Folke 2006). The main goal of this study is to understand not only how a system is directly affected by the disasters but also how changes to telecouplings can have cascading effects. To achieve the goal, we applied the telecoupling framework to systematically analyze the dynamics of flows, causes, effects, and agents involved in multiple telecouplings affected by natural disasters. We used the 2008 Wenchuan earthquake that struck Wolong Nature Reserve (China) as an example, and analyzed the complex and lasting effects of the earthquake on the local CHANS in Wolong arising from changes to multiple telecouplings. In addition to applying the telecoupling framework to understand both the socioeconomic and ecological effects of the earthquake, we discuss implications for the governance of protected areas such as Wolong Nature Reserve and propose specific policy recommendations there and beyond.

WOLONG AS PART OF A TELECOUPLED SYSTEM

Wolong Nature Reserve (102°51′40″-103°25′5″E, 30°45′36″-31°19′25″N) was established in 1963 and is one of the first protected areas for conserving the global conservation icon: giant panda (*Ailuropoda melanoleuca*) in China. The reserve was expanded to its current size of 2000 km² in 1975 (Liu et al. 2001) and harbors over 100 wild giant pandas (Liu et al. 1999, Sichuan Provincial Forestry Department 2015). It lies within a global biodiversity hotspot (Myers et al. 2000, Liu et al. 2003*a*), with over 2200 species of animals and insects as well as 4000 species of plants (Tan et al. 1995). The reserve is also in a tectonically active region within the Longmen Mountain Fracture Zone (Zhang et al. 2014). There are two towns in Wolong, the Wolong and Genda townships, which are home to nearly 1400 households, with a total population of 5000. Most residents are farmers (Liu et al. 2016*b*). The reserve and local community are managed by the Wolong Administration Bureau, which reports to China's State Forestry Administration and the Sichuan Provincial Forestry Department.

Fig. 1. Exchange of energy, materials, and information between protected areas and the rest of the world through telecouplings undergoing natural disasters. Natural disasters may drastically change these telecouplings and generate substantial socioeconomic and ecological impacts in protected areas.

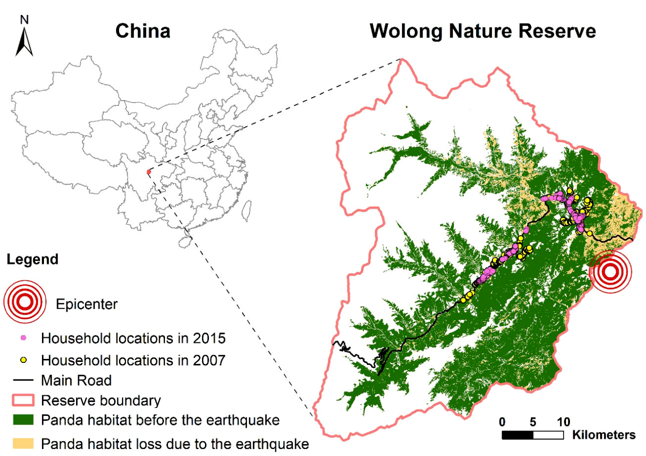


In 1999, with approximately a 100 million Yuan (US15.4 million) investment from government sources, a provincial highway (#303) connecting the reserve with the rest of the world was completed (Wolong Nature Reserve 2008; Fig.2). As the road condition improved, Wolong became part of a telecoupled system closely connected with large cities (e.g., Chengdu, the capital of Sichuan Province) in the region, the rest of China, and the world at large (Liu et al. 2015*a*). The flows of goods, information, and people grew rapidly as a result (Wolong Nature Reserve 2008). In the 1980s, poaching of wildlife remained significant, and illegal timber harvesting was a pressing issue (Wolong Nature Reserve 2008). To help curb illegal use of the forest in the reserve, the Wolong Administrative Bureau implemented a series of conservation policies such as a logging ban and restrictions on fuelwood collection (Wolong Nature Reserve 2008). The government also tried to support local households with new income opportunities such as planting seasonal cash crops (e.g., cabbage), raising livestock, transportation, road construction and maintenance, and participating in ecotourism (e.g., selling souvenirs, or finding temporary employment in hotels or restaurants; He et al. 2008).

EARTHQUAKE

On May 12, 2008, the catastrophic Wenchuan earthquake (Ms 8.0, the most devastating in China since the 1950s) struck southwest China (Zhang et al. 2014). Wolong lies in an area that was severely affected by the earthquake (Wang et al. 2008; Fig. 2). It triggered countless landslides and mudflows. The earthquake also resulted in the deaths of 39 local villagers, 5 staff of the Wolong Nature Reserve, and widespread damage to infrastructure, such as roads, tourism facilities, residential houses, schools, and hospitals (Wang et al. 2008). It also destroyed 12% of the total cropland in the reserve (Yang 2013). Before October 2016, the condition of the provincial road (#303) was too poor to reopen to traffic because of repeated damages by frequent floods, landslides, and mudslides after the earthquake, especially during the summer and fall seasons. Along with the extensive socioeconomic damage, the earthquake also resulted in substantial ecological damage, with approximately 5200 ha of forest, or 6.5% of total forest area in the reserve destroyed (Zhang et al. 2011).

Fig. 2. Map of Wolong Nature Reserve, Sichuan, China. Depicted are the location of epicenter of the 2008 Wenchuan earthquake and the distribution of local households before and after the earthquake. Brown portions labeled “habitat loss” represent areas identified in (Ouyang et al. 2008) as forest loss due to the earthquake.



TELECOUPLINGS BEFORE AND AFTER THE EARTHQUAKE

We compared the five major framework components involved in the main telecouplings linking Wolong and the rest of the world before and after the earthquake. The relevant data in this study were from long-term socioeconomic surveys conducted by the Center for Systems Integration and Sustainability at Michigan State University (An et al. 2001, Hull et al. 2011, Chen et al. 2012, Liu et al. 2012, Yang et al. 2013). Specifically, data about labor migration, tourist visitation, and tourism income were collected from semistructured interviews and structured survey questionnaires given to local households, reserve officials, local business representatives, and tourists (see detailed interview and survey methods in Chen et al. 2012, Liu et al. 2012, 2015*a*, 2016*c*). Annual income and related local household economic data (e.g., household average income, annual income from multiple livelihoods, and annual livestock stock and sales) were obtained from censuses conducted by the Wolong Administration Bureau (Wolong Nature Reserve 2008, Liu et al. 2016*b*).

Flows

The main flows between Wolong and urban systems include movement of people, materials, capital, and information, and have been described elsewhere (Liu et al. 2015*a*). We focus on the main telecouplings that were altered by the earthquake and had consequences on households’ income structures, including labor migration, tourism, trade of agricultural products and livestock, and infrastructure investment from the government.

The proportion of households with labor migrants in Wolong gradually increased from 1998 to 2004 and then decreased in 2006 and 2007 due to more earning opportunities associated with road construction for tourism development inside the reserve (Chen et al. 2012). After 2008, more local people went to nearby large cities such as Chengdu to find temporary employment in restaurants or factories. Nearly 50% of interviewed households had members working in cities outside the reserve in 2014 and 2015 (Fig. 3a). Some fluctuation in labor migration was caused by reconstruction projects in Wolong. For example, some local people found job opportunities from reconstruction projects in 2011, which resulted in a decrease in the proportion of labor migration among locals (Fig.3a).

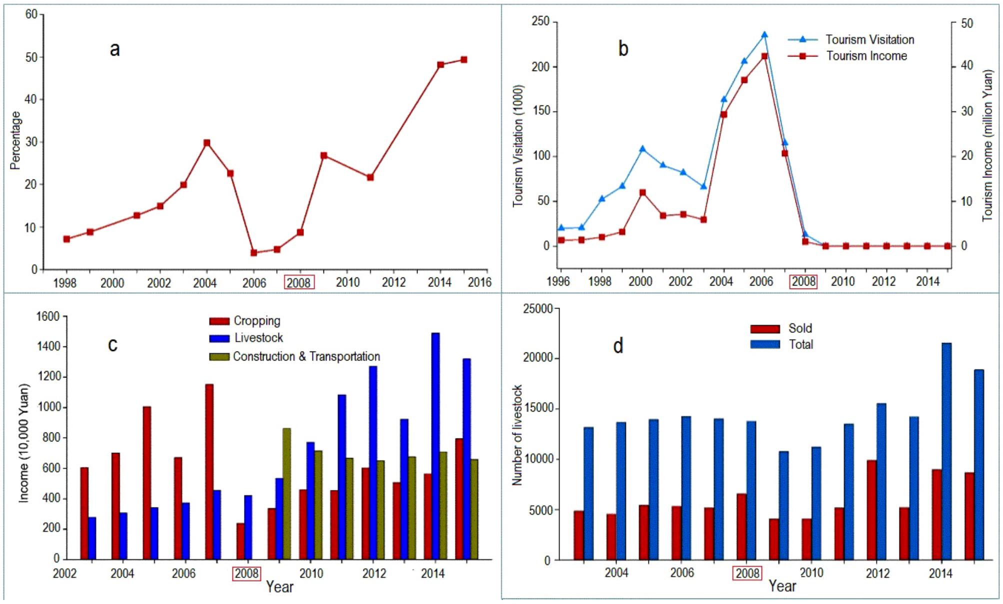
Nature-based tourism involved a significant flow of people before the earthquake, i.e., the number of tourists increased 10-fold from 20,000 in 1996 to almost 200,000 in 2006 (Liu et al. 2012). Local income from tourism also increased during this period (Fig. 3b). These tourists originated from diverse localities (sending systems) across China (over 60% of total surveyed tourists) and other parts of the world (less than 40%; Liu et al. 2015*a*, *b*). The development of tourism in Wolong also attracted many investors to the reserve from the outside (Liu et al. 2016*c*). For example, the largest hotel/restaurant investor before the earthquake was an enterprise based in Shandong Province in eastern China (1700 km away from Wolong), which had invested US$6 million and planned to invest more (~US$48.5 million) to develop scenic spots and advertise ecotourism in Wolong (Wolong Nature Reserve 2008, He et al. 2008). The earthquake and the associated destruction of tourism and transportation facilities led to the collapse of the local tourism industry and eliminated that source of income to local people (Fig. 3b).

Agricultural products (e.g., cash crops such as cabbage), which mainly sell to Chengdu markets, had been a stable and significant income source since the late 1990s in Wolong, but this income source significantly decreased after the earthquake. Specifically, the average share from agricultural products in gross household income was reduced by 25% after the earthquake (2008-2015) compared to before (2003-2007).

Animal husbandry is now the main industry in Wolong (Hull et al. 2014). In 2008, there was an increase in the sales of livestock such as sheep, yaks, and horses, perhaps because of the growing need for cash for postearthquake recovery (Fig. 3c). Because a lot of livestock was sold in 2008, the total number of livestock and the number sold decreased in 2009 (Fig. 3d). However, animal husbandry is less dependent on the seasonally damaged road between Wolong and outside cities because livestock can be maintained for long periods. This made it a safer investment after the earthquake when transportation conditions were poor. The number of livestock in the reserve generally increased from 2010 to 2014, and so did the number sold to areas outside of the reserve (Fig. 3c and 3d). The number of livestock since 2012 has increased to higher levels than pre-earthquake, whereas there was little decrease in 2015 due to normal trade (Fig. 3d).

After the earthquake, infrastructure investment from governments significantly increased. For example, the Hong Kong Special Administrative Region funded almost US$0.5 billion for the reconstruction of roads, schools, hospitals, and conservation facilities in Wolong Nature Reserve (https://www.

Fig. 3. The dynamics of multiple flows between Wolong and the outside cities. (a) The annual percentage of households with labor migrants temporarily working in cities (based on household interview data by researchers in CSIS); (b) annual tourist visitation and income from tourism; (c) annual income from selling agricultural products, livestock trade, and transportation and construction; we conducted an inflation adjustment using 2008 as a baseline; and (d) annual livestock stock and sales in Wolong; we conducted an inflation adjustment using 2008 as a baseline (the data for b, c, and d were from the annual census of the Wolong Administration Bureau).



info.gov.hk/gia/general/201610/28/P2016102800781.htm). As a result of this growing capital flow, local households' income from construction and transportation significantly increased after 2009 (Fig. 3c).

Agents

The earthquake profoundly affected the type, number, and function of agents involved in telecoupling linking Wolong with the rest of the world. Local residents were major agents both before and after the earthquake. Changes in their activities, income, demography, and attitude toward environmental protection can directly or indirectly influence local couplings and telecouplings (Liu et al. 2003*b*, 2013). After the earthquake, more households were involved in labor migration, and local people raised more livestock (Fig. 3a and 3d), whereas the production of cash crops decreased. Tourists and investors were two groups of important agents that almost entirely disappeared after the earthquake because of the aforementioned damages to the road and tourism infrastructures (Wolong Administration Bureau, *personal communication*).

After the earthquake, many Chinese governmental agencies at all levels, from the national to local, were actively involved in the postdisaster reconstruction in Wolong. These efforts included the relocation of households from steep areas to flat areas (Fig. 2), restoration of public utilities (e.g., schools and hospitals, hydropower stations, public telecommunication systems), and ecosystem restoration (e.g., the restoration of giant panda habitat project). These projects were largely completed by May 2011 (http://www.chinanews.com/df/2011/05-09/3026718.shtml). Meanwhile, to facilitate socioeconomic recovery, the Wolong Administration Bureau offered cash incentives to encourage livestock production. The government was also actively involved in planning the reconstruction of the tourism industry (Sichuan Province Academy of Forestry Science and Research 2014).

Causes

Causes of the telecouplings between Wolong and the rest of the world (e.g., cities) are interconnected and can be generally categorized into economic, political, cultural, and ecological domains (Liu et al. 2015*a*). Regarding economic causes, the local people's eagerness for economic development has been an important cause behind almost all telecouplings. The sale of agricultural products, tourism, and labor migration all have the potential to enhance local households' income and thus attract many local households to get involved. Investments from outside investors seeking profitable business also promoted the development of the tourism enterprise in Wolong before the earthquake. Support from governments are also important determinants shaping some telecouplings and can be described as political causes. For example, as a flagship protected area for giant pandas, Wolong has a special political position (e.g., many domestic and foreign political leaders travel to Wolong to see giant pandas) and gets strong support from the central government. Concerning cultural causes, intensive media coverage and scientific research helped Wolong attract broad national and international attention. This made Wolong a popular tourism destination and also helped it gain more governmental support. Wolong's ecological features, such as mountainous scenery, cool summer weather, and rich wildlife including giant pandas, were also causes for attracting researchers and tourists to the reserve.

The widespread infrastructure damage caused by the earthquake and continuing poor condition of the main road to Wolong significantly changed telecouplings and the associated causes. Tourism was stagnant after the earthquake. It was difficult to get cabbage, the main cash crop, to sale because of the damaged road. On the other hand, the financial support from governments and donations from the general public in many other regions of the world facilitated the postdisaster reconstruction and generated many job opportunities for local households. However, in the reconstruction process, about 24% of the cropland was appropriated for the construction of residences and the new Giant Panda Protection and Research Center of China (Yang 2013). This has also been an important reason for Wolong's reduced crop production. The shrinking income from cash cropping and tourism due to the earthquake may have prompted local households to pursue other livelihoods such as raising more livestock and labor migration. Meanwhile, the local government, seeking to spur economic recovery, offered incentives to encourage livestock production. This interacted with the loss in other income opportunities to cause faster increases in livestock production after the earthquake.

Effects

The effects of natural disasters on protected areas through the altering telecouplings are complex. We mainly focus on significant effects on socioeconomic and ecological conditions within the reserve.

The aforementioned changes of main flows, agents, and causes resulted in a series of socioeconomic effects, many of which can be seen in the dynamics of household income. Increasing connections with cities contributed significantly to local economic growth before the earthquake. The gross household income increased from 0.9 million RMB (US$0.5 million) in 1983 to 26.1 million RMB (US$3.4 million) in 2007 (Wolong Nature Reserve 2008). The income structure also indicates the reserve experienced a significant transformation from subsistence-based agricultural economy to a more diversified pre-earthquake economy because of telecouplings, e.g., increase of tourism visitation and trade of cash crops (He et al. 2008, Liu et al. 2012).

Because of the immediate damage from the earthquake, the mean local residents' gross household income decreased to 13.16 million RMB in 2008. This was mainly due to the disrupted crop production and collapsed tourism industry (Figs. 4, 5). Before the earthquake, the main source of income was the sale of agricultural products, and the average proportion of income from agricultural products was significantly less after the earthquake (13%, from 2008 to 2015) compared to before the earthquake (38%, from 2003 to 2007; Fig. 3c). Before the earthquake, tourism attracted the participation of a growing number of local farmers. Among the 217 randomly surveyed households in 2007, approximately 76.5% received income either directly or indirectly from tourism (Liu et al. 2012). This income source was no longer available after 2008 because of the earthquake (Fig. 3b).

Growing income from postdisaster reconstruction jobs, labor migration, and livestock sales (Fig. 4) has helped the gross household incomes of Wolong recover since 2009. For instance, because of the reconstruction of the infrastructure, the average share of income from construction and transportation increased by 9% after the earthquake (2008-2015) compared to before (2003-2007). Moreover, reconstruction of infrastructure also has the potential to enhance the resilience of Wolong to possible future disasters because government-built infrastructures are better able to handle earthquakes. The average proportion of income from livestock production increased by 9% after the earthquake. The average proportion of income from labor migration also increased and was 17% higher after the earthquake (2008-2015) compared to before (1998-2007).

Fig. 4. Average household income change in Wolong from 2003 to 2015 (based on data from the Wolong Administration Bureau); we conducted an inflation adjustment using 2008 as a baseline.

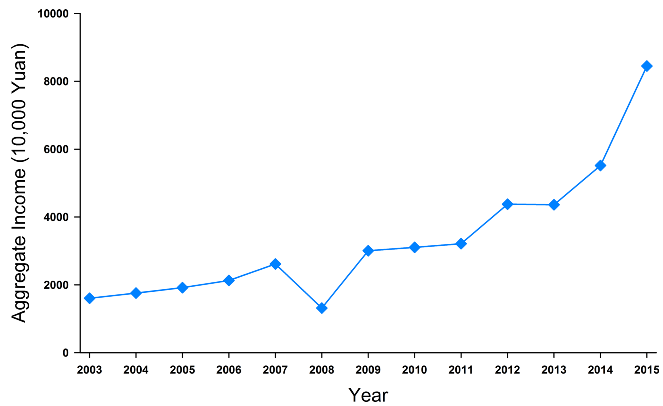
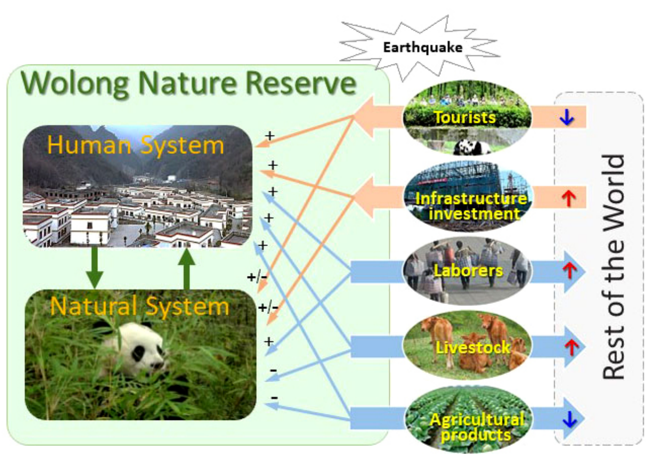


Fig. 5. Changes in telecouplings between Wolong and the outside world due to the 2008 Wenchuan earthquake, and potential effects on the local human and natural systems in Wolong. "+" and "-" indicate positive and negative effects on human or natural systems, respectively. Detailed variation of flows is shown in Figure 3. Upward facing arrows indicate increasing flows, and downward facing arrows indicate decreasing flows.



Although previous studies have shown that the direct impact of the earthquake on giant pandas was negligible (Zhang et al. 2011), the indirect ecological effects on the Wolong through the altered telecouplings are significant (Fig. 5). On the one hand, postdisaster rehabilitation projects facilitated ecological restoration directly and indirectly. For example, vegetation restoration from 2010 to 2011 was helpful for wild giant panda conservation (Zhang et al. 2014). Furthermore, through reconstruction, most local residences were relocated from areas near natural forests to flat areas along the river and main road (Fig. 2). This relocation may reduce human disturbances (e.g., fuelwood collection) on panda habitats (He et al. 2009, Viña et al. 2011). The increase in labor migration may have similar positive ecological effects. A previous study in Wolong indicated that labor migration could reduce the disturbance on panda habitats from local people's activities (e.g., fuelwood collection) because fewer laborers remain in Wolong (Chen et al. 2012).

On the other hand, there are negative ecological effects associated with the changes in telecouplings after the earthquake (Fig. 5). For example, as an alternative income source, local households raised more livestock after the earthquake (Fig. 3d). But pastureland in Wolong is quite limited. Many livestock have begun to graze in the forest, and research has shown that livestock severely degrade bamboo resources and panda habitat (Hull et al. 2014, Zhang et al. 2017). This is because giant pandas and other threatened wildlife practice direct avoidance strategies. Because livestock occupied the study area's only permanent water source, the competition for water during winter was stressful for pandas (Zhang et al. 2017). The ecological effects of certain telecouplings' variation may be dual (Fig. 5). For example, nature-based tourism has the potential to aid in forest recovery, whereas increasing road traffic from tourism may result in the further segregation of panda populations on both sides of the road (Fig. 5; Liu et al. 2012, 2016*c*). The stagnancy or success of tourism industries thus entail complex ecological effects on protected areas.

CONCLUSIONS

Through evaluating the dynamics of flows, agents, and causes of telecouplings triggered by a devastating natural disaster, we demonstrated a comprehensive approach to assessing the complex socioeconomic and ecological effects of natural disasters on protected areas. Our study found that the dynamic interactions among telecouplings caused by the earthquake significantly affected human welfare and biodiversity conservation. As a carrier of several main telecouplings (e.g., tourism, trade in agricultural products), the road linking the protected area and the outside world plays a vital role in the dynamics of telecouplings and their interactions. As of October 2016, the road (including many tunnels that can minimize landslide impacts on the road) between Wolong and Chengdu, the nearest large city, has been restored. The interactions between Wolong and the outside world will again be changed, with altered flows, under this new situation. Further studies on the new dynamics of telecouplings and their interactions are needed in the future.

After devastating natural disasters (e.g., earthquake and volcano eruptions), not only the restoration of human well-being, but also biodiversity conservation, must be considered, otherwise, unexpected ecological damage can occur. In our study, the government encouraged livestock grazing with a cash incentive policy when previous main livelihoods (e.g., nature-based tourism and agricultural production) were blocked by the damaged road. Our results show that although the earthquake did not seriously affect giant panda habitat, livestock expansion has seriously degraded giant panda habitat (Hull et al. 2014, Zhang et al. 2017). We suggest that the local administration implements policy to control the number and activity range of livestock in the reserve, and ban livestock (e.g., yaks and sheep) from giant panda core habitat. Because of the recovered road, tourism has also begun to recover and develop (https://www.info.gov.hk/gia/general/201610/28/P2016102800781.htm). Developing nature-based tourism should be one of the promising alternatives to offset the negative impact of a livestock ban on local livelihoods and help to achieve a win-win situation between human welfare and biodiversity conservation in Wolong (Liu et al. 2016*b*, *c*).

Our study showed that the telecoupling framework provides an effective tool that allows systematic analysis of the interactions of not only local CHANS (Wolong Nature Reserve), but also their relationship with the outside world (Liu et al. 2013, 2015*b* Liu 2014) through multiple telecouplings. In our case, we focused on Wolong itself, which acted as a receiving system for tourism and infrastructure investment, and acted as a sending system for the trade of agricultural products and livestock and labor migration. Accurately monitoring dynamic characteristics of interactions between protected areas and other systems is critical for implementing effective conservation and development policies. The telecoupling framework is effective in this endeavor by helping detect key changes in flows, agents, and causes of telecouplings due to natural disasters, and evaluating socioeconomic and environmental effects. This knowledge can help policymakers propose effective solutions to maximize human well-being and biodiversity in protected areas worldwide. For instance, Hurricane Katrina hit the Gulf Coast of the United States in 2005 and altered relevant telecouplings in destroyed areas. The damage from Katrina resulted in the closure of National Wildlife Refuges and the loss of breeding places for some migratory species such as redhead ducks (Sheikh 2006; https://www.fws.gov/news/ShowNews.cfm?ref=us-fish-and-wildlife-service-conducting-initial-damage-assessments-to-wildl&_ID=3645). Analyzing the effects of the hurricane on species migrations by altering telecouplings (e.g., changed receiving or spillover systems) may lead to better conservation strategies (Liu et al. 2016*b*, Hulina et al. 2017).

As an emerging framework, the challenges of applying the telecoupling framework to study dynamics of systems after natural disasters still exist. For example, in our study, because of the limitation of the data, we do not extensively quantify interactions of multiple telecouplings before and after the earthquake. Moreover, our study mainly focused on local protected areas and did not consider effects of telecouplings on other systems (e.g., cities) because of the lack of relevant data. This should be complemented with future studies that focus on the other systems, e.g., cities as receiving systems for agricultural products and rural labor migration, potential spillover systems like other tourist destinations. To facilitate further theoretical development and feasible applications of the telecoupling framework, we suggest pursuing more empirical studies that quantify interactions and break down a large research system into multiple parts under the framework (Liu 2017). For example, in one study, researchers could focus on a single system (sending, receiving, or spillover) or even a single component (e.g., flows) of a telecoupled system and study other systems or other components later or leave that to other researchers. Findings from these multiple studies under the same telecoupling framework could then be integrated to comprehensively understand the telecoupled systems and provide more effective recommendations for sustainability research and management.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/10238

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