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Research

Multiple telecouplings and their complex interrelationships

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ABSTRACT. Increasingly, the world is becoming socioeconomically and environmentally connected, but many studies have focused on human-environment interactions within a particular area. Although some studies have considered the impacts of external factors, there is little research on multiple reciprocal socioeconomic and environmental interactions between a focal area and other areas. Here we address this important knowledge gap by applying the new integrated framework of telecouplings (socioeconomic and environmental interactions between two or more areas over distances). Results show that even a protected area - i.e., the Wolong Nature Reserve for giant pandas in southwest China - has multiple telecoupling processes with the rest of the world; these include panda loans, tourism, information dissemination, conservation subsidies, and trade of agricultural and industrial products. The telecoupling processes exhibit nonlinear patterns, they change over time, and they have varying socioeconomic and environmental effects across the world. We also find complex relationships among different telecouplings - e.g., amplification, offsetting, spatial overlaps - which cannot be detected by traditional separate studies. Such an integrated study leads to a more comprehensive understanding of distant human-environment interactions and has significant implications for global sustainability and human well-being.

Key Words: *China; conservation; cross-scale interactions; environmental interactions; giant panda (Ailuropoda melanoleuca)*; human-environment interactions; information dissemination; nature reserve; socioeconomic interactions; telecoupling; telecoupling framework; Wolong Nature Reserve

INTRODUCTION

Human-environment interactions are key factors shaping global sustainability and human well-being. They have been widely studied within a particular area, but the world has become increasingly connected over distances, both socioeconomically and environmentally. These connections have often been separately studied. For example, studies on climate teleconnections concentrate on linkages between climate systems that are hundreds and even thousands of kilometers apart (Avissar and Werth 2005) but largely ignore relevant socioeconomic linkages. On the other hand, studies on economic globalization (e.g., Levitt 1983) focus on distant socioeconomic relationships. They pay little attention to environmental interactions, although there have been some separate recent studies on greenhouse gas emissions associated with trade (Peters et al. 2011).

Many studies have reported the effects of globalization and distant drivers on socioeconomic and environmental changes from local to global scales (e.g., Young et al. 2006, O'Brien et al. 2009, DeFries et al. 2010, Lambin and Meyfroidt 2011, Meyfroidt et al. 2013, Stevens et al. 2014). For instance, Adger et al. (2009) argued that the vulnerability of one region may be aggravated by adaptation to economic change and vulnerability in other regions, citing vulnerability introduced by the severe acute respiratory syndrome (SARS) and vulnerability of coffee farmers to markets at distant localities. Walker et al. (2009) illustrated the intertwined social-ecological systems and feedbacks at global scales and advocated for institutional changes to overcome the increasing unwanted outcomes from such global social-ecological interactions. Folke et al. (2011) discussed how increasing global connections (e.g., integrated markets) requires reconnecting human development to the biosphere and a restructuring of institutions to address global challenges (e.g., shocks, feedbacks with a climate dimension due to land-use changes). Österblom and Folke (2015) demonstrated that the Soviet Union dramatically increased fishing in several distant water fisheries, which had profound ecological and socioeconomic effects on large marine ecosystems across the planet, such as regime shifts and responses from other nations including the establishment of fishing zones in coastal waters. While previous studies have made important scientific advances, more comprehensive research is needed to integrate various aspects of these and other distant cross-scale interactions for systematic assessment of drivers, patterns, processes, simultaneous socioeconomic and environmental interactions, feedbacks among different places, impacts beyond the focal systems, relationships among various distant linkages, and implications for governance and policy across the globe.

To address these crucial issues, a new framework of telecoupling (socioeconomic and environmental interactions over distances) has been proposed, to facilitate integrated research and governance (Liu et al. 2013*a*). The framework treats each place as a coupled human and natural system, in which humans and natural components interact not only locally but also across temporal and spatial scales (Liu et al. 2007, Alberti et al. 2011). It provides an explicit approach to account for and internalize socioeconomic and environmental externalities across space. The framework consists of five major interrelated components: coupled human and natural systems; flows of material, information, and energy among systems; agents that facilitate the flows; causes that drive the flows; and effects that result from the flows (Liu et al. 2013*a*). Depending on the direction of flows, systems can be classified as three different types. These include

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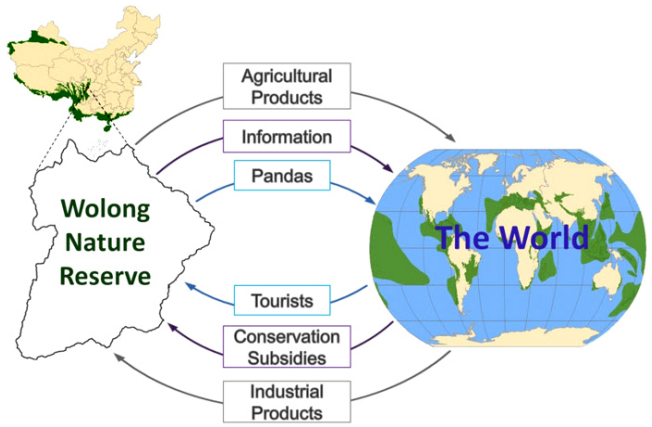
sending systems (e.g., exporting countries), receiving systems (e.g., importing countries), and spillover systems (e.g., countries other than the trade partners). Spillover systems are those that affect and are affected by the interactions between sending and receiving systems. The emergence of a telecoupling can be driven by sending, receiving, or spillover systems. The framework does not predetermine that sending systems are active while other systems are passive. Which factors in which systems trigger or dominate the telecoupling depend on specific circumstances. Also, the same system can be classified as one type of system for one telecoupling and another type of system for another telecoupling. For instance, a city can be a receiving system for food from rural areas and be a sending system for industrial products to rural areas. A telecoupled human and natural system is a network of sending, receiving, and spillover systems over distances. Within each coupled system, there are internal or local couplings. The framework also explicitly considers feedbacks (e.g., human–nature feedbacks within a coupled system and across telecoupled systems).

There has been increasing interest in the telecoupling framework. For example, the framework has been conceptually applied to land change science (Eakin et al. 2014, Liu et al. 2014); species invasion (Liu et al. 2014); payments for ecosystem services programs (Liu and Yang 2013); conservation (Carter et al. 2014, Gasparri et al. 2015); and the trade of food (Garrett et al. 2013), forest products (Liu 2014), energy (Liu et al. 2015*a*), and virtual water (Liu et al. 2015*a*). However, there is little quantification of the telecoupling framework. Furthermore, previous studies focused on one or two telecoupling processes with little consideration to the interrelationships between telecoupling processes.

To demonstrate multiple telecouplings and their complex interrelationships, we apply the telecoupling framework to examine multiple telecouplings between a protected area—i.e., the Wolong Nature Reserve (hereafter 'Wolong')—and the rest of the world. Wolong is a 2000- km^2 protected area located within a global biodiversity hotspot (Liu et al. 2003a, Myers et al. 2000) in southwestern China (Wolong Nature Reserve Administration Bureau 1998) (Fig. 1). It is home to the endangered giant panda (*Ailuropoda melanoleuca*) and more than 6000 other animal and plant species. Wolong also encompasses approximately 5000 local residents (mostly farmers) (State Forestry Administration 2006) who grow crops, raise livestock, and collect timber and nontimber forest products (Li et al. 1992). It is a long-term study site for coupled human and natural systems research (e.g., Liu et al. 1999, An et al. 2006, Linderman et al. 2006, Viña et al. 2008, Chen et al. 2009*b*, Chen et al. 2010, Tuanmu et al. 2011, Yang et al. 2015) and many results and methods from the study site have been applied at regional, national, and international levels (e.g., Liu et al. 2003a, Xu et al. 2006, Yu and Liu 2007, Bawa et al. 2010, Liu and Raven 2010, Viña et al. 2010, An et al. 2014, Bradbury et al. 2014). Here we analyze major components of several telecoupling processes: panda loans, tourism, information dissemination, conservation subsidies, and trade of agricultural and industrial products (Fig. 1), and discuss their interrelationships. We chose these example processes due to their prominence in Wolong and also their data availability, but stress that there are also other telecouplings (e.g., labor migration from Wolong to cities, Chen et al. 2012) which may also interact with these analyzed here.

Fig. 1. Illustration of telecoupling processes between Wolong Nature Reserve in southwest China and the rest of the world. Green areas represent global biodiversity hotspots (Conservation International 2011).



METHODS

Data collection

To achieve our research goal, we integrated the data that we collected and compiled from socioeconomic surveys, censuses, and other data sources (see below).

Panda loans

Wolong is a stronghold for the wild giant panda population. It is also home to the China Conservation and Research Center for the Giant Panda, a research and captive breeding base that houses over 200 pandas, the largest captive population in the world. The panda loan program enables zoos inside and outside China to borrow pandas from the captive breeding center over extended periods of time (from one to several years), which generally involves the payment of a fee. Data on panda loans were obtained from the giant panda registry managed by the China Conservation and Research Center for the Giant Panda (2015).

Tourism

Tourism is one of largest industries in the world (World Travel and Tourism Council 2014). It is an attractive industry for economic reasons. Foreign currency is generated with each international tourist visit. Tourism is an export, with payments flowing into a community, similar to the payments flowing in for locally manufactured or grown goods. With nearly 266 million direct jobs, tourism and its related economic activities produce 9.5% of the gross world domestic product with almost 1 billion international travelers in 2013 (World Travel and Tourism Council 2014). Nature-based tourism, which focuses on observing and appreciating nature, has been the fastest growing sector of tourism since the 1980s (Newsome et al. 2002). To meet the increasing demands for nature-based tourism, many nature reserves around the world have hosted tourists. For example, by the late 1990s approximately 80% of nature reserves in China had developed ecotourism (a type of nature-based tourism). Almost 16% of the nature reserves each hosted more than 100,000 tourists annually (Chinese National Committee for Man and the Biosphere 1998,

Li and Han 2001). Like many other nature reserves, Wolong has attracted a large number of tourists since the early 1980s (Liu 2012).

During the summers of 2006 and 2007 we daily surveyed tourists visiting captive pandas held at the China Conservation and Research Center for the Giant Panda inside of Wolong from gate opening (09:00) to closing (18:00). Every 15 min we invited a tourist that was willing, if at least one was available at the time, to complete a short questionnaire. The questionnaire covered topics related to the origin, socioeconomic profile, and visit plan of the tourist. The combined response rate for both years was >60% and a total of 1063 people completed the interview. Maps that illustrate the countries of origin for international tourists and provinces of origin for domestic tourists were created using ESRI™ ArcMap, where centroids of countries and provinces were used to symbolize the number of tourists from the respective areas. Furthermore, we calculated the geographical distances between the China Conservation and Research Center for the Giant Panda and the centroids of these countries and provinces based on longitude–latitude coordinates and the WGS84 datum reference system. We also obtained historical data on the number of tourists to Wolong since 1980 from local government records (Wolong Nature Reserve 2005, 2010).

To estimate the impacts of tourists on vegetation, field sampling was conducted along four main hiking trails in Wolong between June and August of 2007. Sites (n=64) were sampled at regular intervals of 200 to 300 m. At each site two sets of quadrats (10x10 m) were established: one on the trail and the other 10 m away from the trail (control). All woody plant individuals with heights ≥1 m were counted and the species were recorded. In each quadrat we also established a 1x1 m subquadrat, in which all plant species with heights lower than 1 m were identified and coverage was estimated as the herbaceous vegetation layer.

Information flows

Wolong has become increasingly known both nationally and internationally through the news media and publication of books and articles, as well as through visitors. Of course, information is also constantly entering Wolong from the outside, but here, because of data constraints, we focus only on the information emanating out from the system.

We examined the frequency of the phrase "Wolong Nature Reserve" in English books published since 1980 based on the n-gram corpus data set provided by Google™ Books (Brants and Franz 2006). We also performed a search for "Wolong Nature Reserve" in all international news articles published in the English language since 1980 using the LexisNexis® Academic search engine.

Conservation subsidies

Wolong has received substantial external financial support from the Chinese government and the international community since its establishment as a nature reserve in 1963. Wolong is a national-level nature reserve and overseen by both the central government's State Forestry Administration in Beijing and the Forestry Department of Sichuan Province in Chengdu. Therefore, financial support from the governments is supplied regularly. For instance, a major road construction project was initiated in 1992 financed by a ¥35 million investment (US$1 = ¥6.34 as of May 2012) from the central government (Liu 2012). The goal of this project was to link Wolong to neighboring rural communities and outside markets. International organizations such as the World Wildlife Fund (WWF) have also invested in Wolong since the 1980s. Since the earthquake, the Hong Kong special administrative region government has committed a total amount of HK$1.58 billion (US$204 million as of May 2012) investment for earthquake reconstruction efforts in Wolong (Commissioner's Office of China's Foreign Ministry in the Hong Kong Special Administrative Region 2014).

Conservation subsidies have also been provided to local residents in Wolong to compensate them for participation in conservation efforts. These include the Grain-to-Green Program (since 2000) and the Natural Forest Conservation Program (since 2001, Liu et al. 2008). The Grain-to-Green Program provides subsidies to farmers to convert their cropland on steep slopes to forests. In Wolong, the Natural Forest Conservation Program offers subsidies for local households to monitor the forests to prevent illegal harvesting. Here we focus on the subsidies from the Natural Forest Conservation Program and the Grain-to-Green Program, which have long-term complete data. We obtained data on conservation subsidies from government records on investment in the Natural Forest Conservation Program and the Grain-to-Green Program (Wolong Nature Reserve 2005, 2010) .

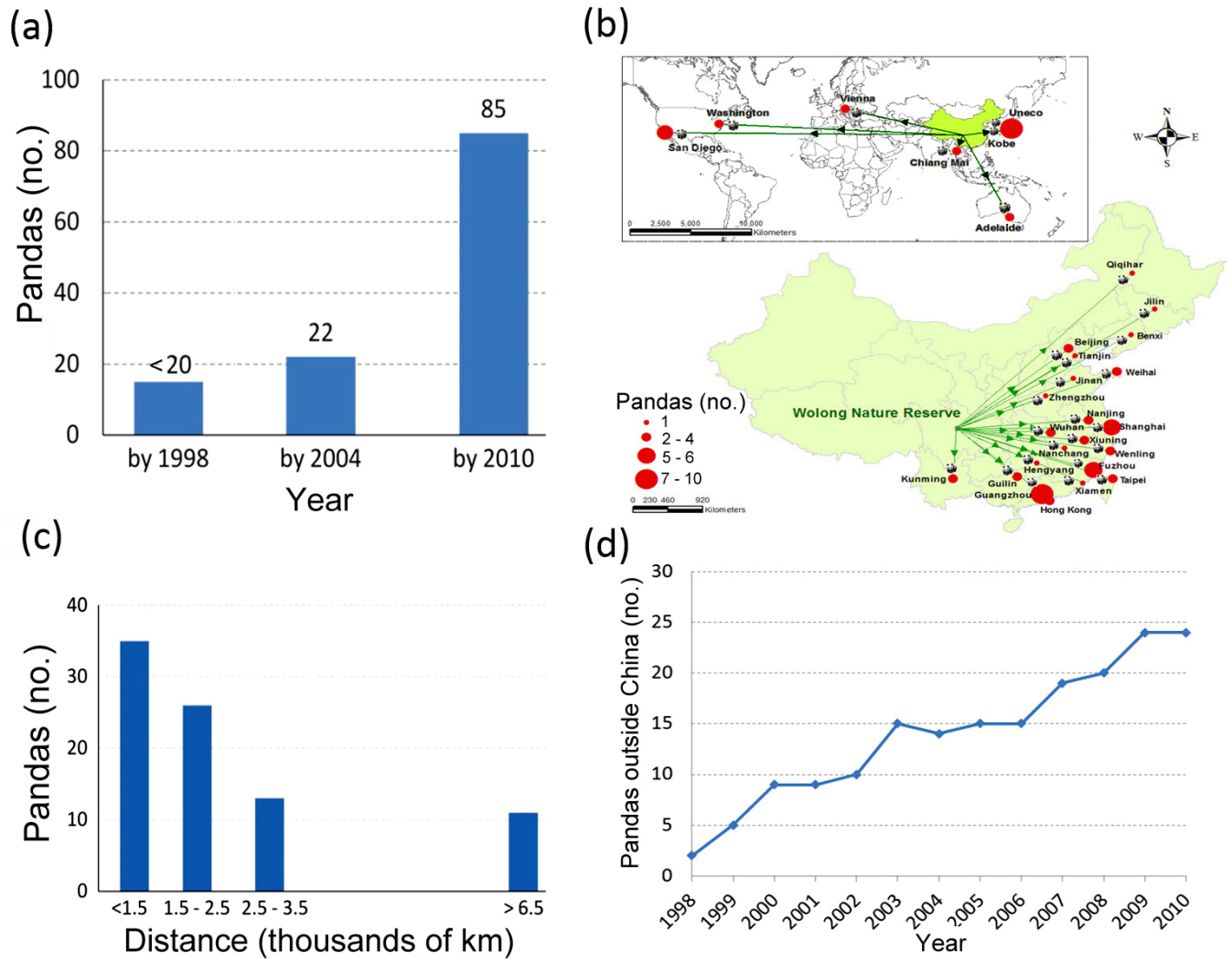
Trade of agricultural and industrial products

Agriculture has been the central livelihood strategy in Wolong for centuries (Ghimire 1997). Households grow subsistence crops for direct household consumption and cash crops to sell to outside markets. Some of the main cash crops include cabbage, carrots, corn, and potatoes. Wolong residents also engage in livestock production, including rearing of yak, goats, sheep, cattle, pigs, and horses, for both subsistence and selling of meat to outside markets.

Increased agricultural production for trade has resulted in an increased demand for industrial products manufactured outside Wolong. For example, in recent years, local people have invested more in agricultural inputs to improve crop production. This investment includes chemical fertilizers (e.g., carbamide, phosphate, potash) (Wolong Administration Bureau 2008). Locals also have used plastic film as a covering for their crops to help maintain soil temperature, increase soil moisture retention, and decrease weeds.

Data on trade were obtained from the yearly socioeconomic census for Wolong between 1998 and 2007 (including variables related to plastic film and fertilizers purchased) and from household surveys. We conducted household surveys on residents of Wolong in the years 1999, 2002 to 2007, 2009, and 2010 (Liu et al. 2013*b*). The survey sample was largely based on a sample drawn in 1999, which selected 220 of the 1056 households in Wolong using a stratified random sampling procedure. A comprehensive list of households was obtained from the local household (Hukou) registration and the agricultural census in 1996. Given that these households were distributed in six administrative villages, we use these villages as strata and selected a random sample from each of them. The size of each sample was proportional to the total number of households in the respective village. In the years after 1999, we attempted to collect information from the original sample of 220 households and randomly selected additional households as replacements if certain households were not available. The overall response rates

Fig. 2. (a) Temporal changes in the number of giant pandas transferred from Wolong to other areas of China, on loan. (b) Spatial distributions of pandas loaned to zoos outside Wolong (in China and in other countries). (c) Distances between Wolong and zoos hosting pandas from Wolong. (d) Temporal changes in the number of giant pandas transferred from Wolong to outside of China, on loan.



were high (>90%). The household survey aimed to cover topics regarding the demographic, socioeconomic, agricultural, energy-use, and policy-related characteristics at the household level. In this study, we derived detailed multiyear variables that may indicate the connections between local households and the outside world. These included percentages of households with incomes from selling the main cash crop (cabbage) and livestock such as goats, cattle, yaks, and horses; and percentages of households purchasing fertilizers from markets outside Wolong.

Data analysis and visualization

We conducted correlation analysis of the relationship between panda loan destinations and origins of tourists across China, using the software program R (R Development Core Team 2005).

We used geographic information systems and statistical programs to make the maps and draw the figures. For example, we created maps depicting all zoos that have ever received captive pandas on loan from the China Conservation and Research Center for the Giant Panda in Wolong. Maps were created using ESRI™ ArcMap and these show both the locations of the hosting zoos and the number of giant pandas they have hosted.

RESULTS

In this section, we first present results related to the six types of telecoupling processes under the telecoupling framework. We then highlight their interrelationships.

Panda loans

The total number of panda loans from Wolong to other places in China and other countries increased from fewer than 20 in 1998 to 85 in 2010. There was a total of 63 new panda loans between 2004 and 2010 (Figure 2a).

Telecoupled systems: In this case, the sending system for pandas is Wolong. The receiving systems are zoos inside and outside

China, such as the Beijing Zoo, the San Diego Zoo, the National Zoo in Washington D.C., and zoos in Europe (e.g., London) and in Asia (e.g., Kobe). A total of 22 cities in mainland China, Hong Kong, and Taiwan received at least one panda from Wolong, with Guangzhou hosting the largest number (i.e., 10) (Fig. 2b). Furthermore, Wolong's pandas also were sent to seven cities in five other countries (Japan, Australia, USA, Thailand, and Austria). A total of 12 went to Japan and seven to the United States in 2010 (Fig. 2b). The spillover systems are many, including areas from which people travel to see the pandas in those receiving systems. Spillover systems also include areas that provide funding for the loans, grow bamboo to feed the pandas, and are affected by other activities related to panda loans.

Agents: The agents include people and organizations that make panda loans possible. On the sending side, agents include the China Society for Wildlife Conservation and the State Forestry Administration, both of which develop policies and agreements. Another agent is the Wolong Nature Reserve Administration Bureau, which implements the policies (e.g., selects which pandas for loans). On the receiving side, agents include people and organizations that lobby and find resources for panda loans. Zoos often seek corporate sponsors to help fund the loans (McMahon 2010). There may also be agents from the spillover systems outside of Wolong and the receiving zoos that help negotiate panda loans. Negotiations often involve individuals with high-level positions in country governments, some of whom have personal vested interests in obtaining pandas. For example, the Prime Minister in the U.K. visited China, while China's Vice Premier traveled to the U.K. as part of the negotiations on the panda loans to the Edinburgh Zoo (Stratton and Branigan 2011).

Flows: The flows include the movement of pandas and people involved in the panda loans. The number of panda loans to other countries increased from two in 1998 to 24 in 2010 (Fig. 2d). As distances increase, the numbers of pandas decrease (Fig. 2c). This trend is nonlinear, however. There were no pandas in places between 3,500 and 6,500 km from Wolong, but beyond 6500 km the numbers of pandas increased (Fig. 2c). Regarding flows of people, panda experts from Wolong provide training to the staff in the receiving systems. The information flows include exchanges of the agreements and, in many cases, money transactions (fees amount to US$1 million/panda/yr).

Causes: The causes behind panda loans include a variety of factors. The receiving systems have strong interests in pandas due to a long history of cultural affinity and fascination with the charismatic panda worldwide (Ellis et al. 2006, Schaller 1994). Interest in scientific research has also grown in the last several decades due to many unique aspects of the panda's biology. Examples include the panda's adaptation to bamboo, narrow reproductive estrus window, and scent communication (Swaisgood et al. 2009). As threats to the panda's wild population increase, the impetus also increases to establish a sustainable population of captive pandas. These pandas could theoretically be used for population rescue via reintroduction (Wildt et al. 2006). A technological cause is rooted in recent improvements in captive breeding and infant care that have allowed for a tripling of the captive panda population from 1970 to 2000 (Zhang et al. 2006). Such success has allowed for more individuals to be available for loans. There are also economic causes in both sending and receiving systems, as zoos can substantially increase their visitation rates, which translates into gains of millions of dollars. The sending system can also be spurred to participate due to expected economic benefits through the loan deals (Buckingham et al. 2013). In addition, there is political will for panda loans by relevant leaders (Buckingham et al. 2013).

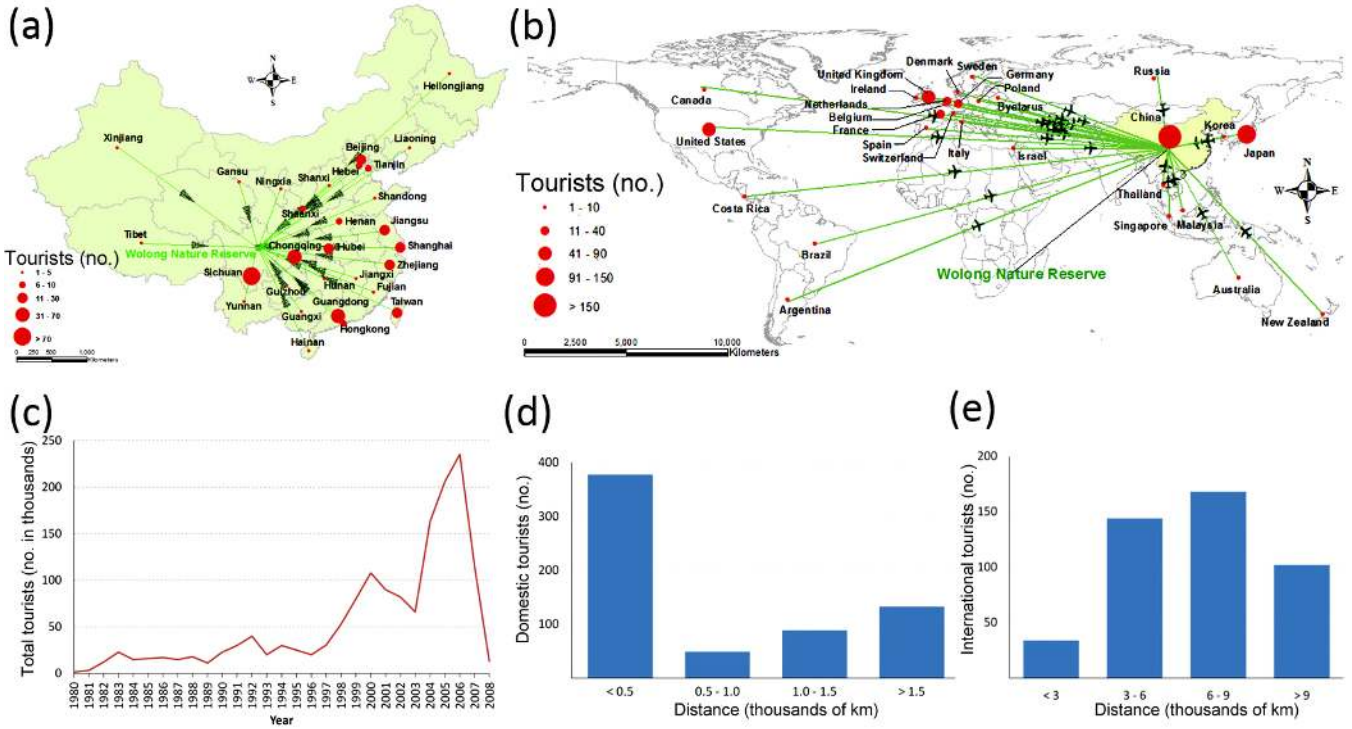
Effects: There are both socioeconomic and environmental effects in the sending, receiving, and spillover systems. The socioeconomic effects include publicity about sending and receiving systems and economic benefits from panda loans. Costs of keeping pandas in zoos are considerable, as the construction of new facilities alone can cost over US$10 million (Buckingham et al. 2013), in addition to operational costs. For the spillover systems, those visiting pandas in the receiving systems pay for entrance fees and travel costs. Visitors to the National Zoo in Washington D.C. to see pandas come from not only the United States, but also many other countries (Smithsonian Conservation Biology Institute 2012). In addition, new panda loans improve social networks for scientific collaboration across countries via participation in international networks such as the Conservation Breeding Specialist Group (Wildt et al. 2006).

The environmental effects include awareness of the importance of panda conservation (Schaller 1994, Ellis et al. 2006) by residents in the sending, receiving, and spillover systems. A lesser-known environmental impact on the receiving system is the large amount of bamboo required to sustain captive pandas (up to 32 kg/day/panda). Zoos often establish bamboo plantations to meet this large and specialized food requirement. Edinburgh Zoo imported bamboo from Holland (a spillover system) at over US$100,000/yr (Brown 2011, Buckingham et al. 2013). Other zoos seek to collaborate with local citizens to grow bamboo on their properties (Buckingham et al. 2013).

Another environmental effect is the CO_2 emissions associated with transporting pandas from the sending systems to the receiving systems, as well as travel of tourists to see the pandas in the receiving systems. For example, a Boeing 777 jet flight emits roughly 29 kg of CO_2/km (Clayton 2014). Given the 8000-km distance between Chengdu and Edinburgh, Scotland (a recent receiving system), transporting a pair of pandas in a Boeing 777 could emit 232,000 kg of CO_2 one way. However, Edinburgh did not have enough bamboo to support the pandas for the trip. Therefore they financed a U.S.-operated plane originating in Memphis, Tennessee to fully load up with bamboo and then travel to Chengdu to pick up the pandas prior to the Edinburgh leg (BBC News Magazine 2011) (i.e., an additional 12,550 km of travel and over 360,000 kg of CO_2). The amount of CO_2 emissions associated with tourists may vary depending on the distance and mode of traveling. But tourist-related emissions would be less per capita than emissions associated with a panda because several hundred tourists can travel on one plane, while one or two pandas take up an entire plane on their own. For example, a passenger traveling in economy class from Detroit, U.S.A. to Beijing, China and then Chengdu, China (closest airport to Wolong) would generate roughly 1705 kg of CO_2 (International Civil Aviation Organization 2014).

Feedbacks from panda loans are many. For example, the first pair of pandas sent to The National Zoo in Washington D.C. garnered such widespread appeal that a second pair of pandas was later

Fig. 3. (a) Spatial distribution of sampled tourists to Wolong from other parts of China (2006–2007). (b) Spatial distribution of sampled tourists traveling to Wolong from other countries (2006–2007). (c) Changes in the total numbers of tourists to Wolong over time. (d) Number of sampled Chinese domestic tourists at different distances between their origins and Wolong (2006–2007). (e) Number of sampled international tourists at different distances between their origins and Wolong (2006–2007).



sent after the first died. Some of the revenues from panda loans have been targeted for panda conservation in the sending system and in spillover systems in other parts of panda habitat. Receiving systems have also undertaken capacity-building endeavors in Wolong, sending experts to both train and learn from Wolong's scientists. On the environmental side, the continued interests in panda loans have raised concerns about the well-being of pandas and there were appeals and discussion about limiting the number of panda loans (Schaller 1994).

Tourism

Telecoupled systems: For tourists, Wolong is the receiving system. The places from which tourists originate are the sending systems; i.e., places elsewhere in China (Fig. 3a) and places in the rest of the world (Fig. 3b). Our tourist surveys indicated that more than half (651) of the 1063 sampled tourists in 2006 and 2007 were from at least 30 provinces and cities of mainland China, Taiwan, and Hong Kong (Fig. 3a). A large number of Chinese tourists lived in the province of Sichuan (28.6%), which is where Wolong is located, and in the neighboring municipality of Chongqing (15.8%). More distant provinces and cities such as Guangdong (6.4%), Beijing (2.7%), and Shanghai (2.0%) also sent tourists to Wolong. Internationally, we recorded 26 different countries of origin. The majority of international tourists were from Japan (13.4%), the United States (7.9%), the United Kingdom (5.0%), France (2.8%), and the Netherlands (2.6%) (Fig. 3b). The spillover systems are areas in the rest of the world that support the supply chain industry of tourism. Spillover systems also include the stopover cities along the travel route to Wolong, such as Beijing, Shanghai, and Chengdu, which provide services to tourists.

Agents: There are diverse agents involved in tourism in Wolong. They include government agencies and officials who develop and implement tourism policies (e.g., the Sichuan Tourism Bureau, the Sichuan Forestry Department, and the Wolong Administration Bureau). Other agents include tourism agencies that facilitate and attract tourists (e.g., investment companies such as Luneng Xinyi Ltd. Co., a subsidiary of a large state-owned enterprise in Shandong province of China; and the Jiuzhaigou Scenic Area Administration). The Wolong Tourism Development Inc., a government-owned company, was established in 1991 to organize and promote visitation to Wolong. In 1997, the company was converted into the Department of Tourism, an official governmental agency under the Wolong Administration Bureau, to be responsible for all tourism planning and management issues (Liu et al. 2015*b*, in press). Agents in the receiving system also include local residents engaged in supporting the industry. Other agents in sending and spillover systems include those who arrange trips for tourists (e.g., tourist agents that make travel arrangements, foreign affairs officers that issue passports, embassies and consulate generals that issue visas). Those who provide services to tourists in stopovers such as Beijing (for international tourists) and Chengdu (for international tourists

and domestic tourists coming from outside Sichuan province) are also agents.

Flows: The number of tourists to Wolong increased dramatically over time (Fig. 3c). Tourism started in the early 1980s and reached a peak in 2006, with an annual visitation of 220,000 people (Fig. 3c). There was a drop in 2003 and a complete stop in tourism after the 2008 Wenchuan earthquake. For the domestic tourists, the largest number of visitors came from the nearby areas (500-km range, e.g., from Sichuan and Chongqing, Fig. 3d). Beyond this distance, the number of tourists dropped markedly, by 87%, and then increased slightly with distance. For foreign tourists (Fig. 3e), the largest numbers occurred at intermediate distances. In other words, there are nonlinear relationships between the numbers of tourists and distances. Aside from tourists, money also flows into Wolong for tourism-related infrastructure. In 2002, for example, the Luneng Company in Shandong province of China invested ¥42 million (¥1 = US$0.1208 in 2002) to upgrade the Wolong Hotel to the four-star level with 668 beds (Wolong Nature Reserve 2005).

Causes: Tourism is affected by economic, political, technological, cultural, and ecological factors. On the one hand, many local people in Wolong are enthusiastic about participating in tourism as they have a strong desire for income from tourism. Government agencies have been actively promoting tourism. Technological advances, especially communication technologies and transportation, have played important roles in promoting Wolong tourism. On the other hand, there are demands for nature-based tourism by people in other parts of China and the world. Wild pandas, natural forests and wildlife, and clean air and water were the top three reasons that motivated the domestic tourists to come to the Reserve. For international tourists, the top three were natural forests and wildlife, wild pandas, and pandas in captivity (Liu 2012). Both external and internal disturbances shaped tourism over time. For example, the SARS epidemic that occurred across China led to a drastic drop in the number of tourists in 2003 (Fig. 3c). In 2008, the 8.0-M_s Wenchuan Earthquake completely stopped tourism in Wolong (Fig. 3c). Wolong was near the epicenter of the earthquake. Most of the infrastructure was destroyed by this disaster and associated landslides. Destroyed infrastructure included tourism facilities and the main road which connected Wolong to outside markets. Furthermore, landslides have become much more frequent since the earthquake. The road has been repeatedly destroyed even after many rounds of repairs. As a result, so far tourism has not yet recovered.

Effects: There are a variety of socioeconomic and environmental effects of tourism. Here we use the data from the 220 households in Wolong that we sampled since 1998 to illustrate the socioeconomic effects of tourism in Wolong. The number of households sampled that participated directly in tourism-related activities increased from 9 (4%) in 1998 to 60 (28%) in 2007. Approximately 76.5% of local rural households received income associated with tourism directly or indirectly (Liu 2012). Local households also received indirect benefits from tourism. For example, a total of 116 households (including 87 households that were not directly involved in tourism) reported having received some income from temporary labor jobs on infrastructure construction. A number of households also reported having earned income from selling locally produced products such as medicinal herbs (14 tourism households and 25 nontourism households). Other households sold honey (6 tourism households and 19 nontourism households) and smoked pork (10 tourism households and 12 nontourism households). Some of these local products were sold to local restaurants, shops, and street vendors, much of which was later sold to tourists. The locals used the remaining products themselves or sold them directly to tourists and markets outside Wolong. The composition of income between tourism households and nontourism households differed substantially. For tourism households, direct and indirect tourism income was most important, and their nonfarm income percentage increased from 40% to 66% between the late 1990s and mid-2000s (Liu 2012). In contrast, nontourism households generally earned more farm income, while their nonfarm income percentage remained basically the same (around 36 to 38%) from the late 1990s to the mid-2000s. Furthermore, the development of tourism has motivated the community to upgrade local infrastructure. Tourism contributed to the transformation of Wolong's traditional subsistence agriculture economy into a diverse, modern, and more service-oriented economy (He et al. 2008, Liu 2012).

Environmental effects of tourism on the receiving system are direct or indirect. For direct effects, tourists influence vegetation along trails. Through field sampling along trailsides, we found that there are more plant species occurring at trailsides than in the forest interior in the shrub, sapling, and seedling layers. Herbaceous species richness at trailsides was also higher than in forest interior (Liu 2012). This effect may be attributed to new niches opening up due to the disturbance created by people and livestock trampling the soil. Fecal deposition by livestock along trails also added nutrients to the soil (Liu 2012). Some tourists from all over the world also donate back to Wolong after visiting, to provide support for captive breeding and research, helping the Reserve to become the largest captive giant panda breeding center in the world. Besides regular donations in the form of cash and goods, donations are also delivered through an adoption program that allows donors to "adopt" a captive panda with the donated funds. For example, from 2005 to 2014, there were at least 59 donations and 177 adoptions (Wolong Panda Club 2015). Tourists also have many indirect effects. The construction of roads, facilities, and other infrastructure has a negative impact on the local ecosystem, e.g., fragmentation of giant panda habitat (Hull et al. 2011). Besides, tourists affect the environment through altering the livelihood of local residents. Some tourists purchase local products, create job opportunities (e.g., having locals as guides or employees at tourism facilities), and bring in new information (e.g., about markets, jobs, and technology). By helping to increase local residents' incomes, tourism has helped increase the affordability of electricity and thus reduce fuelwood collection in panda habitat. For instance, households engaged in restaurant or hotel operation were more likely to decrease their fuelwood consumption compared to those who were not (Liu 2012). Engagement in nature-based tourism activities has enhanced local residents' awareness of conservation issues (Liu et al. 2012).

In terms of effects on sending systems, visits to Wolong may improve tourists' quality of life (e.g., enriching experience) (Neal et al. 2007). Visits may also reduce household spending and environmental impacts in sending systems when tourists are away.

Although the traveling of tourists leaves an environmental footprint (Gössling et al. 2002), it may also have positive environmental effects. For example, many residents from the nearby city of Chengdu spend an extended period of summertime in Wolong due to its cool weather (Liu 2012). If they switch off the air conditioners at their homes when they are away, they can reduce the consumption of energy and reduce greenhouse gas emissions. However, the net impact is unknown due to unavailable data on greenhouse gas emissions from transport and other activities.

For the spillover systems, tourism creates economic benefits that ripple through the chain of tourism-related industries (Balmford et al. 2009). For instance, tourism-related industries outside receiving and sending systems benefit from selling goods (e.g., outdoor clothes and hiking shoes) and providing services to tourists. On the other hand, greenhouse gas emissions as a result of both national and international travel contribute to global climate change and thus affect all systems, including the spillover systems.

Tourism also generates feedback effects. After tourists visit Wolong, they disseminate information to friends and colleagues, thus potentially affecting the probability of visits by others coming from sending systems. The past success of tourism within Wolong also provides an incentive that has attracted a large amount of outside investment for further tourism infrastructure development. One example is the recent construction of a new captive panda breeding center (Sichuan Rebuild 2012). According to Wolong's Master Plan for 2015–2025, proposals have also been put forth for the construction of a large hotel and a mushroom plantation to support future tourism growth (Sichuan Academy of Forestry 2014).

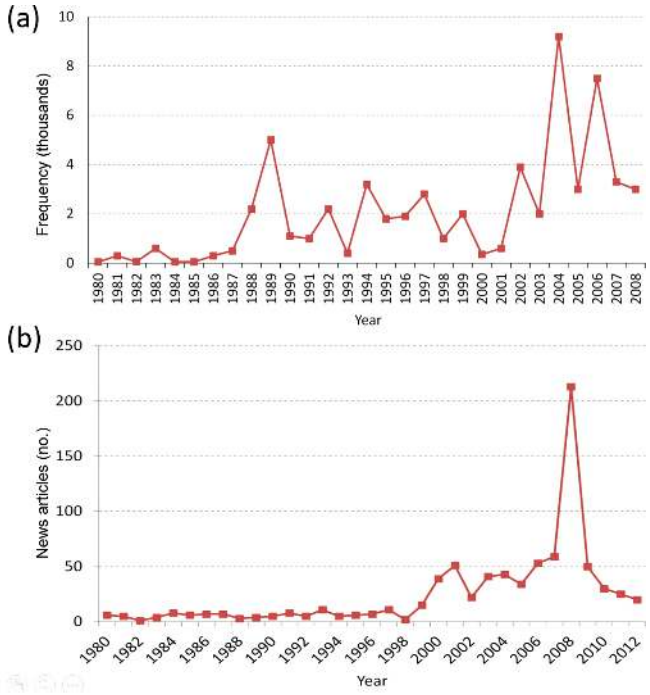
Information dissemination

Telecoupled systems: Wolong is the sending system. The receiving systems are places that published articles and books and created television programming about Wolong, and send visitors to Wolong. Spillover systems are other places that know about Wolong through reading relevant articles and books, watching the news or other programs, and receiving information from visitors to Wolong as well as from the Internet and social media.

Agents: In the receiving system, the main agents are news media outlets and book publishers as well as authors responsible for disseminating information about Wolong. For news media outlets, there are usually major national and international media organizations, such as *The New York Times* (Simons 2003). For book publishers, they include major international publishing houses, such as University of Chicago Press (George Schaller's book *The Last Panda*) (1994). A variety of scholars and reporters have written articles about Wolong. Many news agencies have also created specials on television programs, such as short stories on *Good Morning America* and documentaries on nature channels such as *Animal Planet* (*Pandamonium* 2008). In the sending system, local scientists, conservation organizations, reserve managers, and residents are the main agents in providing information to the news media organizations and publishers. In the spillover system, the main agents are audiences who read news articles and books or watch videos related to Wolong.

Flows: Flows include the movement of information about Wolong and the people who visited Wolong to collect such information. For example, the frequency of the phrase "Wolong Nature Reserve" in English books has increased since 1980, especially after 2000 (Fig. 4a). We found a total of 806 articles using the term "Wolong Nature Reserve", published since 1980 in the international news media in English. The number of articles published each year was under 11 between 1980 and 1998 and then increased to 51 during a 3-year period from 1999 to 2001 (Fig. 4b). The numbers of articles fluctuated between 20 and 60 in each of the remaining years, except for a rapid peak occurring in 2008 (213 articles) (Fig. 4b).

Fig. 4. (a) Temporal changes in the frequency of the words "Wolong Nature Reserve" in published English books (unsmoothed) between 1980 and 2008. (b) Number of international news articles containing the words "Wolong Nature Reserve" and published in the English language from 1980 to 2012, as documented using the LexisNexis® Academic search engine.



Causes: There are a number of factors that have led to the flows of information from Wolong to distant systems. Because of greater emphasis on sustainability worldwide, many global citizens are concerned about endangered and charismatic species like the giant panda, which results in a large amount of research about pandas in Wolong. What's more, as an emblem of China, the panda's important role in diplomacy has also attracted the attention of the media and scientists. Being home to the panda as a global conservation icon, Wolong is an important place for panda conservation. As a flagship national nature reserve, it has received exceptional national and international financial and technical assistance (Liu et al. 2001). Although there are 67 nature reserves for panda conservation (State Council Information Office of the People's Republic of China 2015, Liu 2015), Wolong is one of the first and one of the largest reserves. Tourism is

another mechanism that has helped spread information about Wolong. In addition, Wolong hosts a number of captive pandas in the breeding center and sends many of these pandas to places around the world (through the panda loan program described above). A number of events collectively led to the initial increase in media attention in the 1999-to-2001 period. These included a boom in captive panda breeding (Mouland 2001), the arrival of the second pair of Wolong's pandas to the National Zoo in Washington, D.C. (Pan 2000), and the publication of a paper documenting the rapid decline of panda habitat in Wolong despite its protected status (Liu et al. 2001). The reason for the rapid increase in publications in 2008 stems from the Wenchuan earthquake (see example research articles on the earthquake impacts in Viña et al. 2011 and Yang et al. 2013*a*).

Effects: The effects of information flows out of Wolong are numerous. Information shared about Wolong helps raise awareness among the general public regarding the plight of the endangered giant panda, as well as about broader conservation issues in China and those facing other wildlife species around the world. Furthermore, scientific research related to giant panda conservation can inform the decision-making that surrounds the conservation of other endangered species, not only in Wolong but also across the globe (Liu et al. 2003b, Schaller 1994). In Wolong, visits from journalists promote the local economy. Also, some researchers like ourselves pay local workers to assist with data collection and analysis.

Feedbacks also can occur because the information disseminated out from Wolong helps attract tourists from receiving systems to visit Wolong and to engage in various activities that affect the sending system. Another feedback occurred when people around the world who had heard about or visited Wolong sent donations to support disaster relief after the Wenchuan earthquake (Liu 2012). Also, the Chinese government referred to results from scientific research in Wolong (Liu et al. 2001) for more effective panda conservation.

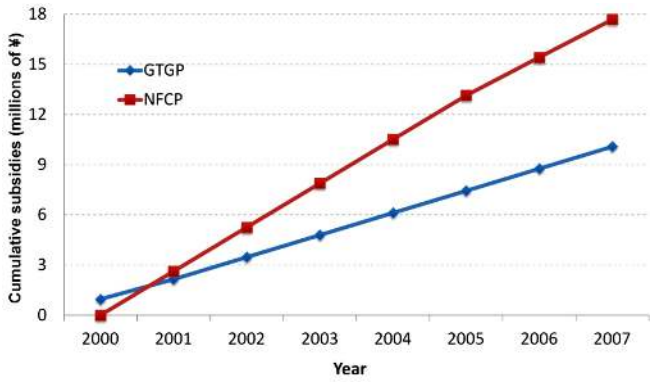
Conservation subsidies

Telecoupled systems: Wolong is the receiving system for conservation subsidies while the rest of the country of China (represented by the Chinese government) is the sending system. The rest of the world is the spillover system, as ecosystem services (e.g., carbon sequestration by forests) provided by Wolong via conservation subsidies can abate global climate change.

Agents: Government officials in China and farmers in Wolong are the agents who provide and receive financial support, respectively. Agents in the spillover system include the general public affected by ecosystem services provided by the conservation subsidy programs.

Flows: The main flows for external financial support are monetary funds. The cumulative amount of the Natural Forest Conservation Program funding between 2001 and 2007 was almost ¥18 million (ranging from ¥2.2 to ¥2.6 million/yr; US$1 = ¥6.34 as of May 2012). The cumulative amount of the Grain-to-Green Program funding between 2000 and 2007 was over ¥10 million (ranging from ¥0.96 to ¥1.32 million/yr) (Fig. 5).

Fig. 5. Cumulative amounts of subsidies to Wolong from the Chinese central government through the Natural Forest Conservation Program (NFCP) and Grain-to-Green Program (GTGP). Data were obtained from government records on investment in the Natural Forest Conservation Program and the Grain-to-Green Program (Wolong Nature Reserve 2005, 2010). The Natural Forest Conservation Program and the Grain-to-Green Program payment rates are flat (i.e., the present values in each corresponding year are not discounted).



Causes: The implementation of the Grain-to-Green Program and the Natural Forest Conservation Program in Wolong was due to both national and local factors. At the national level, the huge floods in 1998 prompted the establishment of these two conservation programs in order to improve soil water retention and prevent erosion (Liu et al. 2008). At the local level, the degradation of forests and panda habitat in Wolong caused the local government to seek ways of minimizing the continuing destruction of forests and panda habitat. There were also economic causes. At the national level, the government recognized the need to improve livelihoods of the millions of rural poor. At the local level, the administration recognized the need to provide alternative forms of income for residents living inside Wolong. These residents were economically limited by related conservation initiatives (e.g., the ban on timber harvesting).

Effects: In the receiving system, external financial support has had many positive effects. The majority of local residents identified positive effects from the the Natural Forest Conservation Program, such as economic gains and environmental benefits (e.g., reducing soil erosion and landslides) (Yang et al. 2013*c*). For example, the subsidies from the Natural Forest Conservation Program and the Grain-to-Green Program accounted for 5% and 8% of the average household income as of 2005 (Liu et al. 2013*b*). On the other hand, the Natural Forest Conservation Program restricts forest use by locals. After the Natural Forest Conservation Program started, electricity consumption in the reserve doubled, and the labor spent on fuelwood collection decreased by nearly half (Yang et al. 2013*c*). These programs have also helped forest and panda habitat recovery (Vina et al. 2011). Forest cover in Wolong decreased from 106,000 ha in 1965 to 70,000 ha in 2001, but recovered to 79,000

ha by 2007, coinciding with the implementation of these programs (Yang et al. 2013*c*). However, the negative effects of the Grain-to-Green Program on household income might outweigh its positive effects. The compensation level (¥3150/ha) might be too low to cover the potential income loss due to the lost cropland. Based on a household survey in 2006, 1 ha of cropland planted with off-seasonal cabbage (a cash crop) could bring as much as 15 times more income than the subsidies provided by the Grain-to-Green Program (Liu et al. 2013*b*).

Feedbacks also occur. The Natural Forest Conservation Program and the Grain-to-Green Program have led to increases in forest cover, which enhances the capacity of carbon sequestration and climate change mitigation. More forest cover may also attract more tourists (Liu et al. 2012). The recovery of forests also improved habitat for many wildlife species, including those crop-raiding species such as wild pigs. Increased crop raiding may motivate farmers to convert more farmland to forestland to reduce future crop losses and to find jobs in cities.

Trade of agricultural products

Telecoupled systems: Wolong is the sending system for trade of agricultural products as Wolong farmers sell products. The receiving systems are diverse, including the cities of Chengdu and Dujiangyan, which are 130 and 50 km away from Wolong, respectively. The spillover systems include other rural areas around China that also sell agricultural products.

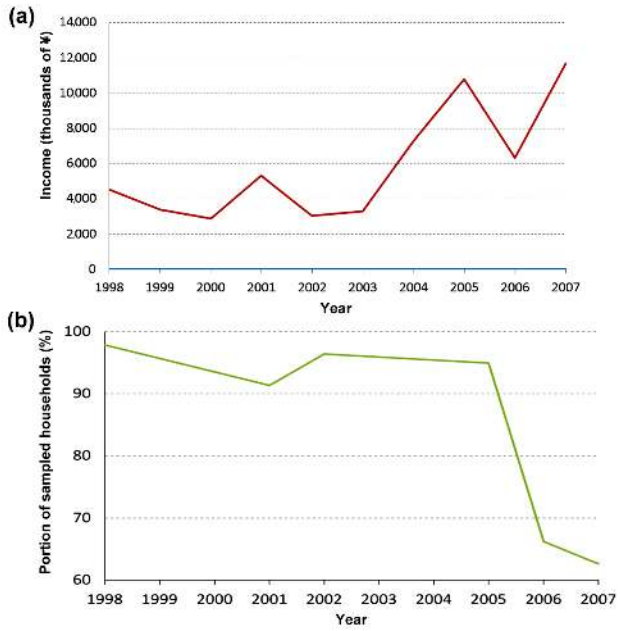
Agents: The agents in the trade of agricultural products include farmers in Wolong, traders, and consumers of agricultural products. Around 80% of Wolong laborers (306 of 381 laborers from 180 surveyed households) were involved in cash crop production in 2007 (Yang et al. 2013*b*). Agents in the spillover system include agricultural sellers and buyers affected by changes in the market as a result of Wolong's trade activities.

Flows: Flows include food products transported out of Wolong and the money coming into Wolong. The total income earned from cabbage and livestock has been generally increasing from around ¥4.5 million in 1998 to nearly ¥9.8 million in 2007 (or ¥11.7 million in 2007, after taking into account China's consumer price index increase of 19.6% across this period and standardizing to 1998 rates (Sichuan Provincial Bureau of Statistics 2007)) (Fig. 6a). However, the percentages of households with these income sources tended to decline from over 90% to just over 60% during the same period (Fig. 6b).

Causes: There is a cultural cause of the agricultural trade stemming from the long history of agriculture in the reserve and the traditions passed down in family lineages. One of the other main causes of agricultural trade is economic. Producing agricultural products for outside markets is an important source of income for Wolong residents. The increase in agricultural production in Wolong is in part attributed to the construction of the road that provides reliable access to outside markets. However, destruction of the road after the 2008 earthquake has severely impacted cash crop production in Wolong because farmers no longer have reliable means to transport their crops.

Effects: The trade of agricultural products has helped farmers in Wolong earn cash and improve their economic conditions. For example, in 2007, Wolong farmers in 159 surveyed households earned ¥1.34 million from selling cabbage, potatoes, and livestock (Liu et al. 2013*b*). At the same time, those agricultural products help meet the demands of people in cities. In the trade of agricultural products, money from selling the products is a strong feedback. Some of the income generated from the trade of agricultural products allows the purchase of agricultural technology (e.g., industrial products) which can help produce more agricultural products.

Fig. 6. (a) Total income from cash crops and livestock in Wolong (discounted to 1998 rates using consumer price index statistics from Sichuan Provincial Bureau of Statistics 2007). (b) Percentage of sampled households with income from both cash crop and livestock.



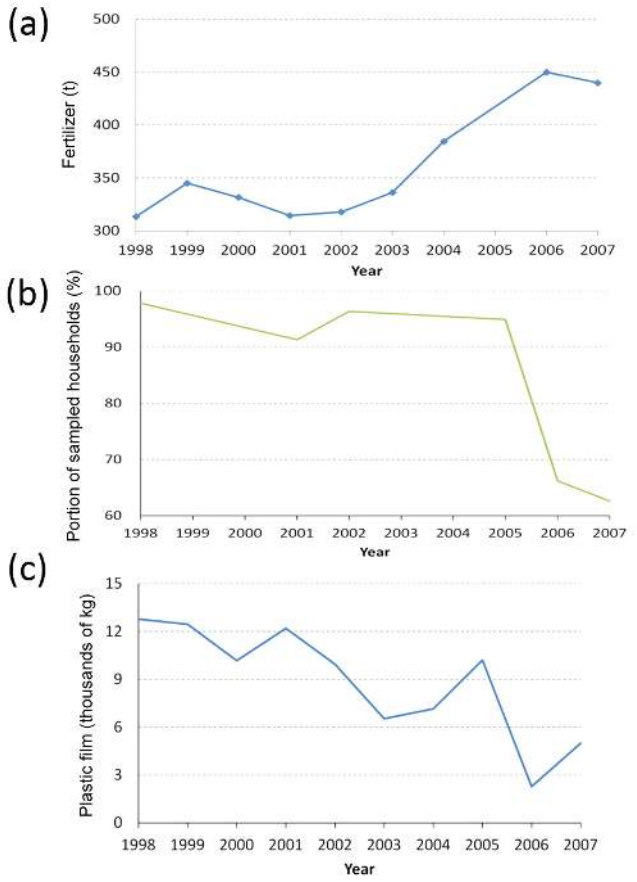
Trade of industrial products

Telecoupled systems: Wolong is the receiving system for industrial products. There are many sending systems, including the same cities that are the receiving systems for agricultural products. Other sending systems are technology hubs in cities farther away such as Beijing, Shanghai, and even as far away as some in the U.S.A. Spillover systems include areas under environmental impacts from technology production and application. For instance, fertilizers applied in Wolong may leach into the Pitiao River, which feeds into the 735-km Minjiang River stretching across Sichuan province.

Agents: Agents in sending systems include manufacturers and suppliers of industrial products such as fertilizers and plastic films that Wolong farmers purchase. Two of China's leading fertilizer production companies with plants in nearby cities include the Sichuan Chemicals and the Sichuan Meifeng Chemical, companies that are part of a greater network of China's industrial sector. Agents in receiving and spillover systems include farmers and the general public who alter their production or consumption patterns of these industrial products, as well as agricultural traders competing with Wolong on the market.

Flows: Flows include money going out of Wolong and industrial products coming into Wolong. The total amount of fertilizers purchased increased from a little over 300 t to 440 t/yr between 1998 and 2007 (Fig. 7a). Just as the trend in the percentages of households with incomes from agricultural products declined, the percentages of households that purchased fertilizers each year also declined over time, from more than 90% to just above 60% (Fig. 7b). The total amount of plastic film purchased per year for the entire reserve decreased over time from nearly 13,000 kg to 5,000 kg although there were some fluctuations (Fig. 7c).

Fig. 7. (a) Total amount of fertilizers purchased by Wolong farmers from outside markets over time. (b) Percentage of sampled households purchasing fertilizers over time. (c). Total amount of plastic film purchased by Wolong farmers over time.



Causes: Many of the aforementioned causes of increased trade of agricultural products also apply to trade of industrial products. To increase agricultural production, large amounts of fertilizers were needed. One other important cause of imported agricultural technology is that technology can improve the efficiency of land use and produce more agricultural products per unit of land. Such efficiency can help people earn more money and alleviate the contradiction between cropland and forest area.

Effects: Purchasing and using fertilizers made in cities has increased agricultural production but has also polluted the local environment (e.g., soil, water) and affected organisms. In 2007, Wolong farmers in 177 surveyed households spent ¥114,000 for fertilizers (Liu et al. 2013*b*). The effects of fertilizers extend to spillover systems. For instance, nitrogenous fertilizer production in China is known for having a large impact on greenhouse gases. Chinese companies mainly use coal as an energy source to produce nitrogenous fertilizers (while the rest of the world mainly uses natural gas) (Kahrl et al. 2010). Greenhouse gas emitted from fertilizer production impacts distant systems all over the world via contributions to climate change. For example, the 440 t of fertilizer applied in Wolong in 2007 (see Fig. 7a) could emit as much as 4092 t of CO_2 (9.3 tCO_2 tN^{-1} including the fertilizer production process) (Kahrl et al. 2010).

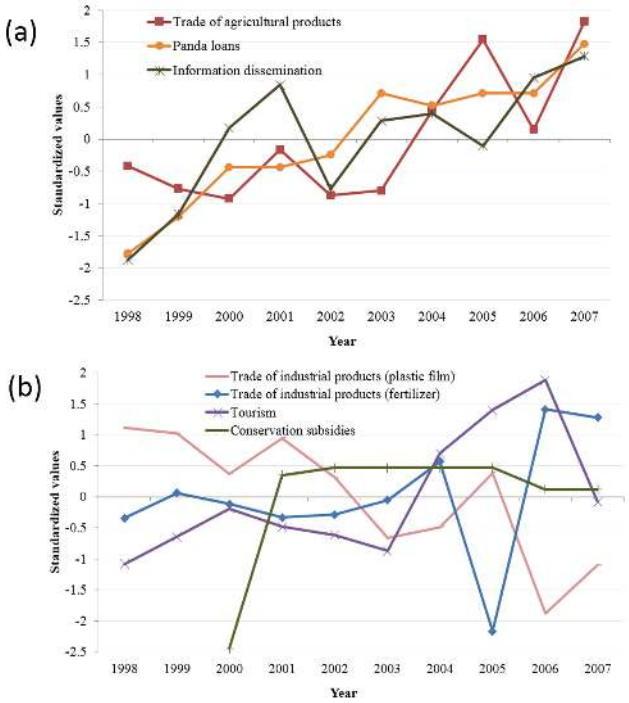
A positive feedback drives this telecoupling. The use of industrial products helps increase agricultural yield, thus generating more income that could be used to purchase more industrial products, including agricultural technology.

Relationships among telecouplings

Among the telecouplings analyzed above, all but one increased in strength over time, until 2008 when the Wenchuan Earthquake occurred (Fig. 8). The telecoupling process with the most pronounced change is the information spread about Wolong (occurrence of words "Wolong Nature Reserve" in published English books and articles). The only telecoupling that decreased somewhat is the purchase of plastic film from outside. This decrease is most likely attributed to the reduction in cropland area due to the implementation of the Natural Forest Conservation Program and the Grain-to-Green Program. All telecouplings except the Natural Forest Conservation Program and the Grain-to-Green Program occurred before or in 1998. The implementation of the Natural Forest Conservation Program and the Grain-to-Green Program began in 2000 (Fig. 8).

The relationships among the telecouplings are complex. They may enhance or amplify each other. Information spread may be a key driver for many other telecouplings, since it increased to a greater degree and occurred earlier than other telecouplings (Fig. 8). For instance, information spread through media exposure has historically been a key driver of the increase in tourism to Wolong (Liu 2012). During the early years of tourism development in Wolong, there was a spike in tourists' arrival in 1983 (from less than 10,000 to over 20,000 visitors). This sudden increase was triggered by one of the first international media reports on Wolong regarding a suspected panda starvation resulting from a mass bamboo flowering and die-off (Liu 2012). Since then, the Chinese government has designated Wolong as a tourist attraction, invested in tourism facilities, and promoted it through the global news media. Thus, the government has increased the exposure of Wolong to the rest of the world. For instance, 24% of visitors to the Wolong breeding center (n=70) who we interviewed in 2005 expressed that they had previously read print media reports on Wolong (and 29% saw television programs) (Liu 2012). In addition, increased investment in tourism and increases in tourist volumes have in turn increased media exposure about Wolong. For instance, a Google search for "Wolong" and "tour" in English yields over 80,000 hits as of September 2014, many of which are promotional tourist packages and tourist recommendations.

Fig. 8. Changes in telecouplings for those with flows (a) leaving and (b) entering Wolong Nature Reserve from 1998 to 2007. Values shown are standardized across years. Trade in agricultural products refers to total income from cash crops and livestock in Wolong. Panda loans are the number of pandas sent out from Wolong to outside zoos, on loan. Information dissemination refers to the number of international news articles containing the words "Wolong Nature Reserve" and published in the English language. Trade of industrial products is presented in two parts: total amount of fertilizers and total plastic film purchased by Wolong residents. Tourism refers to the total number of incoming tourists visiting Wolong. Conservation subsidies are total amounts of funding that Wolong received from the Natural Forest Conservation Program and the Grain-to-Green Program.



Panda loans have significantly affected the international information spread about Wolong. Around 20% of all media reports found in LexisNexis® about Wolong concern panda loans, which is more than any other topic. Such loans allow people from around the world who do not have the opportunity to visit Wolong to still learn about Wolong. Loaned pandas often require multimillion-dollar investments in exhibits, many of which incorporate educational materials to share information about Wolong with visitors. Loaned pandas are also featured on webcams that are geared toward disseminating information to a wide audience. For instance, more than 237,000 hits were recorded on the panda cam website of the National Zoo in Washington D. C. within 1 day after a recent birth of a baby panda (Gresko 2012). This website thus serves as an information portal for Internet users worldwide. Information spread may also encourage donations to Wolong's breeding center. In recent years, such funds have helped pay for the operating costs of a giant panda reintroduction program geared toward releasing pandas to the wild (Pandas International 2012).

Another example is conservation subsidies and tourism. When interviewed, local people in Wolong perceived a potential benefit from the Natural Forest Conservation Program for tourism development, presumably due to their perception that protecting the forest would help attract nature-based tourists (Yang et al. 2013*c*). Another related conservation program called the Grain-to-Bamboo Program has an even greater link to tourism. The Grain-to-Bamboo Program pays local people to plant bamboo, mainly along the roadways, as a supplemental food source for captive pandas in the breeding center and to improve the roadside aesthetic appeal of the reserve to visiting tourists (Yang et al. 2013*c*).

Telecouplings may also offset each other. The trade of agricultural and industrial products is at odds with off-farm income-generation activities. For example, the decrease in the amount of plastic film used may in part be due to an over 50% reduction in an average household's agricultural land as a result of the Grain-to-Green Program. Tourism also provides a source of nonfarm income that may discourage agricultural development, and in turn, agricultural trade. For example, tourist households had an average of 50% less farmland compared to households not engaged in tourism in 2006 (average of 0.63 versus 1.25 Mu, 1 Mu= 0.0667 ha) (Liu et al. 2012). Households with more initial cropland are also significantly less likely to take up tourism as an alternative income source (Yang 2013). Off-farm telecouplings also affect each other. For instance, tourism had a significant positive effect on total household income, but the effect of tourism was also significantly dependent upon the household's participation in the Natural Forest Conservation Program (Yang 2013). Tourism and the Natural Forest Conservation Program participation were antagonistic in affecting total household income because those with lower tourism income had higher total income only if their income from the Natural Forest Conservation Program was also high (Yang 2013). Although tourism provides a potentially higher economic gain for locals who participate, it is a less stable industry compared to agriculture, the Natural Forest Conservation Program, and the Grain-to-Green Program. The instability leaves many locals wary about investing in tourism activities (e.g., see fluctuations in Fig. 3c) (Yang 2013).

There are spatial overlaps between some telecoupling processes. Perhaps this is best illustrated via the relationship between panda loans and tourists (e.g., destinations of panda loans and origins of tourists, Figs. 2b, 3a, Fig. 3b). After excluding the tourists coming from within Sichuan and the nearby Chongqing municipality, there is a significant positive correlation between panda loan destinations and origins of tourists across China ($R= 0.72$, $p< 0.05$). Three of the top four locations are shared between pandas and tourists (Beijing, Guangzhou, Shanghai). Internationally, the top two countries for both pandas and tourists are also shared: Japan and the U.S.A. These similarities reflect the locations with high human populations in developed areas that would be interested, and have the resources, to undertake both international travel and the hosting of pandas in zoos. Loans began increasing several years prior to the boom in tourism (Fig. 8), largely due to the rapid increase in breeding technologies that preceded tourism development. Loans may have encouraged subsequent tourism by raising the international status of Wolong.

Telecouplings may also lead to the formation of other telecouplings. The panda loans are a good example. They induce and are induced by other telecoupling processes such as trade between China and other countries, including procurement of cars, renewable energy, and other resources by China (Buckingham et al. 2013). For instance, the loan of pandas to the Edinburgh Zoo in 2011 was part of a £2.6 billion (US$3.94 billion) collection of business deals, including China securing rights to oil from a Scottish oil refinery (Stratton and Branigan 2011). This loan was also coupled with a deal that would dramatically increase imports of fisheries to China, thus increasing pressure on fish populations in Scotland (Buckingham et al. 2013).

DISCUSSION AND CONCLUSIONS

Here we represent the first effort to study multiple telecouplings across borders and across local to global scales under the telecoupling framework. It uncovers many similar and different spatial–temporal patterns and relationships among multiple telecouplings. The distance-defying patterns illustrated by tourism and panda loans suggest that geographical proximity is not necessarily the only determinant of telecouplings. For example, tourist destination choices are mainly determined by distance and cost. But this process is also heavily shaped by tourist motivations such as discovering new places and experiencing other cultures (Fesenmaier et al. 2006, Nicolau and Mas 2006).

Telecouplings illustrated in this study are quite common around the world. For example, almost all rural areas import technologies, such as fertilizers produced elsewhere. On the other hand, they sell agricultural products to outside markets (Jacoby 2000). Many rural areas are destinations of tourists who live in cities (Lane 1994). Information about various places is disseminated worldwide through publications, mass media, the Internet, and other communication channels. Financial support from external sources for conservation (e.g., payments for ecosystem services) is increasingly common worldwide (Chen et al. 2009*a*). Pandas are endemic to China and panda loans are relatively limited at the global scale. But many countries or places offer other wildlife species such as tigers, zebras, alligators, lions, and wolves to numerous zoos (Braverman 2010). In many ways, other wildlife species in zoos play roles (e.g., education) similar to the role pandas play.

It is much more challenging to study telecouplings than local couplings (human–nature interactions within a system) because telecouplings involve many components that go beyond a single location, across multiple scales, and across administrative boundaries. Naturally it is even more challenging to study and quantify multiple telecouplings simultaneously than one telecoupling at a time. As a result, many research gaps exist. The biggest unknown ones are the spillover systems. In some cases, it is not even clear where the spillover systems are. Furthermore, many other environmental and socioeconomic effects across the telecoupled systems are not measured quantitatively. Feedbacks and relationships among multiple telecouplings require further quantification. The telecoupling framework emphasizes temporal dynamics, not just in the past and in the present (as illustrated here), but also in the future. More work is needed to predict telecoupling-induced surprises and shocks such as sudden social or environmental regime shifts and system collapses, phenomena that are becoming increasingly complex and global in scope (Walker et al. 2009, Biggs et al. 2011, Homer-Dixon et al. 2015). While much remains to be done, this study lays a good foundation for future research and management to enhance positive effects and reduce negative effects of telecouplings on environmental sustainability and human well-being around the world.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/7868

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LITERATURE CITED

Adger, W. N., H. Eakin, and A. Winkels. 2009. Nested and teleconnected vulnerabilities to environmental change. *Frontiers in Ecology and the Environment* 7(3):150-157. http://dx.doi.org/10.1890/070148

Alberti, M., H. Asbjornsen, L. Baker, N. Brozovic, L. Drinkwater, S. Drzyzga, C. Jantz, J. Fragoso, D. Holland, T. Kohler, J. Liu, W. McConnell, H. Maschner, J. Millington, M. Monticino, G. Podestá, R. Pontius Jr., C. Redman, N. Reo, D. Sailor, and G. Urquhart. 2011. Research on coupled human and natural systems (CHANS): approach, challenges, and strategies. *Bulletin of the Ecological Society of America* 92:218-228. http://dx.doi.org/10.1890/0012-9623-92.2.218

An, L., G. He, Z. Liang, and J. Liu. 2006. Impacts of demographic and socioeconomic factors on spatio-temporal dynamics of panda habitats. *Biodiversity and Conservation* 15:2343-2363. http://dx.doi.org/10.1007/s10531-004-1064-6

An, L., A. Zvoleff, J. Liu, and W. Axinn. 2014. Agent-based modeling in coupled human and natural systems (CHANS): lessons from a comparative analysis. *Annals of the Association of American Geographers* 104(4):723-745. http://dx.doi.org/10.1080/00045608.2014.910085

Avissar, R., and D. Werth. 2005. Global hydroclimatological teleconnections resulting from tropical deforestation. *Journal of Hydrometeorology* 6(2):134-145. http://dx.doi.org/10.1175/jhm406.1

Balmford, A., J. Beresford, J. Green, R. Naidoo, M. Walpole, and A. Manica. 2009. A global perspective on trends in nature-based tourism. *PLoS Biology* 7(6):e1000144. http://dx.doi.org/10.1371/journal.pbio.1000144

Bawa, K., L. Koh, T. Lee, J. Liu, P. Ramakrishnan, D. Yu, Y. Zhang, and P. Raven. 2010. China, India, and the environment. *Science* 327:1457-1459. http://dx.doi.org/10.1126/science.1185164

BBC News Magazine. 2011. *Who, what, why: how do you fly a panda 5,000 miles?* 5 Dec 2011. British Broadcasting Corporation, London, UK. [online] URL: http://www.bbc.com/news/magazine-16000130

Biggs, D., R. Biggs, V. Dakos, R. J. Scholes, and M. Schoon. 2011. Are we entering an era of concatenated global crises? *Ecology and Society* 16(2):27.

Bradbury, M., N. Peterson, and J. Liu. 2014. Long-term dynamics of household size and their environmental implications. *Population and Environment* 36:73-84. http://dx.doi.org/10.1007/s11111-014-0203-6

Brants, T., and A. Franz. 2006. *Web 1T 5-gram Version 1*. Linguistic Data Consortium, Philadelphia, Pennsylvania, USA.

Braverman, I. 2010. Zoo registrars: a bewildering bureaucracy. *Duke Environmental Law & Policy Forum* 21:165.

Brown, J. 2011. Zoo orders Chinese food delivery from Holland: Edinburgh-based panda breeding plan described as 'madness' after bamboo is sourced in Netherlands. 08 Nov 2011. *The Independent*. Independent Print Limited, London, UK. [online] URL: http://www.independent.co.uk/environment/nature/zoo-orders-chinese-food-delivery-from-holland-6258681.html

Buckingham, K. C., J. N. W. David, and P. Jepson. 2013. Environmental reviews and case studies: diplomats and refugees: panda diplomacy, soft "cuddly" power, and the new trajectory in panda conservation. *Environmental Practice* 15(03):262-270. http://dx.doi.org/10.1017/s1466046613000185

Carter, N. H., A. Viña, V. Hull, W. J. McConnell, W. Axinn, D. Ghimire, and J. Liu. 2014. Coupled human and natural systems approach to wildlife research and conservation. *Ecology and Society* 19(3):43. http://dx.doi.org/10.5751/es-06881-190343

Chen, X., K. Frank, T. Dietz, and J. Liu. 2012. Weak ties, labor migration, and environmental impacts: towards a sociology of sustainability. *Organization & Environment* 25:3-24. http://dx.doi.org/10.1177/1086026611436216

Chen, X., F. Lupi, G. He, and J. Liu. 2009*a*. Linking social norms to efficient conservation investment in payments for ecosystem services. *Proceedings of the National Academy of Sciences of the USA* 106(28):11812-11817.

Chen, X., F. Lupi, G. He, Z. Ouyang, and J. Liu. 2009*b*. Factors affecting land reconversion plans following a payment for ecosystem service program. *Biological Conservation* 142:1740-1747.

Chen, X., F. Lupi, A. Viña, G. He, and J. Liu, 2010. Using cost-effective targeting to enhance the efficiency of conservation investments in payments for ecosystem services. *Conservation Biology* 24:1469-1478. http://dx.doi.org/10.1111/j.1523-1739.2010.01551.x

China Conservation and Research Center for the Giant Panda. 2015. Registry of giant panda loans. Wolong Nature Reserve, Sichuan, China.

Chinese National Committee for Man and the Biosphere. 1998. *Nature reserves and ecotourism.* Science and Technology Press of China, Beijing, China. (in Chinese)

Clayton, J. 2014. *1 air mile.* BlueSkyModel, Ver. 4.0, December 2014. [online] URL: http://blueskymodel.org/air-mile#average-aircraft

Commissioner's Office of China's Foreign Ministry in the Hong Kong Special Administrative Region. 2014. Paul Chan concludes Sichuan visit. Press release, 07 Mar 2014. Hong Kong. [online] URL: http://www.fmcoprc.gov.hk/eng/xwdt/xjlc/t1134645.htm

DeFries, R. S., T. Rudel, M. Uriarte, and M. Hansen. 2010. Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nature Geoscience* 3:178-181. http://dx.doi.org/10.1038/ngeo756

Eakin, H., R. DeFries, S. Kerr, E. F. Lambin, J. Liu, P. J. Marcotullio, P. Messerli, A. Reenberg, X. Rueda, S. R. Swaffield, B. Wicke, and K. Zimmerer. 2014. Significance of telecoupling for exploration of land-use change. Pages 141-162 *in* K. C. Seto and A. Reenberg, editors. *Rethinking global land use in an urban era*. MIT Press, Cambridge, Massachusetts, USA. http://dx.doi.org/10.7551/mitpress/9780262026901.003.0008

Ellis, S., W. Pan, Z. Xie, and D. Wildt. 2006. The giant panda as a social, biological, and conservation phenomenon. Pages 1-16 *in* D. E. Wildt, A. Zhang, H. Zhang, D. L. Janssen, and S. Ellis, editors. *Giant pandas: biology, veterinary medicine, and management*. Cambridge, UK, Cambridge University Press. http://dx.doi.org/10.1017/cbo9780511542244.002

Fesenmaier, D. R., K. W. Wöber, and H. Werthner. 2006. *Destination recommendation systems: behavioral foundations and applications*. Centre for Agriculture and Biosciences International (CABI), Wallingford, Oxfordshire, UK. http://dx.doi.org/10.1079/9780851990231.0000

Folke, C., A. Jansson, J. Rockström, P. Olsson, S. R. Carpenter, F. S. Chapin III, A.-S. Crépin, G. Daily, K. Danell, J. Ebbesson, T. Elmqvist, V. Galaz, F. Moberg, M. Nilsson, H. Österblom, E. Ostrom, A. Persson, G. Peterson, S. Polasky, W. Steffen, B. Walker, and F. Westley. 2011. Reconnecting to the biosphere. *AMBIO* 40 (7):719-738. http://dx.doi.org/10.1007/s13280-011-0184-y

Garrett, R. D., X. Rueda, and E. F. Lambin. 2013. Globalization's unexpected impact on soybean production in South America: linkages between preferences for non-genetically modified crops, eco-certifications, and land use. *Environmental Research Letters* 8(4):044055. http://dx.doi.org/10.1088/1748-9326/8/4/044055

Gasparri, N. I., T. Kuemmerle, P. Meyfroidt, Y. l. P. de Waroux, and H. Kreft. 2015. The emerging soybean production frontier in southern Africa: conservation challenges and the role of south-south telecouplings. *Conservation Letters*. http://dx.doi.org/10.1111/conl.12173

Ghimire, K. B. 1997. Conservation and social development: an assessment of Wolong and other panda reserves in China. Pages 187-213 *in* Ghimire, K. B., and M. P. Pimbert, editors. *Social change and conservation: environmental politics and impacts of national parks and protected areas*. London, UK, Earthscan Publications.

Gössling, S., C. B. Hansson, O. Hörstmeier, and S. Saggel. 2002. Ecological footprint analysis as a tool to assess tourism sustainability. *Ecological Economics* 43(2):199-211. http://dx.doi.org/10.1016/s0921-8009(02)00211-2

Gresko, J. 2012. After a surprise panda birth in DC, anxiety awaits. 18 Sep 2012. Associated Press, New York, New York, USA.

He, G., X. Chen, W. Liu, S. Bearer, S. Zhou, L. Cheng, H. Zhang, Z. Ouyang, and J. Liu. 2008. Distribution of economic benefits from ecotourism: a case study of Wolong Nature Reserve for giant pandas in China. *Environmental Management* 42(6):1017-1025. http://dx.doi.org/10.1007/s00267-008-9214-3

Homer-Dixon, T., B. Walker, R. Biggs, A.-S. Crépin, C. Folke, E. F. Lambin, G. D. Peterson, J. Rockström, M. Scheffer, W. Steffen, and M. Troell. 2015. Synchronous failure: the emerging causal architecture of global crisis. *Ecology and Society* 20(3):6. http://dx.doi.org/10.5751/es-07681-200306

Hull, V., W. Xu, W. Liu, S. Zhou, A. Viña, J. Zhang, M. Tuanmu, J. Huang, M. Linderman, X. Chen, Y. Huang, Z. Ouyang, H. Zhang, and J. Liu. 2011. Evaluating the efficacy of zoning designations for protected area management. *Biological Conservation* 144(12):3028-3037. http://dx.doi.org/10.1016/j.biocon.2011.09.007

International Civil Aviation Organization. 2014. Carbon emissions calculator. Montréal, Quebec, Canada. [online] URL: http://www.icao.int/environmental-protection/CarbonOffset/Pages/default.aspx

Jacoby, H. G. 2000. Access to markets and the benefits of rural roads. *The Economic Journal* 110(465):713-737.

Kahrl, F., Y. Li, Y. Su, T. Tennigkeit, A. Wilkes, and J. Xu. 2010. Greenhouse gas emissions from nitrogen fertilizer use in China. *Environmental Science & Policy* 13(8):688-694. http://dx.doi.org/10.1016/j.envsci.2010.07.006

Lambin, E. F., and P. Meyfroidt. 2011. Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the USA* 108:3465-3472. http://dx.doi.org/10.1073/pnas.1100480108

Lane, B. 1994. What is rural tourism? *Journal of Sustainable Tourism* 2(1-2):7-21.

Levitt, T. 1983. The globalization of markets. *Harvard Business Review* 61(3):92-102.

Li, C., S. Zhou, D. Xiao, Z. Chen, and Z. Tian. 1992. A general description of Wolong Nature Reserve. *In* Wolong Nature Reserve, and Sichuan Normal College, editors. *The animal and plant resources and protection of Wolong Nature Reserve*. Sichuan Publishing House of Science and Technology, Chengdu, China. (in Chinese)

Li, W., and N. Han. 2001. Ecotourism management in China's nature reserves. *AMBIO: A Journal of the Human Environment* 30(1):62-63. http://dx.doi.org/10.1579/0044-7447-30.1.62

Linderman, M. A., L. An, S. Bearer, G. He, Z. Ouyang, and J. Liu. 2006. Interactive effects of natural and human disturbances on vegetation dynamics across landscapes. *Ecological Applications* 16:452-463. http://dx.doi.org/10.1890/1051-0761(2006)016[0452:IEONAH]2.0.CO;2

Liu, J. 2014. Forest sustainability in China and implications for a telecoupled world. *Asia & the Pacific Policy Studies* 1(1):230-250. http://dx.doi.org/10.1002/app5.17

Liu, J. 2015. Promises and perils for the panda. *Science* 348:642. http://dx.doi.org/10.1126/science.348.6235.642-a

Liu, J., G. Daily, P. Ehrlich, and G. Luck. 2003*a*. Effects of household dynamics on resource consumption and biodiversity. *Nature* 421:530-533.

Liu, J., T. Dietz, S. R. Carpenter, M. Alberti, C. Folke, E. Moran, A. N. Pell, P. Deadman, T. Kratz, J. Lubchenco, E. Ostrom, Z. Ouyang, W. Provencher, C. L. Redman, S. H. Schneider, and W. W. Taylor. 2007. Complexity of coupled human and natural systems. *Science* 317(5844):1513-1516. http://dx.doi.org/10.1126/science.1144004

Liu, J., V. Hull, M. Batistella, R. DeFries, T. Dietz, F. Fu, T. W. Hertel, R. C. Izaurralde, E. F. Lambin, S. Li., L. Martinelli, W. McConnell, E. Moran, R. Naylor, Z. Ouyang, K. Polenske, A. Reenberg, G. de Miranda Rocha, C. Simmons, P. Verburg, P. Vitousek, F. Zhang, and C. Zhu. 2013*a*. Framing sustainability in a telecoupled world. *Ecology and Society* 18(2):26.

Liu, J., V. Hull, E. Moran, H. Nagendra, S. R. Swaffield, and B. L. Turner II. 2014. Applications of the telecoupling framework to land-change science. Pages 119–139 *in* K. C. Seto and A. Reenberg, editors. *Rethinking global land use in an urban era*. MIT Press, Cambridge, Massachusetts, USA. http://dx.doi.org/10.7551/mitpress/9780262026901.003.0007

Liu, J., S. Li, Z. Ouyang, C. Tam, and X. Chen. 2008. Ecological and socioeconomic effects of China's policies for ecosystem services. *Proceedings of the National Academy of Sciences of the USA* 105(28):9477-9482. http://dx.doi.org/10.1073/pnas.0706436105

Liu, J., M. Linderman, Z. Ouyang, L. An, J. Yang, and H. Zhang. 2001. Ecological degradation in protected areas: the case of Wolong Nature Reserve for giant pandas. *Science* 292 (5514):98-101. http://dx.doi.org/10.1126/science.1058104

Liu, J., W. McConnell, and J. Luo. 2013*b*. *Wolong household study [China]*. ICPSR34365-v1. Inter-university Consortium for Political and Social Research, Institute for Social Research, University of Michigan, Ann Arbor, Michigan, USA. [online] URL: http://www.icpsr.umich.edu/icpsrweb/ICPSR/studies/34365/version/1

Liu, J., H. Mooney, V. Hull, S. J. Davis, J. Gaskell, T. Hertel, J. Lubchenco, K. C. Seto, P. Gleick, C. Kremen, and S. Li. 2015*a*. Systems integration for global sustainability. *Science* 347 (6225):1258832.

Liu, J., Z. Ouyang, S. L. Pimm, P. H. Raven, X. Wang, H. Miao, and N. Han. 2003*b*. Protecting China's biodiversity. *Science* 300:1240-1241.

Liu, J., Z. Ouyang, W. Taylor, R. Groop, Y. Tan, and H. Zhang. 1999. A framework for evaluating effects of human factors on wildlife habitat: the case of the giant pandas. *Conservation Biology* 13(6):1360-1370. http://dx.doi.org/10.1046/j.1523-1739.1999.98418.x

Liu, J., and P. Raven. 2010. China's environmental challenges and implications for the world. *Critical Reviews in Environmental*

Science and Technology 40(9):823-851. http://dx.doi.org/10.1080/10643389.2010.502645

Liu, J., and W. Yang. 2013. Integrated assessments of payments for ecosystem services programs. *Proceedings of the National Academy of Sciences of the USA* 110(41):16297-16298. http://dx.doi.org/10.1073/pnas.1316036110

Liu, W. 2012. *Patterns and impacts of tourism development in a coupled human and natural system*. Dissertation. Fisheries and Wildlife, Michigan State University, East Lansing, Michigan, USA.

Liu, W., C. A. Vogt, J. Luo, G. He, K. A. Frank, and J. Liu. 2012. Drivers and socioeconomic impacts of tourism participation in protected areas. *PLoS ONE* 7(4):e35420. http://dx.doi.org/10.1371/journal.pone.0035420

Liu, W., C. A. Vogt, F. Lupi, G. He, Z. Ouyang, and J. Liu. 2015*b*, in press. Evolution of tourism in a flagship protected area of China. *Journal of Sustainable Tourism*.

McMahon, T. 2010. Corporations cuddling up to pandas. 2 Nov 2010. *National Post*. CanWest MediaWorks Publications Inc., Winnipeg, Manitoba, Canada. [online] URL: http://www.canada.com/story.html?id=25701c3a-5e13-4bf8-b8d8-918b3b9204b6

Meyfroidt, P., E. F. Lambin, K. Erb, and T. Hertel. 2013. Globalization of land use: distant drivers of land change and geographic displacement of land use. *Current Opinion in Environmental Sustainability* 5:438-444. http://dx.doi.org/10.1016/j.cosust.2013.04.003

Mouland, B. 2001. Hope at last as the giant panda enjoys a baby boom. 19 Sep 2001. *Daily Mail.* London, UK. [online] URL: http://www.highbeam.com/doc/1G1-78409889.html

Myers, N., R. A. Mittermeier, C. G. Mittermeier, G. A. B. da Fonseca, and J. Kent. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403(6772):853-858.

Neal, J. D., M. Uysal, and M. J. Sirgy. 2007. The effect of tourism services on travelers' quality of life. *Journal of Travel Research* 46 (2):154-163. http://dx.doi.org/10.1177/0047287507303977

Newsome, D., S. A. Moore, and R. K. Dowling. 2002. *Natural area tourism: ecology, impacts, and management*. Channel View Publications; Clevedon, England, UK, and Buffalo, New York, USA.

Nicolau, J. L., and F. J. Más. 2006. The influence of distance and prices on the choice of tourist destinations: the moderating role of motivations. *Tourism Management* 27(5):982-996. http://dx.doi.org/10.1016/j.tourman.2005.09.009

O'Brien, K., B. Hayward, and F. Berkes. 2009. Rethinking social contracts: building resilience in a changing climate. *Ecology and Society* 14(2):12.

Österblom, H., and C. Folke. 2015. Globalization, marine regime shifts and the Soviet Union. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 370 (1659):20130278. http://dx.doi.org/10.1098/rstb.2013.0278

Pan, P. P. 2000. Meet the pandas; zoo bringing home pick of China's litter. 19 Nov 2000. *The Washington Post*. Washington, D.C., USA. [online] URL: http://www.highbeam.com/doc/1P2-556874.html

Pandamonium. 2008. Directed by Amanda Feldon. ITN Factual Productions, London, UK, 2008. [online] URL: http://www.imdb.com/title/tt2842562/?ref_=nm_flmg_dr_3

Pandas International. 2012. Reintroduction program – 2012. Littleton, Colorado, USA. [online] URL: http://www.pandasinternational.org/wptemp/program-areas-2/reintroduction-program/reintroduction-program-2012/

Peters, G. P., J. C. Minx, C. L. Weber, and O. Edenhofer. 2011. Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences of the USA* 108(21):8903-8908.

R Development Core Team. 2005. *R: a language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria.

Schaller, G. B. 1994. *The last panda*. University of Chicago Press, Chicago, Illinois, USA.

Sichuan Academy of Forestry. 2014. *The overall planning of Wolong National Nature Reserve in Sichuan, China*. Sichuan, China. (in Chinese)

Sichuan Provincial Bureau of Statistics. 2007. *Sichuan statistical yearbook, 1998–2007*. Sichuan, China. (in Chinese) [online] URL: http://www.sc.stats.gov.cn/tjcbw/tjnj/index.html

Sichuan Rebuild. 2012. SDEV inspects HK-funded reconstruction projects in Wolong. Press release, 05 2014 Mar 2014. The Hong Kong Construction Sector 5.12 Reconstruction Joint Conference, Hong Kong Special Administrative Region. http://www.512rjc.hk/en/info/press_releases_20140305.htm

Simons, C. 2003. Where little pandas come from. 5 Jan 2003. *The New York Times*. The New York Times Company, Manhattan, New York, USA. [online] URL: http://www.nytimes.com/learning/students/pop/20030106snapmonday.html

Smithsonian Conservation Biology Institute. 2012. *The National Zoo at 125.* Smithsonian National Zoological Park, Washington, D.C., USA. [online] URL: http://www.americanbison.si.edu/the-national-zoo-at-125/

State Council Information Office of the People's Republic of China. 2015. Press conference on the Fourth National Panda Survey Results. Beijing, China. (in Chinese) [online] URL: http://www.scio.gov.cn/xwfbh/gbwxwfbh/fbh/Document/1395514/1395514.htm/

State Forestry Administration. 2006. *The third national survey report on the giant panda in China*. Science Publishing House, Beijing, China. (in Chinese)

Stevens, K., B. Irwin, D. Kramer, and G. Urquhart. 2014. Impact of increasing market access on a tropical small-scale fishery. *Marine Policy* 50:46-52. http://dx.doi.org/10.1016/j.marpol.2014.05.007

Stratton, A., and T. Branigan. 2011. Giant pandas from China help seal new business deals with UK. 10 Jan 2011. *The Guardian*. Guardian News and Media, London, UK. [online] URL: http://www.theguardian.com/world/2011/jan/10/pandas-china-uk-oil-refinery-deal

Swaisgood, R. R., F. Wei, D. E. Wildt, A. J. Kouba, and Z. Zhang. 2009. Giant panda conservation science: how far we have come. *Biology Letters* 6(2):143-145. http://dx.doi.org/10.1098/rsbl.2009.0786

Tuanmu, M.-N., A. Viña, G. Roloff, W. Liu, Z. Ouyang, H. Zhang, and J. Liu. 2011. Temporal transferability of wildlife habitat models: implications for habitat monitoring. *Journal of Biogeography* 38:1510-1523. http://dx.doi.org/10.1111/j.1365-2699.2011.02479.x

Viña, A., S. Bearer, H. Zhang, Z. Ouyang, and J. Liu. 2008. Evaluating MODIS data for mapping wildlife habitat distribution. *Remote Sensing of Environment* 112:2160-2169. http://dx.doi.org/10.1016/j.rse.2007.09.012

Viña, A., X. Chen, W. J. McConnell, W. Liu, W. Xu, Z. Ouyang, H. Zhang, and J. Liu. 2011. Effects of natural disasters on conservation policies: the case of the 2008 Wenchuan earthquake, China. *AMBIO* 40(3):274-284.

Viña, A., M.-N. Tuanmu, W. Xu, Y. Li, Z. Ouyang, R. DeFries, and J. Liu. 2010. Range-wide analysis of the giant panda habitat: implications for conservation. *Biological Conservation* 143:1960-1969. http://dx.doi.org/10.1016/j.biocon.2010.04.046

Walker B., S. Barrett, S. Polasky, V. Galaz, C. Folke, G. Engström, F. Ackerman, K. Arrow, S. Carpenter, K. Chopra, G. Daily, P. Ehrlich, T. Hughes, N. Kautsky, S. Levin, K.-G. Mäler, J. Shogren, J. Vincent, T. Xepapadeas, and A. de Zeeuw. 2009. Looming global-scale failures and missing institutions. *Science* 325 (5946):1345-1346. http://dx.doi.org/10.1126/science.1175325

Wildt, D., X. Lu, M. Lam, Z. Zhang, and S. Ellis. 2006. Partnerships and capacity building for securing giant pandas ex situ and in situ: how zoos are contributing to conservation. Pages 520–539 *in* D. E. Wildt, A. Zhang, H. Zhang, D. L. Janssen, and S. Ellis, editors. *Giant pandas: biology, veterinary medicine and management*. Cambridge University Press, Cambridge, UK. http://dx.doi.org/10.1017/cbo9780511542244.023

Wolong Administration Bureau. 2008. *Annual report on the rural economy of Wolong Nature Reserve*. Department of Social and Economic Development, Sichuan, China. (in Chinese)

Wolong Nature Reserve. 2005. *Chronicles of Wolong Nature Reserve*. Sichuan, China. (in Chinese)

Wolong Nature Reserve. 2010. *Wolong socio-economic report 1998–2010*. Sichuan, China. (in Chinese)

Wolong Nature Reserve Administration Bureau. 1998. *Wolong Nature Reserve master plan*. Sichuan, China. (in Chinese)

Wolong Panda Club. 2015. Wolong Panda Club. [online] URL: http://www.pandaclub.cn/english/index.html

World Travel and Tourism Council. 2014. *Travel & tourism, economic impact 2014—world*. London, UK. [online] URL: http://www.wttc.org/-/media/files/reports/economic%20impact%20research/regional%20reports/world2014.pdf

Xu, W., Z. Ouyang, A. Viña, H. Zheng, J. Liu, and Y. Xiao. 2006. Designing a conservation plan for protecting the habitat for the giant pandas in the Qionglai Mountain Range, China. *Diversity and Distributions* 12(5):610-619. http://dx.doi.org/10.1111/j.1366-9516.2006.00236.x

Yang, W. 2013. *Ecosystem services, human well-being, and policies in coupled human and natural systems*. Dissertation. Fisheries and Wildlife, Michigan State University, East Lansing, Michigan, USA.

Yang, W., T. Dietz, D. B. Kramer, X. Chen, and J. Liu. 2013*a*. Going beyond the Millennium Ecosystem Assessment: an index system of human well-being. *PLoS ONE* 8(5):e64582.

Yang, W., T. Dietz, D. Kramer, Z. Ouyang, and J. Liu. 2015. An integrated approach to understanding the linkages between ecosystem services and human well-being. *Ecosystem Health and Sustainability* 1(5):19. http://dx.doi.org/10.1890/ehs15-0001.1

Yang, W., T. Dietz, W. Liu, J. Luo, and J. Liu. 2013*b*. Going beyond the Millennium Ecosystem Assessment: an index system of human dependence on ecosystem services. *PLoS ONE* 8(5): e64581.

Yang, W., W. Liu, A. Viña, J. Luo, G. He, Z. Ouyang, H. Zhang, and J. Liu. 2013*c*. Performance and prospects of payments for ecosystem services programs: evidence from China. *Journal of Environmental Management* 127:86-95.

Young, O., F. Berkhout, G. Gallopin, M. Janssen, E. Ostrom, and S. van der Leeuwd. 2006. The globalization of socio-ecological systems: an agenda for scientific research. *Global Environmental Change* 16:304-316. http://dx.doi.org/10.1016/j.gloenvcha.2006.03.004

Yu, E., and J. Liu. 2007. Environmental impacts of divorce. *Proceedings of the National Academy of Sciences of the USA* 104:20629-20634. http://dx.doi.org/10.1073/pnas.0707267104

Zhang, Z., A. Zhang, R. Hou, J. Wang, G. Li, L. Fei, Q. Wang, I. K. Loeffler, D. E. Wildt, T. L. Maple, R. McManamon, and S. Ellis. 2006. Historical perspective of breeding giant pandas ex situ in China and high priorities for the future. Pages 455–568 *in* D. E. Wildt, A. Zhang, H. Zhang, D. L. Janssen, and S. Ellis, editors. *Giant pandas: biology, veterinary medicine, and management*. Cambridge University Press, Cambridge, UK. http://dx.doi.org/10.1017/cbo9780511542244.020