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Synergies and tradeoffs among Sustainable Development Goals across boundaries in a metacoupled world

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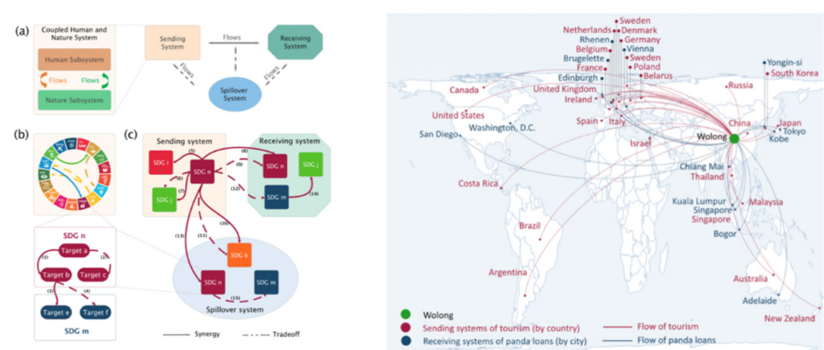
HIGHLIGHTS

- A new framework is proposed to evaluate SDG synergies and tradeoffs.
- SDG interactions within and across boundaries impacted by flows are emphasized.
- Metacoupling and telecoupling frameworks capture SDG interactions.
- Spillover effects favor or hinder multiple SDGs and targets of different systems.
- 17 synergies and 2 tradeoffs occur within Wolong and across 67 panda reserves.

GRAPHICAL ABSTRACT



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ABSTRACT

Synergies and tradeoffs among the United Nations Sustainable Development Goals (SDGs) within specific locations have been widely studied. However, there is little understanding of SDG synergies and tradeoffs across spatial/administrative boundaries although the world is increasingly interconnected and the United Nations aims to achieve SDGs everywhere by 2030. To fill such an important gap, we introduce a new theoretical framework and develop a general procedure of applying the framework to empirically evaluate SDG synergies and tradeoffs within and across boundaries, based on the concept of metacoupling. We work through our framework using the examples of tourism and panda loans between the globally important Wolong Nature Reserve for panda conservation and the rest of the world to evaluate their effects on six SDGs in Wolong and the other 66 panda reserves. Our analyses uncover a total of 17 synergies and two tradeoffs, of which 10 synergies and one tradeoff are internal to Wolong, while seven synergies and one tradeoff occur across reserve boundaries. Given the first empirical evidence about cross-boundary synergies and tradeoffs, it is our hope that this study provides a foundation for further research to reveal more SDG synergies and tradeoffs across boundaries worldwide. The findings will be essential to enhance SDG synergies and reduce tradeoffs across boundaries for achieving SDGs everywhere.

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1. Introduction

The 17 United Nations Sustainable Development Goals (SDGs) with 169 targets adopted by 193 countries in 2015 present a potential future of shared economic prosperity, social inclusion, and environmental sustainability (United Nations, 2015). Understanding synergies and tradeoffs among SDGs is key to ensuring that progress toward achieving one SDG does not occur at the expense of progress in others (Le Blanc, 2015; Lu et al., 2015; Nilsson et al., 2016, 2018; Borrion et al., 2017; Pradhan et al., 2017; Allen et al., 2018; Breuer et al., 2019). Although the United Nations emphasizes that SDGs should be achieved everywhere (e.g., SDG 1 is to "End poverty in all its forms everywhere." (United Nations, 2015)) and the world is increasingly connected socioeconomically and environmentally (Liu, 2018; Nesme et al., 2018), there is little understanding of SDG synergies and tradeoffs across spatial or administrative boundaries. Many studies have evaluated synergies and tradeoffs among different targets of an individual or multiple SDGs across different sectors within specific places (Gao and Bryan, 2017; Hutton et al., 2018; IPCC, 2018; Mainali et al., 2018; Lusseau and Mancini, 2019; Nerini et al., 2019; Maes et al., 2019; Elder and Olsen, 2019), but little attention has been explicitly paid to synergies and tradeoffs across boundaries (Bennich et al., 2020). Although a few studies have considered effects of actions in one place on SDGs in other places (Sachs et al., 2017, 2018; Obersteiner et al., 2016; Engström et al., 2019), such as impacts of developed countries' high consumption levels on developing countries' ability to achieve SDGs (Sachs et al., 2017, 2018) and potential impacts of local energy system transformations on other SDGs in other places (Engström et al., 2019), none of them explicitly evaluated SDG synergies and tradeoffs among different places.

Spatial interactions may have enormous influences on progress toward SDGs in different locations (Liu, 2018). For example, efforts for achieving SDG(s) in location A may promote or hinder progress toward SDG(s) in location B, C, etc. These influences will determine whether or not SDGs can be achieved "everywhere" as the United Nations has aimed for. Also, impacts on SDGs may occur at other levels (e.g., local and regional) besides the national and international levels. Studying impacts at all levels is important because achieving SDGs everywhere requires efforts worldwide and achieving SDGs at local and regional levels is a foundation for achieving SDGs at national and international levels (Xu et al., 2020). Furthermore, besides places with direct connections, other places may also be indirectly affected. However, a recent review paper on SDG interactions indicated few studies focused on geographic spillover effects or SDG interactions across scales and boundaries (Bennich et al., 2020). Addressing all these research gaps requires an integrated framework and empirical evaluation. In this paper, we develop such a framework and demonstrate its application using empirical data.

2. Methods

2.1. Framework of SDG synergies and tradeoffs within and across boundaries

Here, we propose an integrated framework of SDG synergies and tradeoffs within and across boundaries (Fig. 1), based on the conceptual framework of metacoupling (Liu, 2017) (Fig. 1a), which addresses socioeconomic-environmental interactions within a coupled human and natural system (intracoupling) and across systems (i.e. telecoupling among distant systems and pericoupling among adjacent systems). Flows of information, energy, people, organisms, goods, and matter, facilitated by agents affected by various causes with various effects, link internal subsystems as well as different parts of the world together. In addition to the sending systems (e.g., origins of tourists) and adjacent or distant receiving systems (e.g., destinations of tourists) linked by various flows, the metacoupling framework emphasizes the often-overlooked spillover systems, which are places that affect, or are affected by, the interactions between sending and receiving systems (Liu, 2017; Liu et al., 2018). Although the metacoupling framework, as a new frontier for global sustainability (Hull et al., 2019; Hull and Liu, 2018; Kapsar et al., 2019; Dou et al., 2020b; Herzberger et al., 2019; Yao et al., 2020), has been applied to a number of important issues such as global marine fishing (within as well as between adjacent and distant exclusive economic zones) (Carlson et al., 2020), and has been recognized with the "Innovations in Sustainability Science Award" by the Ecological Society of America, it has not been applied to SDG interactions.

As defined in previous studies (Nilsson et al., 2016, 2018; Borrion et al., 2017; Pradhan et al., 2017), SDG synergies within a system emerge when multiple SDGs or multiple targets of individual SDGs in the same system are enhanced simultaneously while SDG tradeoffs occur when one or more targets of one or multiple SDGs are enhanced at the cost of hampering other targets or SDGs (Fig. 1b). Synergies or tradeoffs within a SDG (Fig. 1b) exist because a target may favor or hinder progress in another within the same goal (Pradhan et al., 2017). SDG synergies and tradeoffs are affected by flows, when multiple targets or SDGs respond positively or negatively to the flows. One example of synergy is that preserving uncultivated land (SDG target 15.1) increases agricultural yields (SDG target 2.3) by increasing pollination (Morandin and Winston, 2006), which is a type of ecosystem service flow. Besides, one flow that aims to enhance one target/SDG may also affect multiple other targets/SDGs. For example, sustainable management of coral reefs (through the material, energy, and information flows from human subsystem to natural subsystem) can provide more habitat for fish populations (SDG target 14.2) and improve reef quality for tourism (SDG target 8.9) (Bellwood et al., 2004). The effects of flows on SDGs can also be in opposite directions (i.e. enhancing one SDG target while diminishing another), leading to a tradeoff. An example of a tradeoff is using coal to improve energy access (SDG target 7.1), which contributes to climate change (SDG 13) and acidifies the oceans (SDG target 14.3) through carbon emissions (Nilsson et al., 2016). Moreover, we also emphasize indirect SDG synergies and tradeoffs by evaluating the effects of flows at different stages. The enhanced or compromised targets/SDGs by the first flow may, in turn, favor or hinder other targets/SDGs through associated flows. In this case, the later SDG synergies and tradeoffs are indirectly caused by the first flow that aims to enhance or compromise one specific target/SDG. The above mechanisms and examples assume flows and effects occur within one system (e.g. one country) and do not consider the cross-boundary flows and SDG interactions.

In our proposed framework (Fig. 1c), which integrates the metacoupling framework and SDG interactions, SDG synergies and tradeoffs within and across boundaries are considered simultaneously. Cross-boundary flows (e.g. tourism), initiated to achieve a specific SDG target in a certain system, may enhance or compromise other SDGs both locally and across boundaries, generating direct or indirect SDG synergies and tradeoffs through the certain flows (e.g. tourism) and other associated flows (e.g. movement of financial and human capital). Unlike SDG synergies and tradeoffs within a system only occur among different targets, synergies across boundaries may emerge for the same SDG target when a SDG target in one system favors the same SDG target in other systems while tradeoffs occur for the same SDG target when one SDG target in one system is enhanced at the cost of hampering the same SDG target in another system. SDG synergies and tradeoffs across boundaries can occur between sending and receiving systems, and between sending (or receiving) systems and spillover systems (Fig. 1c). Besides the direct synergies and tradeoffs (within an individual SDG or between different SDGs) that occur within a system (Fig. 1b) and across boundaries, there are indirect synergies and tradeoffs across boundaries due to flows related to SDGs (Fig. 1c), because the enhanced or compromised SDG in other systems may, in turn, generate SDG synergies and tradeoffs within and among SDGs. This approach is particularly useful because it addresses interactions among different geographic or administrative locations.

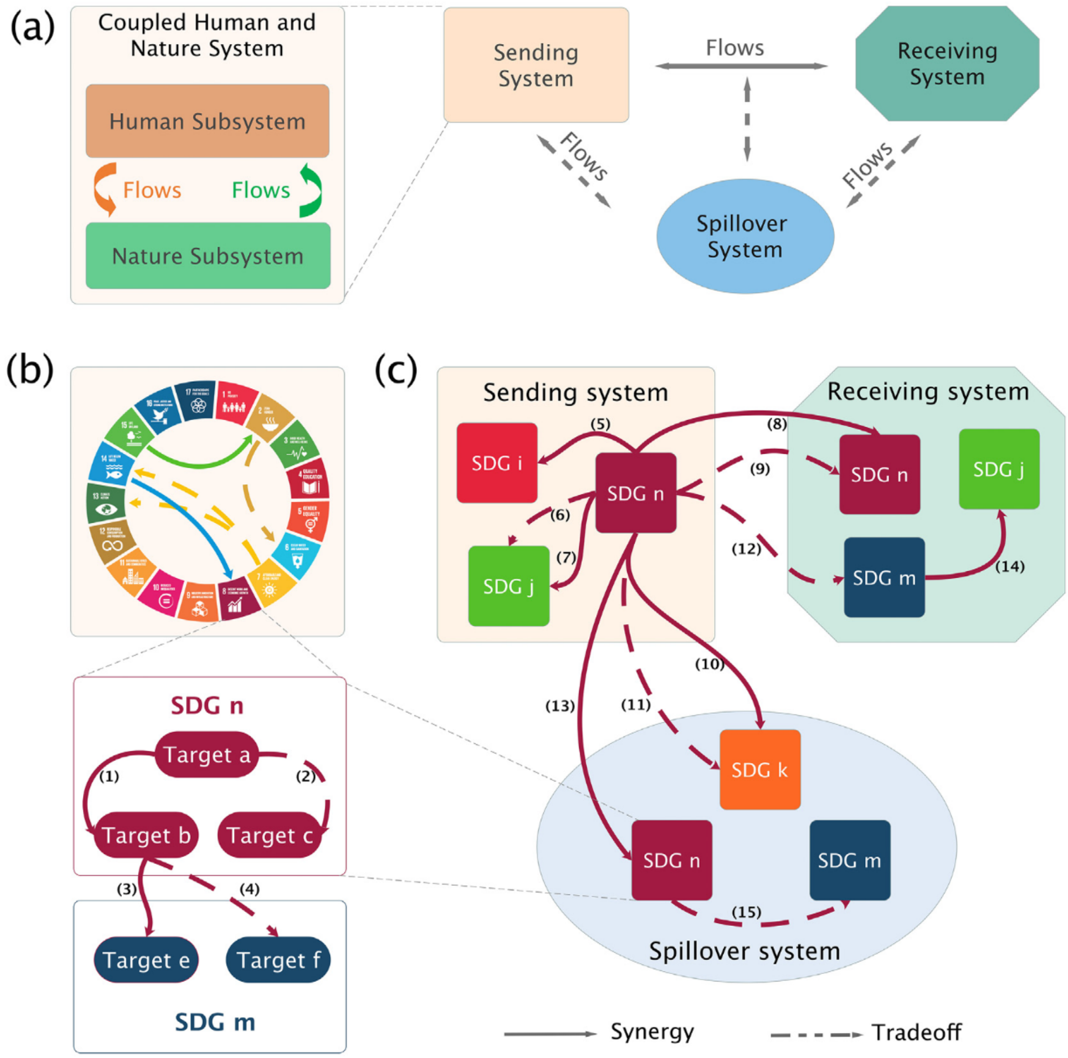


Fig. 1. Framework for evaluating SDG synergies and tradeoffs within and across boundaries. (a) The conceptual framework of metacoupling (Liu, 2017). Within a coupled system, human and natural subsystems interact through various flows between them. Cross-boundary flows (of information, energy, people, organisms, goods, and matter) between the sending systems (e.g., origins of tourists) and receiving systems (e.g., destinations of tourists) may affect the spillover systems (which affect and/or are affected by the interactions between sending and receiving systems). (b) Illustration of SDG synergies and tradeoffs within a coupled system. Besides the interactions between different SDGs (e.g. SDGs n and m), synergies (arrow 1) or tradeoffs (dashed arrow 2) within an SDG (e.g., SDG n) exist because a target may favor or hinder progress in another within the same SDG. In addition, the enhanced or compromised targets/SDGs by the first flow (arrow 1) may, in turn, favor or hinder other targets/SDGs through associated flows (e.g. movement of financial and social capital). In this case, the later SDG synergies (arrow 3) and tradeoffs (arrow 4) are indirectly caused by the first flow (arrow 1). (c) Illustration of SDG synergies and tradeoffs within and across boundaries. Flows (e.g. tourism), which might be efforts toward achieving a specific SDG target in a certain system (e.g. SDG n in sending system), may enhance or compromise other SDGs both in the certain system and in other systems (e.g., both receiving and spillover systems), generating direct or indirect SDG synergies and tradeoffs through the certain flows (e.g. tourism) and other associated flows (e.g. financial and social capital). For SDG n, synergies (arrows 8 and 13) and tradeoffs (arrow 9) occur across boundaries. Similar to synergies (arrow 1) and tradeoffs (arrow 2) within a system, synergies (arrow 8) and tradeoffs (arrow 9) could also exist simultaneously between two systems. Synergies (arrow 10) and tradeoffs (arrows 11 and 12) occur between different SDGs across boundaries. Synergies and tradeoffs between a pair of SDGs could also exist simultaneously both within a system (arrows 6 and 7 between SDGs n and j) or across systems (arrows 10 and 11 between SDGs n and k). In addition, similar to indirect synergies (arrow 3) and tradeoffs (arrow 4) within a system, the enhanced or compromised SDG in the other systems may, in turn, generate SDG synergies (e.g. arrow 14 between SDGs m and j in receiving system) and tradeoffs (e.g. arrow 15 SDGs n and m in spillover system) within and across SDGs. In this case, linkages 14 and 15 are indirect synergies and tradeoffs across boundaries due to flows related to SDGs within a system.

To demonstrate the application of the framework of SDG synergies and tradeoffs, we conducted an empirical study of the 67 nature reserves in China established for conserving the world-famous giant pandas (*Ailuropoda melanoleuca*), with a focus on Wolong Nature Reserve, the flagship reserve for panda conservation (Figs. 2 and S1). Based on the proposed framework (Fig. 1c), we first identified sending, receiving and spillover systems due to tourism in Wolong and panda loans (pandas from Wolong loaned to outside zoos); then tracked associated flows and linked the quantitatively measured effects in response to tourism and panda loans with relevant SDG indicators (Table S1) (IAEG-SDGs, 2016); and finally examined SDG synergies and tradeoffs within and across system boundaries.

2.2. Study areas

Nature reserves for panda conservation are excellent as a demonstration for applying the framework of SDG synergies and tradeoffs. They are part of global protected areas for biodiversity conservation (Viña et al., 2010). Like numerous protected areas in developing countries, many panda reserves have local residents and constitute coupled human and natural systems (Chen et al., 2012). Furthermore, they are part of metacoupled human and natural systems because they are interconnected with the rest of the world (Schaffer-Smith et al., 2018). They also occupy large land areas (e.g., 2000 km^2 for Wolong Nature Reserve alone (Tuanmu et al., 2011; Yang et al., 2013)), much larger than the

Fig. 2. Flows of tourism and panda loans between Wolong and the rest of world. Wolong sent 28 pandas to 14 overseas zoos in 12 countries (1998–2017) and received tourists from 28 countries (according to our survey of 1063 tourists in Wolong during the summer of 2006 and 2007).

territories of some countries such as Curaçao (444 km^2) that was used to demonstrate the application of a framework of infrastructure and SDGs (Adshead et al., 2019). Thus, understanding SDG synergies and tradeoffs within and beyond panda reserves can provide important insights for achieving global SGDs.

Wolong Nature Reserve is a high-profile reserve within a global biodiversity hotspot (Liu et al., 2003a). Like many other places worldwide, Wolong has interactions with the rest of the world through various flows (Linderman et al., 2005; Baird and Fox, 2015; Dou et al., 2020a; Gupta et al., 2020; Gurney et al., 2017). Here we focus on two major cross-boundary processes (tourism and panda loans) (Fig. 2). Both flows are related to pandas (global conservation icon) representing inflows (people from outside to see the pandas in Wolong) and outflows (pandas from Wolong to outside zoos).

Tourism accounts for one in 11 jobs worldwide (World Tourism Organization, 2015), and its contribution is recognized in SDG target 8.9: "By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products." Like many other protected areas, to meet the increasing demands for nature-based tourism which focuses on observing and appreciating nature (Newsome et al., 2002), Wolong has developed tourism for over 30 years and attracted numerous tourists from around the world (Fig. 2) to enjoy the natural forests, wildlife, clean air and water in addition to the captive giant pandas (He et al., 2008; Liu et al., 2016b). Besides Wolong, 19 other panda reserves in Sichuan Province promoted tourism with an annual visitation of over 8.2 million tourists (Forestry Department of Sichuan Province, 2015).

The international panda loan program has long symbolized a close relationship of China with other countries (Buckingham et al., 2013). The Giant Panda Cooperative Research and Breeding Agreements (one example of SDG target 17.6 (United Nations, 2015)) are established which allow zoos outside China to borrow captive pandas for a number of years for a fee (up to $1 million/panda/year). The funds are used to establish the Giant Panda International Collaboration Fund (GPICF) which supports conservation in China, such as capacity building and scientific research in panda reserves (State Forestry Administration, 2016). From 1996 to 2017, Wolong signed international collaboration agreements with 14 zoos in 12 countries and sent 28 pandas to those zoos (Fig. 2). Although panda loans are relatively limited at the global scale (Liu et al., 2015), many countries offer other wildlife species such as polar bears, tigers, zebras, alligators, lions, and wolves to numerous zoos (Braverman, 2010). Similar to many other live animals and plants for trade and loans (Hedges et al., 2006; Roe, 2008; Nijman, 2010; CITES, 2013; Martin, 2018), the pandas for loans are either wild-caught (or rescued) or from captive populations developed from wild-acquired founders (Traylor-Holzer et al., 2015). In many ways, other wildlife species in zoos play roles (e.g., exhibitions and research) similar to the roles of pandas (Liu et al., 2015). In addition, panda loans enhanced the captive panda reintroduction program, similar to other 424 vertebrate species which were translocated for reinforcement or reintroduction of threatened species, reestablishment of ecological functions and processes, and wilderness recreation (Seddon et al., 2007, 2014).

Tourism to and panda loans from Wolong share characteristics with other globally common and important spatial processes such as international trade and migration, as many studies indicate (Liu et al., 2013, 2015; Fang et al., 2016; Hulina et al., 2017; Sun et al., 2018; Hull et al., 2019). For instance, they consist of sending, receiving, and spillover systems, which are connected through various flows (e.g., movement of people, information, money, goods and services, organisms.)

2.3. Methods for studying tourism

We conducted tourist surveys and household surveys to identify the sending, receiving and spillover systems, and to measure the effects of tourism. Concerning Wolong, we reviewed publications and government work reports and interviewed reserve administrators to gather tourism-related information, including tourism history, annual visitor arrivals, income from tourism, and economic development. We derived data from a longitudinal survey of 220 households in Wolong from 1999 to 2007 to investigate the effects of tourism on local residents. The Wolong household survey can be open accessed from Inter-university Consortium for Political and Social Research (https://www.icpsr.umich.edu/web/ICPSR/studies/34365). We also compiled data from a survey of 1063 tourists in Wolong during the summer of 2006 and 2007 (Liu et al., 2015; Liu et al., 2016b) to identify national-level tourist source areas (sending systems) and their other traveling destinations (potential spillover systems). Furthermore, we conducted a comprehensive literature search of published journal articles, government reports, and the official websites for data on pandas and infrastructure upgrades in Wolong and other panda reserves. We then conducted a literature review on tourism development in the spillover systems. We also interviewed reserve administrators to gather tourism-related information, especially connections with tourism in Wolong. We carried out interviews with 2285 households in 26 panda reserves in 2015 (Fig. S2). Fourteen of the 26 surveyed panda reserves were in the Greater Jiuzhaigou Loop Touring Area (Fig. S2). Samples were selected via a stratified random sampling design. Questions included demographics, household income, and traveling information, which indicated residents' connections with other panda reserves. We linked the effects in response to the tourism with SDG targets and indicators in the receiving and spillover systems, but not to the sending systems of tourists due to the lack of relevant data. [See Sections 1.1 and 1.2 of the Supplementary Materials and Methods for additional details.]

2.4. Methods for studying panda loans

We first thoroughly searched publications, government reports, and the official websites of panda reserves for data on panda loans and infrastructure upgrades in Wolong and the other panda reserves. The purpose of this search was to connect possible effects of panda loans, such as partnership and panda reserve development, with targets and indicators of SDG 15 (life on land) and SDG 17 (partnerships for the goals). Then, we interviewed staff members of the Conservation and Research Center for the Giant Panda based in Wolong and obtained a list of research projects (2004–2017) supported by the GPICF to see if the funds promoted scientific research (SDG target 9.5) in Wolong. Last, we carried out a literature search to examine if the GPICF enhanced scientific research in panda reserves, as well as possible research collaborations, and to make connections with targets and indicators of SDG 9 (industry, innovation, and infrastructure). We searched journal articles (1996–2017) by setting criteria keywords “Giant Panda International Collaboration Fund” and “大熊猫国际合作资金” (in Chinese) as the funding agency (Fig. S3). The Web of Science database was used for searching articles published in English, and the Chinese National Knowledge Infrastructure database for articles published in Chinese. We linked the effects in response to the panda loans with SDG targets and indicators in the sending and spillover systems, but not to the receiving systems of pandas due to the lack of relevant data. [See Sections 1.1 and 1.3 of the Supplementary Materials and Methods for additional details.]

3. Results

Results show a total of 17 synergies and two tradeoffs among six SDGs within and across system boundaries (Fig. 3). Wolong was the receiving system for tourism and the sending system for panda loans; the source areas of tourists (28 countries, according to our survey of 1063 tourists in Wolong) were the sending systems for tourism and the destination areas of pandas (14 overseas zoos in 12 countries from 1998 to 2017) were the receiving systems for panda loans (Fig. 2); and the spillover systems were the other panda reserves which were indirectly affected by the tourism in and panda loans from Wolong. Beyond the two directly related SDGs, SDG 8 (decent work and economic growth) and SDG 17 (partnerships for the goals), tourism in, and panda loans from, Wolong enhanced or compromised other SDGs both locally (i.e., within Wolong) and across boundaries (i.e., the other 66 panda reserves, as spillover systems).

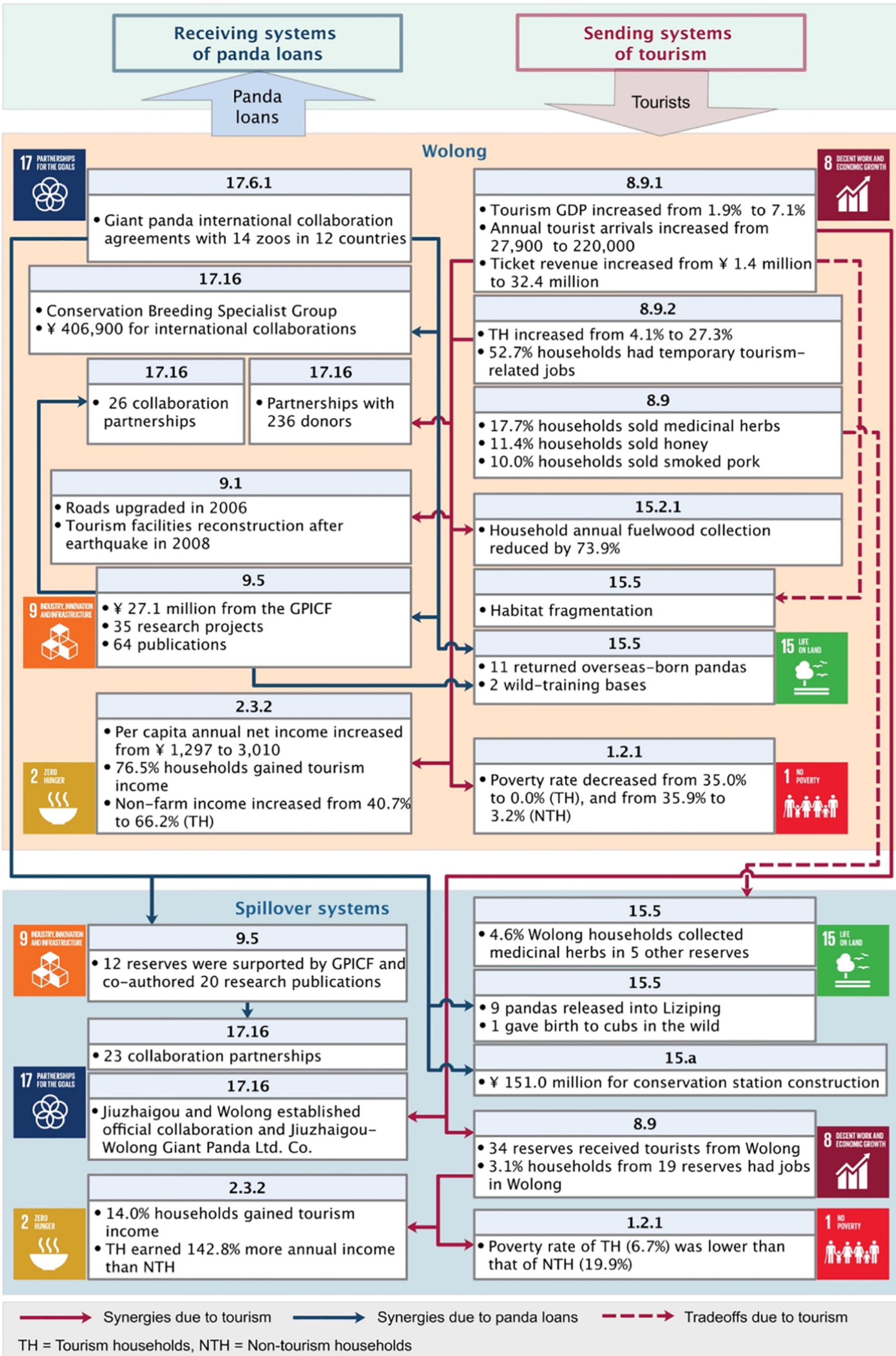
3.1. SDG synergies and tradeoffs within a system boundary

Ten synergies and one tradeoff occurred within a system (Wolong) (Fig. 3). Below are more specific findings.

One synergy occurred within an individual SDG. We found that the implementation of the panda loan agreements (SDG indicator 17.6.1) increased Wolong's participation in scientific collaboration to share knowledge, expertise, and technology (SDG target 17.16). One example is that Wolong participated in the Conservation Breeding Specialist Group (Traylor-Holzer et al., 2015; Wildt et al., 2006). Moreover, according to interviews with staff members, Wolong received ¥ 406, 900 RMB (1 RMB = 0.15 USD as of 2017) from the GPICF to support Wolong's collaboration with international partners in 2017. This synergy within Wolong occurred through across boundary flows due to panda loans: financial flows from GPICF and bidirectional information with partners.

Nine synergies and one tradeoff existed among multiple SDGs. In Wolong, tourism had contributed to promoting economic growth (SDG indicator 8.9.1) by increasing tourism GDP from 1.9% to 7.1% (1996–2006), creating jobs (SDG indicator 8.9.2) by increasing tourism-participating households from 4.1% to 27.3% (1998–2006), and promoting local products (SDG target 8.9) (17.7%, 11.4%, and 10.0% households sold medicinal herbs, honey, and smoked pork to tourists, respectively) (Liu et al., 2016b). SDGs 1 (no poverty), 2 (zero hunger), 9 (industry, innovation and infrastructure), and 17 synergized with SDG 8 in Wolong, because tourism greatly contributed to reducing the poverty rate (SDG indicator 1.2.1) from 35.0% to 0.0% among households participating in the tourism industry (1998–2006), increased income (SDG indicator 2.3.2) by 132.1% (1990–2006) for tourism households, upgraded regional infrastructure (SDG target 9.1), and strengthened multi-stakeholder partnerships (SDG target 17.16) with 236 donors, including 177 individuals and companies, who “adopted” and named captive pandas for a fee (2005–2014). These synergies occurred mainly through the money flows associated with tourism. SDG 15 (life on land) both synergized and traded off with SDG 8 in Wolong. On one hand, tourism reduced flows of forest products (as fuelwood collected by local residents) from forests and panda habitats to households by 73.9% from 1998 to 2007 (Tables S4 and S6) and favored forest recovery (SDG indicator 15.2.1) (Liu et al., 2015). On the other hand, tourists, as flows from the human subsystem to nature subsystem, disturbed local ecosystems as hiking trails extended into large patches of highly suitable panda habitat (SDG target 15.5), including the core zone of the reserve (Liu et al., 2016b).

As for panda loans, from 2004 to 2017, SDGs 9 and 15 synergized with SDG 17 in Wolong because panda loans, through financial flows, strengthened scientific research (SDG target 9.5), with ¥ 27.1 million from the GPICF supporting 35 research projects and resulting in 64 published articles (Fig. S3), and supported two training bases for giant panda reintroduction (SDG target 15.a); and increased the captive


Receiving systems of panda loans
Sending systems of tourism
Panda loans
Tourists
Wolong
17 PARTNERSHIPS FOR THE GOALS
17.6.1
• Giant panda international collaboration agreements with 14 zoos in 12 countries
17.16
• Conservation Breeding Specialist Group
• ¥ 406,900 for international collaborations
17.16
• 26 collaboration partnerships
17.16
• Partnerships with 236 donors
9.1
• Roads upgraded in 2006
• Tourism facilities reconstruction after earthquake in 2008
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
9.5
• ¥ 27.1 million from the GPICF
• 35 research projects
• 64 publications
2 ZERO HUNGER
2.3.2
• Per capita annual net income increased from ¥ 1,297 to 3,010
• 76.5% households gained tourism income
• Non-farm income increased from 40.7% to 66.2% (TH)
8 DECENT WORK AND ECONOMIC GROWTH
8.9.1
• Tourism GDP increased from 1.9% to 7.1%
• Annual tourist arrivals increased from 27,900 to 220,000
• Ticket revenue increased from ¥ 1.4 million to 32.4 million
8.9.2
• TH increased from 4.1% to 27.3%
• 52.7% households had temporary tourism-related jobs
8.9
• 17.7% households sold medicinal herbs
• 11.4% households sold honey
• 10.0% households sold smoked pork
15.2.1
• Household annual fuelwood collection reduced by 73.9%
15.5
• Habitat fragmentation
15 LIFE ON LAND
15.5
• 11 returned overseas-born pandas
• 2 wild-training bases
1 NO POVERTY
1.2.1
• Poverty rate decreased from 35.0% to 0.0% (TH), and from 35.9% to 3.2% (NTH)
Spillover systems
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
9.5
• 12 reserves were surported by GPICF and co-authored 20 research publications
17 PARTNERSHIPS FOR THE GOALS
17.16
• 23 collaboration partnerships
17.16
• Jiuzhaigou and Wolong established official collaboration and Jiuzhaigou-Wolong Giant Panda Ltd. Co.
2 ZERO HUNGER
2.3.2
• 14.0% households gained tourism income
• TH earned 142.8% more annual income than NTH
15 LIFE ON LAND
15.5
• 4.6% Wolong households collected medicinal herbs in 5 other reserves
15.5
• 9 pandas released into Liziping
• 1 gave birth to cubs in the wild
15.a
• ¥ 151.0 million for conservation station construction
8 DECENT WORK AND ECONOMIC GROWTH
8.9
• 34 reserves received tourists from Wolong
• 3.1% households from 19 reserves had jobs in Wolong
1 NO POVERTY
1.2.1
• Poverty rate of TH (6.7%) was lower than that of NTH (19.9%)
Synergies due to tourism
Synergies due to panda loans
Tradeoffs due to tourism
TH = Tourism households, NTH = Non-tourism households

panda population (SDG target 15.5) through panda flows, with 11 of the 18 pandas born at international zoos returned to Wolong. In addition, SDG 15 synergized with SDG 9 in Wolong through the panda translocation flows (reintroduction program), which is an example of advancing knowledge (SDG target 9.5) for conservation (SDG target 15.5) through information flows. Moreover, scientific research (SDG target 9.5) promoted Wolong's partnerships with three government agencies and 18 research institutions in China and five international research institutions (SDG target 17.16) through information flows (Fig. S4).

3.2. Direct SDG synergies and tradeoffs across system boundaries

Four synergies and one tradeoff occurred between Wolong and spillover systems (other panda reserves). Below are more specific findings.

One synergy occurred within an individual SDG (Fig. 3). Tourism in the spillover systems was enhanced because of tourism in Wolong, which illustrated the SDG synergy across boundaries occurred when the same SDG targets in different systems respond positively due to the flow initiated in one system. Our survey in 2015 demonstrated that 37.5% of tourism households (households with tourism-related income) in Wolong were in the chauffeur business, driving tourists from Wolong to 34 other reserves (Figs. S6 and S7), which is the continuation of the tourism flow to Wolong. Our survey of tourists in Wolong showed that 17.1% planned to visit Jiuzhaigou and 9.6% to Huanglong on the same trip during the summers of 2006 and 2007. In addition, tourism in Wolong enhanced labor flows from the spillover systems by providing job opportunities (SDG indicator 8.9.2). Our survey indicated that 3.1% of households from 19 other reserves (Fig. S8) had temporary jobs on tourism-related projects in Wolong, such as road and hotel construction after the Wenchuan 8.0 M_s earthquake in 2008.

Three synergies and one tradeoff were observed among multiple SDGs. Considering tourism, SDGs 17 and 15 in spillover systems interacted with SDG 8 in Wolong. We found that Jiuzhaigou built a partnership (SDG target 17.16) with Wolong for tourism development. In 2005, official collaboration was established between the Wolong Administration Bureau and the Jiuzhaigou National Scenic Area Administration, and a new company, Jiuzhaigou-Wolong Giant Panda Ltd. Co., was established to manage tourism operation in Wolong (Liu et al., 2016b), which involved both financial and social capital flows between Wolong and Jiuzhaigou. Notably, SDG 15 in the spillover systems traded off with SDG 8 in Wolong because tourism in Wolong resulted in similar negative effects on giant panda habitat (SDG target 15.5) in other reserves. Results from our survey showed that 4.6% households in Wolong collected medicinal herbs (human interferences associated with collecting medicinal herbs rank third on the list of threats to giant pandas and their habitats (Forestry Department of Sichuan Province, 2015)) in five other panda reserves (Fig. S9) around 2014, and sold the herbs to tourists in Wolong. In this case, the tradeoff occurred because the tourism flow to Wolong increased labor flows to and products flows from the spillover systems.

Through panda loans and associated flows of financial support (GPICF) and panda reintroductions, SDGs 9 and 15 in the spillover systems synergized with SDG 17 in Wolong. We found that researchers in 12 other reserves were supported by GPICF to conduct scientific research (SDG target 9.5) and had co-authored 20 publications from 2005 to 2017 (Figs. S3 and S5). SDG 15 in the spillover systems synergized with SDG 17 in Wolong as well. First, the panda loan program enhanced the capacity of other reserves to undergo conservation (SDG target 15.a). Besides lack of funding (Liu et al., 2003b), reserves struggled with their enforcement and monitoring capabilities (Lü and Kemf, 2001; Liu et al., 2016a), and ¥ 151.0 million RMB of the GPICF were allocated to building conservation stations in other reserves from 2003 to 2013 (Forestry Department of Shaanxi Province, 2017; Forestry Department of Sichuan Province, 2015). Second, supported by the GPICF, nine captive pandas in Wolong were successfully reintroduced into the wild in other reserves (Fig. S10), increasing the genetic diversity of the small isolated panda populations (SDG target 15.5).

3.3. Indirect SDG synergies across system boundaries

Three indirect SDG synergies were observed among multiple SDGs between Wolong and spillover systems. SDGs 1 and 2 in the spillover systems indirectly synergized with tourism (SDG target 8.9) in Wolong because of increases in tourism and flows of money in the spillover systems. Our household survey in 26 reserves showed that 14.0% of households gained income associated with tourism in 2014. The annual income (SDG indicator 2.3.2) of tourism households was significantly higher than that of non-tourism households (households without tourism-related income); tourism households earned 142.9% more than non-tourism households in 2014. The poverty rate (SDG indicator 1.2.1) among tourism households was also significantly lower than that among non-tourism households in 2014. As for panda loans, the enhanced scientific research (SDG target 9.5) in 12 other reserves (spillover systems) promoted collaborative partnerships (SDG target 17.16) between the 12 reserves and two government agencies and 21 research institutions (Fig. S4) through cross-boundary financial flows from GPICF and bidirectional information with partners. Under this situation, SDG 17 in Wolong indirectly synergized with SDG 17 in spillover systems through directly enhancing SDG 9 in those systems.

4. Conclusions and discussion

Our framework of SDG synergies and tradeoffs within and across boundaries explicitly addresses increasingly important but largely neglected spatial interactions in the context of SDG interactions. It lays a foundation for quantitative evaluations of SDG synergies and tradeoffs across boundaries. The quantitative information is essential for more effective management to achieve SDGs in "everywhere" (from local to global). The framework provides general guidance to the empirical evaluation in this study and future research.

Our study has developed a general procedure of using the framework to guide the identification of tradeoffs and synergies within and across boundaries. First, it is important to examine whether a system of interest has interactions (flows) with outside. If yes, assess the types, directions and magnitudes of the flows as well as the characteristics of relevant systems (e.g., locations, socioeconomic-ecological conditions in sending, receiving, and spillover systems). Second, analyze the effects of the flows using appropriate indicators. Third, match the indicators with relevant SDGs and SDG targets. Forth, evaluate SDG synergies and tradeoffs within and across boundaries.

The presence of many more synergies than tradeoffs between SDGs in our study is contrary to the general belief in widespread tradeoffs (Bowen et al., 2017; Gao and Bryan, 2017), but consistent with recent findings that synergies are dominating (International Council for Science, 2017; Weitz et al., 2018). Our finding may be because the cross-boundary interactions (tourism and panda loans) mainly generate benefits, suggesting the additional need to take spatial interactions across boundaries into account when evaluating factors that affect SDGs. The presence or absence of synergies and tradeoffs may also be affected by data availability. Furthermore, although there was usually either synergy or tradeoff between a pair of SDGs in a place, we found that synergy and tradeoff between a pair of SDGs could also exist simultaneously in the same place as suggested in our framework (Fig. 1c). For

Fig. 3. SDG synergies and tradeoffs within and across places due to tourism and panda loans. Bold numbers indicate specific SDG targets and indicators (Table S1) (IAEG-SDGs, 2016). TH = Tourism households, NTH = Non-tourism households, GPICF = Giant Panda International Collaboration Fund. See Supplementary Results for more details. Credit (SDG symbols): United Nations (United Nations, 2015).

example, SDG 15 (life on land) both synergized and traded off with SDG 8 (decent work and economic growth) simultaneously in Wolong due to tourism, although SDG 15 has many tradeoffs with SDG 8 and other SDGs (Pradhan et al., 2017).

In this study, both direct and indirect SDG interactions under our proposed framework (Fig. 1c) were identified. With more data and ability to track effects of flows, it is possible to detect more tradeoffs and synergies, such as tradeoffs between SDG indicators 8.1.1 (annual growth rate of real GDP per capita) and 8.4.1 (material footprint, material footprint per capita, and material footprint per GDP) within certain countries (Pradhan et al., 2017). Across systems, evidence has accumulated to suggest the widespread competition between tourist destinations (Cracolici and Nijkamp, 2009; Ritchie and Crouch, 2003). Similar to Wolong, the enhanced tourism in other panda reserves may have increased human disturbance on the local ecosystems of those reserves, generating an indirect tradeoff between SDGs 8 and 15 across places due to the tourism in Wolong. Moreover, we recognize that our estimation of effects on spillover systems and linkages among SDGs is conservative. For example, carbon emissions associated with tourism (Lenzen et al., 2018) and panda loans (Liu et al., 2015) may lead to tradeoffs with SDG 13 (climate change) at the global scale. Furthermore, other negative effects of tourism may cause more tradeoffs. For instance, noise pollution caused by tourists may scare away wildlife such as giant pandas (Ware et al., 2015; Luo et al., 2018), and the increased waste and sewage from tourism reduce water quality (Luo et al., 2018).

Within the planetary boundaries (Steffen et al., 2015) of finite resources, balancing neoliberal economic agendas, environmental conservation, and social inclusion is a challenge for achieving sustainability from local to global scales. Our results suggest that, in the metacoupled Anthropocene (Liu, 2017), attempts to achieve the 2030 SDG agenda should take into consideration cross-boundary interactions that affect SDG synergies and tradeoffs. Moreover, to minimize tradeoffs and amplify synergies among SDGs, it is essential to incorporate spillover systems into policymaking (Liu et al., 2018). The implication is that efforts toward achieving a specific SDG target in a system may enhance or compromise other SDGs in both the system of interest and other systems. By tracking the flows, quantitatively evaluating impacts on SDG synergies and tradeoffs across different places would help policymakers to avoid achieving SDGs in one place at the expense of other places. Even if there are inevitable tradeoffs among different places, the results would help develop policies to provide appropriate compensation for the places that suffer from cross-boundary interactions. Furthermore, new policies may be developed to further enhance synergies among different places. Emergent insights may include the importance of governing the flows and SDG interactions across boundaries.

The approaches and findings in this study can provide generic insights for cross-boundary SDG interactions beyond panda reserves in China. We anticipate that specific synergies and tradeoffs may differ in different places and under different cross-boundary processes (e.g. climate change, wilderness loss, consumption and trade of resources, and geopolitical influences). It is our hope that the framework and approaches developed in this study can stimulate more empirical research on SDG synergies and tradeoffs across different places to achieve all SDGs worldwide.

Data availability statement

The survey data that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Zhiqiang Zhao: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Meng Cai:** Investigation, Writing - original draft, Writing - review & editing, Visualization. **Fang Wang:** Investigation, Resources, Software, Writing - review & editing, Funding acquisition. **Julie A. Winkler:** Writing - review & editing, Funding acquisition. **Thomas Connor:** Writing - review & editing, Investigation. **Min Gon Chung:** Writing - review & editing, Resources. **Jindong Zhang:** Investigation, Resources, Data curation, Writing - review & editing. **Hongbo Yang:** Investigation, Data curation, Writing - review & editing. **Zhenci Xu:** Investigation, Writing - review & editing. **Ying Tang:** Investigation, Writing - review & editing. **Zhiyun Ouyang:** Resources, Writing - review & editing. **Hemin Zhang:** Resources, Project administration. **Jianguo Liu:** Conceptualization, Methodology, Supervision, Resources, Writing - original draft, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary materials

Supplementary materials, methods, results, figures (S1–S10), and tables (S1–S5) to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.141749.

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