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

Integration across a metacoupled world

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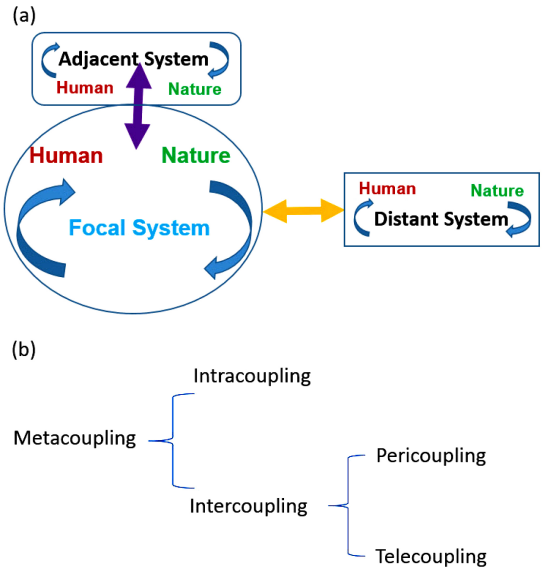
ABSTRACT. Human-nature interactions are complex and have important implications for achieving sustainable development goals and addressing other global challenges. Although numerous studies have explored human-nature (or human-environment) interactions and generated useful insights, they are largely disintegrated. Because conceptual frameworks are the foundation of quantitative and qualitative integration, many have been proposed but focus mainly on human-nature interactions within a specific system. To reflect human-nature interactions between distant coupled systems, the framework of telecoupling (socioeconomic and environmental interactions over distances) has been developed. However, no framework has explicitly integrated human-nature interactions between adjacent coupled systems, let alone within a coupled system as well as between adjacent and distant coupled systems simultaneously. To fill such an important gap, in this paper I present an integrated framework of metacoupling: human-nature interactions within a system (intracoupling), between distant systems (telecoupling), and between adjacent systems (pericoupling). A metacoupled system is a set of two or more coupled systems that interact internally as well as nearby and far away, facilitated by agents affected by various causes with various effects. By differentiating and integrating intracoupling, pericoupling, and telecoupling, the metacoupling framework advances a systems perspective on global sustainability and human well-being. The framework can help uncover hidden systemic connections such as spillovers and feedbacks that may not be apparent when focusing on a particular system. To demonstrate the utility of the metacoupling framework, I illustrate its application to human-nature interactions within a global flagship nature reserve as well as between the reserve and the rest of the world. The illustration suggests that the framework has the potential to help holistically understand and integrate human-nature interactions from local to global scales, over time, and among organizational levels. Finally, I offer suggestions for operationalizing the metacoupling framework and discuss the need for new policy, governance, and management for a sustainable future across the metacoupled world.

Key Words: *Anthropocene; connection; conservation; coupled human and natural systems; globalization; human-environment interactions; human-environmental systems; human-nature interactions; intercoupling; intracoupling; metacoupling; metacoupling framework; metacoupled systems; Paris Agreement; pericoupling; social-ecological systems; sustainability; sustainable development goals; telecoupling; telecoupling framework*

INTRODUCTION

Human-nature interactions have increased in magnitude and extent enormously during the Anthropocene (Steffen et al. 2007, Caro et al. 2012). The main reason behind such a remarkable increase is the exponential rise in global human population and consumption. On one hand, humans have drastically changed nature (Crutzen 2006, Steffen et al. 2007, Zalasiewicz et al. 2015, Bertelsmeier 2017). On the other hand, humans have been substantially affected by changes in nature such as natural disasters and climate change (Toya and Skidmore 2007). What happens in a specific system not only affects that system but also other systems nearby and far away (Fig. 1a). For example, deforestation in the Amazon generates global impacts by emitting CO_2 (Pütz et al. 2014). The Ebola outbreak originating in West Africa profoundly affected people and the environment in these countries and sent shock waves to neighboring nations and many distant countries around the world (Omoleke et al. 2016). Brazil has exported millions of tons of soybeans to China and other countries (Sun et al. 2015), leading to a wide range of socioeconomic and environmental impacts in these countries and beyond. Biofuel mandates in Europe and the USA have caused cascading effects on food, energy, water, and land worldwide (Liu et al. 2013). Although no single study can address all complex human-nature interactions, it is essential to consider and integrate the most relevant and important human-nature interactions across local to global scales to achieve various human development and conservation goals such as the Aichi Biodiversity Targets, Paris Agreement, and United Nations'

Fig. 1. (a) A schematic diagram illustrating a focal coupled human and natural system, an adjacent system, and a distant system, as well as their interactions (indicated by arrows). (b) Metacoupling consists of intracoupling and intercoupling, which in turn includes pericoupling and telecoupling.



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Sustainable Development Goals (Future Earth, http://www.futureearth.org; United Nations, http://www.un.org/sustainabledevelopment/sustainable-development-goals).

Numerous studies have explored human-nature interactions and generated useful insights, but they are largely not integrated. In other words, most of the previous studies of human-nature interactions were conducted separately and not linked together. For example, studies on human-nature interactions within a system are not connected to those in other systems. Scholars and institutions have called for integrated approaches to avoid unintended consequences and achieve sustainable goals in the Anthropocene. Because conceptual frameworks are the foundation of quantitative and qualitative integration, many have been proposed (Liu et al. 2016*a*), and most frameworks focus on human-nature interactions within a specific place (Binder et al. 2013, National Science Foundation 2014). A place can be viewed as a coupled human and natural system (coupled system for short, e.g., social-ecological system, human-environment system; Turner et al. 2003, Liu et al. 2007, Folke et al. 2011). To reflect human-nature interactions between distant coupled systems (Liu et al. 2015*a*), the framework of telecoupling (socioeconomic and environmental interactions over distances) has been developed (Liu et al. 2013). However, no frameworks have explicitly integrated human-nature interactions between adjacent coupled systems. When issues between adjacent systems are discussed, focuses have usually been on either environmental issues such as pollution crossing the border between Canada and the USA (Wotawa and Trainer 2000) or socioeconomic issues such as human migrants from Mexico to the USA (Ryo 2013) rather than socioeconomic and environmental issues simultaneously. Furthermore, no frameworks simultaneously integrate human-nature interactions within a coupled system as well as between adjacent and distant coupled systems.

This paper proposes a holistic framework of metacoupling that integrates human-nature interactions within a system (intracoupling), between adjacent systems (pericoupling), and between distant systems (telecoupling); discusses ways to operationalize the framework; and suggests the need for new policy and management. The framework advances a systems perspective on global sustainability by differentiating and integrating intracoupling, pericoupling, and telecoupling. To demonstrate the utility of the metacoupling framework and make the conceptual distinctions concrete, this paper illustrates the framework with examples drawn mainly from human-nature interactions within a high-profile nature reserve and between the reserve and the rest of the world. The concepts and approaches are broadly applicable to study and govern human-nature interactions across planet Earth, and have the potential of helping address global challenges such as achieving the United Nations Sustainable Development Goals.

OVERVIEW

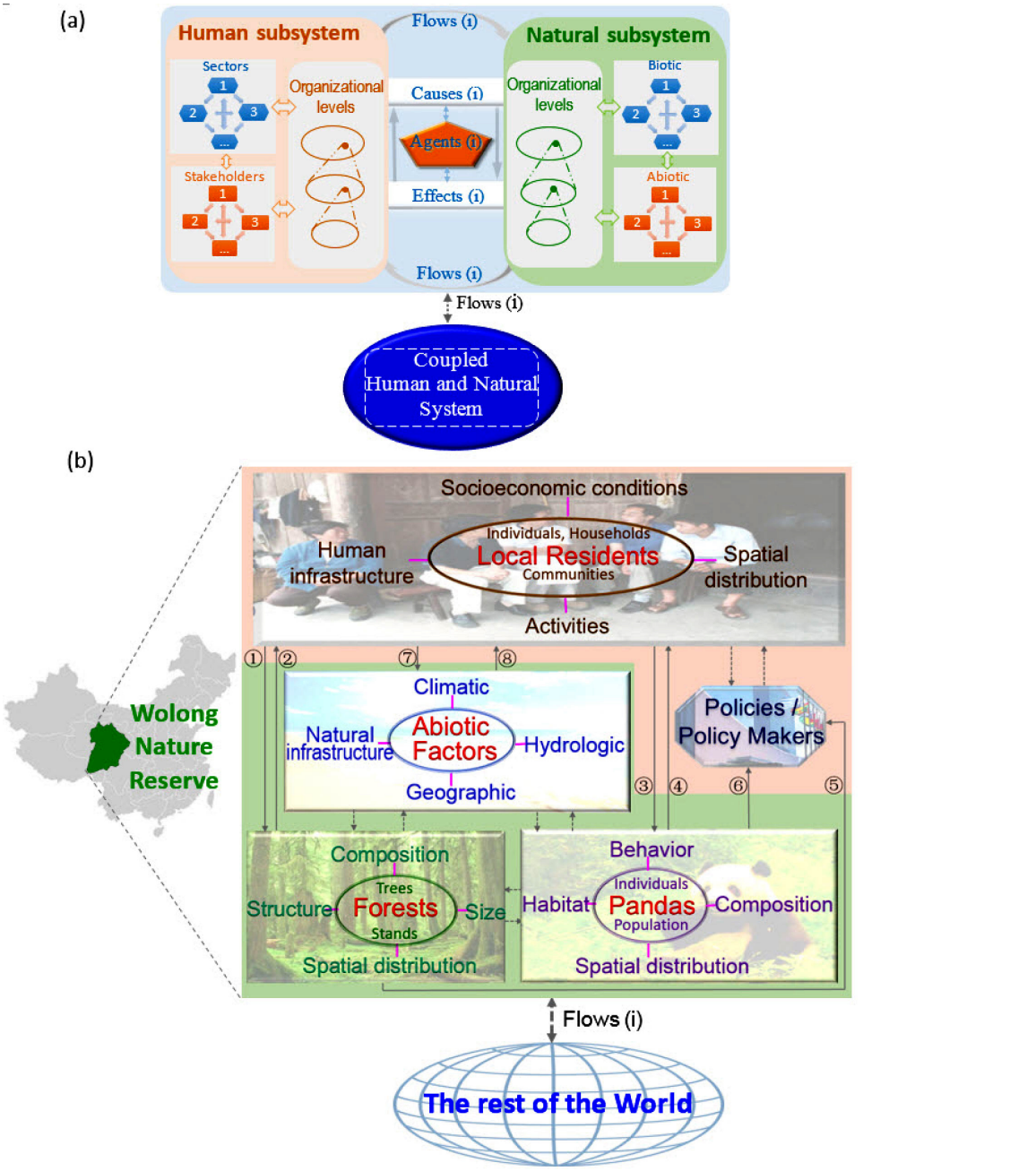
To systematically understand human-nature interactions (couplings), they can be classified into three major types: human-nature interactions within a coupled system (intracoupling), between distant coupled systems (telecoupling), and between adjacent coupled systems (pericoupling). Together, they constitute metacoupling. The metacoupling framework encompasses frameworks of intra-, tele-, and pericoupling as well as their interrelationships. Intracoupling can also be called internal coupling, while pericoupling and telecoupling are couplings between two or more systems (or intercouplings; Fig. 1b). The metacoupling framework uses a multilevel analytic approach, because metacoupled human and natural systems are both vertically and horizontally structured. A metacoupled system is partially analogous to the concept of metapopulation in ecology, meaning a set of populations connected ecologically through dispersal (Hanski 1998), but a metacoupled system is more comprehensive because it includes other types of interactions besides ecological connections. Although the metacoupling framework can accommodate all human-nature interactions, in practice not all interactions are studied in a research project or reported in a single publication. The selected interactions are determined by factors such as data availability, expertise, time, funding, space limitation, researchers' interests, scientific significance, and management priorities.

In this paper I illustrate the metacoupling framework and its usefulness by applying it to analyze some human-nature interactions within Wolong Nature Reserve in China and those between Wolong and the rest of the world. The use of this example does not mean that all the coupled systems under this framework would need to be similar, i.e., as socially defined spatial regions. Wolong is a 2000-km² protected area within a global biodiversity hotspot in southwestern China (Liu et al. 1999*a*, 2003*a*, Myers et al. 2000). It is home to the world-famous giant panda (*Ailuropoda melanoleuca*) and over 6000 other animal and plant species. Wolong also is home to approximately 5000 residents (mostly farmers) in more than 1100 households (Liu et al. 2016*b*). Between 1982 and 2012, the numbers of local residents and households in Wolong increased by 35% and 128%, respectively (An et al. 2016). The reserve boundary was defined by the government according to mountain ridges, panda habitat conditions, and village locations. Like other places, there are many human-nature interactions within Wolong, e.g., timber harvesting, fuelwood collection; between Wolong and distant areas, e.g., panda loans, tourism, trade of agricultural products, information dissemination, labor migration (Chen et al. 2012*a*, Liu et al. 2015*a*); and between Wolong and adjacent areas, e.g., panda movement across reserve boundaries, human immigration to the reserve through marriage, exchanges of goods and products, water outflows from the rivers inside the reserve. Some of the human-nature interactions, e.g., timber harvesting or fuelwood collection, existed before the reserve was established, while other interactions, e.g., panda loans and tourism, emerged after the reserve's establishment. For the sake of illustration, I use two examples for each type of human-nature interaction.

INTRACOUPLING FRAMEWORK

The intracoupling framework conceptualizes human-nature interactions within a coupled human and natural system as reciprocal processes including feedbacks (Fig. 2a). Examples of intracoupling processes include harvesting, farming, consumption, road construction, house construction, fishing, mining, grazing, fuelwood collection, collection of herbal medicine, hunting, poaching, genetic engineering, bioengineering, ecological engineering, restoration, polluting the environment, manufacturing, boating, and birding. A coupled system consists of five major components: subsystems, agents, flows, causes, and effects. There are two main subsystems (Fig. 2a). The human subsystem consists

Fig. 2. (a) General conceptual framework of intracoupling (human-nature interactions within a coupled system). A coupled system includes human and natural subsystems with interacting components at different organizational levels (modified from Liu et al. 2016*a*). Arrows represent the directions of flows between subsystems. Causes, agents, effects, and flows refer to those related to intracoupling, which is indicated by the letter i within parentheses. (b) Application of the framework to Wolong Nature Reserve. Each flow is represented by an arrow and associated with relevant causes, agents, and effects (they are not shown for the sake of simplicity). Arrows 1 and 3 indicate flows of local residents to forests and panda habitats to carry out various activities, respectively, while arrows 2 and 4 refer to timber/nontimber products collected by local residents from forests and panda habitats to households. Arrows 5 and 6 refer to information about forests and conditions of pandas and their habitats disseminated to policy makers. Arrows 7 and 8 show the reciprocal impacts of local residents and abiotic factors. Dashed arrows indicate interactions within human or natural subsystems. Spillover systems due to intracoupling may include other parts of the world, e.g., the rest of the world in terms of CO_2 emissions.



of diverse stakeholders, e.g., workers, farmers, and government officials, in various sectors, e.g., agriculture. The natural subsystem includes different abiotic, e.g., climate, and biotic, e.g., plants and animals, elements. Human and natural subsystems and their constituents influence each other at the same and across organizational levels (Fig. 2a). These influences are achieved through the flows of material, energy, and information within and between subsystems. Flows are facilitated or hindered by agents, e.g., stakeholders and animals. Causes are reasons behind intracouplings, e.g., timber harvesting, which generate socioeconomic and ecological effects, e.g., new houses, deforestation (Fig 2a). Human-nature interactions within a coupled system can also generate spillover effects (or off-site effects or spatial externalities) beyond the system boundary (van Noordwijk et al. 2004). Where these spillover effects occur can be called a spillover system, which is another coupled system (Fig. 2a). Spillover effects are common. Economists have studied economic externalities (Anselin 2003) and ecologists have explored ecological externalities (Halpern et al. 2008). However, few studies have explored socioeconomic and environmental spillover effects simultaneously. Furthermore, a spillover system has rarely been treated as a coupled system, and other components of the system (subsystems, agents, flows, causes) are seldom studied.

The intracoupling framework proposed here builds on but differs in several ways from previous frameworks of human-nature interactions (e.g., Millennium Ecosystem Assessment 2005, Ostrom 2009, Binder et al. 2013, National Science Foundation 2014, Liu et al. 2016*b*). First, it differentiates and conceptualizes the interrelationships among agents, flows, causes, and effects. Second, it explicitly specifies that interactions within a system can generate spillover effects on other systems nearby and/or far away. Third, it is connected and consistent with frameworks for interactions between adjacent and/or distant systems (see sections below). As a result, the intracoupling framework is more realistic and comprehensive than previous frameworks in reflecting patterns and processes in the real world.

In Wolong, many human-nature interactions exist at multiple organizational levels, involving local residents (individual people, households, and communities), forests (individual trees, forest stands), pandas (individual pandas, populations), and policy makers and reserve managers (individuals, and groups; Fig. 2b). Through various human activities, e.g., fuelwood collection or timber harvesting, local residents affect forest characteristics, such as type, e.g., deciduous or coniferous, areal extent, spatial configuration, e.g., continuous or fragmented, and structure, e.g., canopy cover and species composition. The flows between human and natural subsystems consist of movement of timber and fuelwood from forests to households and individuals from households to forests (Fig. 2b). The causes include the need to have fuelwood for cooking and heating (An et al. 2001). Local residents and reserve managers (agents in the framework) regulate and monitor resident activities such as timber harvesting and fuelwood collection (Yang et al. 2013). Because forests provide cover and contain understory bamboo species, staple food for pandas (Schaller et al. 1985, Reid and Hu 1991, Taylor and Qin 1993), changes in forest characteristics can affect panda habitat, behavior, and distribution (Schaller et al. 1985).

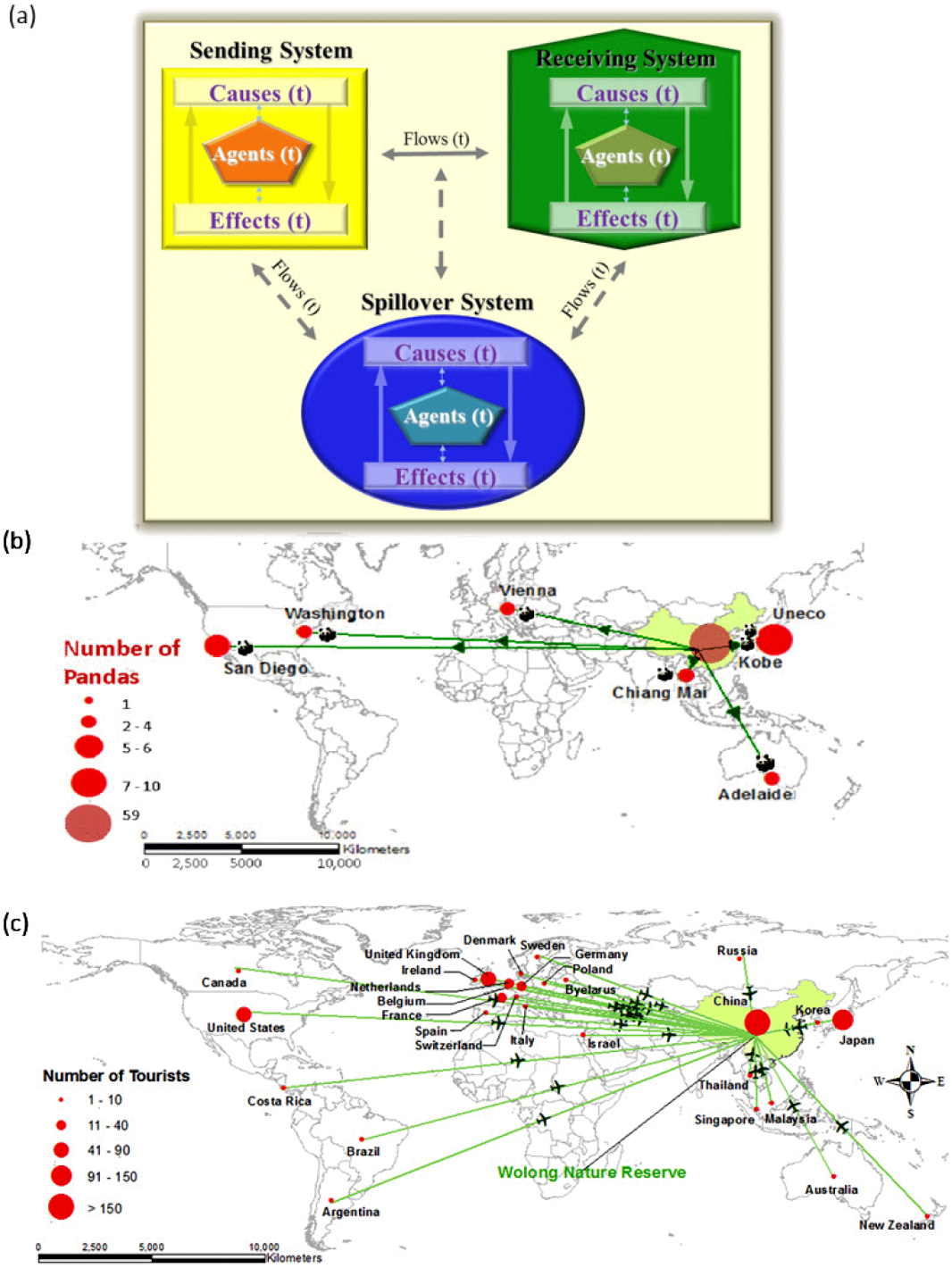
The effects of human activities on forests, e.g., deforestation, and panda habitat, e.g., loss and fragmentation, generate feedbacks that affect human conditions, e.g., socioeconomic and demographic, and activities (Fig. 2b). For example, as forests shrink, they become more distant from households, making the extraction of timber and nontimber forest products more difficult and time consuming (He et al. 2009) and resulting in degradation and fragmentation of panda habitat (Liu et al. 2001, Viña et al. 2007), which may lead to less tourism. To counter the loss of forests, Wolong has been implementing several programs such as the Grain-to-Green Program (GTGP) in 2000, which encourages farmers to return steep hillside cropland to forest by providing cash, grain, and tree seedlings (Liu et al. 2008), and the Natural Forest Conservation Program (NFCP) in 2001, which bans logging and provides cash for households to monitor forests to prevent illegal harvesting. These and other policies together have led to a progressive restoration of forest cover and panda habitat in Wolong (Viña et al. 2007, 2011, 2016*a,b*, Tuanmu et al. 2016).

Human-nature interactions within Wolong also generate spillover effects. For example, fuelwood consumption in Wolong emits CO_2 into the atmosphere that spills beyond Wolong and can affect the rest of the world through contributions to climate change (Fig. 2b). A major cause of the CO_2 emitted in Wolong flows to spillover systems is atmospheric circulation. Agents in Wolong and other systems cannot control atmospheric circulation and thus cannot directly prevent spillover of CO_2 emitted in Wolong to other systems. However, agents can indirectly reduce or prevent CO_2 flows from Wolong to spillover systems by helping reduce fuelwood consumption and thus CO_2 emissions from Wolong. For example, a small hydropower station built over a river inside Wolong provides reliable electricity to Wolong residents despite negative impacts on some aquatic organisms in the river, and the government provides subsidies to Wolong residents so they can afford to replace fuelwood with electricity (Liu et al. 2016*b*).

TELECOUPLING FRAMEWORK

The telecoupling framework guides research and management of human-nature interactions over distances (Fig. 3a; Liu et al 2013). Telecoupling is an umbrella concept that includes trade, migration, species invasion, payments for ecosystem services, technology transfer, knowledge transfer, information dissemination, air circulation, water transfer, transfer of pollutants/waste, and foreign direct investment (Liu et al. 2013). The framework consists of five major components: systems, flows, agents, causes, and effects (Fig. 3a). A telecoupled system encompasses two or more coupled systems linked through flows. Depending on the direction of flows, e.g., movement of material, energy, information, people, goods, or services, a system can be treated as a sending, receiving, or spillover system (affected by the flows between sending and receiving systems). Although sending and receiving systems are distant, spillover systems can be distant and/or adjacent to other systems (Fig. 3a). Each coupled system includes three interconnected components: agents, causes, and effects (Fig.3a). Although these components are embedded within a coupled system, regarding them as separate can help emphasize their roles in telecouplings and their relationships with other components. Causes are reasons behind the formation of a telecoupling that produces socioeconomic and environmental effects across the telecoupled system. Agents boost or impede various flows. Each component encompasses many dimensions or elements. For

Fig. 3. (a) General conceptual framework of telecoupling (human-nature interactions between two or more distant coupled systems; modified from Liu et al. 2013). It shows five major components and interrelationships—systems (sending, receiving, and spillover), flows, agents, causes, and effects related to telecoupling, which is represented by letter t within parentheses. (b) Application of the telecoupling framework to Wolong Nature Reserve showing locations of zoos in China and in other countries that received pandas from Wolong (from Liu et al. 2015*a*). (c) Application of the telecoupling framework to Wolong Nature Reserve showing sampled tourists to Wolong (2006–2007) from sending systems in China and in other countries (from Liu et al. 2015*a*). Spillover systems are areas affected by panda loans from Wolong and tourism to Wolong.



instance, corporations, government agencies, households, and individuals can be agents that produce environmental and socioeconomic effects. Two example telecouplings with opposite flow directions are shown in this section. Although the telecoupling framework and the examples are described in Liu et al. (2013, 2015*a*), a brief overview here lays a foundation for the remaining sections of this paper.

In addition to wild pandas, Wolong has a breeding base with more than 200 captive pandas (Liu et al. 2015*a*). The panda loan program allows zoos to borrow captive pandas (Fig. 3b) for a period of several years and often involves a fee (as much as US$1 million per panda per year). The total number of panda loans (flows) increased from fewer than 20 in 1998 to 85 in 2010 (Liu et al. 2015*a*). The sending system for pandas is Wolong, while the receiving systems include many zoos around the world such as the Beijing Zoo and the National Zoo in Washington, D.C. (Fig. 3b). There are many spillover systems, such as areas from which people go to see the pandas in the receiving systems. The agents encompass people and organizations that facilitate panda loans, like China's State Forestry Administration, which designs policies and agreements. Panda loans occur because of a number of causes (Liu et al. 2015*a*), such as strong interest in pandas (Schaller 1993). Panda loans generate both socioeconomic and environmental effects across the telecoupled systems. Socioeconomic effects include facility construction and operation costs (Buckingham et al. 2013) and entrance fees and travel costs for those who visit the zoos (Liu et al. 2015*a*). The environmental effects include CO_2 emissions from transporting pandas between sending and receiving systems. Feedbacks also occur from panda loans. For instance, the first pair of pandas sent to The National Zoo in the USA garnered such widespread appeal that a second pair of pandas was later sent after the first pair died (Liu et al. 2015*a*).

The number of tourists to Wolong increased dramatically, peaking in 2006 with 220,000 visitors (Liu et al. 2016*c*), declined in 2007 because of road construction, and almost completely stopped after the devastating Wenchuan earthquake in 2008 (Viña et al. 2011). Wolong is the receiving system for tourists (Fig. 3c), while the sending systems include many places in China and the rest of the world. Surveys of 1063 tourists in 2006 and 2007 indicated that they came from 30 provinces and cities of mainland China, Taiwan, and Hong Kong and 26 countries (Fig. 3c). Among the spillover systems are areas that support the tourism industry and stopover cities, e.g., Chengdu, en route to Wolong. Many agents are involved in Wolong's tourism, including government agencies that develop and implement tourism policies, e.g., the Sichuan Tourism Bureau. Tourism is determined by ecological, cultural, political, economic, and technological causes. For example, pandas, natural forests and wildlife, and clean air and water in Wolong are top ecological draws (Liu et al. 2012). Socioeconomic and environmental effects of tourism are diverse. For instance, during the peak tourism development stage in 2006, 76.5% of Wolong households earned income from tourism directly or indirectly (Liu et al. 2012). Tourism also generates economic benefits to spillover systems, e.g., areas in which outdoor clothes and hiking shoes are manufactured. Environmental effects include tourists' influences on vegetation along trails, donations to support breeding and research, i.e., the Wolong Panda Club (http://pandaclub1.kepu.net.cn/english/index.html, and CO_2 emissions from tourists' travel to Wolong (Liu et al. 2015*a*). Tourism also produces feedback effects. For example, tourists to Wolong share experiences and information with friends and colleagues, prompting others to visit Wolong (Liu et al. 2015*a*).

PERICOUPLING FRAMEWORK

The pericoupling framework (Fig. 4a) addresses human-nature interactions between adjacent systems. Pericoupling processes share some characteristics with telecoupling processes, but the distance between systems and associated attributes differ. For example, trade between adjacent countries is a pericoupling process while trade with faraway countries is a telecoupling process, and tourism with tourists from a neighboring region is a pericoupling process while tourism with tourists from a distant region is a telecoupling process. In many situations, pericouplings play significant roles in shaping human-nature dynamics. The pericoupling framework complements the telecoupling framework (Liu et al. 2013) and has different agents, flows, causes, and effects. Two examples with opposite flow directions between Wolong and abutting areas illustrate pericouplings.

Unlike in the panda loan program, wild pandas in Wolong may move to areas next to the reserve (Fig. 4b). The agents facilitating the flows (panda movements) include wild pandas and government agencies, e.g., Wolong Administration Bureau, that protect the panda habitat and movement corridors. There are two major causes behind the movement. First, like other animals, pandas move around to find food and mates and avoid potential risks. Second, pandas do not recognize reserve boundaries when no artificial barrier, e.g., fence, prevents their movement. The effects of panda movement across the boundaries include food and mates obtained and risks avoided. In terms of systems, the reserve is the sending system, and the abutting areas are receiving systems (Fig. 4b). The spillover systems are other areas that are affected by or affect panda movement.

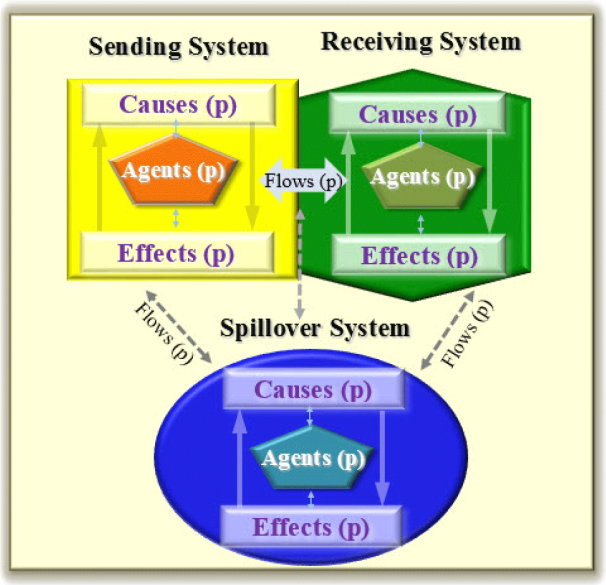
Regarding the second example, people from adjacent areas immigrate into the reserve through marriage. In 2010, among the 370 married women in the 287 households interviewed, 49 women (flows) were born in neighboring counties (Fig. 4b). The main cause behind the immigration is economic, because the living standard in Wolong is higher than in the abutting counties. Among the agents are the immigrants and matchmakers. After a woman marries and moves to Wolong, she may introduce other women in her hometown to men in Wolong. Such social networks have played an important role in marriage-based immigration. Adjacent areas are sending systems while the reserve is the receiving system (Fig. 4b). Spillover systems include areas affected by immigrants. Immigration through marriage has both socioeconomic and ecological effects. For instance, it increases the number of people and households and creates a higher demand for natural resources inside the reserve.

METACOUPLING FRAMEWORK

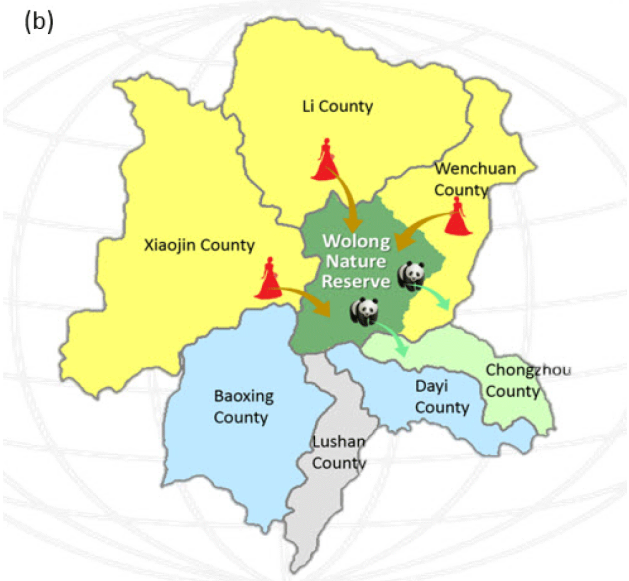
The preceding three sections focus on intracouplings (Fig. 2), telecouplings (Fig. 3), and pericouplings (Fig. 4) separately. In reality, they often occur simultaneously and constitute metacouplings (Fig. 5a). Although all three types of couplings have agents, flows, causes, and effects (Fig. 5a), there are differences, similarities, and interrelationships among them (Table 1). For example, flows in intracouplings refer to those

Fig. 4. (a) General conceptual framework of pericoupling (human-nature interactions between two or more adjacent coupled systems; modified from Liu et al. 2013). It demonstrates five major components and interrelationships: systems (sending, receiving, and spillover), flows, agents, causes, and effects related to pericoupling, which is represented by letter p within parentheses. (b) Application of the pericoupling framework to Wolong Nature Reserve showing immigration to Wolong from adjacent areas through marriage and panda movement across reserve boundaries. For marriage, counties (Xiaojin, Li, Wenchuan) that sent brides to Wolong are sending systems, and other neighboring counties and distant areas may be spillover systems.

(a)



(b)



within a system, and flows in telecouplings and pericouplings are between systems. Some couplings may share the same causes and agents, which may generate similar, different, or joint effects (Table 1). Agents in different systems or subsystems may work together to make a coupling possible. The relationships among couplings are complex. They may enhance or offset each other, e.g., flows and effects of telecouplings may amplify or dampen those of pericouplings. Spillover systems induced by intracouplings, pericouplings, and telecouplings may or may not overlap. Another interrelationship is that different types of couplings may be converted into each other. For instance, after someone in one system is married to a person from an adjacent system (pericoupling), the latter may carry out activities within the receiving system (intracoupling).

Applying the metacoupling framework to Wolong (Fig. 5b) reveals complex interrelationships among intracoupling, pericoupling, and telecoupling. Reducing the negative effects of local residents on panda habitat can increase the number of pandas in the wild. More wild pandas may enhance panda movement across boundaries and increase panda loans because wild pandas are added to the breeding base, which produces more pandas for loans and for tourists to view. More tourists can help local people earn more income, thus attracting more women from neighboring areas to marry men inside the reserve. However, too many immigrants through marriage may increase pressure on panda habitat inside the reserve, thus reducing the number of pandas and generating negative cascading effects, e.g., reduction in panda movement, panda loans, and tourists.

The interrelationships may be nonlinear. Changes in intracouplings may have nonlinear responses to pericouplings and telecouplings, or vice versa. For instance, the increase in the number of pandas may not linearly elevate the number of tourists, and the rising number of tourists may not increase immigrants from adjacent areas linearly. These nonlinear responses may be affected by many factors such as natural disasters and policies. For example, the 2008 earthquake essentially stopped tourism in Wolong because the road into the reserve was destroyed (Liu et al. 2015*a*). The relationships may have time lags and legacy effects (Liu et al. 2007). For instance, income from tourism allowed some households to afford more education for their children, thus increasing the probability of those kids going to college and reducing pressure on panda habitat (Liu et al. 1999*b*). However, such a reduction may be delayed because elementary and high school education takes 12 years. Once the kids go to college, they usually settle in cities and do not have children in Wolong (Liu et al. 2003*b*). Thus, such an action has lasting legacy effects in terms of reduction in human pressure on panda habitat.

The interrelationships can also generate new types of couplings or strengthen existing ones. For instance, the need to build more tourism facilities has prompted local residents to collect sand and rocks in the rivers of Wolong. Tourists' demands for local products such as herbal medicine stimulate residents' interest in producing more local products.

OPERATIONALIZING THE METACOUPLING FRAMEWORK

To turn the metacoupling framework from a conceptual construct to a more useful tool, it is important to make it operationalizable. This section highlights needs and tools for framework

Fig. 5. (a) General conceptual framework of metacoupling (human-nature interactions within and between adjacent and distant coupled systems, integrated frameworks of Figs. 2a, 3a, and 4a). Letters i, p, and t within parentheses after causes, effects, agents, and flows refer to intracoupling, pericoupling, and telecoupling, respectively. There may be three corresponding types of spillover systems. (b) Application of the metacoupling framework to Wolong Nature Reserve (a combination of Figs.2b, 3b, 3c, and 4b).

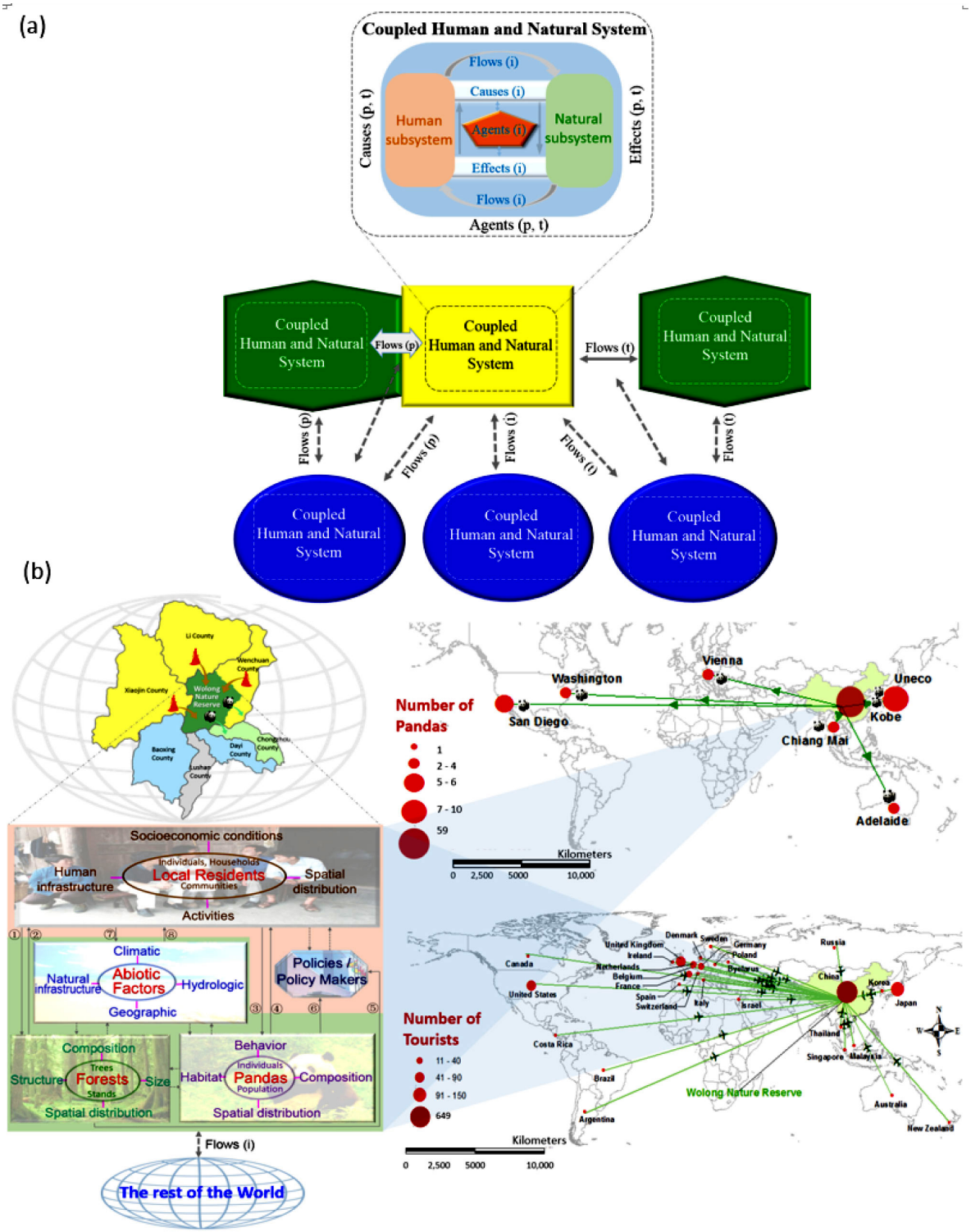


Table 1. Comparisons among intracoupling, pericoupling, and telecoupling.[†]

	Intracoupling	Pericoupling	Telecoupling
Definition	Human-nature interactions within a coupled human and natural system	Human-nature interactions between adjacent coupled human and natural systems	Human-nature interactions between distant coupled human and natural systems
Sending system	Not applicable (only one focal system is of interest)	System that sends information, energy, material, people, organisms, and capital to adjacent system(s)	System that sends information, energy, material, people, organisms, and capital to distant system(s)
Receiving system	Not applicable (only one focal system is of interest)	System that is adjacent to and receives information, energy, material, people, organisms, and capital from sending system(s)	System that is distant from and receives information, energy, material, people, organisms, and capital from sending system(s)
Spillover system	System that is affected by or affects human-nature interactions within the focal system.	System that is affected by or affects interactions between adjacent sending and receiving systems	System that is affected by or affects interactions between distant sending and receiving systems
Number of coupled human and natural systems involved	One or more (one focal system, with or without spillover system[s])	Two or more (sending and receiving systems, with or without spillover system[s])	Two or more (sending and receiving systems, with or without spillover system[s])
Distance between coupled human and natural systems	Focal and spillover systems can be adjacent or distant	Sending and receiving are adjacent, spillover systems can be adjacent or distant from sending or receiving systems	Sending and receiving are distant, spillover systems can be adjacent or distant from sending or receiving systems
Flows	Movement of information, energy, material, organisms, people, and/or capital between human and natural subsystems within a system, as well as between the system and spillover system	Movement of information, energy, material, organisms, people, and/or capital between adjacent sending and receiving systems as well as with spillover systems	Movement of information, energy, material, organisms, people, and/or capital between distant sending and receiving systems as well as with spillover systems
Agents	Entities that are involved in human-nature interactions within a system	Entities that are involved in human-nature interactions between adjacent systems	Entities that are involved in human-nature interactions between distant systems
Causes	Reasons behind intracoupling	Reasons behind pericoupling	Reasons behind telecoupling
Effects	Socioeconomic and environmental consequences of intracoupling	Socioeconomic and environmental consequences of pericoupling	Socioeconomic and environmental consequences of telecoupling
Origin and destination of flows	Focal system, spillover system	Sending, receiving, and spillover systems	Sending, receiving, and spillover systems
Locations of agents, causes, and effects	Focal system, spillover system	Sending, receiving, and spillover systems	Sending, receiving, and spillover systems
Complexity of governance and management	Low	Medium	High

[†]Note: The table considers only a simplified version of human-nature interactions. For example, there may be multiple sending, receiving, and spillover systems. Some sending, receiving, and spillover systems of intracoupling, pericoupling, and telecoupling may overlap.

operationalization, definition of system boundaries, distance and scale, procedure, and feasibility.

Needs and tools for framework operationalization

Studying metacouplings is important to understand and solve global challenges such as air pollution, biodiversity loss, climate change, conservation, disease spread, economic development, ecosystem services, energy shortages, food security, human well-being, land degradation, sustainability, species invasion, and water pollution and shortages. To address these and other challenges, many important questions regarding metacouplings need to be answered. For instance, how do metacouplings emerge, evolve, and dissolve? How do human and natural systems become coupled, what does it take to decouple systems, and how do decoupled systems become recoupled? Do intracoupling, pericoupling, and telecoupling emerge at the same time or in a particular order? Do they dissolve in the same order as their emergence? Do they become stronger and weaker in a synchronized manner? What is the relative importance of intracoupling, pericoupling, and telecoupling in system dynamics, resilience, vulnerability, and sustainability? How does the relative importance change over time and across space? What factors affect their relative importance? How do intracoupling, pericoupling, and telecoupling interact with each other, e.g., amplify and offset? How does telecoupling drive changes in intracoupling or pericoupling, and vice versa? How do feedbacks among them propagate?

Answering these and other related questions requires the operationalization of the metacoupling framework, which can benefit from a portfolio of tools that have been used in telecoupling research and in other fields. For example, because both telecoupled and metacoupled systems are essentially networks, network science may offer valuable tools for analyzing system dynamics and interrelationships (Bodin and Prell 2011). Statistical methods have been widely employed to detect the patterns of flows and effects (Silva et al. 2017). Remotely sensed data have proved to be powerful in detecting effects of telecouplings on landscape changes across local to regional scales (Sun et al. 2017). General solutions and more effective ways are

needed to merge data on biophysical and socioeconomic issues by accumulating and going beyond case-by-case experiences. Agent-based modeling (ABM) is increasingly used in many fields such as land use and land cover change and coupled human and natural systems, but the agents are often limited to those within a coupled human and natural system (Parker et al. 2003, Janssen and Ostrom 2006, Chen et al. 2012*b*, Schulze et al. 2017). As the first effort, a group of interdisciplinary researchers have proposed developing a telecoupled agent-based model (TeleABM) to simulate telecoupling processes, e.g., international trade, as well as their socioeconomic and environmental effects under the telecoupling framework (Liu et al. 2014). Telecoupling Toolbox, which contains a suite of new spatially explicit tools, has been developed to study dynamics of telecoupled systems (Tonini and Liu 2017). TeleABMs and Telecoupling Toolbox should be expanded toward the development of metacoupled agent-based models (MetaABMs) and Metacoupling Toolbox to simulate dynamics of metacoupled systems.

Identification of system boundaries

As in other types of research, setting system boundaries is important because different boundaries require different research times, efforts, and other resources; and because they may lead to different results. The metacoupling framework is flexible in terms of system boundaries, which may be determined by a given problem, issue, resource, agent, action, policy, and/or process. Systems do not necessarily need to be defined by spatial units. Some systems have natural boundaries, like watersheds with geologic and other characteristics that govern the way water drains to the defining point, and like islands or biomes with distinct biophysical edges. A social system might be defined by cultural networks or political boundaries. In the discipline of system dynamics, the system boundaries are determined relative to behavior(s) of interest, and a system is defined as the structural components and causal connections that lead to the behavior(s). Very frequently, coupled systems are defined by geographical, political, administrative, and management boundaries, e.g., continental, national, subnational, regional, provincial, state, county, township, village, nature reserve, protected area (Asbjornsen et al. 2015, Dong and Sherman 2015, Rammer and Seidl 2015, Boone and Lesorogol 2016, Giuliani et al. 2016, Iwamura et al. 2016, Moritz et al. 2016, Noel and Cai 2017, Shindler et al. 2017, Tesfatsion et al. 2017), which may include both social and natural boundaries, e.g., in the example of Wolong Nature Reserve as an administrative unit. Such a definition has some advantages. One advantage is that data such as gross domestic products and population are collected within those boundaries. Although natural and socioeconomic boundaries often do not overlap well, boundaries of some biophysical data such as those from satellites can be tailored to be consistent with those of socioeconomic data (Viña et al. 2007). Another advantage is policy relevance of research findings because policies are usually developed and implemented within those boundaries. As a result, such research is directly useful for management and governance. Of course, there are also downsides in that many natural processes such as animal movement and environmental flows do not recognize those political and administrative boundaries. However, some natural processes also may disregard natural boundaries, and some social processes may ignore political and administrative boundaries. For example, animals and moisture in the atmosphere may move across different watersheds, and people may cross governmental borders illegally.

The metacoupling framework reconciles and takes into account natural, management, political, and administrative boundaries. For example, in the real world, pandas and people regularly cross the reserve boundary, thus they should be part of the system naturally defined by these flows and interactions rather than the reserve boundaries. However, another reality is that the reserve is managed separately from areas outside the boundary. To account for interactions within a system boundary as well as those nearby and far away, the concepts and frameworks of intra-, peri-, tele-, and metacoupled systems are proposed to help capture the two realities. Finally, it should be emphasized that defining system boundaries depends on research goals and that the growing body of empirical research may help identify the most objectively correct ways to differentiate between focal and adjacent systems or adjacent and distant systems.

Distance and scale

Distance can be physical (physical length between objects such as Euclidean distance) or geographical (distance between geographical coordinates along the Earth's surface in terms of latitude and longitude). It can also be defined socially or institutionally (Eakin et al. 2014). Socially close people can be physically distant, or vice versa (Friis and Nielsen 2017).

Distance is also a relative concept, depending on the questions and subjects of interest. Even for the same distance, different transportation tools may change a person's perception of long vs. short distances. For example, if a person can drive, 20 kilometers is short, but if the person has to walk, 20 kilometers is long. Although such relativity may be sometimes confusing, it provides flexibility for various studies. For example, the size of an aquatic ecosystem can range from a small pond, e.g., 10 m^2, to large lakes such as Lake Michigan, 58,000 km^2. Such an enormous variation in ecosystem size gives ecologists flexibility to explore ecological patterns and processes across local to global scales. Similarly, the telecoupling framework with a relative distance concept has been consistently operationalized. Among the previous telecoupling studies, the distances between sending and receiving systems range from 100 km to thousands of kilometers (Liu and Yang 2013, Liu 2014).

The metacoupling framework further addresses the challenge in defining distances that the telecoupling framework encounters, i.e., how far is distant? One can use the pericoupling and telecoupling frameworks to address interactions between systems that are nearby, e.g., those sharing boundaries, and far away, e.g., those not sharing boundaries, respectively. Thus, no matter how distance is defined, one of these two frameworks can be used. Furthermore, if one is not interested in differentiating short vs. long distances, he or she can treat pericoupling and telecoupling together as intercoupling (Fig. 1b).

The metacoupling framework can help address human-nature interactions across local to planetary scales. It connects cross-scale processes. A system at any scale can have intracoupling, pericoupling, and telecoupling. For example, a county has human-nature interactions within the county (intracoupling), with neighboring counties (pericoupling), and with distant

counties within a state (or province) and beyond (telecoupling). Similarly, a nation has human-nature interactions within the nation (intracoupling), with neighboring nations (pericoupling), and with distant nations (telecoupling). Planet Earth has human-nature interactions within itself (intracoupling), with neighboring planets (pericoupling), and with distant planets (telecoupling).

As scales vary, systems may also differ for the same types of relationships. For example, regarding relationships between adjacent systems at local and national scales, Wolong's adjacent systems include seven counties (Fig. 4b), while China's adjacent systems include a dozen nations. Each adjacent coupled system may have a different interaction with the focal coupled system.

Operationalization procedure

Operationalizing the metacoupling framework may consist of six interrelated phases (Fig. 6a).

Phase one: Set research goals, including the formulation of specific objectives, questions, and hypotheses. These are shaped by researchers' interest, scientific significance, and other factors. If possible, it is good to work with relevant stakeholders to codesign, coproduce, and coimplement the research during this and later phases.

Phase two: Define focal system(s) or systems(s) of interest. The definition of focal system(s) is determined by a number of factors such as research goals, objectives, questions, and feasibility including data availability and logistics. Wolong Nature Reserve is the focal system for this paper because it is a high-profile reserve, has relevant data, and has experienced two decades of coupled system studies (Liu et al. 2016*b*).

Phase three: Review literature and if necessary conduct additional studies on flows, agents, causes, and effects. One way to do this is to trace them across space. Where the flows start and end are the system boundaries. Entities that affect the flows are viewed as agents, reasons behind the flows are causes, and consequences from the flows are effects. In the Wolong case, previous observations indicate that Wolong experiences multiple types of internal, adjacent, and distant human-nature interactions through various flows such as movement of pandas and people (e.g., Liu et al. 2015*a*). Furthermore, preliminary studies on the interactions between Wolong and adjacent areas helped to identify system boundaries, flows, agents, causes, and effects related to Wolong metacouplings.

Phase four: Identify intracoupling, pericoupling, telecoupling, as well as sending, receiving, and spillover systems. They are selected based on available data as well as relevance and importance of flows, agents, causes, and effects. For the Wolong case, some examples of intracoupling, pericoupling, and telecoupling were selected according to their importance and data availability as well as their interrelationships. The types of coupling and directions of flows determined sending, receiving, and spillover systems. Data availability also dedicated the selection of the counties sharing boundaries with Wolong as adjacent systems for pericoupling analysis, and other places as distant systems for telecoupling analysis.

Phase five: Further study various components of the metacoupling framework and their interrelationships. This includes qualitative descriptions and quantitative measures of metacoupling components (agents, flows, causes, and effects) in each system and among systems, how and to what extent the different types of couplings interact with each other within and across systems, and how and why they change over time and across space. Figs. 2b, 3b, 3c, 4b, and 5b illustrate results from such further research in Wolong.

These phases are not necessarily sequential because important system components or processes may have been misrepresented or overlooked during earlier phase(s). Thus, some or even all phases may need to be cycled through more than once (Fig. 6a). In the Wolong case, one of the original flows chosen in the third phase was movement of water between Wolong and adjacent areas. After the fifth phase, the third phase was revisited and panda movement across Wolong boundaries was chosen to replace water flow, because panda movement helps better illustrate the interrelationships among different types of couplings as it links closely with another intracoupling (forest harvesting that affects panda habitat) and telecoupling (panda loans that have reciprocal interactions with movement of wild pandas).

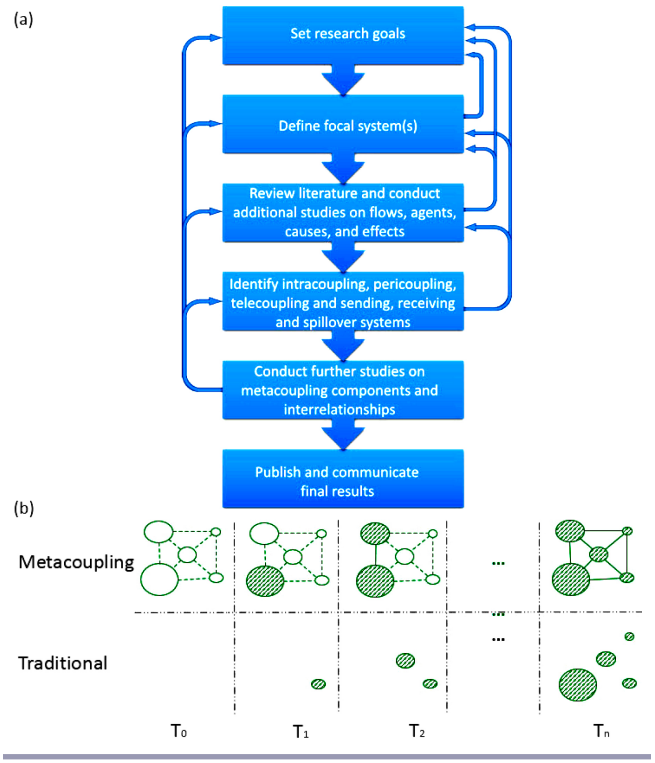


Fig. 6. (a) General procedure for operationalizing the metacoupling framework. (b) Comparison between metacoupling research approach vs. traditional research approach. Empty circles refer to unaddressed issues, while shaded circles are issues that have been addressed. The circle sizes illustrate relative importance of the issues. Dashed lines show connections among issues that exist in the real world but have not been discovered and integrated by researchers. Solid lines refer to the connection among issues established by researchers. T0, …, Tn indicate time period 0, …, n, respectively.

Phase six: Communicate the results through publications in peer-reviewed journals and books, give presentations in meetings and classrooms, engage relevant stakeholders in discussions of the results, and make results available through news and social media. Previous research results from Wolong have been widely published (e.g., Liu et al. 2015*a*, 2016*b*), communicated with various government agencies such as Wolong Nature Reserve Administration and China's State Forestry Administration to improve reserve management policies and human well-being, used as classroom materials for elementary to graduate schools, and distributed to news media such as *The New York Times* and China's Central Television Network (Revkin 2001, CCTV.com 2008), as well as social media like Facebook (Michigan State University Center for Systems Integration and Sustainability, https://www.facebook.com/MichStateCSIS).

The multiphase procedure helps capture system complexities such as heterogeneity and dynamics while ultimately defining systems in a spatially explicit manner. Friis and Nielsen (2017) raise the concern that defining systems a priori could mask the complexity and fluidity of human-nature interactions in telecoupling research and could miss the detection of outcomes of telecoupling. The systems under the metacoupling framework are not finalized a priori. The second and third phases are equivalent to the process of treating the system and its boundaries as epistemological constructs described by Friis and Nielsen (2017). They lay the foundation for the fourth and fifth phases, which are equivalent to an understanding of systems as ontological entities, e.g., places and regions as "real" systems (Friis and Nielsen 2017). Going through the second and third phases before finalizing all system boundaries (the fourth phase) can avoid the potential problems that Friis and Neilsen (2017) are concerned about. To save space, the results from the second and third phases are not presented separately in this paper; they are incorporated in the fourth and fifth phases.

Feasibility

To achieve feasibility, it is necessary to foster collaborations among researchers and stakeholders across the focal, adjacent, and distant systems. Although it would be ideal to address all components and their interrelationships simultaneously, it is usually not feasible because of various constraints, e.g., financial resources or time. A feasible and systematic approach is to divide the entire operationalization work into smaller interconnected projects under the metacoupling framework (Fig. 6b) and integrate the results from those projects as they are progressing.

The metacoupling approach would take several steps. The first step would be to conceptually identify all important components and relationships under the metacoupling framework (Fig. 6b). The middle steps would address different components and integrate them. The number of middle steps would depend on the number of components and resources (Fig. 6b). With two or more projects completed, they can begin to be integrated to explore their relationships. The final step would be to integrate all components (Fig. 6b), making the complete operationalization of the framework. As systems change, some or all steps should be repeated to account for temporal dynamics.

The metacoupling approach overcomes two major shortcomings of the traditional approach to human-nature interactions (Fig. 6b). First, the traditional approach often works on various aspects of human-nature interactions independently because it does not place them under an integrated framework like the metacoupling framework. Researchers usually pay attention to one type of coupling, while other and perhaps more important types of couplings may be ignored. Second, even after all types of couplings are addressed in the traditional approach, they remain largely unconnected and their interrelationships are underappreciated or overlooked (Fig. 6b).

Long-term research in Wolong inspired the development and operationalization of the metacoupling framework. The work became more comprehensive over time in terms of research scope, skills, expertise, experience, and data. For example, early in the research, one student led biophysical analysis (Linderman et al. 2005) and another led socioeconomic analysis (e.g., An et al. 2002) to understand patterns and mechanisms of changes in panda habitat. Integrating their work helped discover habitat degradation and reasons behind the degradation (Liu et al. 2001, Liu et al. 2016*b*). Researchers started with intracouplings (e.g., Liu et al. 1999*b*) and have completed some studies on telecouplings (He et al. 2008, Chen et al. 2012*a*, Liu et al. 2015*a*) and pericouplings (An et al. 2001). A major reason behind such a procedure is that intracouplings were dominant in the early years of research in Wolong. With increased telecouplings and pericouplings over time, the research focuses changed accordingly. Integrating the data collected over time by different team members has helped quantify more components of the metacoupling framework (e.g., Chen et al. 2009, Yang et al. 2013, Liu et al. 2015*a*, 2016*b*). Although many concepts of the metacoupling frameworks were not developed until recently, the culmination of data and insights generated over a period of more than two decades in Wolong enabled development and operationalization of the metacoupling framework.

Applying the telecoupling framework, which the metacoupling framework builds upon, indicates that the metacoupling framework can be widely applied in a consistent, systematic, reproducible, and feasible manner. Although the telecoupling framework is relatively new (Liu et al. 2013), it has been applied to address many different issues, such as trade (of food, energy, sand, forest products, industrial products, and virtual water; Liu 2014, Wicke 2014, Liu et al. 2015*a,b*, Silva et al. 2017, Torres et al. 2017), land use and land cover change (Eakin et al. 2014, Liu et al. 2014, Sun et al. 2017, Dou et al., *in press*), species invasion (Liu et al. 2014), species migration (Hulina et al. 2017), tourism (Liu et al. 2015*a*), water transfer (Deines et al. 2016, Liu et al. 2016*a*, Yang et al. 2016*a*), urbanization (Fang and Ren 2017), wildlife transfer (Liu et al. 2015*a*), foreign direct investment (McKinney 2014), payment for ecosystem services (Liu and Yang 2013, Liu et al. 2016*a*), knowledge transfer (Liu et al. 2015*a*), conservation (Carter et al. 2014, Gasparri et al. 2016, Liu et al. 2016*b*, Wang and Liu 2017), economic development (Yang et al. 2016*b*), and fisheries (Lynch and Liu 2014, Carlson et al. 2017).

NEED FOR NEW POLICY, GOVERNANCE, AND MANAGEMENT

The metacoupling framework and examples above demonstrate the need for new policy and practices to effectively govern and manage metacouplings. Intracoupling is often easier to deal with, whereas the policies that could influence pericouplings and telecouplings are more difficult to address effectively because they

transcend judiciary boundaries. However, they matter—and sometimes are essential and more important—than intracoupling. Interactions among intracouplings, pericouplings, and telecouplings may create even more challenges for governance and management.

Governing metacoupled systems can benefit from the experiences of governing complex systems (Duit and Galaz 2008, Djalante 2012, Folke 2016) because metacouplings result in increased systemic complexity and metacoupled systems are among the most complex systems in the world. The metacoupling framework can help address complex features such as nonlinearity (Garmestani 2014, Blenckner et al. 2015, Monfared et al. 2016), bifurcations (Suweis and D'Odorico 2014, Monfared et al. 2016), oscillations (Innes et al. 2013, Chaffin and Gunderson 2016), time lags (Hamann et al. 2016, Rova and Pranovi 2017), legacy effects (An et al. 2014, Waylen et al. 2015), path dependence (Hukkinen 2003, Manson 2008, Nykvist and von Heland 2014), and surprises associated with emergent properties (Heckbert et al. 2010, Reyes-Garcia et al. 2016). The governance of metacoupled systems should pay serious attention to the need for agility in response to various changes and for avoiding different types of lock-ins (Hukkinen 2003, Schlüter et al. 2009, Waylen et al. 2015, Laborde et al. 2016).

Although many separate studies and management practices have been conducted on issues related to intracoupling (Nagendra and Ostrom 2014, Kramer et al. 2017), pericoupling (McDonald et al. 2001, Gu et al. 2011, Trammell et al. 2011, Mukwada et al. 2016), or telecoupling (Wicke 2014, Chignell and Laituri 2016, Fang and Ren 2017), little has been researched and governed regarding complex interactions such as synergies and trade-offs among intracoupling, pericoupling, and telecoupling. Efforts are needed to study and evaluate how information about metacouplings can be useful for policy makers and managers to achieve sustainability across local to global scales; how policy makers and managers can increase synergetic effects and reduce trade-offs of metacouplings on biodiversity, ecosystem services, natural resources, and the environment; and what policies are needed to effectively manage and govern metacoupled systems for addressing global challenges such as achieving the United Nations Sustainable Development Goals. Because it is premature to propose realistic policies in the context of metacoupling given the early stage of relevant research, this section illustrates the need for new metacoupling policy, governance, and management by highlighting two examples.

Metacoupling interactions

Because intracoupling, pericoupling, and telecoupling play different roles but interact in shaping system dynamics, they increase the complexity of policy development and management. For example, when a disaster strikes a system and causes devastating damage, immediate rescue efforts usually rely on people from adjacent systems because people inside the focal system may lack the ability to rescue themselves and people in distant places take more time to reach the impacted area than those in adjacent places. This is what happened to Wolong when the 2008 earthquake struck. The first responders were from places nearby, followed by rescue teams and materials from more distant places, including major funding for reconstruction from Hong Kong (about 1400 km from Wolong). After the earthquake, local people had to rely on local fuelwood for cooking because no electricity was available. When the electricity was finally restored, fuelwood use and its impact on panda habitat were reduced substantially. The recovery and reconstruction process took several years; thus, it is important to examine how these efforts can be better coordinated for higher efficiency in terms of reducing impacts on the environment while improving human well-being more quickly.

Besides disaster rescue and recovery, new policies related to Wolong are needed to coordinate reduction in fuelwood collection and timber harvesting, human immigration and panda movement, tourism and panda loans, and so on. For example, because adjacent habitats are important for panda movement, more efforts are needed to protect them. One way to do so is to improve human well-being in adjacent areas so they rely less on resources from panda habitat areas. Because most of the benefits from tourism in Wolong have been captured by tourism companies, directing a larger share of the tourism benefits to local residents may help increase electricity affordability and reduce fuelwood consumption (He et al. 2008). Also, more profits from the panda loans should help Wolong residents contribute to panda conservation (Liu et al. 1999*b*, Tuanmu et al. 2016) by helping them purchase electricity to reduce fuelwood consumption and habitat destruction. Profit sharing can also improve children's education so more children can go to college, settle elsewhere, and reduce future human population growth and impacts on panda habitat.

Collective actions on intracoupling, pericoupling, and telecoupling are also essential to address global challenges. Achieving the United Nation Sustainable Development Goals is a good example, because it requires collective and coordinated efforts within a specific area as well as between adjacent and distant areas. To eliminate hunger across the world (Goal #2), for instance, it is necessary to not only increase yield in areas suitable for food production, but also to export food to other areas that lack sufficient food. Similarly, for Goal #14 (ocean conservation), it is important to protect the terrestrial systems near and far away from the oceans because pollutants from terrestrial systems flow into oceans (Zeng et al. 2015). Some of these issues have been recognized, but the metacoupling framework can help integrate all important system components systematically.

Spillover systems

Spillover systems are the least understood systems. They can result from not only telecoupling (Liu et al. 2013, Liu et al. 2015*a*), but also pericoupling and intracoupling as explicitly recognized for the first time by the metacoupling framework illustrated above. They may be more complex than those generated from telecoupling alone. For example, CO_2 emissions from forest harvesting in Wolong and tourist travel to Wolong all contribute to the global CO_2 pool, but their magnitudes and effects differ (Liu et al. 2015*a*). To govern and manage spillover systems, it is necessary to first understand them. If the spillover systems suffer from negative effects, it is important to provide adequate compensation to offset those negative effects. There is awareness of and willingness to pay for carbon offsets in some travel-related activities (Choi and Ritchie 2014), and similar methods can be applied to offset the cost of CO_2 emissions from tourism and forest harvesting in Wolong and beyond.

CONCLUSIONS

The metacoupling framework is a conceptual foundation that offers a holistic approach to integrating human-nature interactions around the world. Viewing the world through the metacoupling framework is useful because it can raise awareness of systemic connections that may not be immediately apparent when focusing on one particular system. The framework provides a new tool for thinking about the close interactions among separate components. One novel aspect is that it incorporates interactions within and among adjacent and distant systems. This integration across space can also examine the effects at different scales, aggregate the effects at fine to broad scales, or disaggregate the effects at broad to fine scales. Such integration is essential to assess synergies and trade-offs within and among multiple systems nearby and faraway. Socioeconomic and environmental externalities can be accounted for across space and over time. With cooperation among researchers and stakeholders with relevant expertise, the framework has the potential to help discover hidden ecological and socioeconomic patterns and processes, and generate useful information for addressing global challenges such as achieving the United Nations Sustainable Development Goals. There is a great need to develop new policy, governance, and management for a sustainable future across the metacoupled planet.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/9830

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