Framing ecosystem services in the telecoupled Anthropocene

Jianguo Liu*, Wu Yang[†], and Shuxin Li

Around the globe, previously isolated localities are rapidly forming connections over increasing spatial extents, through the flow of ecosystem services (ES). With the intensification of human demands, systematic research on ES over distances is urgently needed. We apply a new integrated framework of telecoupling (ie socioeconomic and environmental interactions between different places) to analyze the causes, effects, agents, and dynamics of ES flows. We focus on the world's largest water-transfer project – China's South–North Water Transfer Project – as a basis for discussion about the broad utility of the telecoupling framework and important implications for effective governance of ES across telecoupled human and natural systems. Integration through the use of the telecoupling framework holds promise for creating sustainable solutions and avoiding unintended negative effects across multiple systems in an interconnected world.

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Ecosystem services (ES) and human societies are unevenly distributed across landscapes (MA 2005; Brauman *et al.* 2007; Liu 2013). Many ES (including food, fuel, and clean water) are produced locally, but their benefits extend regionally, nationally, and even globally; for instance, although carbon (C) sequestration and C storage in forests occur at local scales, their associated benefits are spread worldwide. In cities, for example, ES are relatively scarce, while human population density and demands for such services are high. In other words, the divergence between the supply of and demand for ES is increasing (Burkhard *et al.* 2012). Meeting the demand for distant ES requires either transporting those services from distant locations through processes such as transfer or trade, or travelling to locales that provide the desired services (eg ecotourism).

Research on ES around the world has been progressing rapidly since the publication of the influential Millennium Ecosystem Assessment (MA 2005). For example, theoretical and methodological innovations have improved the assessment, mapping, and valuation of ES, and have enhanced understanding of the links between ES and human well-being (Naidoo and Ricketts 2006; Daily and Matson 2008; Nelson *et al.* 2009; Yang *et al.* 2013, 2015). However, to date, much of this research has focused either on geographic areas that provide and deplete ES or on socioeconomic and environmental interactions over distances (eg trade impacts on the movement of ES) independently. Some studies have attempted to identify beneficiaries, map the spatial flows of ES, and evaluate the impacts on beneficiaries' well-being (Keeler *et al.* 2012; Bagstad *et al.* 2014; Dalin *et al.* 2014), but research on the provisioning, transfer, and benefits to human from ES is largely fragmented. While these disparate research foci have generated useful insights, achieving sustainability and enhancing human well-being requires a more thorough understanding of socioeconomic and environmental interactions over distances (Liu *et al.* 2013).

Here, we apply a new integrated framework of telecoupling (Liu *et al.* 2013) to systematically analyze the causes, effects, agents, and dynamics of ES flows over distance. Using water transfers over large distances in China as an example, we apply the telecoupling framework to ES supply and demand, and discuss implications for the governance of ES over distances.

In a nutshell:

- Socioeconomic and environmental interactions over distances – collectively termed "telecoupling" – are intensifying, affecting ecosystems and people worldwide
- A new integrated framework of telecoupling provides a holistic approach to understanding and managing ecosystem services (ES) over distances
- Applying this framework to research on ES flows, such as inter-basin water transfers, demonstrates the usefulness of the framework
- Future research on ES should include an examination of issues relating to telecoupling

*Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI *(liuji@msu.edu); [†]current address: Conservation International, Arlington, VA*

Overview of the telecoupling framework

The telecoupling framework (Liu *et al.* 2013) treats each location as a coupled human and natural system where humans and natural components interact (Liu *et al.* 2007). To date, research on coupled human and natural

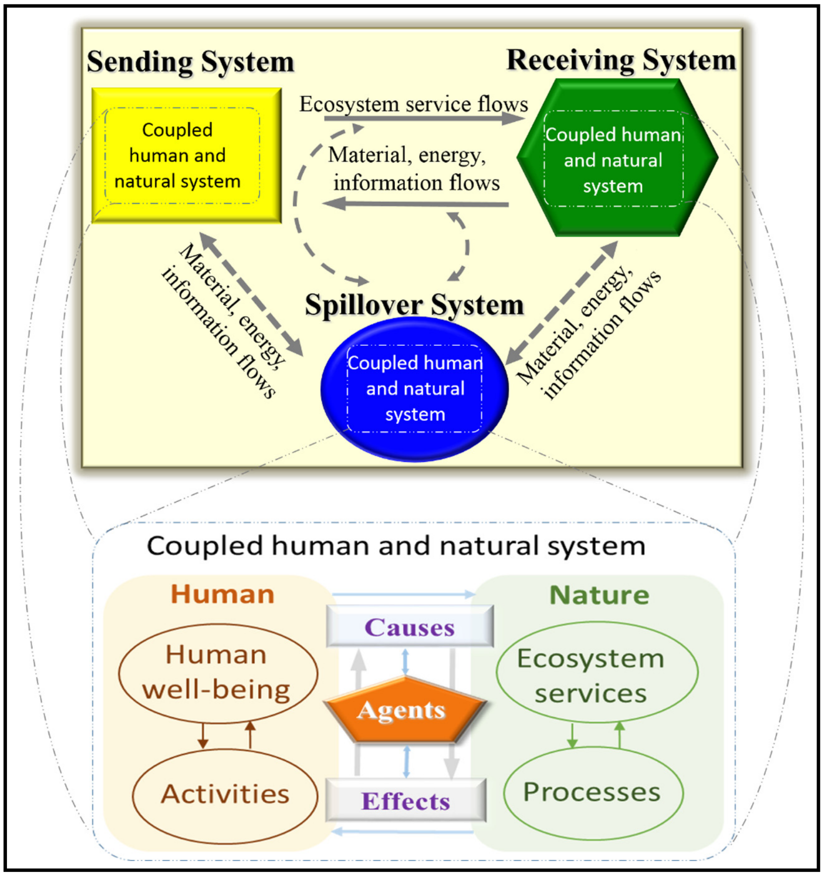

Figure 1. *Framing ES in a telecoupling context (adapted from Liu* et al. *2013). A "sending" system provides ES to a "receiving" system, and may influence another system (the "spillover" system) in the process. Feedbacks occur among different systems as a result of material energy, and information flows. Each system represents a coupled human and natural system, with two major components: humans and nature (inset). The human component consists of human well-being (eg health), activities (eg consumption), and other elements (eg population size, not shown). The nature component consists of ES (eg clean water), processes (eg predation), and other elements (eg biodiversity, not shown). The causes, agents, and effects of telecoupling processes, such as flows of ES between systems, may occur within each system. For example, causes may include human activities and ecological processes that affect flows of ES with the facilitation of agents, such as traders and government officials, whereas effects may include impacts of a telecoupling process on ES and human well-being. Arrows indicate the direction of these influences.*

systems has largely focused on one specific site; telecoupling, on the other hand, refers to socioeconomic and environmental interactions that take place between multiple separate locations, which may be considerable distances apart. The telecoupling framework contains five main interrelated components: systems, agents, flows, causes, and effects (Figure 1). A telecoupling is generated by agents that promote or interfere with the flows (exchanges of material, energy, and information) among the systems (coupled human and natural systems); depending on the direction of the flows, systems can be classified as sending systems (sites of origin), receiving systems (destinations), or spillover systems, which affect and are affected by the interactions between sending and receiving systems (Figure 1). Causes are drivers or factors that produce a telecoupling between two or more systems, which generate socioeconomic and environmental effects in one or more of the systems. In addition, the framework explicitly considers feedbacks (ie reciprocal interactions among different coupled systems; Figure 1). The characteristics of the telecoupling framework, and the ways in which it differs from other frameworks, are discussed in greater detail in WebPanel 1.

Water transfers worldwide and in China

Transfer of real water and trade in "virtual water" are essential for alleviating water stress due to the uneven global and regional distribution of water resources and water demand. Virtual water (ie water used to produce the traded goods at the place of production) is embedded within many ES (eg agricultural products). Globally, between 1996 and 2005, the total annual volume of traded virtual water was 2.32 trillion cubic meters (Mekonnen and Hoekstra 2011; Hoekstra and Mekonnen 2012). This relieves water stress in the receiving systems because water in the sending systems (production areas) is used to produce the traded products. In terms of real water, the earliest water-transfer project can be traced back to 2500 BCE, when the Sumerians dug ditches in southern Mesopotamia to divert water from the Tigris and Euphrates rivers for irrigation. To date, more than 40 countries, including China, have constructed over 350 major inter-basin water-transfer projects that redirect approximately 540 billion cubic meters of water annually, accounting for 14% of total global annual water withdrawals (Gupta and van der Zaag 2008).

China is faced with a marked geographic disparity in human demand for and uneven distribution of water resources. Rainfall is more abundant in southern China than in the northern part of the country. As a result, China trades heavily in water: from 1996–2005, the country annually imported 119.2 billion cubic meters and exported 142.7 billion cubic meters of virtual water (Mekonnen and Hoekstra 2011). One of the world's earliest inter-basin water-transfer projects – the 200-km-long Hangou waterway, which connected the

Yellow River with the Huai River (Liu and Zheng 2002) – was constructed in 486 BCE. Since the 1950s, China has implemented 12 major projects that divert over 9 billion cubic meters of water annually from 10 rivers to 13 river basins/cities/counties (Liu and Yang 2012) (WebTable 1), and several additional water-transfer projects are currently in the planning and development stages.

China's South–North Water Transfer Project under the telecoupling framework

While water transfer is a feat of engineering, the water that is being transferred represents an ES. Other ES related to water-transfer projects include flood and drought control, food provision, and improved navigation capacity (Panel 1). We use China's South–North Water Transfer Project (SNWTP) as a case study to demonstrate the application of the telecoupling framework in ES research and management (Figure 1). The SNWTP is the world's longest and largest water-transfer project. After nearly half a century of planning and discussion, construction of the controversial SNWTP officially started in 2002 (Yang and Zehnder 2005); the initial phases of both the Eastern Route (1150 km) and the Middle Route (1240 km) were completed in 2013 and 2014, respectively. However, the Western Route (700 km) is not expected to be finished until 2050 (WebTable 1). The objective of the SNWTP is to transfer water from

Panel 1. Ecosystem services related to the South–North Water Transfer Project (SNWTP)

The primary goal of the South–North Water Transfer Project (SNWTP) is to divert clean fresh water from the Yangtze River basin in southern China to northern China. The provision of clean water from the south to the north is the most important ecosystem service (ES) related to the SNWTP. Its flow over distances is a telecoupling process.

Many other ES are affected by this process, as shown below. All are directly related to the "effects" component (eg mitigating the water shortage and ameliorating groundwater depletion in receiving systems) and indirectly related to other components of the telecoupling framework. As such, there are flows related to corresponding ES across systems (eg flows of food from northern China to southern China, flows of ecotourists from various parts of the world to the attractions created by the SNWTP).

Flood and drought control

The SNWTP constructs or upgrades dams and reservoirs, which enhances the ability to regulate floods and control drought in water sending, receiving, and some spillover systems (eg regions along the water-transfer routes). For example, it is estimated that the occurrence of large floods in the middle and lower reaches of the Hanjiang River will be reduced from once every 10–20 years to once every 100 years (Li and Ji 2014).

Navigational improvements

Many channels have been repaired, upgraded, and widened to facilitate water transfer, and the resulting increase in water levels improves navigation conditions. For instance, the first phase of the Eastern Route enhanced the Beijing–Hangzhou Grand Canal, which is 2500 years old and 1794 km in length. This made the Grand Canal an even more important water transport artery, with cargo throughput increasing to 13.5 million metric tons (People's Daily 2014).

Food provision

The transferred water will be important for agricultural use in northern China, the chief grain production area in the country. For example, given sufficient water, yield in 1.06 million ha of wheat field may increase from 2250–3000 kg per ha to 6000–7500 kg per ha (Wei and Song 2014). However, the high level of water extraction may impair food production in the sending areas.

Nature-based recreation and tourism

Some sites associated with the SNWTP will likely become new tourist attractions (Xiong and Li 2014), with many opportunities for nature-based recreation and other activities (eg boating, hiking and cycling along the channel banks, scenic river viewing).

Hydrological and climatic regulation

The large amount of water transfer may alter hydrological and climatic conditions in water sending, receiving, and spillover systems (Zhang *et al.* 2007). The impacts of such alteration may be negative or positive, depending on the specific contexts.

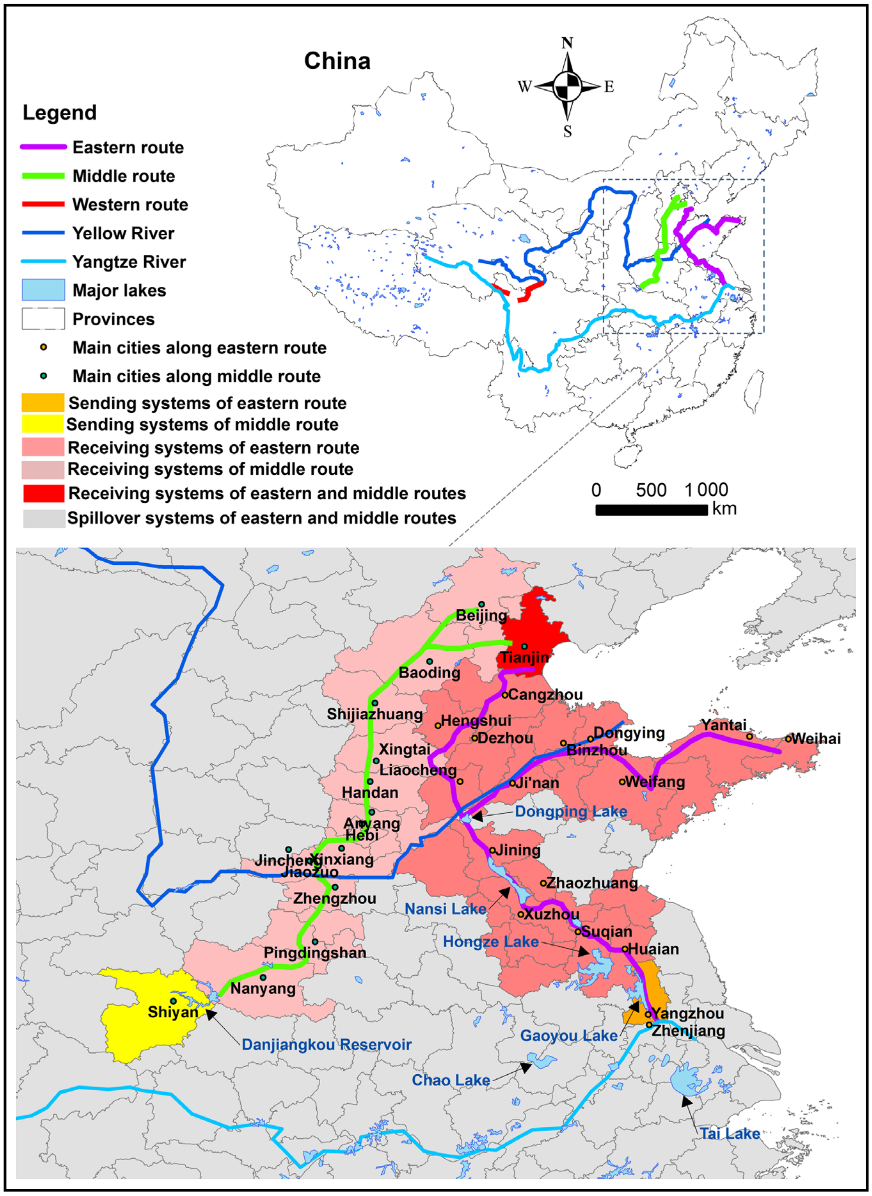

Figure 2. *A schematic diagram of the South–North Water Transfer Project (SNWTP). The lower part of the figure (inset map) highlights the sending, receiving, and spillover systems, as well as the main cities located along the Eastern and Middle routes. Many spillover systems such as those outside of China are not shown.*

the Yangtze River basin in southern China to alleviate water shortages in northern China, where the demand for water continues to rise (Yang and Zehnder 2005). Most of the diverted water is intended for urban residential and industrial use, with the remainder destined for agricultural and other purposes (Dong and Wang 2011).

Systems

The sending systems of the SNWTP (Figure 2) are the source areas of the water, including the downstream region of the Yangtze River for the Eastern Route (eg Hongze Lake and Gaoyou Lake), the Danjiangkou Reservoir (Figure 3a) for the Middle Route, and the upstream region (eg Yalong River basin) of the Yangtze River for the Western Route (Figure 2; Table 1). However, the water quality of the sending systems for the Middle and Eastern routes is problematic; for example, although the Danjiangkou Reservoir is among the largest reservoirs in China, with a storage capacity of 17.5 billion cubic meters, the reservoir is exposed to ever-larger inputs of nutrients and subsequent phytoplankton growth, leading to increased risk of eutrophication (Zheng and Han 2012). Poor water quality necessitates additional water-treatment costs that so far equal approximately one-third of the total investment for the completed first phase of the Eastern Route.

The receiving systems of the SNWTP are the water-transfer destinations – five provinces (Hebei, Henan, Shandong, Anhui, and Jiangsu) and two major cities (Beijing and Tianjin) (Figure 2; Table 1). Beijing (Figure 3b) and Tianjin, along with the province of Jiangsu, represent China's economic, political, and cultural centers, whereas the other four provinces are important areas of agricultural production. All of these provinces and cities are experiencing rapid population growth and skyrocketing water demands.

Although sending and receiving systems have attracted research attention (Dong *et al.* 2011; Ling and He 2011), spillover systems, which affect and are affected by the SNWTP, are largely overlooked. There are numerous spillover systems, including locations both within and outside China, that provide materials, energy, technology, labor, and/or financial resources for project construction or for maintenance of the water-transfer processes (Figure 2; Table 1). Along the transfer routes, precipitation contributes to water flows, while leakages (eg evaporation) reduce the volume of water reaching the receiving systems. The Middle Route of the SNWTP requires the displacement (hereafter "resettlement") of about 345 000 people (CCO SNWTP 2013); resettlement areas are one example of a spillover system (Figure 3c). The Yangtze Delta is another spillover system, given that the reduction in the discharge of the

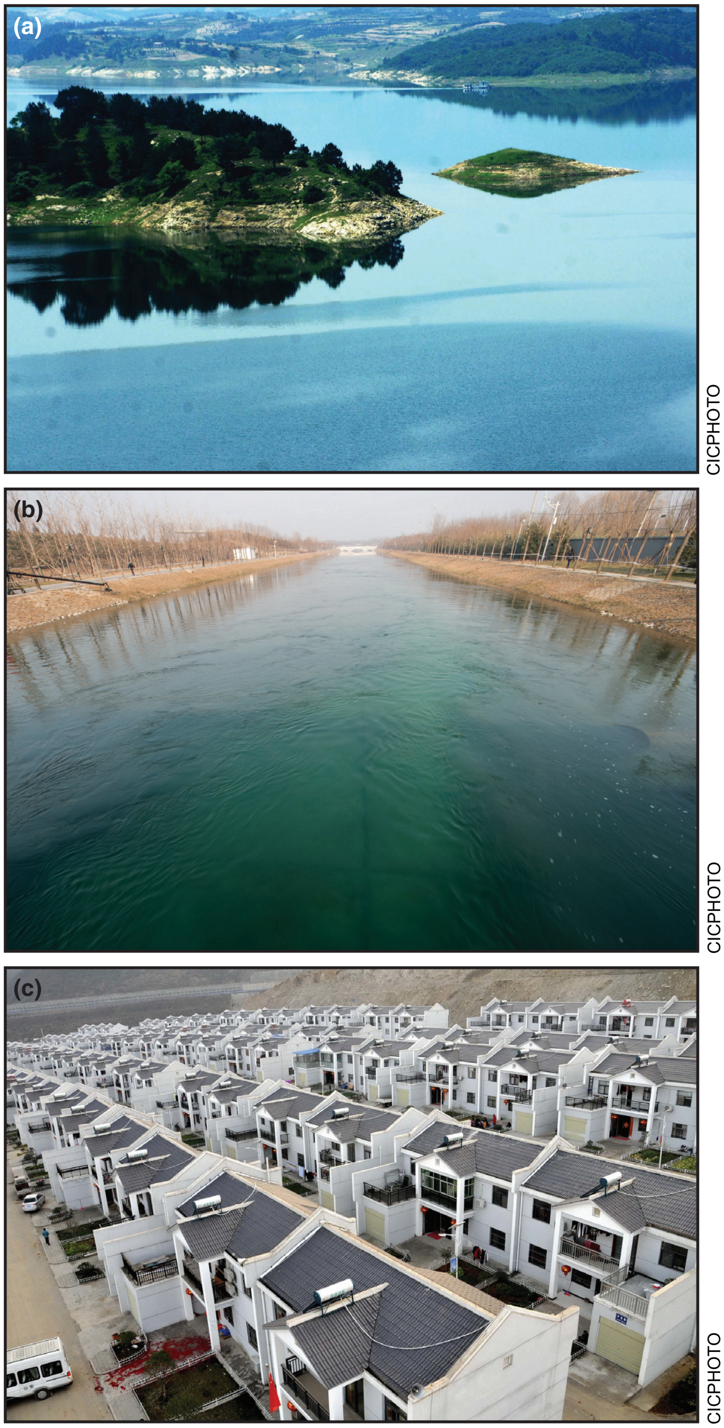

Figure 3. *Sending, receiving, and spillover systems of the SNWTP. (a) A sending system: Danjiankou Reservoir, Hubei Province. (b) A receiving system: water enters Beijing from the channel of the Middle Route. (c) A spillover system: resettled area in Shiyan, Hubei Province, as a result of the displacement by the construction of the Middle Route.*

Yangtze River as water is removed will lead to increasing seawater encroachment into the delta (Zhang 2009).

Flows

The total volume of water diverted by the SNWTP will be around 44.8 billion cubic meters annually, with 14.8 billion cubic meters, 13.0 billion cubic meters, and 17.0 billion cubic meters transferred through the Eastern, Middle, and Western routes, respectively. The total cost is expected to be 486 billion yuan (US$1 = 6.37 yuan as of November 2015), although the actual financial investment is likely to be much higher due to the enormous amount of work involved (Wang 2012). For the Eastern Route, for instance, it is estimated that 5.6 billion cubic meters of soil and rock will have to be excavated, and that 1.0 billion cubic meters of earth and rock fill, 4.9 million cubic meters of concrete, and 6.5 million cubic meters of stone masonry will be required; in addition, 51 pumping stations, with a total capacity of 0.5 million kilowatts and using 12.6 billion kilowatt-hours of electricity, will need to be built.

In addition to the financial, material, and energy flows, the SNWTP involves numerous information flows and the design of several new types of advanced equipment and technologies. For instance, the Tuanhe River Aqueduct Project, which forms part of the Middle Route, set three new global standards for aqueducts: the largest inner diameter (9 m), the longest single span (40 m), and the greatest maximum flow (420 cubic meters per second) (CCO SNWTP).

Agents

To help overcome the project's technological and engineering challenges, thousands of experts – representing government agencies, corporations, banks, and non-governmental organizations – have been recruited both domestically and internationally (Table 1), in addition to millions of laborers. The SNWTP Construction Committee Office was established at the central government level, under the State Council (China's chief administrative authority, chaired by the Premier and including heads of various ministries and other high-level agencies), with seven divisions overseeing general affairs, investment planning, finance, construction management, environmental protection, land acquisition and resettlement, and supervision for the entire project. At the local and regional levels, there are construction committees in each affected city and province.

Causes

There are multiple reasons (ecological, socioeconomic, political, and technological) for pursuing the SNWTP initiative, but one takes prominence: 90% of the national annual runoff occurs in southern China, whereas 45% of crops are grown in the North China Plain (Liu and Zheng 2002; Shao *et al*. 2003). The relative water scarcity in northern China is further aggravated by the uneven temporal distribution of water resources. Runoff in the rainy season, from June to September, may account for 60% and 80% of the annual runoff in southern and northern China, respectively (Liu and Zheng 2002). North China Plain was also experiencing high population growth rate (~7.6% annual growth between 1980 and 2000, particularly due to regional population immigration in big cities such as Beijing and Tianjin) and consequently a rapid increase in total water consumption (climbing at an annual rate of ~8% between 1980 and 2000) (Zhang 2009). Gross domestic product in the cities of Tianjin and Beijing has increased by 90- and 100-fold, respectively, between 1980 and 2010 (NBS 2011); rapid economic growth is exacerbating water scarcity and accelerating water demand. In addition, a relative absence of environmental awareness among members of the public promotes inefficient (and often wasteful) water usage, hinders attempts to reduce water consumption, and helps to maintain high

Table 1. Summary of five major components in the telecoupling framework for the South–North Water Transfer Project (SNWTP)

		South–North Water Transfer Project (SNWTP)
Systems	Sending	•Eastern Route: downstream of Yangtze River •Middle Route: Danjiangkou Reservoir •Western Route: upstream of Yangtze River
	Receiving	•Eastern Route: Shandong, Hebei, Anhui, and Jiangsu provinces, and the city of Tianjian •Middle Route: Hebei and Henan provinces, cities of Beijing and Tianjin •Western Route: Qinghai, Gansu, Shaanxi, and Shanxi provinces and the Inner Mongolia Autonomous Regions
	Spillover	•Hubei and Henan provinces in China, along with numerous other locations in both China and other countries
Flows	Material and energy	•Real water •Labor and money •Concrete, other materials and equipment
	Information	•Techniques
Agents		•Central and local governments of China •Companies inside and outside China •Individuals inside and outside China
Causes	Environmental	•Water scarcity (natural shortage and severe water pollution) in northern China and abundant water in southern China •45% of country's cropland is in northern China
	Socioeconomic	•Rapid population growth and even faster growth in household numbers •Rapid economic development •Increase in water consumption
	Political	•First proposed by Chairman Mao and later promoted by many central government leaders •Political interests in large-scale projects
	Technological	•Advances in science and technology
Effects	Environmental	•Water supply, flood and drought control •Water-pollution control and treatment, as well as pollution spread •Land-cover and land-use change •Hydrological and climatic change •Spread of invasive/alien species and diseases •Saltwater intrusion and salinization •Biodiversity loss •Other unknown effects in spillover systems
	Socioeconomic	•Hydropower provision and shipping •Economic growth and employment opportunities •Displacement of people •Avoided socioeconomic losses from floods and droughts •Increased socioeconomic losses from other natural disasters •Other unknown effects in spillover systems

demand. Political interference and influence in infrastructure development represents another driver. The SNWTP, for example, was first formally proposed by Chairman Mao Zedong in 1952 and has been promoted by many successive central government leaders, who routinely used massive development projects as a means of demonstrating their power and political achievements. Economic growth and advances in science and technology over recent decades have provided the financial and technological basis for the implementation of the SNWTP.

Effects

The SNWTP has both positive and negative environmental and socioeconomic impacts on sending, receiving, and spillover systems, affecting climatological, hydrological, and socioeconomic conditions and processes. It changes the distribution of water and soil moisture, the water and energy balances between the land surface and the atmosphere, the livelihoods of resettled people, and the labor market of communities receiving these translocated groups. According to government statistics (CCO SNWTP 2013), the total annual economic benefits from the new water supply, flood control, shipping, and other ES will be as high as 55 billion yuan (in 2002 constant price – ie using the price in 2002 as the base year to adjust changes that result from inflation). Overall, the SNWTP will most likely have net negative environmental impacts in southern China but overall net benefits (5.7% net environmental benefits or 4.7 billion yuan in 2002 constant price) annually in northern China (Lin *et al.* 2012).

For sending systems, there are two potential environmental impacts: the permanent destruction of vegetation during dam construction and river impoundment, and the substantial hydrological changes to the natural river corridor that will result from water extraction (Yan *et al.* 2012). However, there will also be positive impacts for water-sending systems; for instance, the storage capacity of the Danjiangkou Reservoir will increase by 3.3 billion cubic meters, reducing potential flooding that may affect more than 700 000 people. In addition, the first phase of the Eastern and Middle routes is expected to create 180 000 jobs annually during the construction phase (CCO SNWTP 2013).

For receiving systems, the SNWTP will reduce water exploitation pressures; planned groundwater exploitation in the North China Plain will decline by 1 billion cubic meters per year between 2010 and 2020 (Zhang *et al.* 2009). In Beijing, the SNWTP is expected to reduce water shortages and help stabilize land subsidence (Yang *et al.* 2012). There are, however, potential negative impacts in water-receiving areas; for instance, the spread of invasive and/or alien species in the North China Plain would be unavoidable (Zhang 2009).

Given the relative paucity of research on spillover systems, their effects remain largely unquantified. The most widely recognized spillover effect is that the extraction of water from the downstream section of the Yangtze River will reduce the river's discharge volume to the East China Sea, so that the Yangtze Delta will suffer from saltwater intrusion as a result of the reduced amount of freshwater input. Reduced discharge from the Yangtze would increase salinity levels substantially, and consequently threaten water security for Shanghai (Chen *et al.* 2013). The large amount of diverted water will markedly alter the riverine environment in the downstream reaches of the Han River, a tributary of the Yangtze and the source of water for the Middle Route of the SNWTP (Zhang 2009). In the Han River basin, grain production relies heavily on freshwater resources that will be further jeopardized – in quantity and quality – by climate change and eutrophic events, particularly during the spring and early summer months (Li *et al.* 2009; Nakayama and Shankman 2013). The project will result in extensive changes to the hydrological conditions of lakes in the

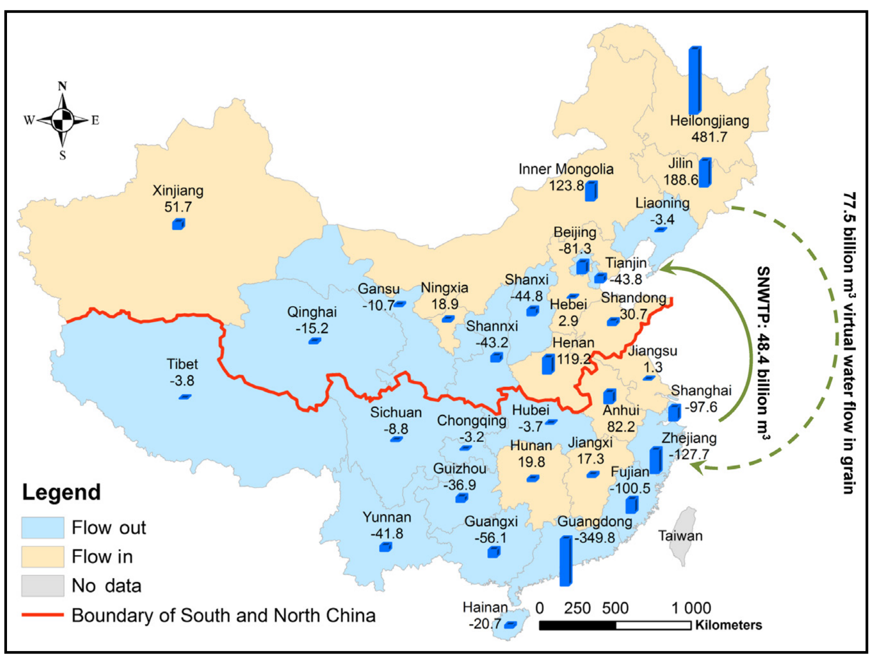

Figure 4. *Spatial patterns of real and virtual water transfer in China. Virtual water flow via grain shipments was estimated for the year 2010 (Wu* et al. *2012). Bars represent net virtual water flow for each province, with units of* 1×10^8 *cubic meters.*

water-sending areas; for instance, water levels in Dongping Lake are projected to rise by 2 m, leading to an estimated decrease of 320–400 metric tons per square kilometer in aquatic plant biomass and influencing other components of the aquatic ecosystems, such as herbivore communities (Zhou *et al.* 1994; Wan *et al.* 2003).

Such large-scale water transfers may affect both human and natural components of the sending systems. The resulting effects in sending systems may then be transmitted to the receiving systems via information flows (eg news reports, press releases of scientific publications, protests by affected stakeholders) and thus form powerful feedbacks (Figure 4). Such feedbacks may influence the higher levels of administration in charge of the water-receiving systems (ie the central government) to take relevant environmental and socioeconomic actions. For example, a study in the city of Shiyan in Hubei Province (the location of the Danjiangkou Reservoir; Dong and Wang 2011) suggested that a total of 16.3 billion yuan – an amount four times that of the planned budget for ecological projects (4.3 billion yuan) – should be given to residents of the water-sending areas as compensation for the ES lost during construction of the first phase of the Middle Route. The State Council is planning more payments for ecosystem services (PES) projects along the middle and lower reaches of the Han River to compensate for lost benefits in the water-sending areas (Zheng and Han 2012). In addition, more virtual water may be transferred from northern China (including water-receiving areas from the SNWTP) to southern China (including some water-sending areas), as real water flow from the SNWTP may lead to the production of more grain in northern China (Figure 4). In 2010, a total of 77 billion cubic meters of virtual water flowed from northern China to southern China as a result of the grain trade, a 15% increase over 2009 (Wu *et al.* 2012).

Turning telecoupling research into policy and actions

Thus far, hundreds of PES programs have been implemented at both local and global scales to manage and sustain ES (Chen *et al.* 2010; Yang *et al.* 2013). PES have largely revolved around the providers of and/or beneficiaries of the ES, but spillover systems have largely been ignored (Liu and Yang 2013). This is also true for the SNWTP, where discussion has focused on compensation for lost or reduced ES for inhabitants around the sending systems (eg Danjiangkou Reservoir area; Figure 2).

Given their importance in maintaining resilience and ensuring sustainability, feedbacks should be systematically incorporated into decision-making processes. If remotely located consumers are required to pay the full costs of producing, transporting, and consuming ES, it may help trigger feedback mechanisms by, for instance, providing incentives to lower rates of consumption (ie increasing efficiency) and reducing environmental impacts.

The telecoupling framework also underscores why ES exploited at sites distant from their original sources should be managed in a more holistic fashion. The transfer of a single ES (eg clean water) often involves multiple other ES (Panel 1). As a case in point, the volume of virtual water flowing from northern to southern China via grain shipments is greater than the volume of real water transferred from southern to northern China (Figure 4). To decrease water demand, grain production in northern China could be restricted, thus minimizing the need for water transfer. Although water-use efficiency can be improved (eg switching to crop types or varieties that require less water), efforts to reduce grain production in northern China are not currently feasible, given the country's population growth and increasing food requirements, as well as southern China's limited agricultural opportunities (eg shortage of cropland). Moreover, physically relocating large numbers of people from the north to the south is not a realistic option to reduce water demand in northern China. These and other constraints suggest that large trade-offs and complex relationships are associated with the provision of multiple distant ES; on the one hand, producing food requires large amounts of clean water (and other resources, such as land), whereas transferring clean water over long distances is costly but can help overcome inherent constraints (eg shortage of agricultural land in water-abundant regions, difficulties in displacing residents from water-stressed regions). Quantifying the complexity of multiple ES and other components of telecoupled systems is essential when addressing practical questions (Liu *et al.* 2015) such as: How should multiple ES be provided and managed? How much and to whom should compensation be paid for ES?

Conclusions

The integrated telecoupling framework provides a new analytic approach to understanding and managing ES. This framework also helps to advance ES research and governance, identify knowledge gaps, guide study design, clarify and systematically integrate the relationships among various components, develop relevant policies (Liu *et al.* 2015), inform the specifications of quantitative models, and enhance interactions among researchers and stakeholders. Placing various studies under the framework can help examine their interrelationships, and facilitate their comparisons and contrasts. By treating telecoupled systems as an integrated network in which each coupled system is a node, the framework thus allows advanced methods, such as network analyses, to be applied more effectively.

The framework emphasizes that ES influence coupled human and natural systems, which collectively constitute a telecoupled system with emergent properties, at different spatial scales. By enabling researchers and policy makers to consider often overlooked issues, such as existing or potential feedbacks among systems (sending, receiving, and spillover), the framework could aid in the governance of ES. Because previous research on human–nature feedbacks focused primarily on individual coupled systems instead of across multiple coupled systems, an improved understanding of cross-system feedbacks represents an important conceptual advance (Hull *et al.* 2015). Filling knowledge gaps will better inform decision making. Quantifying not only the impacts (both positive and negative) on systems but also how current policy interventions affect ES and human well-being will facilitate the development and evaluation of future policies. The framework reveals that decisions about ES are being made not only at the local scale of production or consumption but also increasingly by distant agents, and that those decisions are influenced by interactions between different ES markets. Further applications of this telecoupling framework may help to enhance sustainability and human well-being in numerous other settings worldwide.

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Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/16-0188.1/suppinfo

WebPanel 1. Characteristics of the telecoupling framework

Telecoupling is a natural extension of "coupling" across two or more distant places ("tele" = distant). Similar to "ecosystem services" that encompasses a diverse array of service types, telecoupling includes multiple forms of distant interactions and can facilitate understanding of interrelationships among these interactions (Liu *et al*. 2015a). The telecoupling concept is more comprehensive than most other perceptions of distant interactions in traditional disciplinary research. For example, it extends the conceptualization of teleconnection in atmospheric science that refers to the relationships between climate anomalies at distant locations by encompassing socioeconomic interactions, and expands economic globalization (interactions between distant human systems) by incorporating environmental interactions (Liu *et al*. 2013).

The telecoupling framework differs in several ways from other coupled-system structures, such as those analyzed by Binder *et al*. (2013). The latter focus primarily on interactions within a coupled system, while the former also explicitly considers socioeconomic and environmental interactions between the focal and other coupled systems. Although some researchers consider impacts of external factors, they do not explicitly incorporate the reciprocal impacts (eg feedbacks). (3) Some studies take interactions between sending and receiving systems into account, but they largely ignore spillover systems. The telecoupling framework provides an explicit approach that internalizes socioeconomic and environmental externalities across space (Brock and Xepapadeas 2010; Bithas 2011).

Although distant transfers of ecosystem services (eg clean water) have been ongoing for a long time, the magnitude and impacts of these activities have greatly increased in recent decades (the Anthropocene) (Mekonnen and Hoekstra 2011; Hoekstra and Mekonnen 2012). Furthermore, the contexts of ecosystem-service transfers differ considerably from those in the past. For example, global human population has more than doubled, from 3 billion to 7 billion, over the past 50 years, and the proportion of people living in cities has increased from 29% in 1950 to 51% in 2011 and is projected to reach 69% in 2050 (Bloom 2011). Such profound demographic changes should be the subject of systematic research, using integrated approaches such as the telecoupling framework. So far, this has been successfully applied to a number of important issues, such as conservation (Gasparri *et al*. 2015); global land-use and land-change science (Eakin *et al*. 2014; Liu *et al*. 2014; Wicke 2014); international land acquisitions (Liu *et al*. 2014); species invasions (Liu *et al*. 2013, 2014); payments for ecosystem-service programs (Liu and Yang 2013); trade in food (Liu *et al*. 2013), forest products (Liu 2014), and energy (Liu *et al*. 2015b); as well as to tourism, wildlife loans, and information dissemination issues (Liu *et al*. 2015a).

WebTable 1. China's major water transfer projects

Date of construction	Date of completion	Location/project	Sending	Receiving	Total investment (billion yuan)	Volume diverted (billion m^3 $year^{-1}$)	Maximum diversion discharge (m^3 $second^{-1}$)	Length of transfer (km)	Irrigated area (million ha)
1958	1972	Yunnan Province	Yi'nihe River	Jinshajiang River	0.43	NA	33	NA	0.01
1961	1977	Jiangsu Province	Yangtze River	Huaihe River	0.18	2.40	470	400	2.80
1963	1965	Guangdong Province	Dongjiang River	Hong Kong	NA	0.62	NA	83	0.17
1976	1995	Gansu Province	Datonghe River	Yongdeng County	2.95	0.44	36	70	0.06
1982	1983	North China Region	Luanhe River	Tianjin City	1.13	0.70	100	234	NA
1987	1994	Yunnan Province	Erhai Lake	Binchuan County	0.07	0.05	10	41	0.06
1989	1991	Hebei Province	Qinglong River	Qinhuangdao City	0.24	0.17	14	63	0.43
1989	1994	Hebei Province	Yellow River	Baiyangdian Lake	NA	1.25	320	779	NA
1993	2000	Jilin Province	Western Songhuajiang River	Changchun City	2.68	0.33	11	55	NA
1993	2011	Shanxi Province	Yellow River	Shanxi Province	17.34	1.20	48	452	NA
2008	NA	Northeastern China	Songhua River	Liaohe River	NA	4.40	500	656	2.85
2002	2020*	Eastern Route of SNWTP	Yangtze River	Yellow River	100	148	1000	1150	2.26
2003	2030*	Middle Route of SNWTP	Yangtze River	Huaihe and Haihe Rivers	100	130	800	1240	2.32

Date of construction	Date of completion	Location/project	Sending	Receiving	Total investment (billion yuan)	Volume diverted (billion m^3 $year^{-1}$)	Maximum diversion discharge (m^3 $second^{-1}$)	Length of transfer (km)	Irrigated area (million ha)
Planned	2050	Western Route of SNWTP	Yangtze River	Yellow River	300	170	NA	700	2.33
Planned	NA	Guangdong Province	Xijiang River	Eastern Zhujiang River Delta	23.60	2.07	NA	95	NA
Planning	NA	Anhui Province	Yangtze River	Chaohu Lake, Huaihe River	28	0.80	300	269	0.97
Planning	NA	Yunnan Province	Jinshajiang River	Lijiang River, and Dali, Kunming, Yuxi Cities etc.	62.90	3.40	NA	900	NA
Planning	NA	Zhejiang Province	Qiandao Lake	Hangzhou City	20	1.69	NA	271	NA

Notes: SNWTP, South–North Water Transfer Project; NA, not available. *The first phase of the Eastern Route and Middle Route were completed in 2013 and 2014, respectively. For projects that have not been completed yet, the total investments are planned costs; actual costs are often higher due to inflation, increasing relocation costs, and so on. Adapted from Liu and Yang (2012).

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