Telecoupling Toolbox: Spatially explicit tools for studying telecoupled human and natural systems

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Abstract
Telecoupling is a novel interdisciplinary umbrella concept that enables natural and social scientists to understand and generate information for managing how humans and nature can sustainably coexist worldwide. The telecoupling framework gains its distinction by enabling researchers to dive deeply into systemic complexities, even if systems are far away from each other. It is also ambitious in its aim to meet challenges unencumbered by disciplines. To understand the forces affecting sustainability across local to global scales, it is essential to build a comprehensive set of spatially explicit tools for describing and quantifying multiple reciprocal socioeconomic and environmental interactions over distances. Here we introduce the Telecoupling Toolbox, the first set of tools developed to map and identify the five major interrelated components of the telecoupling framework: systems, flows, agents, causes, and effects. The modular design of the toolbox allows the integration of existing tools and software to assess synergies and tradeoffs associated with policies and other local to global interventions. We show applications of the toolbox using two representative telecoupling case studies that address a variety of socioeconomic and environmental issues. The results suggest that the toolbox can systematically map and quantify multiple telecouplings under various contexts while providing users with an easy-to-use interface. It is our hope that the innovative, free and open-source toolbox can provide a useful platform to address globally important issues, such as land use and land cover change, species invasion, migration, flows of ecosystem services, and trade of goods and products.

Key Words: *Cross-scale interactions; decision-support tools; environmental interactions; human-environment interactions; socio-economic interactions; spatially explicit tools; telecoupling; telecoupling framework; coupled human-natural systems; CHANS*

INTRODUCTION

Throughout the 20th and 21st centuries, the world has undergone significant changes, and increased interactions between human and natural systems over large distances often led to unexpected outcomes with profound implications for sustainability (Reid et al. 2010). These increased interactions are a direct consequence of globalization and expansion in human population. Spread of exotic species, trade exchanges, and technology transfer occur more quickly and are more predominant than ever before (Liu et al. 2013). With an increase in global trade, several essential subsistence needs historically fulfilled by local resources, e.g. water and food, are increasingly being outsourced (Kastner et al. 2011, Konar et al. 2011). Although increased distant interactions and feedbacks between human and natural systems may have large socioeconomic and environmental impacts at multiple spatial scales (e.g., landscape, regional, global), scientific research has often focused on socioeconomic or environmental interactions alone, and thus has been hobbled to fully represent what happens in the real world. For example, traditional international trade research has focused on socioeconomic interactions between trade partners, keeping studies on environmental impacts separate (Liu et al. 2013). The complexities of coupled human and natural systems (CHANS) across the globe can no longer be fully understood in isolation. Such global challenges require the integration of research from different geographic locations and diverse disciplines to be fully understood.

In recent years, the conceptual framework of telecoupling has been introduced to provide a much-needed integrated approach to systems research that explicitly examines socioeconomic and environmental interactions between coupled human and natural systems over distances (Liu et al. 2013, 2015). The telecoupling framework consists of five major interrelated components: coupled human and natural systems; flows of material, information, and energy among systems; agents that facilitate the flows; causes that drive the flows; and effects that result from the flows. The direction of flows determines whether a system can be considered a sending system (e.g. exporting country), receiving system (e.g. importing country), or spillover system (e.g. countries affected by the trade between exporting and importing countries). Spillover systems are those that have an influence on or are influenced by the interactions between sending and receiving systems.

The growing interest in the telecoupling framework has resulted in a number of applications to important issues, such as land-change science (Eakin et al. 2014, Liu et al. 2014, Sun et al. 2017), the trade of food (Garrett et al. 2013), trade of forest products (Liu 2014), trade of energy and virtual water (Fang et al. 2016, Liu et al. 2015), water transfer (Deines et al. 2015, Yang et al. 2016), species invasion (Liu et al. 2014), payments for ecosystem services programs (Liu and Yang 2013), species migration (Hulina et al. 2017), foreign investment (Yang et al. 2016), and conservation (Carter et al. 2014, Gasparri et al. 2016, Wang and Liu 2016). Just as the framework is a new way of looking at things, research on telecoupling requires new tools to give researchers a way to explore telecoupling complexity for generating new insights. However, tools for systematic operationalization of the telecoupling framework are lacking. To address this important gap and help systematically study telecoupling and operationalize the telecoupling framework, we have developed the first set of software tools to comprehensively describe and quantify multiple reciprocal socioeconomic and environmental interactions over distances. In this paper, we provide an overview of the function and structure of the Telecoupling Toolbox as well as two example applications.

TOOLBOX FUNCTION

The Telecoupling Toolbox is designed for a broad audience of users from many disciplines and both the public and private sectors interested in applying the telecoupling framework to various issues (e.g. agricultural production and trade, payments for ecosystem services programs or subsidies for conservation, tourism, spread of invasive species, wildlife migration, and many others). As an e-tool (computer-based or Web-based application intended to make specific tasks easier), the toolbox provides a single, integrated environment to help users map systems, agents, and flows at any spatial scale, while offering descriptive and quantitative tools to better understand the leading factors and the different socioeconomic and environmental effects of telecouplings on scales ranging from the parcel to the planet.

The Telecoupling Toolbox is characterized by a number of predominant features (Table 1).

Feature	Description
Spatially-explicit	The five components of the telecoupling framework (systems, agents, flows, causes, effects) are associated with specific location(s) in geographical space
Multi-scale	The spatial scale of analysis can range from the parcel to the planet, depending on the specific application and desired resolution
Extendible	The toolbox can be expanded to accommodate a larger number of tools as deemed appropriate to comprehensively describe the wide range of telecoupling applications
Modular	The toolbox is subdivided into smaller logical modules that map, describe or quantify the desired components of the telecoupling framework to balance the different goals of each user
Interactive	Users can benefit from the full functionalities available within a GIS software, such as pan, zooming, and selecting objects that are defined within a geographical space
Open source	The source code and documentation used to develop the toolbox are freely available and hosted on a publicly available online repository

Table 1. Main features of the Telecoupling Toolbox and their description.

One of the most fundamental aspects is the spatially explicit nature of each toolbox component. The toolbox is developed within a geographic information system (GIS) environment to account for the spatial location of the five major components of the framework (systems, agents, flows, causes, effects). In some cases, the spatial location can be representative of a larger administrative area (e.g. centroid) or identify the actual geographical location of the object being mapped (e.g. buildings, roads, parks). Correctly defined spatial locations are necessary to visualize objects and entities within a true geographical context while allowing users to consider spatial distance when analyzing interacting coupled human and natural systems across boundaries.

The toolbox is designed as multi-scalar, a necessary feature to accommodate different types of telecoupling applications and needs of each user. This allows more flexibility when mapping and analyzing the components of the telecoupling framework from local to global scales. For example, users limited by data availability and resolution can still make use of the toolbox to describe the telecoupling of interest (e.g. tourism) at the scale determined by the research questions. In some cases, specific tools found within the toolbox work at pre-determined spatial resolutions, thus guiding the user to collect and organize data at the required scale.

By design, the toolbox can be extended with as many tools as necessary to comprehensively describe a wide range of telecoupling processes as well as quantifying multiple socioeconomic and environmental effects. For example, the tools needed to describe and quantify tourism can be very different from those needed to describe trade of food or animal migration across regions. Custom tools can be developed side by side along with existing third-party tools. The integration of existing tools and software, e.g., InVEST (Sharp et al. 2016), can help assess synergies and tradeoffs associated with policies and other local to global interventions, thus answering questions like: Where do goods, information, and ecosystem services originate and where are they consumed? How do conservation subsidy programs affect human population, wildlife habitat quality, water quality, and recreation? How will climate change and human population expansion impact the natural environment and biodiversity? What are the main factors causing the flow of goods, information, or ecosystem services between sending and receiving areas? How will an investment to increase local eco-tourism affect the natural environment and benefit the local population?

Another important characteristic of the Telecoupling Toolbox is its modularity. Following common good software development practices, the toolbox is subdivided into smaller logical modules that map, describe or quantify the desired components of the telecoupling framework to meet different user needs. Each module can be run independently or in sequential logical order with other tools, e.g. where an output file is needed as input for a different tool.

The full set of functionalities available within GIS software, such as panning, zooming to, or selecting a location of interest, make the toolbox interactive. Interactivity becomes important not only to improve the user experience as a whole, but also to make sure the components of the telecoupling framework are mapped and visualized at the correct spatial scale for the application of interest. For example, when working at multiple scales across the globe, it is important that the user is able to zoom in and out to the desired areas before assigning a real spatial location to all objects and entities involved in the study. Moreover, the toolbox includes tools that let users directly interact with the mapping environment.

In order to promote transparency and spark collaborations between users from different fields, all source code, sample data, and documentation used to develop the Telecoupling Toolbox are freely available and hosted on a public online repository (https://github.com/f-tonini/telecoupling-toolbox).

TOOLBOX STRUCTURE

The Telecoupling Toolbox is developed as a custom toolbox within ESRI's ArcGIS software (ESRI 2016) and at the time of writing is compatible with versions 10.3.1 or later. In ArcGIS, geoprocessing tools and script tools are grouped into toolsets, which are then collected into toolboxes. The toolbox is made of five nested toolsets corresponding to each component of the telecoupling framework (Fig. 1). Inside each toolset, we developed several script tools in Python (van Rossum 2016) or R (R Core Team 2016) to accomplish specific tasks such as qualitatively or quantitatively display and describe multiple coupled human-natural systems and their interactions on a map.

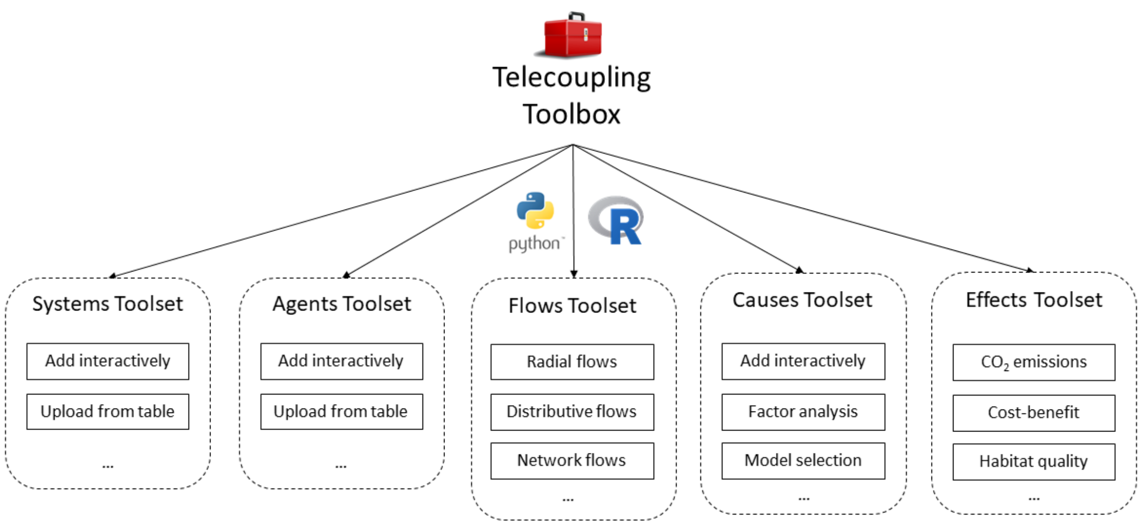

Fig. 1. Structure of the Telecoupling Toolbox and its components. The toolbox includes five toolsets related to each component of the telecoupling framework (systems, agents, flows, causes, effects). Each toolset is made of several custom Python and R script tools that qualitatively or quantitatively accomplish specific geoprocessing tasks within ESRI's ArcGIS software environment.

Systems toolset

The Systems toolset contains custom script tools meant to map and visualize the geographical location of all areas interconnected within the telecoupling of interest. Systems are divided into sending, receiving, and spillover. The available tools allow the user to either interactively add a desired number of systems along with their definitions and names to the map, or draw them from a local file on disk listing all systems and their attributes (including XY coordinates) in a tabular format. Each system is assigned a custom symbology and a permanent spatial location that can later be used with any analysis tools that involve them directly or indirectly.

Agents toolset

The Agents toolset contains script tools to map and visualize the geographical locations of all entities (e.g. people, households, organizations, etc.) that facilitate the flow of goods, information, or ecosystem services between sending and receiving systems. Like the Systems toolset, the available tools give the user a choice between adding agents to the map interactively or uploading them from a local file on disk storing agents and their attributes in a tabular format. Each agent is assigned a custom symbology and a permanent spatial location that, similarly to telecoupled systems, can later be used with any analysis tool or model that involved them directly or indirectly. For example, if one of the tasks were to run spatial statistics methods that inspect spatial patterns and characteristics of the agents, or, alternatively, run a spatially explicit agent-based model, the spatial location of each agent would be a requirement.

Flows toolset

The Flows toolset contains script tools that can map and visualize the spatial flow of goods, information, or ecosystem services between sending and receiving systems. Because of the diverse nature of flows, depending on the physical material (e.g. wildlife, commodities, cars, water) or virtual material (e.g. energy, currency, knowledge, information) being transferred between two or more locations, this toolset can be expanded to contain as many tools as needed to accurately represent them. For example, transportation of commodities or wildlife via airplane will most likely follow the geodesic routes taken by the carrier to fly across the globe. These types of flows, called radial flows, are calculated and drawn on a map using script tools that read origin and destination locations from a local file on disk storing spatial coordinates and additional quantitative attributes (e.g. quantity of material transported and/or monetary payment) in a tabular format. Other types of flows, such as material transported by boats or road vehicles, are better suited for tools that follow some types of networks (e.g. road or stream network). Finally, transfer of virtual material, such as information or currency, is represented by tools that map radial flows given that all matters is the spatial distance between two locations, not represented over a specific network. News media and publication of books and articles heavily contribute to disseminate information on certain topics across the globe. Several online portals, such as LexisNexis® Academic search engine, enable the users to search through large databases for specific terms or academic publications on a subject of interest. Users interested in mapping information flows can run a tool that extracts the geographical location of a published article, news, or book from an HTML report file from the LexisNexis database. Any tool contained within the flows toolset is meant to represent all these different types of flows and can be expanded as necessary.

Causes toolset

The Causes toolset contains script tools that qualitatively describe or statistically assess the potential factors causing the flow of goods, information, or ecosystem services between sending and receiving systems. The term “cause” should not be confused with causality from a statistical point of view, where only a well-designed experimental design can identify real causes of a measured variable of interest. From a qualitative stand point, this toolset gives users the opportunity to pick from a set of pre-defined categories of potential causes (e.g. ecological, economic, political, technological), which can then be further described verbally and placed on the map associated with a spatial location near the telecoupled system of interest (i.e. sending, receiving, spillover). The latter is just a simple way to qualify a number of causes that would otherwise be impossible to characterize without having any empirical dataset to analyze. If such a dataset exists, users can then choose from a number of quantitative statistical methodologies such as ordinary-least-squares (OLS) model selection (Hutcheson 2011) or factor analysis for mixed data (Hair Jr. et al. 2010). These tools aim to isolate and identify the most important factors associated with an observed quantity of interest. For example, flows of tourists to a certain region could be due to a number of socioeconomic or environmental factors. Surveys are typically designed to record a large number of variables that can be analyzed to identify latent factors (groups of variables defining specific common characteristic among them) or the most relevant ones to explain the observed visitation rate of tourists.

Effect toolset

The Effects toolset contains script tools that quantify socioeconomic and environmental effects directly or indirectly caused by a flow of goods, information, or ecosystem services between sending and receiving systems. Some of the script tools contained inside this toolset have been developed from scratch, while others have either been modified from existing ArcGIS geoprocessing tools or have been linked to external third-party software (e.g. InVEST). Among the tools built from scratch, users can estimate environmental impacts such the estimated overall amount of CO_2 emission resulting from all the flows of material transported across telecoupled systems. The total amount will be affected not only by the number of trips taken by a carrier but also by its type and carrying capacity. A smaller vehicle may need to take multiple trips to transport a quantity demanded by the receiving system but it could also produce less CO_2 if more energy efficient compared to larger ones. Economic effects expressed in terms of total costs and revenues for each telecoupled system can be calculated using the cost-benefit analysis tool. This tools simply sums up all costs and revenues to calculate final returns of investment for each system. By using this tool, users can tie each monetary returns to a defined geographical location, thus helping with the exploration of spatial patterns of gains and losses. The types of costs and revenues will vary depending on the nature of the chosen telecoupling, but the tool is flexible to accommodate for such situations. For example, costs and revenues involved in tourism will be different from the type and number of those involved with the transfer of wildlife species between zoos or between zoos and wildlife breading centers or the wild across the globe. A modified OLS regression tool from ArcGIS can be used to estimate socioeconomic and environmental effects based on a number of chosen factors (explanatory variables) identified by the user as potential causes of a telecoupling. For example, if used in conjunction with the OLS model selection tool within the Causes toolset, OLS regression can use the factors that were deemed statistically most important in explaining tourism visitation rates and make estimates based on alternative scenarios.

EXAMPLE APPLICATIONS

Background

In order to demonstrate applications of the Telecoupling Toolbox, we chose two separate case studies of telecoupling processes: wildlife transfer and tourism between the Wolong Nature Reserve (China) and the rest of the world. The reserve is a 2000-km^2 protected area located within a biodiversity hotspot of global interest (Myers et al. 2000, Liu et al. 2003) in southwestern China (Wolong Nature Reserve Administration Bureau 1998) (Fig. 2). The reserve is a long-term study site for coupled human and natural systems research (Liu et al. 1999, An et al. 2006, Linderman et al. 2006, Viña et al. 2008, Chen et al. 2009, 2010, Tuanmu et al. 2011, Yang et al. 2015) and some results from the area have been applied at multiple local-to-international levels (Liu et al. 2003, Xu et al. 2006, Yu and Liu 2007, Bawa et al. 2010, Liu and Raven 2010, Viña et al. 2010, Bradbury et al. 2014, An et al. 2014).

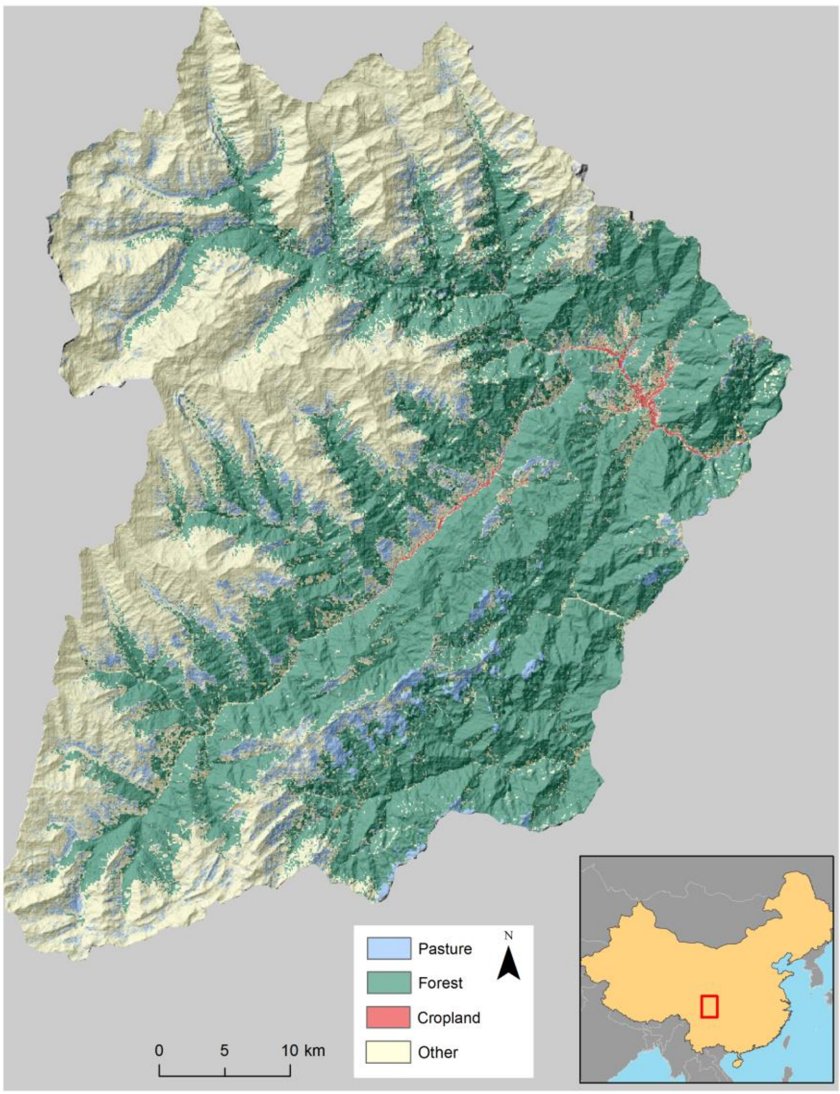

Fig. 2. The Wolong Nature Reserve, China, and its satellite-derived 2007 land cover classification.

The reserve is home to the world-renowned giant panda (*Ailuropoda melanoleuca*) and more than 6,000 other animal and plant species (Liu et al. 2015). The area is a coupled human-natural system with interactions between the natural environment with its approximately 5,000 local residents (State Forestry Administration 2006) whose main livelihoods rely on crops, livestock, and collection of timber and non-timber forest products (Li et al. 1992). Previous studies have focused on this area for research on coupled human-natural systems (Liu et al. 1999, An et al. 2006, Linderman et al. 2006, Viña et al. 2008, Chen et al. 2009, 2010, Tuanmu et al. 2011, Yang et al. 2015). Thanks to its wild natural environment and an active captive breeding center housing the largest population of giant pandas in the world (over 200), the Wolong Nature Reserve has attracted a large number of tourists since the early 1980s (Liu et al. 2015). At the same time, the China Conservation and Research Center for the Giant Panda in Wolong has expanded the number of exchange agreements to loan pandas to zoos across the globe over an extended period of time and involving the payment of a fee (Liu et al. 2015).

Datasets and tools

We chose the panda loan and nature-based tourism as case studies for their established prominence in the reserve and also their data availability. Data on panda loans were obtained from the giant panda registry (China Conservation and Research Center for the Giant Panda 2015). Information on the number of pandas lent to other institutions was only available as an aggregate number for each year. For tourism, data come from a daily survey conducted during the summers of 2006 and 2007 at the captive breeding center, on visiting tourists from all over the world. The survey recorded a number of socioeconomic and demographic variables, trying to characterize tourists coming to the reserve (Liu et al. 2013). In both case studies, some missing or incomplete data had to be simulated for the sole purpose of illustrating the use of specific script tools within the Telecoupling Toolbox. The same script tools within Systems, Agents, and Flows toolsets were used to map and describe these telecoupled components in both case studies. Systems were mapped as points representing the centroid of each country involved in the telecoupling and symbolized based on their categories (sending, receiving, spillover). All agents regardless of the entity represented (e.g. household, organization) were also mapped as points with spatial coordinates corresponding to their best available known location. We described telecoupling leading causes by using the Factor Analysis for Mixed Data tool (Causes toolset). Although this tool can be applied to both case studies presented herein, we only report its results for the panda loan example.

Environmental effects associated with transportation of pandas across of the globe, e.g. CO_2 emissions, and socioeconomic effects, e.g. profits and losses deriving from the exchange agreements, were estimated using tools within the Effects toolset (Fig. 3).

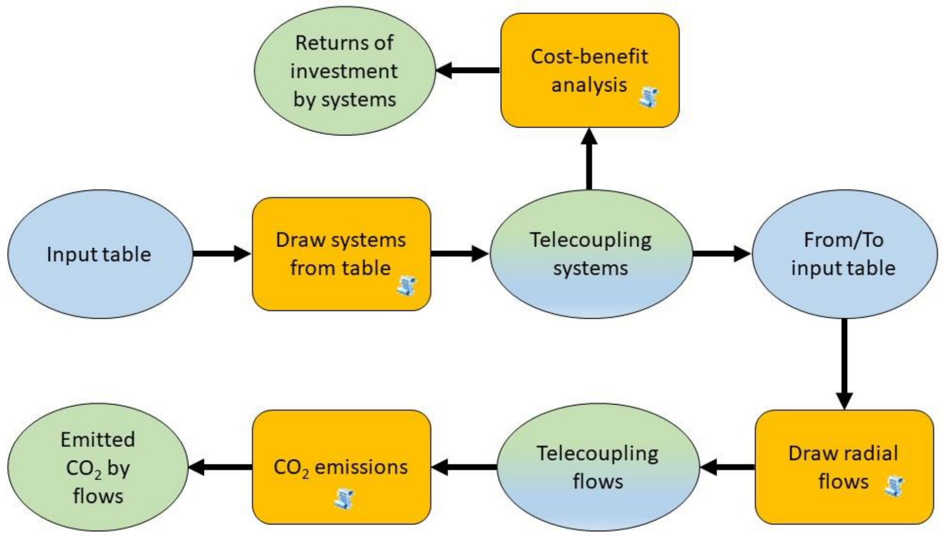

Fig. 3. Flowchart showing an example of how separate geoprocessing tools contained in the Telecoupling Toolbox (orange boxes) can be interconnected and linked together. The example analysis workflow involves mapping telecoupling systems and flows, and calculating CO2 emissions for each mapped flow and returns of investment for each telecoupling system. Inputs are represented as oval cyan-shaded boxes, outputs are shown as oval green-shaded boxes, and mixed cyan-green shades represent outputs that can be also used as inputs for a different tool.

Specifically, costs for receiving systems were derived from the fee paid for the transfer, the food necessary to feed the animals once transferred to the zoos, and transportation fees. At the same time, revenues from panda loans might be indirectly assessed if information on ticket fees for a panda exhibit at receiving zoos was available. On the other hand, the sending system might have more revenues than just the fee paid for as part of the agreements, such as increased tourist fees at the captive breeding center.

For tourism, we focused on negative environmental effects, such as potential habitat degradation for wild pandas. Threats to wild pandas' habitat include built human environment, e.g., hotels, restaurants, resting areas for tourists, houses and roads, as well as cropland. Even if forested areas are the main environment to sustain pandas (Tuanmu et al. 2011), their fragmentation and proximity to built environments caused by zoning redesign will impact the risk of habitat degradation. For this case study, we used the 1998 zoning designation for the reserve (Hull et al. 2011) and assessed whether increased tourism had indirect effects on habitat degradation under current development policies. In 2009, the reserve modified its zoning designation in an effort to enhance conservation of wild pandas' habitat. We used this modified re-zoning as a scenario and tested whether it would have had an impact on habitat degradation had that been implemented between 2001 and 2007, instead of the old 1998 zoning. In order to calculate habitat degradation, we used the Habitat Quality tool (Effects toolset) which links to the equivalent InVEST 3.3.1 model. For validation and detailed explanation of equations used by each of the InVEST models, we invite the reader to consult the official documentation provided by the NatCap project (Sharp et al. 2016). This indicator is a relative score (relative to the study area) between 0 and 1, and depends on the impact of threats on habitat, the level of accessibility of each cell on the landscape (e.g. zoning restrictions), the sensitivity of each land cover type to the various threats, and threat levels to panda habitat among a chosen set. Therefore, habitat degradation can be considered as a weighted average of all the aforementioned threats, with a level of 1 assigned to the biggest threat (e.g., buildings). Cropland and primary roads were assigned threat levels of 0.5 and 0.7, respectively. Data on land cover for the nature reserve was available for years 2001 and 2007 (Liu et al. 2016), encompassing a period of time where tourism in the reserve has continually increased (Liu et al. 2015).

Results

Panda loans

The sending system (Wolong Nature Reserve, as a whole or the actual location of the captive center if more spatial accuracy is needed), the receiving systems (worldwide zoos involved in panda loans) and a spillover system (Holland), which provides bamboo for pandas in Edinburg (Scotland) Zoo (Brown 2011), were all mapped using tools within the Systems toolset (Fig. 4).

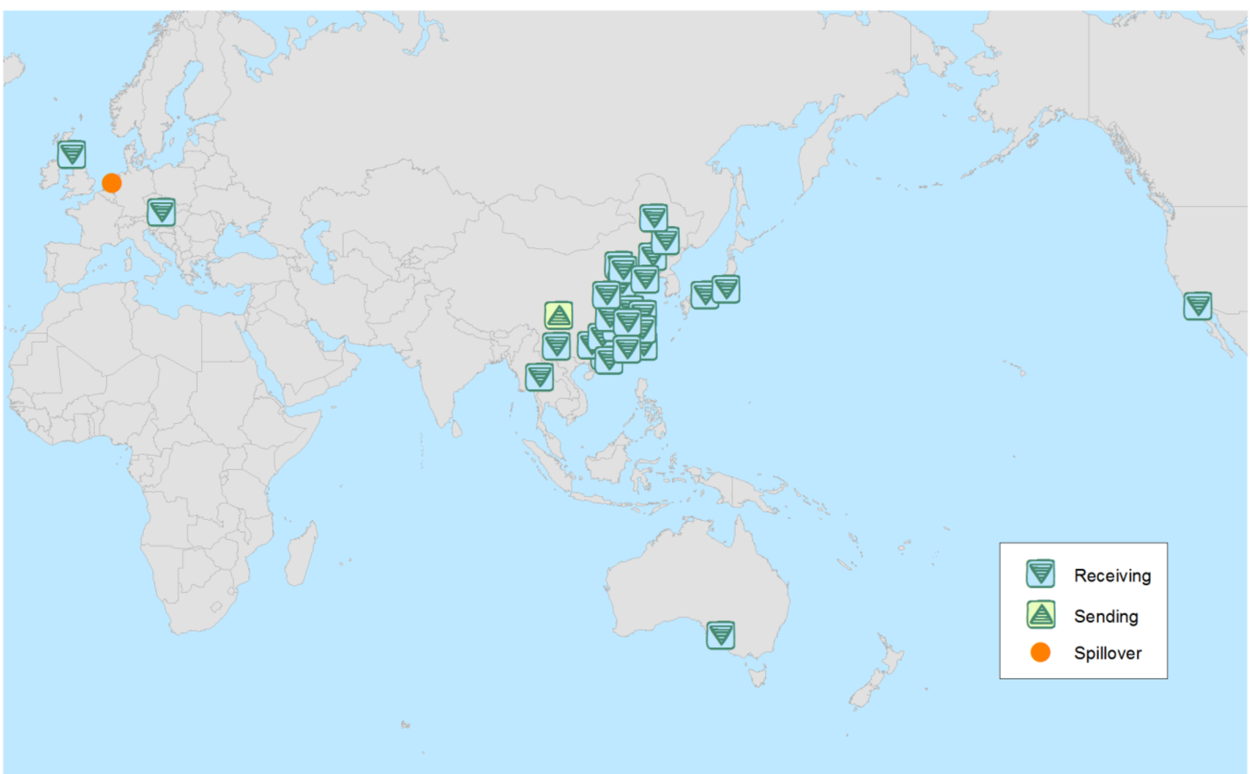

Fig. 4. Sending, receiving, and spillover systems involved in panda loans. The Wolong Nature Reserve is the only sending system, while several worldwide zoos represent the receiving

systems. Holland is marked as a spillover system because it is indirectly involved in the telecoupling by growing bamboo (Brown 2011) needed to feed pandas hosted at the Edinburgh Zoo. Each telecoupled system is represented as a centroid of the respective country.

People and organizations that participated in or made the panda loan possible were considered "agents" in the telecoupling process and were mapped using tools within the Agents toolset (Fig. 5). Agents in the sending system include the China Society for Wildlife Conservation and the State Forestry Administration as well as the Wolong Nature Reserve Administration Bureau. In the receiving system, agents consist of zoo corporate sponsors that help fund panda loans. Agents in the spillover system are comprise of people who may help negotiate the loan, who cultivate and transport bamboo for pandas in sending or receiving systems, or who indirectly participate in the panda loan. All agents were mapped as points with XY coordinates, using the best available information on the exact location of the represented entity.

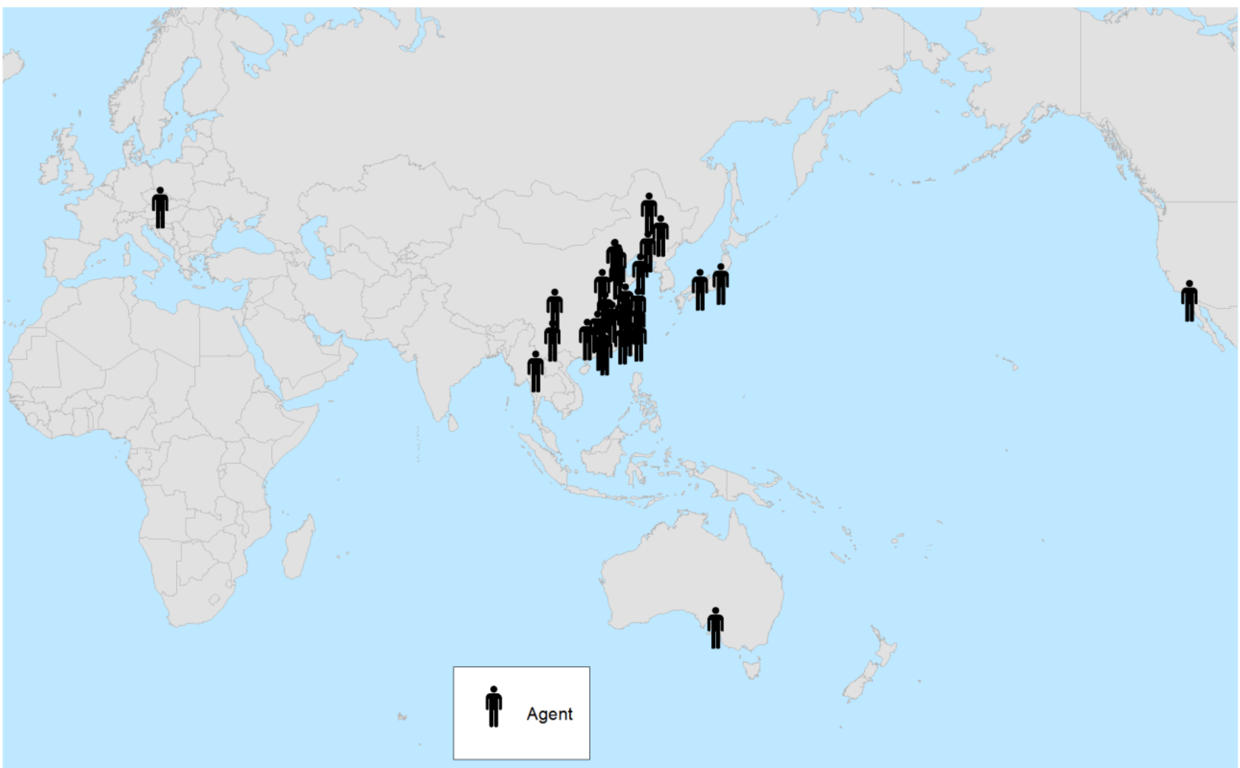

Fig. 5. Agents involved in panda loans. A number of people and organizations are part of the global telecoupling process across sending, receiving, and spillover systems. Each agent is represented as a point with a spatial location based on the best available information.

Flows involved in the panda loan were represented by transportation of wildlife via airplane carriers and were calculated using the radial flow tool within the Flows toolset (Fig. 6). In this case, geodesic lines well represent the flow, given that they represent the shortest distance between any two points on the surface of the earth and that is often the way airplanes travel across the globe. The number of pandas transported from the reserve to other zoos has increased between 2000 and 2010, but more animals are transferred at shorter distances (within China) compared to those at farther foreign locations. Monetary flows, such as the payment of fees following the loan agreements, goes the opposite direction, i.e. from receiving to sending system. Payments for international panda loans have been estimated around 1 million USD per panda each year (Liu et al. 2015).

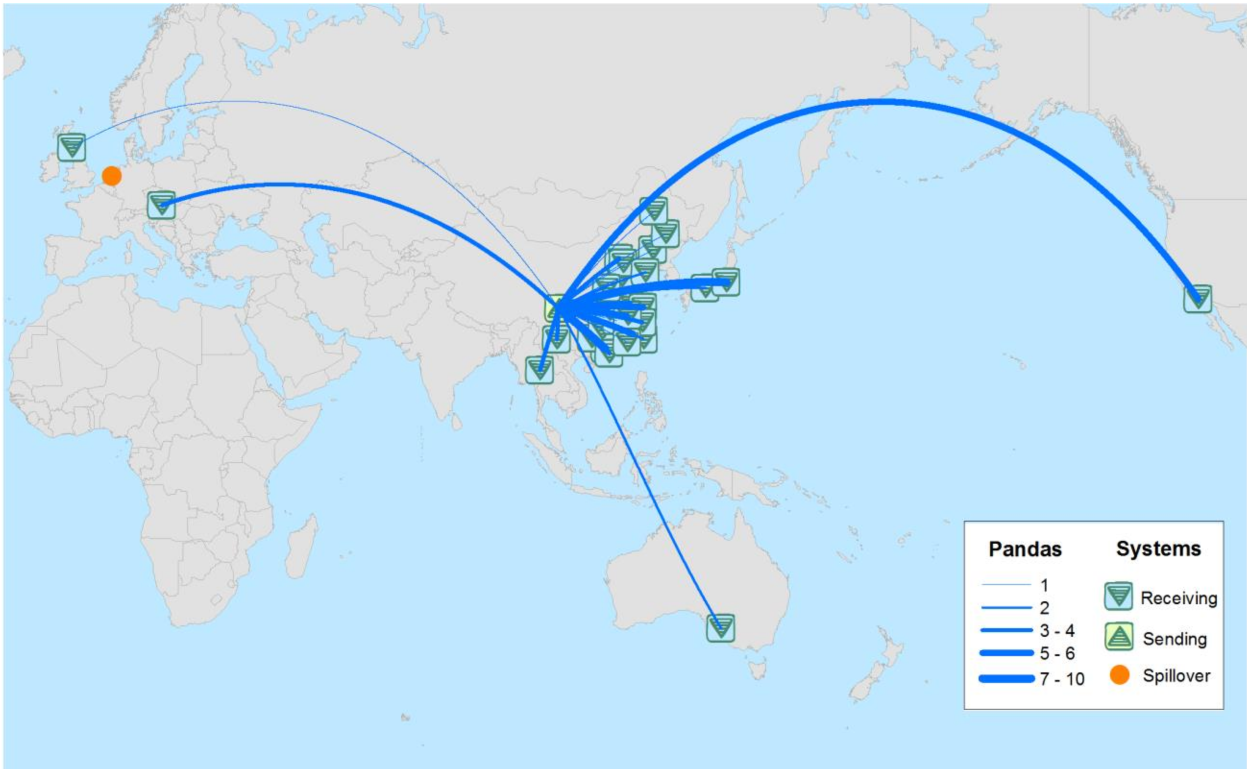

Fig. 6. Flows of pandas across telecoupled systems. The thickness of each geodesic line is proportional to the number of units transported.

Causes behind panda loans include several factors, such as a long history of cultural affinity for the charismatic giant panda, scientific interest for research purposes, and political will. Given the lack of empirical data, we simulated responses from a hypothetical survey as if it had been submitted to a sample of people involved in the panda loan process. The simulated variables included a dichotomic (yes-no) value whether or not the telecoupled system has political interests, money availability for the panda loan, cultural affinity for pandas on a scale 1-10, and maximum availability of pandas. Results from the factor analysis for mixed data tool show that the first three dimensions already explain ~85% of variance observed in the dataset (Table 1).

The number of pandas lent, fees paid (which is proportional to the number of pandas), availability of money and cultural affinity for pandas all are commonly well represented in the first extracted dimension, while availability of pandas seems to define the second dimension (Table 2). None of the selected variables are well defined in the third dimension, given the high contribution shown in the first two. The political will to engage in the panda loans between systems seems to contribute more to define the first dimension while helping to separate the telecoupled systems into two different groups (Fig. 7a).

	Dim.1	Dim.2	Dim.3	Dim.4	Dim.5
Variance	3.209	0.966	0.868	0.512	0.444
% of variance	53.489	16.105	14.473	8.538	7.395
% of variance (cumulative)	53.489	69.594	84.067	92.605	100.000

Table 2. Leading factors behind panda loans: Eigenvalues, percentage of variance, and cumulative percentage of variance explained by the first five dimensions (Dim.) extracted by the factor analysis.

Quantitative	Dim.1	ctr	cos2	Dim.2	ctr	cos2	Dim.3	ctr	cos2
Pandas	**0.914**	26.023	0.835	-0.198	4.046	0.039	0.264	8.056	0.070
Fees	0.914	26.023	0.835	-0.198	4.046	0.039	0.264	8.056	0.070
Money_avl	**0.770**	18.488	0.593	0.123	1.560	0.015	0.259	7.700	0.067
Affinity_s	**0.716**	15.959	0.512	0.023	0.055	0.001	-0.393	17.746	0.154
Pandas_avl	0.313	3.052	0.098	**0.931**	89.772	0.867	0.034	0.130	0.001

Categories	Dim.1	ctr	cos2	Dim.2	ctr	cos2	Dim.3	ctr	cos2
no	-2.010	8.254	0.674	0.135	0.412	0.003	1.284	46.035	0.275
yes	0.536	2.201	0.674	-0.036	0.110	0.003	-0.342	12.276	0.275

Table 3. Leading factors behind panda loans: coordinates, contribution (ctr), squared-cosine (cos2) for each of the first three extracted dimensions (Dim.) by the factor analysis for quantitative and categorical variables. Pandas: number of pandas loaned. Fees: fees paid. Money_avl: money availability. Affinity_s: social affinity. Pandas_avl: panda availability; i.e., total number of pandas available for loan. Categories represent political will (yes–no).

The graph of the variables (Fig. 7b) confirms what is shown in Table 2 regarding the association between each variable and the first two extracted dimensions. The graph of the quantitative variables on the unit circle (Fig. 7c) tells which quantitative variables are mostly correlated with each other as well as with the first two dimensions. The number of pandas lent along with money availability and cultural affinity all contribute to explain the first dimension (as shown in Table 2), with a positive correlation indicating that financial availability and affinity to pandas all contribute to seeing a higher number of pandas lent between systems. At the same time, pandas' availability is positively correlated with the aforementioned variables, but defines a separate dimension in the factor analysis.

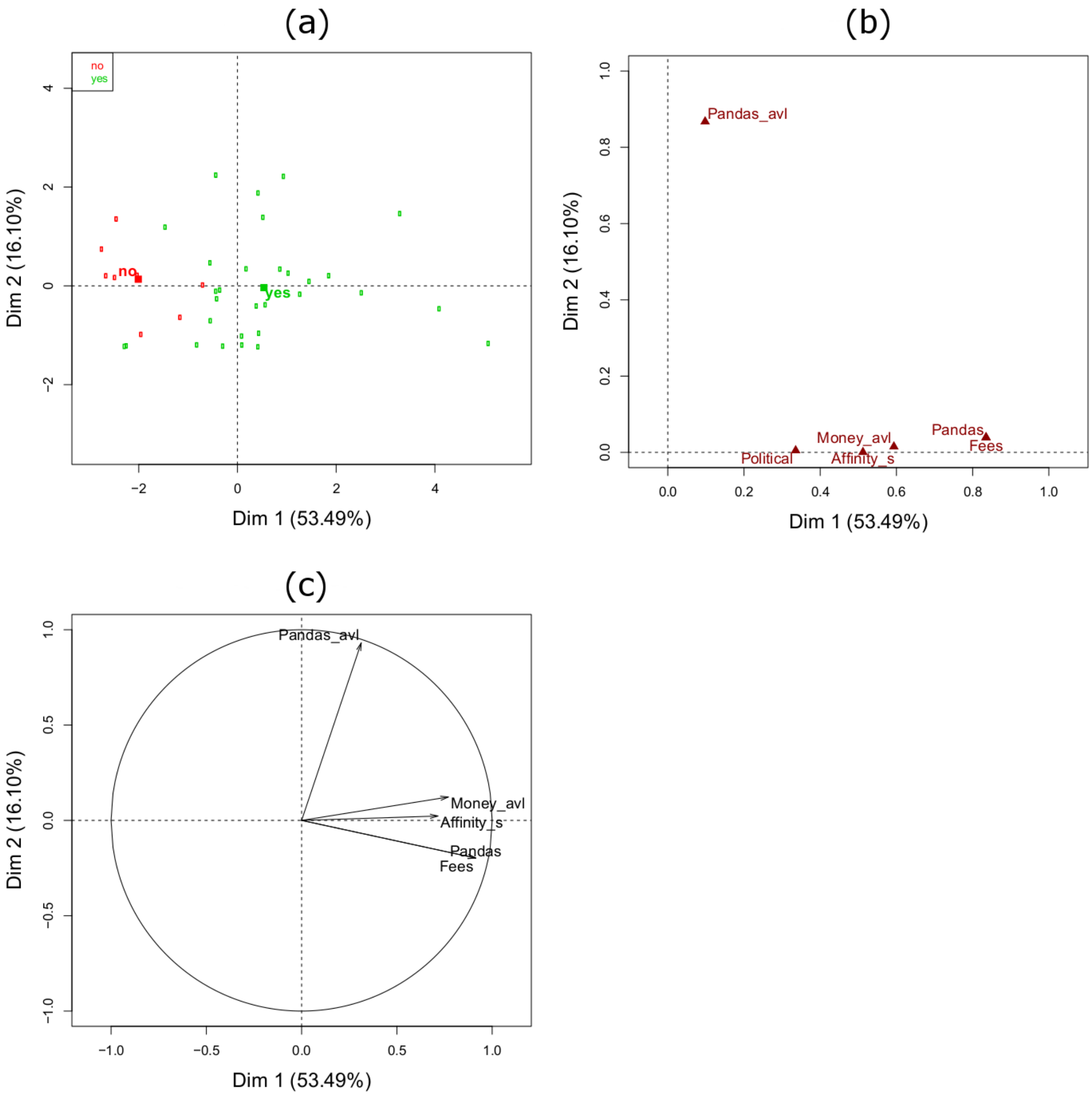

Fig. 7. Plots produced in the output report by the factor analysis for the mixed data tool (Causes toolset) of the Telecoupling Toolbox. (a) Individual factor map, with units colored based on categories from the political will variable (red = no, green = yes); (b) graph of the variables; (c) graph of the quantitative variables on the unit circle.

Transportation of pandas worldwide comes with a number of direct and indirect socioeconomic and environmental effects. CO_2 emissions affect not only sending and receiving systems but contribute to climate that may be reflected at the global scale. The CO_2 emissions tool estimated and mapped how much CO_2 on average has been emitted in the atmosphere as a result of several trips (Fig. 8). Assuming transportation by Boeing 777 jets, which emit roughly 29 kg of CO_2/km, and that a single animal could be carried on the same airplane for each trip, the total amount of CO_2 emitted in the atmosphere was roughly 5.2 million Kg.

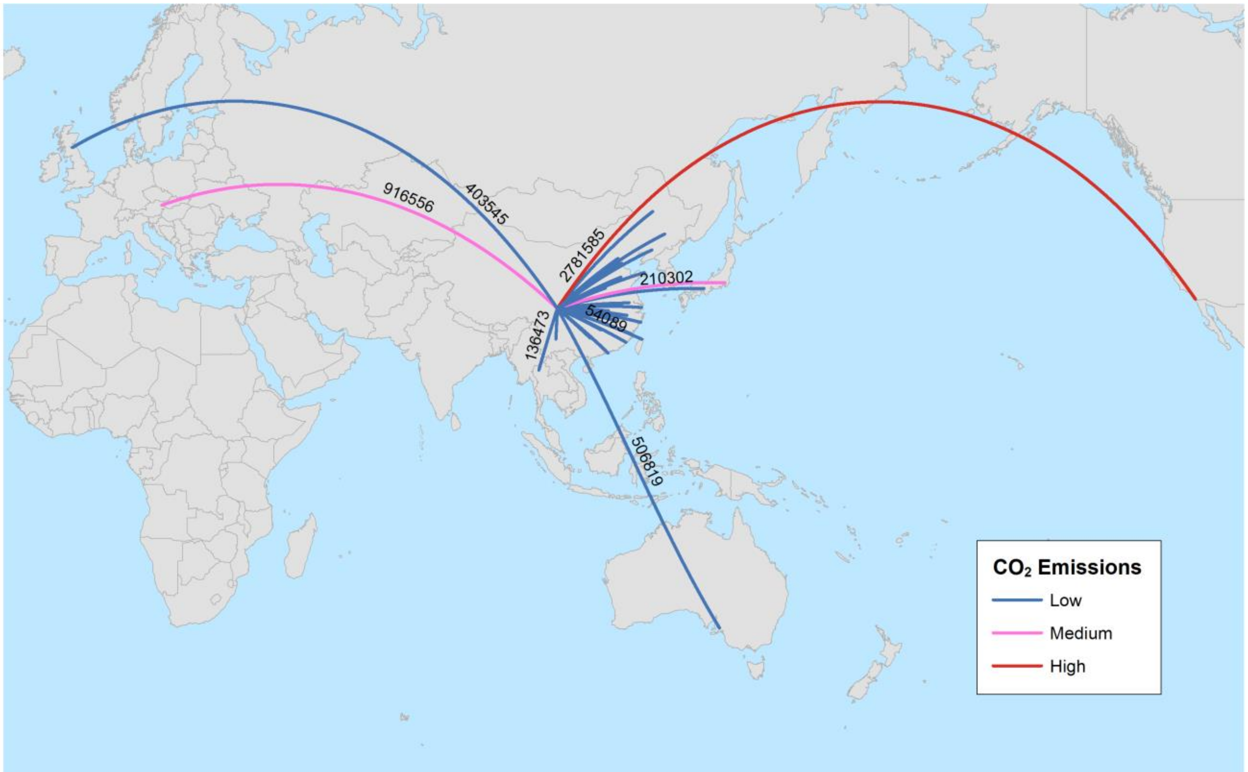

Fig. 8. Environmental effects associated with the transportation of pandas across the globe in terms of CO2emissions. Values are expressed in kilograms, assuming an amount roughly equal to 29 kg/km emitted by Boeing 777 jets. Total CO2 emissions were calculated based on the number of pandas transferred and on the assumption that each airplane can carry a single unit per trip. Lower emissions are shown in blue, medium emissions in magenta, and high emissions in red.

Costs and revenues were summed up to calculate net returns on investment across the telecoupled system (Fig. 9). Small returns were estimated for Holland, a spillover system with revenues from sales of bamboo grown to feed pandas at the Edinburg zoo.

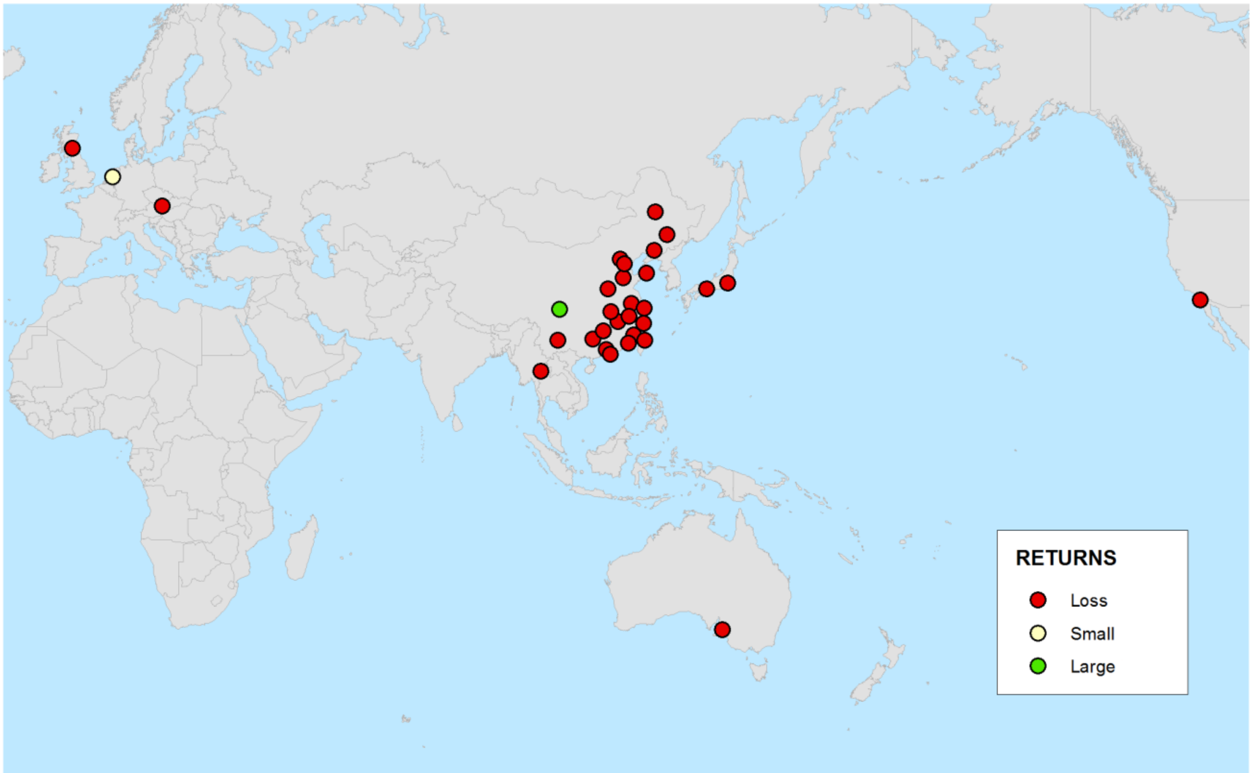

Fig. 9. Economic effects associated with panda loans across the telecoupled system. Values represent returns of investment (revenues – costs). Negative returns (losses) are shown in red, small positive returns (profits) in yellow, and large profits in green. A lack of data on indirect revenues from tourism in both the sending and receiving systems caused the receiving systems to show only losses from panda loans. At the same time, costs involved in production of bamboo in Holland were not considered, and thus show only profits.

Tourism

Telecoupled systems, agents, and flows involved with tourism to the Wolong Nature Reserve were mapped with the same tools used for panda loans (Fig. 10). In this case, agents were identified as the Sichuan Tourism Bureau, the Sichuan Forestry Department, the Wolong administration Bureau, the Dept. Tourism under Wolong Administration Bureau, as well as a number of investment companies (e.g. Luneng Xinyi Ltd. Co., Jiuzhaigou Scenic Area Administration) that developed new infrastructures in the reserve to accommodate increasing tourism, and all local residents who directly or indirectly got involved in tourism-related activities (e.g. jobs, sale of products).

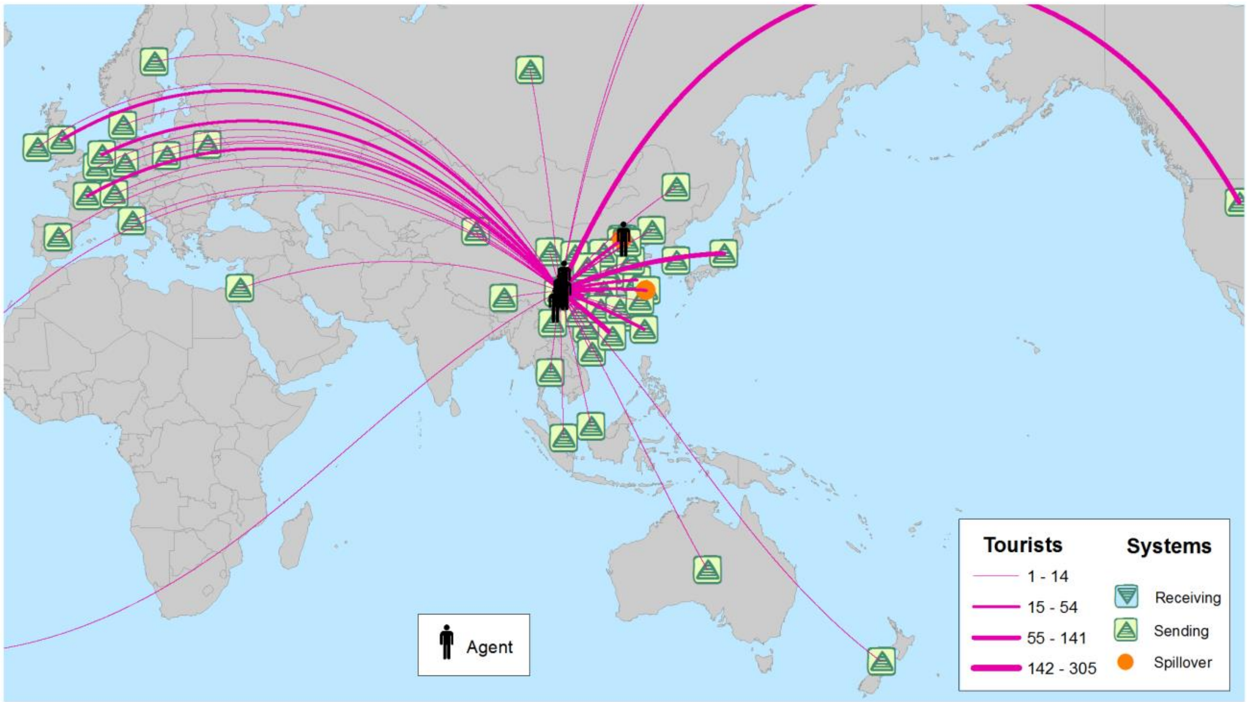

Fig. 10. Systems, agents, and flows of tourists involved in the tourism case study for the Wolong Nature Reserve, China.

As usual, spillover systems are harder to clearly identify than sending or receiving systems. In this case, we represented spillover areas worldwide that support the supply chain industry of tourism, e.g. stopover cities along travel routes to Wolong such as Beijing, Shanghai, and Chengdu, providing services to tourists. For this reason, certain systems can be both sending and spillover systems, depending on the original locations of tourists. For instance, if tourists come from Chengdu, then Chengdu is the sending system. If tourists come from Beijing and make a stop and receive services in Chengdu, then Chengdu is the spillover system. Because systems and agents were mapped and associated with a permanent spatial location by the tool, users can zoom in/out to the desired spatial extent to make sure all components are visualized appropriately. Similarly to panda loans, we chose to represent flows of tourists as geodesic lines, given that most transportation occurred via airplane carriers. Given the lack of information on specific days of travel for each tourist surveyed, flow lines were represented as an aggregated number of tourists over multiple weeks. The large majority of tourists came from within China, but we can still observe a large variety of countries of origin across the globe. As recorded by the survey, most Chinese tourists come to Wolong Nature Reserve not only for its natural environment but also to escape summer heat.

Between 2001 and 2007, the reserve has experienced both an increase and decrease in degradation of panda habitat within the experimental and buffer zoning designation from 1998 (Fig. 11a). Specifically, areas in close proximity of the easternmost corner of the main road crossing the reserve have seen an increased degradation, probably due to the presence of expanded development. The spotted red areas in the central/North-East sections of the reserve have also experienced an increase in degradation, in part due to new development of infrastructures. However, decreased intensity of cropland may have contributed to a slight decrease in habitat degradation near built areas. Any habitat falling within the core zoning of 1998 (Fig. 11b) is safe given that law prohibits development. If the re-zoning scenario of 2009 (Fig. 11d) had been implemented between 2001 and 2007, a few more areas in the western section of the reserve would have been protected from degradation. However, the new zoning design would have not significantly altered the increase/decrease of habitat degradation observed within the developed areas in the central and northeastern sections of the reserve.

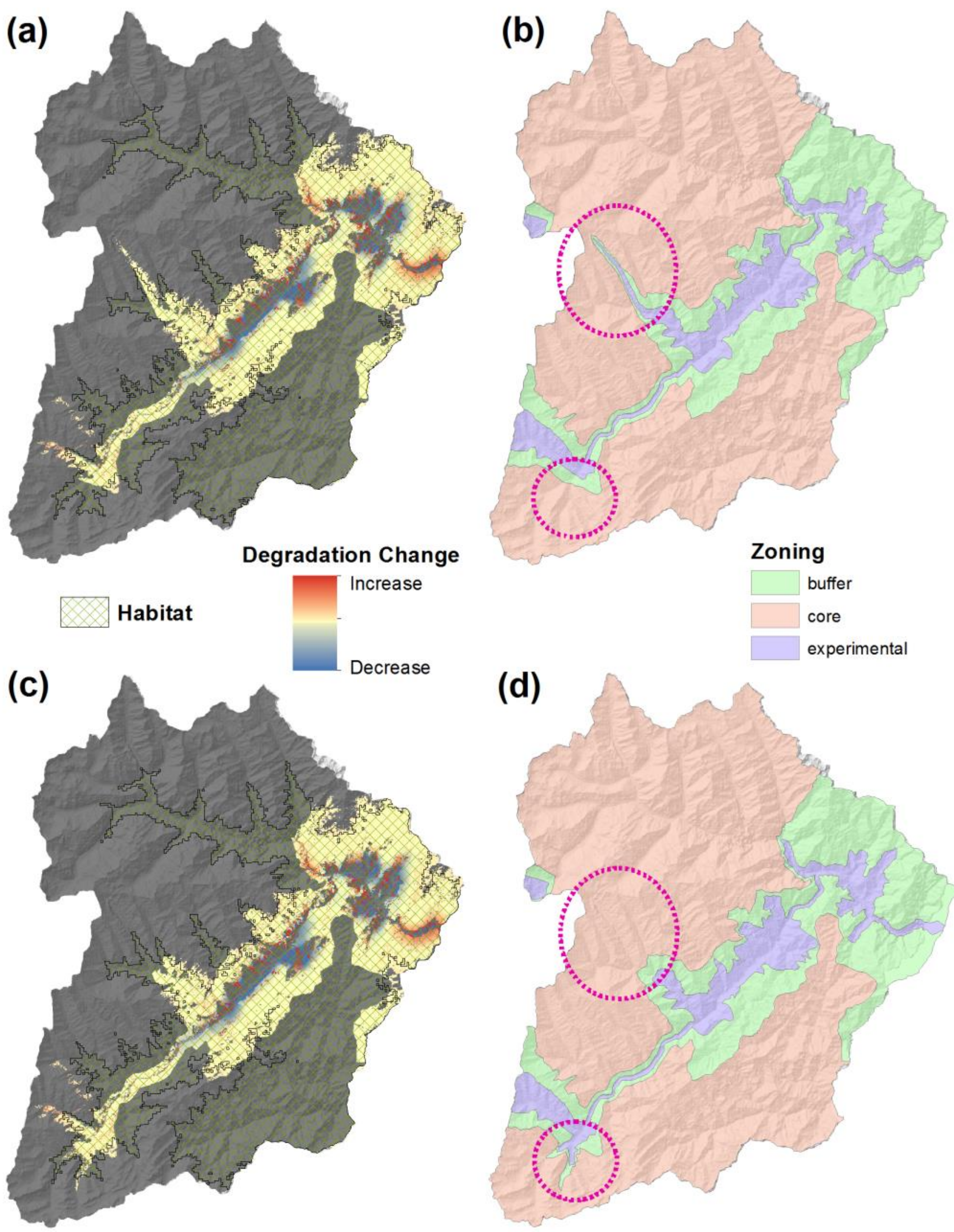

Fig. 11. Change in habitat degradation for wild pandas between 2001 and 2007 in the Wolong Nature Reserve, China. (a) Increased/decreased degradation under (b) 1998 zoning designation. (c) Potential increased/decreased degradation under (d) scenario of 2009 zoning designation.

Habitat degradation is calculated as defined by the Habitat Quality InVEST 3.3.1 model (Sharp et al. 2016). Red indicates an increase (worsening); blue indicates a decrease (improvement). Development is allowed in both experimental and buffer areas, while core areas are protected by law. Areas where zoning designation has changed are circled.

DISCUSSION

The interdisciplinary umbrella concept of telecoupling has received increased attention in recent years because it provides an integrated approach that explicitly examines socioeconomic and environmental interactions between coupled human and natural systems over distances. In this paper, we presented the Telecoupling Toolbox, a new suite of spatially-explicit software tools developed to systematically operationalize (e.g., describe and quantify) the telecoupling framework. By using the existing functionalities and multi-scalar visualization capabilities of a GIS software environment (i.e. ESRI's ArcGIS), our custom toolbox provides a single, integrated environment to help users map systems, agents, and flows from local to global scales. In addition, the toolbox offers descriptive and quantitative tools to determine the causes and assess how changes in coupled human and natural systems are likely to change flows of benefits and costs to people and the environment over distances. While systems, agents, and flows tools are mostly developed to assign a spatial location and visualize all components within the same mapping environment, causes and effects tools have the biggest potential for quantifying multiple socioeconomic and environmental interactions between coupled human and natural systems. One of the added values of our toolbox is its integrated, modular, and extendible nature. Instead of having to install and separately run standalone versions of other third-party software tools to accomplish specific tasks, e.g. quantification of ecosystem services in InVEST (Sharp et al. 2016), we allow for the integration of multiple tools within the same GIS environment. Moreover, we take advantage of the new R-bridge library (https://r-arcgis.github.io/) to combine the power of ArcGIS and R software (R Core Team 2016) to solve spatial problems and use the plethora of statistical tools to leverage more complicated analysis tasks where needed.

The Telecoupling Toolbox can be especially useful for exploring the outcomes of alternative management and climate scenarios or evaluating trade-offs and feedbacks between focal areas and other interacting areas. For example, changes in crop production in one area caused by changes in distant food demand or the natural environment (e.g. climate) will likely have repercussions on the global climate through carbon emissions, market prices, and socioeconomic feedbacks on revenues of all partners involved in the trade chains. Users could utilize the telecoupling toolbox to better describe the entire system and entities involved in a given flow of material/energy while accounting for multiple effects and feedback on both the socioeconomic and natural systems at any affected location. Some of the script tools inside the toolbox can help stakeholders decide where to best allocate economic resources to ensure their investments are sustainable and secure. Although we acknowledge that at the time of writing the toolbox does not have several of the tools that would be needed to understand a wider range of telecoupling processes, such as international trade, species invasion, or animal migration, we are undergoing steady updates and improvements that aim at that. In its current state, users can look at telecoupling processes such as those presented in the manuscript, i.e. wildlife transfer (panda loan) and tourism, or others such as crop production, payments for conservation programs, and flows of information.

In this paper, we applied the toolbox to the telecoupled human and natural systems represented by the Wolong Nature Reserve, China, and the rest of the world. In the applications to the panda loan and tourism, the toolbox was used to map and visualize relevant systems, agents, and flows. Statistical methodologies such as the factor analysis for mixed data tool helped describing potential factors facilitating the flow of pandas between the Wolong reserve and zoos across the globe. Although we acknowledge that true causality is difficult to determine in observational studies like the ones presented herein, it is nevertheless useful to look at potential factors associated with the flow of interest. For cases where empirical datasets are incomplete or missing, thus making it impossible to statistically determine potential factors, we recommend using the interactive tool within the Causes toolset to at least qualitatively describe them. The sample data provided with the toolbox should not only allow users to better understand and practice with each tool but also suggest what type of empirical data (spatial and non-spatial) needs to be collected and compiled. Our goal is not to cover all possible applications and build multiple datasets at different spatial scales, but rather leave users enough flexibility to choose their preferred data sources and construct datasets appropriately to their studies. For the applications demonstrated in this paper, we relied on existing data sources as well as estimated or simulated some values from scratch in order to run the tool. In real-world situations, a lack of data should stimulate users to acquire what is necessary to run the tools of interest and have results that are more meaningful to adjust or implement socio-environmental policies.

Results showed that it is currently possible to quantify multiple direct socioeconomic and environmental effects, such as returns of investment on exchange agreements, habitat degradation, and CO_2 emissions. Indirect effects and feedbacks that are indirectly related to the flow between telecoupled systems are harder to assess or tease apart from other factors. For example, degradation in wild pandas' habitat can be indirectly caused by expanded infrastructures needed to accommodate tourists. When relevant empirical data are available, the toolbox can also estimate indirect effects and feedbacks. The set of spatially-explicit tools we developed hides the entire complexity of analysis running behind the scenes, which should help focus the users' attention on input data requirement rather than modeling algorithm and calculations used. However, this information can still be readily found in the user guide and tutorial handbook provided along with the Toolbox. To facilitate the visualization of some tool output, we pre-defined custom symbology associated with it, e.g. when representing telecoupling systems typologies, or agents. However, users have full control of the symbology within the GIS software and this component was left entirely open to accommodate the different needs and visualization preferences for each output (quantitative and qualitative).

CONCLUSIONS

The Telecoupling Toolbox and its first set of analysis tools reported in this paper, represent a useful and comprehensive platform for operationalizing the telecoupling framework that no other tools are currently able to do. The interconnected world is experiencing dramatic changes where complex interactions and feedbacks between human and natural systems across scales and borders are becoming more predominant than ever before. The telecoupling framework has been introduced to conceptually understand today's hyper-connected world and help achieve sustainable development goals. The Telecoupling Toolbox systematically maps and quantifies the five major interrelated components of the telecoupling framework: systems, flows, agents, causes, and effects. Through the modular design, the toolbox flexibly integrates existing tools and software to assess synergies and tradeoffs associated with policies and other interventions. The results from the case studies illustrate the toolbox's multiple functions with an easy-to-use interface. The toolbox is capable of addressing globally important issues, such as land use and land cover change, species invasion, migration, flows of ecosystem services, and trade of goods and products. Facing the complexity of quantifying major direct and indirect causes and effects related to these globally important issues, the toolbox offers a new way forward for natural and social scientists across various disciplines, practitioners, and stakeholders to generate and use integrative information for managing how humans and nature sustainably coexist.

The innovative and open-source Telecoupling Toolbox also provides a solid foundation to enlarge and amplify the toolbox in the future. Updated and new versions of the Telecoupling Toolbox will be released periodically when new script tools are added or modifications made to existing tools to fix errors or improve their functionalities. We plan on developing more custom tools (e.g., add modules on other telecoupling processes such as migration, species invasion, foreign investment; quantify interactions among multiple telecouplings) and including additional third-party tools to enhance the comprehensive set of analyses available to users within the same integrated GIS platform. Examples of potential external tools include EnviroAtlas (Pickard et al. 2015) to help users analyze ecosystem goods and services that are critically important to human well-being, and trade models similar to those developed by the Global Trade Analysis Project – GTAP (Aguiar et al. 2016). Although the present toolbox was developed to work within ESRI's ArcGIS software environment, and thus limited to the Microsoft Windows platform, we are planning a concurrent transition to a web-based application. The major advantage of this transition will be to free up users from the hassle of installing several required software and libraries, while engaging and connecting a larger number of people through an interface that can be more easily understood and widely shared across government, business, and other organizations. Moreover, a web-based application can provide a standardized set of shared spatial data layers for users that are unable to find relevant sources for their study areas. We believe that such added features will help further expand the applicability and elevate the power of the telecoupling tools.

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