Journal of Land Use Science

ISSN: 1747-423X (Print) 1747-4248 (Online) Journal homepage: https://www.tandfonline.com/loi/tlus20

Land-use changes across distant places: design of a telecoupled agent-based model

Yue Dou, James D.A. Millington, Ramon Felipe Bicudo Da Silva, Paul McCord, Andrés Viña, Qian Song, Qiangyi Yu, Wenbin Wu, Mateus Batistella, Emilio Moran & Jianguo Liu

To cite this article: Yue Dou, James D.A. Millington, Ramon Felipe Bicudo Da Silva, Paul McCord, Andrés Viña, Qian Song, Qiangyi Yu, Wenbin Wu, Mateus Batistella, Emilio Moran & Jianguo Liu (2019): Land-use changes across distant places: design of a telecoupled agent-based model, Journal of Land Use Science, DOI: 10.1080/1747423X.2019.1687769

To link to this article: https://doi.org/10.1080/1747423X.2019.1687769

Published online: 17 Nov 2019.

JOURNAL OF LAND USE SCIENCE
https://doi.org/10.1080/1747423X.2019.1687769

ARTICLE

Land-use changes across distant places: design of a telecoupled agent-based model

Yue Dou[a,b], James D.A. Millington[c], Ramon Felipe Bicudo Da Silva[d], Paul McCord[a], Andrés Viña[a], Qian Song[e], Qiangyi Yu[e], Wenbin Wu[e], Mateus Batistella[d,f], Emilio Moran[a,g] and Jianguo Liu[a]

[a]Center for Systems Integration and Sustainability, Michigan State University, East Lansing, USA; [b]Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, The Netherlands; [c]Department of Geography, King's College London, London, UK; [d]Center for Environmental Studies and Research, State University of Campinas, Campinas, Brazil; [e]Key Laboratory of Agricultural Remote Sensing (AGRIRS), Ministry of Agriculture and Rural Affairs/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, China; [f]Embrapa Agricultural Informatics, Brazilian Agricultural Research Corporation, Brasília, Brazil; [g]Center for Global Change and Earth Observations, Michigan State University, East Lansing, USA

ABSTRACT

Land-use changes across distant places are increasingly affected by international agricultural trade, but most of the impacts and feedback remain unknown. The telecoupling framework – an analytical tool for examining socioeconomic and environmental interactions over distances – can be used to conceptualize the impacts of agricultural trade on land-use change and feedbacks across borders of importing and exporting countries and across spatio-temporal scales of land systems. We apply the framework to design an agent-based model (TeleABM) that represents land-use changes in telecoupled systems to investigate how local land-use changes are affected by flows. The Brazil–China telecoupled soybean system is used as a demonstration. With examples of research questions, we explore the possible applications of this model for assessing farm-level income, fertilizer usage, deforestation, and agricultural intensification, as a tool to quantify socio-ecological impacts between distant places and holistically inform sustainable land-practices across system boundaries.

ARTICLE HISTORY
Received 26 April 2019
Accepted 23 October 2019

KEYWORDS
Telecoupling; agent-based model; agricultural trade; land-use change; local land-use decision; land system

1. Introduction

Useful insights to address grand challenges in global sustainability research have emerged from the domain of land systems science in recent decades (Foley et al., 2005; ICSU, 2010; Turner, Lambin, & Reenberg, 2007; Verburg et al., 2016, 2015). Land systems science integrates land-use activities and biophysical dimensions using the coupled human-natural system framework (CHANS) with the ultimate objective of fostering sustainable land-use practices in urban and rural environments and across locations and scales. Observing changes in land uses and understanding the causes and consequences of these changes have been a main scientific objective in land systems science (Verburg et al., 2016).

Agricultural trade is necessary to balance the demand and supply from different countries and regions in order to improve global food security (Godfray et al., 2010). Many studies have concluded that the drivers of local land-use changes originate at broad scales from global sources. One example

CONTACT Jianguo Liu liuji@msu.edu Center for Systems Integration and Sustainability, Michigan State University, East Lansing, USA

is international agricultural and food trade spurring deforestation in the Amazon and Cerrado biomes in Brazil (Barona, Ramankutty, Hyman, & Coomes, 2010; Nepstad et al., 2014; Richards, Walker, & Arima, 2014). However, little is known about how these local land-use changes affect distant locations, especially the feedbacks between them. Yet these impacts and feedbacks can be significant. For instance, policies in Vietnam restricting logging helped reforestation in that country but also resulted in drastic deforestation displaced into other tropical locations (Meyfroidt & Lambin, 2009). Therefore, understanding land-use changes and their connections are important for governing land systems.

Unfortunately, most land-use change studies using classic place-based analytical perspectives and, more recently, process-based approaches (Castella & Verburg, 2007; Friis et al., 2016; Luus, Robinson, & Deadman, 2011) are often conducted in a local context, overlooking important drivers of farmers' land-use decisions that originate from distant places. This is particularly true with global agricultural trade. Land-use changes occurring outside of the focal location following a policy change have received some attention, including investigations of leakage and indirect land-use changes (Fuchs et al., 2019; Lapola et al., 2010; Meyfroidt & Lambin, 2009; Richards, 2015; Seto et al., 2012). However, agricultural trade affects both exporting and importing countries. To understand land-use changes within both exporting and importing countries, more effective modelling and analytical approaches are needed. Two such approaches are the telecoupling framework and agent-based modelling (ABM) (Liu et al., 2013; O'Sullivan et al., 2015; Verburg et al., 2016).

The telecoupling framework investigates socioeconomic and environmental interactions over distances (Figure 1), and has been conceptually and empirically applied to a variety of issues (Kapsar et al., 2019; Liu, 2014; Liu et al., 2018, 2015; Seto & Reenberg, 2014; Wang & Liu, 2016; Yang et al., 2016). Some

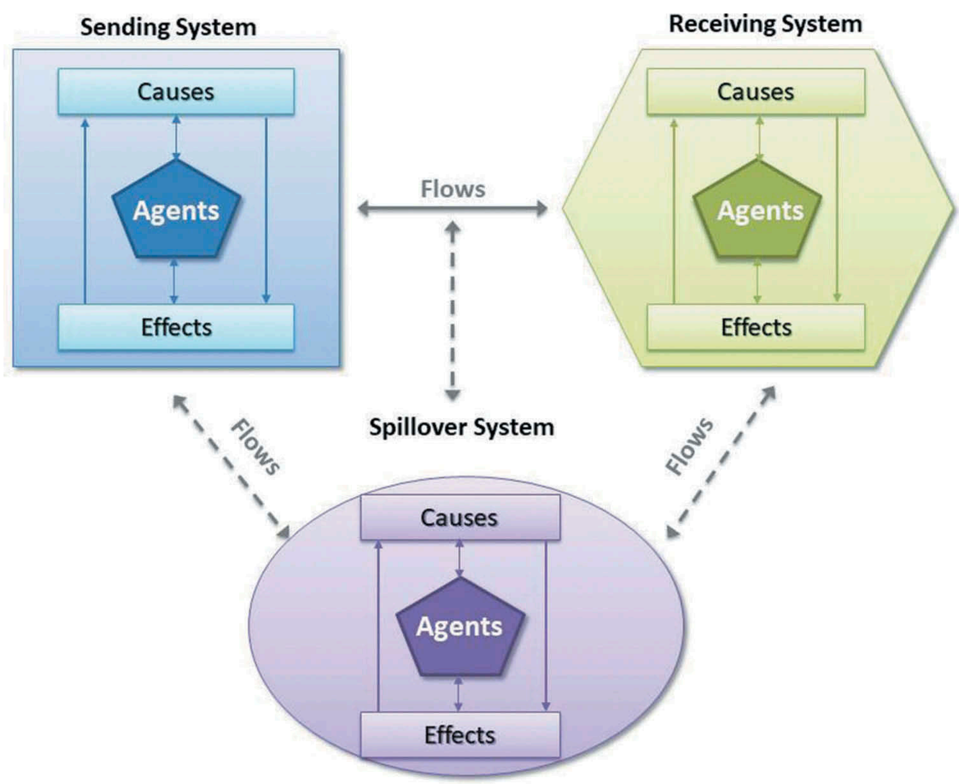

Figure 1. The Telecoupling framework that includes systems, causes, agents, effects, and flows connecting systems (adapted from Liu et al., 2013).

special land-use change effects, such as the cascading and spillover effects in exporting regions (sending systems) can be identified using the telecoupling framework (Dou, Silva, Yang, & Liu, 2018; Silva et al., 2017). Studies have also shown that agricultural trade affects soil nitrogen and organic carbon within importing countries (receiving systems) (Sun et al., 2018; Tong et al., 2017). Yet a comprehensive model that can operationalize the telecoupling framework and simulate land-use changes in distant places is still lacking (Millington, Xiong, Peterson, & Woods, 2017; Verburg et al., 2019).

In this paper, we present the design of an ABM of telecoupled systems (TeleABM). Through the model design process, we aim to advance the understanding of land-use changes in telecoupled systems and propose solutions on how to model these changes based on current land-use modelling approaches. This model represents distantly coupled sending and receiving systems and simulates the patterns of land-use change in the two places simultaneously. Using the telecoupled soybean example (Dou et al., 2018; Silva et al., 2017; Sun, Tong, & Liu, 2017), we focus on the agricultural land-use changes made by local farmers in one place and the deforestation and agricultural land uses made by local farmers in another place. This model emphasizes the flows and feedbacks (e.g. agricultural trade) connecting two remote locations within a telecoupled system rather than merely focusing on the land-use change processes that are taking place at a local level in a single location.

As a computational modelling tool, TeleABM allows users to reproduce the spatial pattern of agricultural land uses, test various hypotheses, and simulate different scenarios in telecoupled systems. For instance, we can use TeleABM to explore how crop prices and food demands influence land uses nearby and faraway, or to simulate the direct and indirect impacts on land-use changes from disruptive climate and political scenarios. Through these simulations, we aim to identify how tominimize negative impacts and achieve sustainable land-use practices in all participating regions (Liu et al., 2018; Liu, Hertel, Nichols, Moran, & Viña, 2015). This paper is the first attempt to model telecoupled land-use dynamics and the flows and feedbacks for landscapes in both agricultural exporting and importing regions. It is our hope that this paper can also raise awareness of land-use flows and feedbacks between land systems across long distances.

2. ABMs in practice and the gaps for representing land-use changes in telecoupled systems

Agent-based models are effective tools for land systems simulation (An & Liu, 2010; Deadman, Robinson, Moran, & Brondizio, 2004; Huber et al., 2018; Liu et al., 2007; Murray-Rust et al., 2014; Parker, Manson, Janssen, Hoffmann, & Deadman, 2003). However, current ABMs cannot simulate telecoupled systems (Table 1), because each ABM is the representation of a single-location land system, and because the feedbacks between local and far-away land-use changes are not explicitly represented (Figure 2). Every model case stands as an independent land system without a role in a telecoupled system. The telecoupled land-use system, however, can link different land systems and simulate how one local system affects the other and vice versa. Building on previous extensive ABM reviews (Huber et al., 2018; Liu et al., 2007; Parker et al., 2008, 2003; Robinson et al., 2007), we used 13 ABMs that simulate agricultural land uses (Table 2) and investigate farmers' land-use decisions as examples to briefly review current ABM applications, particularly focusing on how to use them to

Table 1. Gaps among current ABM applications for telecoupled land systems.

	Current applications	Gaps to represent telecoupled land systems
Components	one local/regional land system as a coupled human-natural system (CHANS)	no receiving/sending/spillover systems, and no flows between the systems
Impacts	local land-use changes	no land-use changes caused by factors from distant systems
Interactions	mostly within-scale and some cross-scale	no distant interactions
Feedbacks	only local feedbacks between agents and environment within one system	no feedbacks between systems

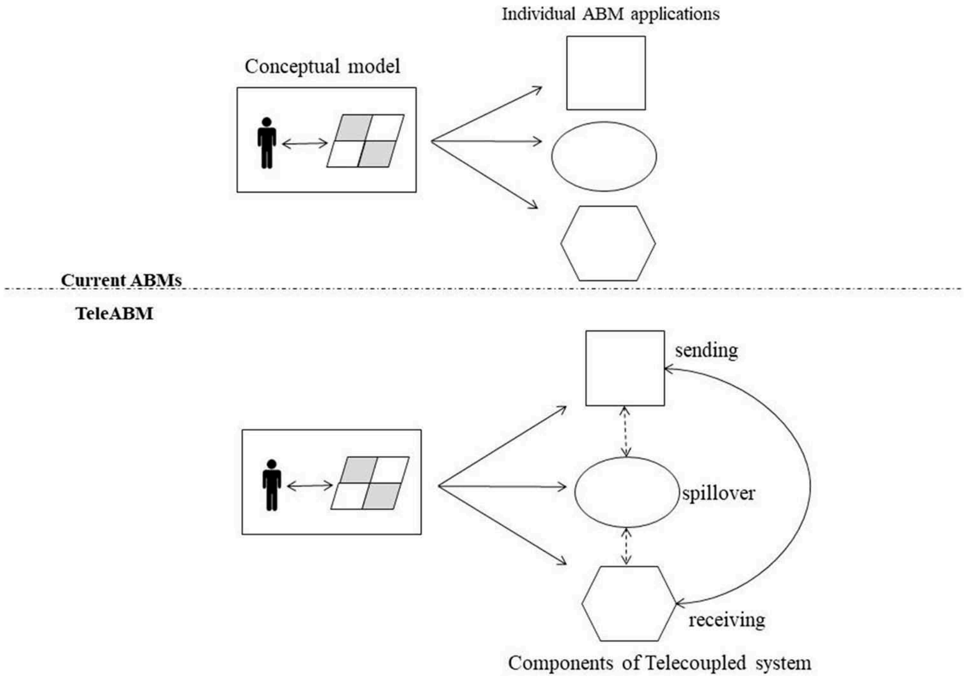

Figure 2. The differences between current ABM applications and a telecoupled ABM. TeleABM links multiple land systems through flow, while current ABMs are only individual land system representation without flows connecting them.

model telecoupled systems. If the same model structure and settings have been used for different land systems, we consider them as one model.

We identified two gaps in existing models if they are to be adopted for telecoupled systems. First, most of these models were used for a specific single system, such as MARIA for the communities in the Amazon estuary (model 2 in Table 2), or the Wolong model that studies the impacts of human actions on panda habitats in China (model 3 in Table 2). Some modelling frameworks have been developed for different cases, of which the Competition for Resources between Agent Functional Types (CRAFTY) framework is one example (model 12 in Table 2). While CRAFTY aims to incorporate land-use behaviors at the country scale (i.e. CRAFTY-Sweden), or even the continental scale, it does not seek to link land systems in different places. Other ABMs such as MP-MAS (model 6 in Table 2) are also designed for implementation to different cases, however, not for telecoupled land systems.

The second gap is that often these models only simulate land-use changes within its own boundary under the influence from external factors (e.g. labor, capital, or crop price in the market representation in Table 2), representing no flows and feedbacks to other places. A long-standing issue in land-use change modelling, if often implicitly negotiated, is the need to establish the system boundaries (in space, time and process) to define what should be represented and included in a model structure (Brown, 2004; Lane, 2001; Millington, Demeritt, & Romero-Calcerrada, 2011). Most land-use ABM applications assume a model boundary to endogenously represent processes of change within a (single) landscape, separate from other regions of the world; representation of the influence of the world beyond the landscape (i.e. beyond the model boundary) is represented through exogenous 'boundary conditions' (e.g. scenarios of annual demand for a particular crop from 'the market').

However, for an ABM of telecoupled systems representing multiple landscapes (like ours), land-use changes in multiple landscapes are affected by flows exchanged across model boundaries such that boundary conditions for each landscape will be the result of processes endogenously simulated

Table 2. Description of classic ABM applications.

Model ID and Name	Access to external labor/capital/work	Market representation	Agents interactions	References
1 LUCITA	Local labor pool	Fixed price	N/A	Cabrera et al., 2012; Deadman et al., 2004
2 MARIA	Local labor pool and off-farming work	Price is given as input files	N/A	Cabrera et al., 2010
3 Wolong	N/A	N/A	Social norm in 2014 version	An & Liu, 2010; Chen et al., 2014
4 CORMAS	Short-time credit	Price is given as input file	Social statue	Barnaud et al., 2008, 2007
5 LUDAS	Off-farm	Fixed price	Neighborhood effect	Le et al., 2012, 2010, 2008; Villamor et al., 2012
6 MP-MAS	Off-farm income	Price is influenced by amount of supply	Household groups	Balmann, 1996; Berger, 2001; Berger et al., 2006; Berger and Ringler, 2002; Berger and Schreinemachers, 2009; Happe, 2004; Happe et al., 2006; Schreinemachers, 2005; Schreinemachers and Berger, 2006b, 2011, 2006a
7 SYPIRA	Off-farm labor	Price is given as input files in scenarios (e.g. historical, monotonically increasing,)	Institution and neighborhood effect (environment)	Manson, 2006, 2005; Manson and Evans, 2007
8 LUCIM	Off-farming activities	Price is given as input file	Neighborhood effect (of forest)	Evans and Kelley, 2008, 2004
9 FEARLUS	N/A	Price is given as input file	Neighborhood effect	Gotts et al., 2003; Gotts and Polhill, 2009; Polhill et al., 2010; Polhill and Parker, 2007
10 Valbuena	N/A	Price is given as input file	N/A	Valbuena et al., 2010, Valbuena et al., 2008
11 PALM	Off-farm working	Fixed price	N/A	Matthews, 2006
12 CRAFTY	N/A	N/A	N/A	Blanco et al., 2017; Holzhauer et al., 2019; Murray-Rust et al., 2014
13 Evans	Off-farm labor	Commodity price is given as model input	Diffusion of land-use practices	Evans et al., 2011

in other landscapes. Take crop prices as an example: crop prices influence farmers' land-use decisions in both sending and receiving systems and changes of crop prices result in different crop productions. In turn, the production may, therefore, cause fluctuations in crop prices in these landscapes due to the supply and demand variations. However, crop price is mostly given to the existing models in Table 2 exogenously, representing only a one-directional impact from price to landscape. An interface that opens the landscape boundary and internalizes the flows is needed for the telecoupled agent-based model to couple various systems (shown as the arrows connecting the systems in Figure 2).

3. Design of an agent-based model that represents telecoupled systems

We demonstrate our design focusing on land-use changes caused by the soybean trade (detailed descriptions of this telecoupled system can be found in following sections and in the literature (Dou et al., 2018; Liu et al., 2013; Silva et al., 2017; Sun et al., 2017; Yao, Hertel, & Taheripour, 2018)) and refer to our model as TeleABM. Two steps have been realized to address the identified two gaps (i.e. lack of representing more than one location in a model and the need to internalize flows across locations): first, we describe the sending and receiving systems, and how to represent local farmers' agricultural decisions influenced by environmental constraints and other factors from two different places in a hierarchical structure; then, we discuss the flows connecting the two systems and how to represent the flows and feedbacks between multiple hierarchical systems in one model including how policy changes in one system will affect agricultural decisions in another system through international trade. Below we describe how these two steps are achieved. In addition, we describe how to parameterize these steps into a computational model.

3.1 Overview of the telecoupled Brazil–China soybean system

3.1.1 The sending and receiving systems

Soybeans are one of the top internationally traded crop commodities (Food and Agriculture Organization of the United Nations, 2016)). We begin by identifying Brazil as the sending system since it is the global leader in soybean exports (Figure 3(a)). The largest importer of soybeans, China, is identified as the receiving system. We exclude spillover countries now and will include them in the future (e.g. emerging soybean-producing countries in South America). Our primary research interests are the feedbacks between the land-use changes in Brazil (e.g. the expansion of soybean-planted area) and the land-use changes in China (e.g. the decline of soybean-planted area). Therefore, instead of focusing on the entire country of Brazil and China, we model important soybean production regions in both countries (Figure 3(b)). Heilongjiang Province in the northeast of China (HLJ) and the state of Mato Grosso (MT) of Brazil were chosen as the focal study systems (Figure 3(b)). The soybean planted area in MT increased from 2.9 million hm^2 in 2000 to 9.0 million hm^2 in 2015 (i.e. a more than 310% increase) (Table 3) (Instituto Brasileiro de Geografia e Estatistica, n.d). In the meantime, the soybean planted area in HLJ declined from 2.9 million hm^2 to 2.4 million hm^2 and the proportion of soybean areas in the total planted area dropped from 30.7% to 16.0% (Heilongjiang Provincial Bureau of Statistics & Survey Office of the National Bureau of Statistics in Heilongjiang, n.d.).

3.1.2 The flow between sending and receiving systems

There are two flows in this model: (1) the soybeans produced and traded between the sending and receiving systems and (2) the corresponding price of soybeans in both systems affected by the traded quantity (Figure 4). The trade agents at the regional scale in the sending system convert the soybean price from international market to local currency and purchase soybeans from local soybean producers in MT. Harvested soybeans are then sent by trading companies from Brazil to China and facilitated by government agencies with tariff and trading agreements. This soybean flow changes

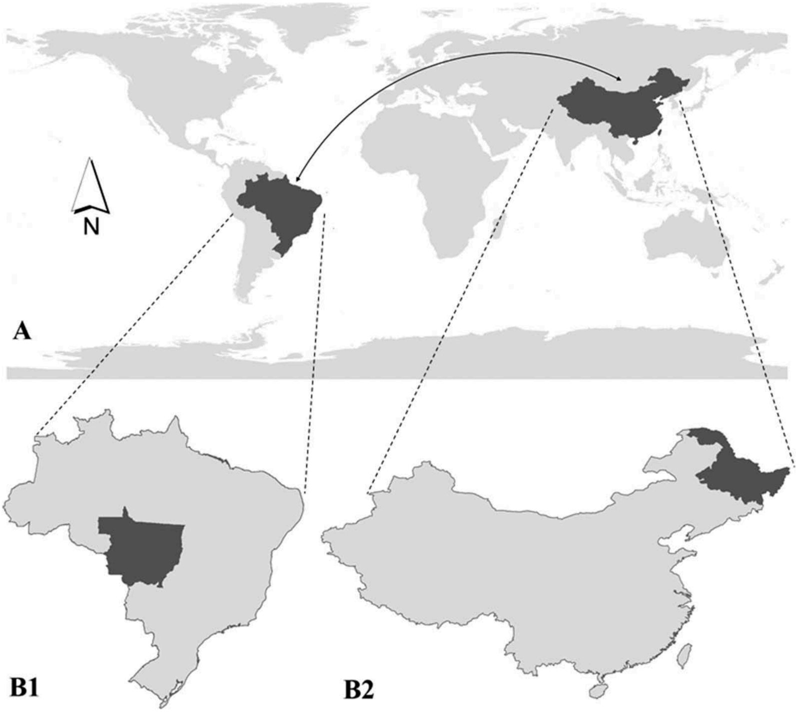

Figure 3. Receiving and sending systems in the telecoupled soybean system. A: sending and receiving countries connected through flows of soybeans; B1: Major soybean production region in the sending system; B2: Major soybean production region in the receiving system. Note B1 and B2 are in the same scale (1: 70,000,000). The dark-shaded area in B1 and B2 is the focal regions in the two countries.

Table 3. Focal regions in sending and receiving countries.

	Mato Grosso State (MT)	Heilongjiang Province (HLJ)
Population (1000)	11, 244	38,120
GDP (billion USD)	93	2193
Area (1000 hm^2)	152,106	47,300
Agricultural area (1000 hm^2)	165,501	39,583
Arable land (1000 hm^2)	21,468	11,990
Forest and other natural vegetation (1000 hm^2)	98,694	24,430
Pasture land (1000 hm^2)	45,339	4,333

Note: HLJ data is the year of 2015, from HLJ yearbook. MT data is the year of 2014, from IBGE.

the soybean price in China through the supply–demand relationship, and this price is distributed by regional trade agents to farmer agents in HLJ, therefore affecting their land-use decisions. Other flows, such as carbon emissions caused by soybean transportation or knowledge diffusion, are not considered in this design.

3.2 Representing the land-use changes in telecoupled system

3.2.1 How to represent sending and receiving systems in one model?

Several approaches from current applications could be adopted to create an integrated TeleABM. For example, the CRAFTY framework could be used to represent agricultural land-use changes across large extents in multiple regions due to the general form of land-use representation and competition (e.g. Blanco, Brown, Holzhauer, Vulturius, & Rounsevell, 2017). Different agent functional types (AFTs are generalized traits of individual land-users) and agents within each type compete for land based

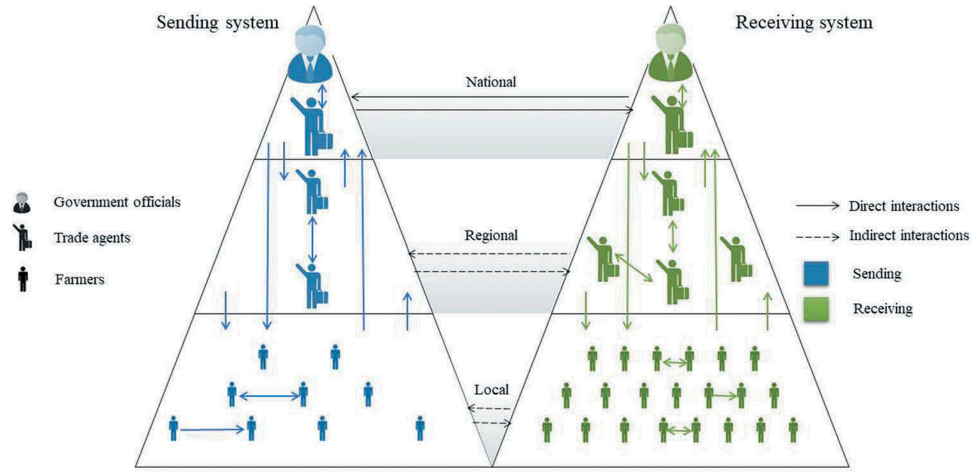

Figure 4. Flow between the sending and receiving systems. The left pyramid represents the sending system and right pyramid is the receiving system. They have similar agent structure across scales. Different colors represent agents and interactions from different systems. The size and number of agent figures are a relative representation of power of influence in the model. For instance, there may be thousands of farmers at the local level that only manage a few landscape grids in the receiving system, but only a few hundred farmers in the sending system and each manages a large quantity of land cells.

on the available capital at every land grid cell, optimizing the agents' utility. The total land-use change should meet the demand of various ecosystem services. The CRAFTY framework could be used to simulate large-scale land-use changes in two countries (e.g. Brazil and China) and use additional modelling approaches (e.g. system dynamics) to connect flows of production and consumption between these and other countries (Millington et al., 2017). Such a large-scale approach would require generalised representation of land-use change at local levels.

However, we are interested in representing finer details of farmers' land-use trajectories and crop rotation practises. This is important because rotation history affects soil properties and crop yields, which in-turn affects agents' subsequent land-use decisions and ultimately, their well-being. This type of information cannot be obtained using CRAFTY, because it does not track the history and trajectory of agent attributes and behaviors, which leaves no room to analyze the legacy of various scenarios on individual farmers. Furthermore, we want to investigate the supply chain process and the corresponding impact on telecoupled land uses, which is not readily represented by CRAFTY.

We do not mean to single out CRAFTY in an unduly negative light; no existing ABMs and frameworks have been designed with the intention of simulating telecoupled systems. Thus, instead of implementing an existing model that was created to achieve different goals we develop our own model following a hierarchical structure, drawing upon empirical data and examples to identify shared features and functions of agents and environments in the soybean-telecoupled system. These shared features and functions are represented as abstract modules in TeleABM, and each system can calibrate and implement these abstract modules to sending and receiving systems (Figure 2).

To explain the design here, we use the soybean farmer agent as an example. We can follow the agent typology method (Valbuena, Verburg, & Bregt, 2008) that has been widely used in ABM applications to characterize soybean farmer agents based on their views, farm attributes, and external factors that affect their land-use decisions. Therefore, each farmer agent can be an abstract class that contains the same attributes (e.g. agent identification, property location, capital, labour, and cost), same decision variables (e.g. risk attitudes, innovation attitudes), same farm practices (e.g. crop choices and tillage options), and interfaces with the same external factors that can be used to describe any farmer. These basic attributes and farm practices can be implemented based on information gathered during fieldwork and secondary data collection (e.g. census data, regional agricultural statistical information).

In addition, more distinct attributes and behavioral options can be added when constructing the human component of sending and receiving systems (e.g. the land use for rice paddy only exists in the receiving system, while the land use for cotton is only present in the sending system). The same design approach applies to the natural component of the land system, with an abstract representation of the vegetation, soil dynamics, crop yield, and the potential to include more functions (e.g. carbon emissions, soil organic carbon storage).

3.2.2 How to represent flows between the sending and receiving systems in the model?

To internalize flows as identified in the second gap, we need to quantify the relationship between land-use outputs from one system and the land-use input in the other system. In our model, this is the relationship between soybean production from the sending system and the soybean price in the receiving system, and vice versa. We could adopt a price function that is similar to AgriPolis (Happe, Balmann, Kellermann, & Sahrbacher, 2008; Happe, Hutchings, Dalgaard, & Kellerman, 2011; Happe, Kellermann, & Balmann, 2006). The assumption in AgriPolis is that the regional price of one commodity is affected by the aggregated production in the supply area. However, this assumption, focusing only on the change caused by accumulative quantity from the supply side, has limitations when transferred to a telecoupled system. For example, the price of soybeans in sending and receiving systems is affected by various other factors, such as transportation costs, currency exchange, government subsidies, and environmental variations. In other words, AgriPolis only internalizes relationship of price and quantity within one system but not breaking the boundary conditions and linking two landscapes.

Instead of AgriPolis, a regional price function, we could use the empirically calculated elasticity (measures a percentage change in price caused by the percentage change of commodity-traded quantity) of soybean trade to simulate the change of soybean price caused by land-use changes in the sending and receiving countries. This empirical elasticity can be found in the literature (Reimer, Zheng, & Gehlhar, 2012). We can covert this price to regional and local soybean price by calibrating with other costs (e.g. transportation) and regional factors. The representation of flows is explained in the next section.

3.3 Parameterizing and interpreting TeleABM

TeleABM can be used to answer 'what-if' questions under alternative scenarios to better understand the telecoupled land systems and evaluate special land-use effects (e.g. cascading effects, spillover effects). Example questions could include 'if China increases its tariff on imported Brazilian soybeans, can we expect less deforestation in Brazil?' and 'if the Brazilian soybean region experiences a severe drought, what impact will this have on future land uses in both Brazil and China?' We list several variables and outputs at different levels (in Table 4) that one can obtain from TeleABM simulations. Using a sample question about 'environmental regulation', we demonstrate the kind of simulated land-use changes that we can analyse using TeleABM results.

Research question: What are the land-use outcomes in both the sending and receiving systems if environmental regulations in the sending system are removed?

Affected variables: Environmental regulations in the sending system in this example are the zero-deforestation moratorium (Dou et al., 2018; Gibbs et al., 2016) and the Legal Reserve, a rule under the Brazilian Forest Code that enforces landowners to preserve a certain portion (i.e. 70% in the Amazon biome and 30% in the Cerrado biome) of their rural property as native vegetation (Gibbs et al., 2015). If the two regulations were removed, farmers could freely convert forest and grassland on their properties to agricultural lands, such as deforestation to single-soybean or double cropping. This would result in pixel-level land-use change and farm-level land-use proportion change (A_c/A_t). At the regional level (e.g. municipality), we would expect to see agricultural expansion rather than intensification (e.g. compare the area of single cropping and double cropping) resulting in greater

Table 4. Variables and outputs of TeleABM.

Analysis Level	Sending System Variables	Receiving System Variables	Flow Variables
Pixel	Land Use: single cropping (e.g. soybeans, corn, cotton, other); double cropping (e.g. soybean-corn, soybean-cotton, other); pasture land; forest; Y^t_c (kg/ha): crop yield based on climate and fertilizer use at year t; F^t_c (N kg/ha): fertilizer usage per pixel, this will change based on farmer's attributes and the choice of single/double cropping	Land Use: reclaimed agricultural land: from natural land use to agricultural land use; one of the three agricultural land uses: rice paddy, corn, and soybeans; Y^t_c (kg/ha): crop yield based on fertilizer use, land-use history, and climate; Rotation history: past land-use trajectory; F^t_c (N kg/ha): fertilizer usage per crop, this will change based on farmer's attributes and the rotation history	Not applicable
Farm	I^t (R$): farm income calculated from crop price and production, and subtract farm cost; A_c/A_t: proportion of different crops (A_c) compared to total property area A_t	I^t (yuan): farm income calculated from crop price and production, subsidy, and subtract farm cost; A_c/A_t: proportion of different crops (A_c) compared to total property area A_t	Not applicable
Regional	$Q_c{}^t$ (ton): total production of different crops at year t; $p^t{}_s$ (R$/kg): local soybean price in the sending system; Transportation cost	$Q_c{}^t$ (ton): total production of different crops at year t; $p^t{}_r$ (yuan/kg): local soybean price in the receiving system	EQ^t (ton): soybean exported from the sending to receiving system at year t
National and International	*ZD*: zero-deforestation environmental regulation, dummy (0 = no, 1 = yes) Forest Code: dummy (0 = no, 1 = yes)	subsidy on crops	$_{ep:}$ bilateral import elasticity, which measures the percentage changes of traded quantity ΔEQ with respect to one percent changes in soybean price Δp; $P^t{}_{fob}$: international soybean prices; P_{fuel}: international price for fuel

deforestation. This would be because single cropping has a higher yield (Y_c) and a lower cost than double cropping in the sending system. Multiplying the soybean yield ($Y_{soybean}$) and total areas ($A_{soybean}$), therefore the total exported quantity EQ^twould also be changed. The traded quantity change (ΔEQ) would, therefore, affect the international soybean price (P_{fob}) and then next year's local soybean prices in the sending (p_s) and receiving (p_r) systems, and subsequently change land use and production in the following rounds. Results in the receiving system might be accelerated soybean conversion to corn (cultivating corn several years in a row instead of corn-soybean annual rotation) and rice paddy, because greater soybean production from the sending system reduces the international soybean price and the local soybean price in the receiving system.

Possible quantitative assessment of the model outputs: Because only environmental regulations are lifted and all the other settings are held constant compared to the baseline scenario, differences in the following outputs can be considered as the results caused by these regulations and telecoupling: (1) the total area of single cropping $\sum_{i=0}^{n}\left(A^t_{single_cropping}\right)$in the sending system over time from $n$farmer agents, the total area of double cropping $\sum_{i=0}^{n}\left(A^t_{double\_cropping}\right)$ and the deforested areas A_{def}, (2) the total area of soybeans $\sum_{i=0}^{n}\left(A^t_{soybean}\right)$ and other crops in the receiving system over time ($\sum_{i=0}^{n}\left(A^t_{corn}\right)$, $\sum_{i=0}^{n}\left(A^t_{ricepaddy}\right)$), (3) the total regional fertilizer usage $\sum F^t_c$ from the sending and receiving system respectively, and (4) the average and distribution of farm income I^t.

4. Modelling platform and empirical implementation

4.1 Implemented modelling schedules and platform

Regarding the implementation, TeleABM operates on an annual basis and is divided into major modelling phases of human land-use decisions (farmer agents take into account internal and external variables and decide land uses for next round), land cell changes (including land-use type change, bio-physical condition updating) and annual accounting by trade and government agents (trade soybeans, disseminate price, check for subsidy and tariff condition). When both sending and receiving systems are simulated, international trade agent is initialized and will facilitate the trade

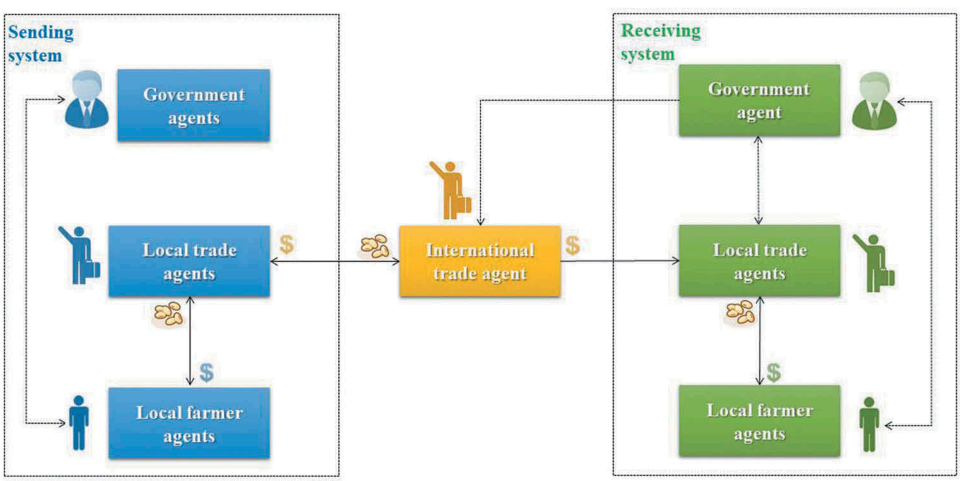

Figure 5. Agents and feedbacks between sending and receiving systems in TeleABM (adapted from (Dou et al., in review)).

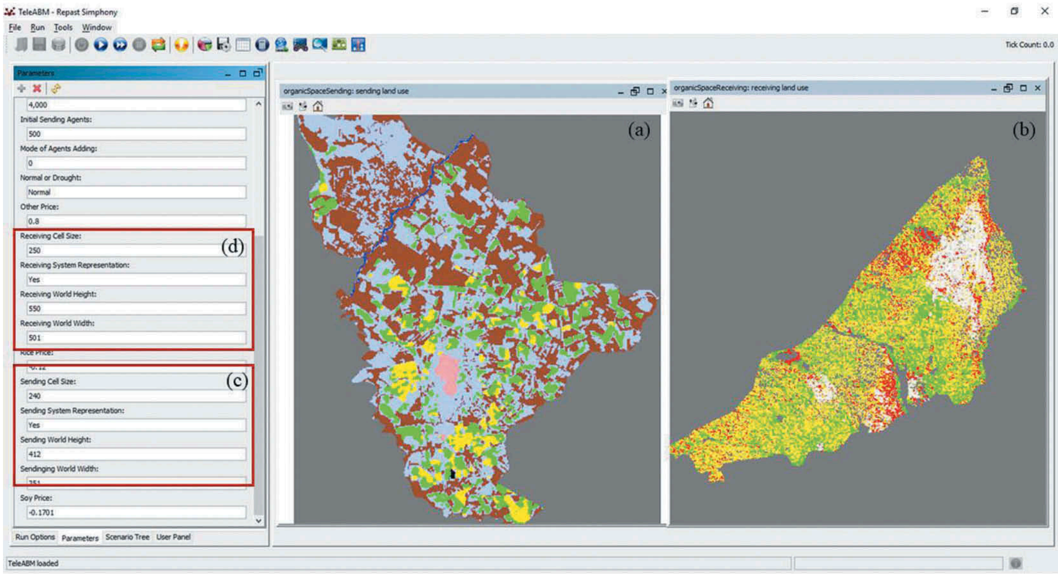

Figure 6. The graphic user interface of TeleABM for simulating the telecoupled land-use changes. In this model, the sending system is a municipality, Sinop, Mato Grosso, Brazil (a), and the receiving system is a county (equivalent to the municipal level in Brazil), Gannan, Qiqihaer, China (b). The observed land-use trend in the past 15 years in Sinop, the sending system, includes agricultural expansion into native vegetation and pasturelands, and agricultural intensification (e.g. from single soybean to soybean-cotton double cropping). While in Gannan, the receiving system, the main land-use change is soybean transition to corn and rice paddy. On the left panel (a), light blue represents grassland, brown represents forest, green is single soybean, yellow is soybean-corn, and black is single cotton. On the right panel (b), blue is water body, green is soybean land, yellow is corn, white is rice paddy, and brown is built-up land. At the beginning of simulation, users can choose which system to simulate and specify parameters for each system: (c) is for the sending system and (d) is for the receiving system.

and disseminate the crop price (Figure 5). A manuscript with full details of implementing this telecoupled land system is submitted for publication (Dou et al., n.d).

The whole model is programmed on RePast Simphony, a multi-agent modelling platform (https://repast.github.io/). It is also designed to be flexible to model land-use changes in other telecoupled systems (Figure 6). The most unique features of TeleABM are that it can simulate a telecoupled system and the flows between sending and receiving systems, as described below:

(1) Representation of both sending and receiving systems. Users can use TeleABM to simulate only the sending system and its land-use changes, only the receiving system and its land-use changes, or both the sending and receiving systems and their telecoupled interactions during one simulation.
(2) Telecoupling flows. Farmer agents' land-use changes in the sending system affect farmer agents' land-use changes in the receiving system. The total soybean production from the sending system is the aggregated result of farmers' land-use decision-making, which influences the soybean price in the receiving system thus impact the decision-making and land-use changes of the farmer agents in this system. The aggregated results of land-use changes in the receiving system will affect the receiving government agent's decision on tariff or subsidy which will affect the land-use changes in the sending system.

4.2 Constructing an empirical TeleABM: next steps

TeleABM faces more than the conventional challenges of developing a single ABM empirically (Evans, 2012; Grimm & Railsback, 2012; Millington et al., 2011; Ngo & See, 2012; O'Sullivan et al., 2015) as we have two dynamically interacting simulations of distinct systems.

4.2.1 Inform agents empirically

Empirical methods to get ground-truth data and inform agents have been reviewed systematically (Robinson et al., 2007; Smajgl, Brown, Valbuena, & Huigen, 2011). Several methods are highlighted here for TeleABM, and the choice of the method is based on the characteristics of agents and their land-use behaviors in the telecoupled system.

The scope and agent characteristics of the sending and receiving systems are different. In the receiving system, the number of farming households and the average size of farmland are different from the sending systems. In addition, the land-use phenomena and research questions in the two systems are also different. Therefore, different data-acquiring methods should be used in the two focal regions.

4.2.1.1. Survey. Using questionnaires with mostly closed-ended questions to collect quantitative information on individuals, households, and communities. Usually, a fraction of the population is sampled randomly or stratified to capture the distribution of characteristics of the entire population (Robinson et al., 2007). This collection provides a foundation for defining agent typology and parameterizing agent functional types. Many ABMs are informed by surveys, hence a wide collection of references (An & Liu, 2010; Chen, Vina, Shortridge, An, & Liu, 2014; Huang, Parker, Sun, & Filatova, 2013) is available.

4.2.1.2. Mental modelling. A type of participatory modelling approach that engages experts and stakeholders' knowledge and encourages the communication between stakeholders and modellers during the modelling process (Özesmi & Özesmi, 2004; van Vliet, Kok, & Veldkamp, 2010; Voinov & Bousquet, 2010). It generates a fuzzy cognitive map as a visual representation of the system, consisting of nodes (or variables, concepts) and their causal relations. A number of studies have used this method to reveal important concepts and relationships of the coupled human-natural systems based on stakeholders' knowledge (Diniz, Kok, Hoogstra-Klein, & Arts, 2015; Gray et al., 2015; Murungweni et al., 2011).

4.2.2 Validation

Validation of ABMs includes two parts: the decision-making process and the model outcome (Evans, 2012; Millington et al., 2011). Participatory approaches can be used to validate the decision-making process (Barreteau & Le Page, 2011). Many other non-participatory techniques have been developed to validate the outcomes of ABMs (Evans, 2012), such as pattern-oriented validation (Castella & Verburg, 2007; Grimm et al., 2005) and ratio of variant and invariant regions (Brown, Page, Riolo, Zellner, & Rand, 2007). However, TeleABM validation requires two sequential processes: validation of the sending/receiving system simulation independently, and then validation of the flow between them. The first validation procedure can obtain common model validation processes. For instance, pattern-oriented validation or pixel-based ROC curve (Receiver Operating Characteristic curve) can be applied (e.g. the simulated pattern of soybean area decline at both regional and household levels in the receiving system can be compared with empirical patterns, and details can be found in the article of TeleABM implementation (Dou et al., n.d)). Once plausible patterns are produced and validated in each ABM (sending and receiving) independently, we can run simulations of the telecoupled system to see if the flow representation is accurate. This can be done by comparing the simulated local soybean price in both sending and receiving systems to the empirical data (e.g. which we demonstrate here as a validation example in Figure 7). Using the validated model, one can then compare outputs from different scenarios to the baseline scenarios and thereby explore how

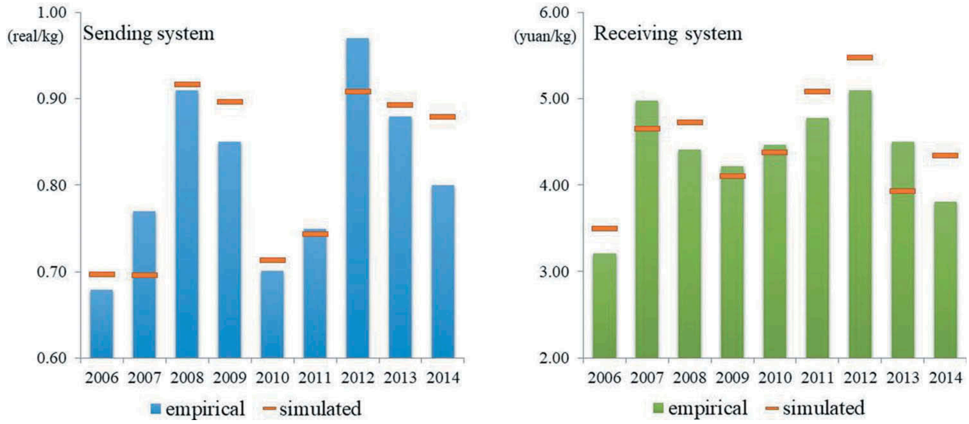

Figure 7. Simulated soybean price and empirical soybean price (Dou et al., in review). The unit in the two systems is local currencies: real/kg and yuan/kg, respectively. This step is only conducted after the validation of two independent landscape systems.

e.g. environmental regulation in the sending system accelerates the conversion from soybean land to rice-paddy in the receiving system.

5. Conclusions

In this paper, we have outlined a conceptual design for an ABM that represents telecoupled land-use changes using the soybean trade between China and Brazil as a case example. Our proposed model is grounded by the telecoupling framework and goes beyond typical agent-based models in at least two aspects: (1) representing land-use changes in more than one coupled human-natural system and (2) representing flows and feedbacks between these multiple systems for allowing a simultaneous simulation across system boundaries. We present the design of TeleABM with potential solutions which is well grounded on existing ABM applications and alternative modelling approaches, particularly representing the flow between the sending and receiving systems. We parameterize crop price as a key variable in addition to the traditional location-specific ABM parameterization, which would not only affect the national-level policy making, but also influence farm-level land-use decision-making.

To identify causes and effects of telecoupled interactions, and more importantly to assess causality, is a critical step yet still lacking in telecoupling studies (Carlson et al., 2018). Based on empirical data from both sending and receiving systems, TeleABM can offer insights and explanations on the causes and effects of land-use changes in telecoupled systems by running counterfactual analysis and scenario simulations (e.g. no soybean trade scenario). Particularly since the land-use changes are simulated from pixel-level and farm-level, this grants us opportunities to investigate cross-scale effects, such as the influence of the international trade on local farmers' land-use changes and local environmental conditions, or the other way around as local policies affect international trade and land-use changes in telecoupled places. We offer this design to researchers, particularly land-use scholars, seeking to employ quantitative models with the telecoupling framework, as well as for land-use changes and ABM modellers that are looking for alternative frameworks for conceptual innovation.

Acknowledgments

We thank editors L. Rasmussen, C. Hickman, and D. Muller, and two anonymous reviewers for the valuable comments on an early version of the manuscript and S. Nichols for the editing of the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research is supported by National Science Foundation Award [DEB-1518518], Complex Dynamics of Telecoupled Human and Natural Systems; Michigan AgBioResearch. It is also supported by the Fundação de Amparo à Pesquisa do Estado de São Paulo [14/50628-9 and 15/25892-7] and by the UK Natural Environment Research Council (grant number NE/M021335/1) via Belmont Forum CRA13 Type 2 project, 'Food Security and Land Use: The Telecoupling Challenge'.

ORCID

Yue Dou http://orcid.org/0000-0001-6320-5482
James D.A. Millington http://orcid.org/0000-0002-5099-0001
Ramon Felipe Bicudo Da Silva http://orcid.org/0000-0002-3480-4539
Mateus Batistella http://orcid.org/0000-0001-7748-5497

References

An, L., & Liu, J. (2010). Long-term effects of family planning and other determinants of fertility on population and environment: Agent-based modeling evidence from wolong nature reserve, China. *Population & Environment*, *31*(6), 427–459.

Barnaud, C, Bousquet, F, & Trebuil, G. (2008). Multi-agent simulations to explore rules for rural credit in a highland farming community of northern thailand. *Ecological Economics*, *66*(4), 615–627. doi: http://dx.doi.org/10.1016/j.ecolecon.2007.10.022

Barnaud, C, Promburom, T, Trébuil, G, & Bousquet, F. (2007). An evolving simulation/gaming process to facilitate adaptive watershed management in northern mountainous thailand. *Simulation & Gaming*, *38*, 398–420. doi:10.1177/1046878107300670

Barona, E., Ramankutty, N., Hyman, G., & Coomes, O.T. (2010). The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environmental Research Letters*, *5*(2), 024002.

Barreteau, O., & Le Page, C. (2011). Using social simulation to explore the dynamics at stake in participatory participatory research. *Journal of Artificial Societies and Social Simulation*, *14*(4), 12–15.

Berger, T. (2001). Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. *Agricultural Economics*, *25*(2–3), 245–260. doi:10.1111/agec.2001.25.issue-2-3

Berger, T., & Ringler, C. (2002). Trade-offs, efficiency gains and technical change – modeling water management and land use within a multiple-agent framework. Quarterly Journal of International Agriculture, 41(1), 119–144. Retrieved from http://www.ifpri.org/publication/tradeoffs-efficiency-gains-and-technical-change-modeling-water-management-and-land-use

Berger, T., & Schreinemachers, P. (2009). Agent-based land use models for teaching, extension and collaborative learning. In S. J. Goetz & F. Brouwer (Eds.), New Perspectives on Agri-environmental Policies: A multidisciplinary and transatlantic approach (Routledge Explorations in Environmental Economics) (pp. 1–18). Routledge

Berger, T, Schreinemachers, P, & Woelcke, J. (2006). Multi-agent simulation for the targeting of development policies in less-favored areas. *Agricultural Systems*, *88*(1), 28–43. doi:10.1016/j.agsy.2005.06.002

Balmann, A. (1996). Farm-based modelling of regional structural change: A cellular automata approach. *European Review of Agricultural Economics*, 24(August 1995), 85–108.

Blanco, V., Brown, C., Holzhauer, S., Vulturius, G., & Rounsevell, M.D.A. (2017). The importance of socio-ecological system dynamics in understanding adaptation to global change in the forestry sector. *Journal of Environmental Management*, *196*, 36–47.

Brown, D.G., Page, S., Riolo, R., Zellner, M., & Rand, W. (2007). Path dependence and the validation of agent-based spatial models of land use. *International Journal of Geographical Information Science*, *19*(2), 153–174.

Brown, J.D. (2004). Knowledge, uncertainty and physical geography : Towards the development of methodologies for questioning belief. *Transactions of the Institute of British Geographers*, *29*(3), 367–381.

Cabrera, A. R., Deadman, P., & Brondizio, E. S., & Pinedo-Vasquez, M. (2010). Exploring the choice of decision making method in an agent based model of land use change. In D. A. Swayne, W. Yang, A. A. Voinov, A. Rizzoli, & T. Filatova (Eds.), 2010 International Congress on Environmental Modelling and Software (p. 373). Retrieved from https://scholarsarchive.byu.edu/iemssconference/2010/all/373/?utm_source=scholarsarchive.byu.edu%2Fiemssconference%2F2010%2Fall%2F373&utm_medium=PDF&utm_campaign=PDFCoverPages

Cabrera, R., Deadman, P., & Moran, E., Brondízio, E. S., & Vanwey, L. K. (2012). Exploring demographic and lot effects in an abm/lucc of agriculture in the brazilian amazon. In A. Heppenstall, A. Crooks, L. See, & M. Batty (Eds.), Agent-Based Models of Geographical Systems (pp. 663–676). doi.10.1007/978-90-481-8927-4_33

Carlson, A.K., Zaehringer, J.G., Garrett, R.D., Silva, R.F.B., Furumo, P.R., Rey, A.N.R., … Liu, J. (2018). Toward rigorous telecoupling causal attribution: A systematic review and typology. *Sustainability*, *10*(12). doi:10.3390/su10124426

Castella, J.-C., & Verburg, P.H. (2007). Combination of process-oriented and pattern-oriented models of land-use change in a mountain area of Vietnam. *Ecological Modelling*, *202*(3–4), 410–420. Retrieved from: http://www.sciencedirect.com/science/article/pii/S0304380006005436

Chen, X., Vina, A., Shortridge, A., An, L., & Liu, J. (2014). Assessing the effectiveness of payments for ecosystem services: An agent-based modeling approach. *Ecology and Society*, *19*(1), 7.

Deadman, P., Robinson, D., Moran, E., & Brondizio, E. (2004). Colonist household decisionmaking and land-use change in the Amazon rainforest: An agent-based simulation. *Environment and Planning B: Planning and Design*, *31*(5), 693–709. Retrieved from: http://www.envplan.com/abstract.cgi?id=b3098

Diniz, F.H., Kok, K., Hoogstra-Klein, M.A., & Arts, B. (2015). Mapping future changes in livelihood security and environmental sustainability based on perceptions of small farmers in the Brazilian Amazon. *Ecology and Society*, *20*(2), art26.

Dou, Y., Silva, R.F.B.D., Yang, H., & Liu, J. (2018). Spillover effect offsets the conservation effort in the Amazon. *Journal of Geographical Sciences*, *28*(11), 1715–1732.

Dou, Y., Yao, G., Herzberger, A., Silva, R.F.B., Da, Song, Q., Hovis, C., … Liu, J. (n.d.). Land-use changes across distant places: Implementation of a telecoupled agent-based model. *Journal of Artificial Societies and Social Simulation, (In review)*.

Evans, A. (2012). Chapter 15 uncertainty and error. In M. Batty, A.T.A.T. Crooks, L.M.L.M. See, A.J.A.J. Heppenstall, A.T.A. T. Crooks, L.M.L.M. See, & W. Lane (Eds.), *Agent-based models of geographical systems* (pp. 309–346).Dordrecht, Netherlands: Springer. doi:10.1007/978-90-481-8927-4.

Evans, T. P, & Kelley, H. (2004). Multi-scale analysis of a household level agent-based model of landcover change. *Journal Of Environmental Management*, *72*(1–2), 57–72. doi:10.1016/j.jenvman.2004.02.008

Evans, T. P, & Kelley, H. (2008). Assessing the transition from deforestation to forest regrowth with an agent-based model of land cover change for south-central indiana (usa). *Geoforum*, *39*(2), 819–832. doi:10.1016/j.geoforum.2007.03.010

Evans, T. P, Phanvilay, K, Fox, J, & Vogler, J. (2011). An agent-based model of agricultural innovation, land-cover change and household inequality: the transition from swidden cultivation to rubber plantations in laos pdr. *Journal Of Land Use Science*, *6*(2–3), 151–173. doi:10.1080/1747423X.2011.558602

Foley, J., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., … Snyder, P.K. (2005). Global consequences of land use. *Science*, *309*(5734), 570–574.

Food and Agriculture Organization of the United Nations. (2016). *FAOSTAT statistics database*. Retrieved from http://www.fao.org/faostat/en/#data

Friis, C., Nielsen, J.O., Otero, I., Haberl, H., Niewohner, J., & Hostert, P. (2016). From teleconnection to telecoupling: Taking stock of an emerging framework in land system science. *Journal of Land Use Science*, *11*(2), 131–153.

Fuchs, R., Alexander, P., Brown, C., Cossar, F., Henry, R.C., & Rounsevell, M. (2019). Why the US–China trade war spells disaster for the Amazon. *Nature*, *567*(7749), 451–454.

Gibbs, H.K., Munger, J., L'Roe, J., Barreto, P., Pereira, R., Christie, M., … Walker, N.F. (2016). Did ranchers and slaughterhouses respond to zero-deforestation agreements in the Brazilian Amazon? *Conservation Letters*, *9*(1), 32–42.

Gibbs, H.K., Rausch, L., Munger, J., Schelly, I., Morton, D.C., Noojipady, P., … Cerrado, E. (2015). Brazil's Soy Moratorium. *Science*, *347*(6220), 377–378.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., … Toulmin, C. (2010). Food security: The challenge of feeding 9 billion people. *Science*, *327*(February), 812.

Gotts, N.M., & Polhill, J. G., & Law, A. N. R. (2003). Aspiration levels in a land use simulation. Cybernetics & Systems, *34*(21), 663–683. Retrieved from doi10.1080/716100277

Gotts, Nicholas, & Polhill, J. G. (2009). When and How to Imitate Your Neighbours : Lessons from and for FEARLUS. Journal of Artificial Societies and Social Simulation, *12*(3), 1–2. Retrieved from http://jasss.soc.surrey.ac.uk/12/3/2.html

Gray, S.A., Gray, S., de Kok, J.L., Helfgott, A.E.R., O'Dwyer, B., Jordan, R., & Nyaki, A. (2015). Using fuzzy cognitive mapping as a participatory approach to analyze change, preferred states, and perceived resilience of social-ecological systems. *Ecology and Society*, *20*(2). doi:10.5751/ES-07396-200211

Grimm, V., & Railsback, S.F. (2012). Pattern-oriented modelling: A "multi-scope" for predictive systems ecology. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1586), 298–310.

Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W.M., Railsback, S.F., … DeAngelis, D.L. (2005). Pattern-oriented modeling of agent-based complex systems: Lessons from ecology. *Science*, *310*(11), 984–987.

Happe, K. (2004). Agricultural policies and farm structures. Agent-based modelling and application to EU-policy reform. (Institute of Agricultural Development in Central and Eastern Europe, IAMO; Vol. 30). Retrieved from http://ideas.repec.org/p/wpa/wuwpot/0504011.html

Happe, K., Balmann, A., Kellermann, K., & Sahrbacher, C. (2008). Does structure matter? The impact of switching the agricultural policy regime on farm structures. *Journal of Economic Behavior & Organization*, *67*(2), 431–444.

Happe, K., Hutchings, N.J., Dalgaard, T., & Kellerman, K. (2011). Modelling the interactions between regional farming structure, nitrogen losses and environmental regulation. *Agricultural Systems*, *104*(3), 281–291.
Happe, K., Kellermann, K., & Balmann, A. (2006). Agent-based analysis of agricultural policies: An illustration of the agricultural policy simulator AgriPoliS, its adaptation and behavior. *Ecology and Society*, *11*(1). Retrieved from http://www.ecologyandsociety.org/vol11/iss1/art49/main.html
Heilongjiang Provincial Bureau of Statistics, & Survey Office of the National Bureau of Statistics in Heilongjiang. (n.d.). *Heilongjiang statistical yearbook*. Beijing: China Statistics Press.
Holzhauer, S, Brown, C, & Rounsevell, M. (2019). Modelling dynamic effects of multi-scale institutions on land use change. *Regional Environmental Change*, *19*, 733–746. doi:10.1007/s10113-018-1424-5
Huang, Q., Parker, D.C., Sun, S., & Filatova, T. (2013). Effects of agent heterogeneity in the presence of a land-market: A systematic test in an agent-based laboratory. *Computers, Environment and Urban Systems*, *41*, 188–203.
Huber, R., Bakker, M., Balmann, A., Berger, T., Bithell, M., Brown, C., … Finger, R. (2018). Representation of decision-making in European agricultural agent-based models. *Agricultural Systems*, *167*, 143–160.
ICSU. (2010). Grand challenges in global sustainability research : Research priorities for the decade. Paris: *International council for science*.
Instituto Brasileiro de Geografia e Estatistica. (n.d.). Agencia de Noticias. Retrieved March 1, 2019, from https://sidra.ibge.gov.br/tabela/825
Kapsar, K.E., Hovis, C.L., Silva, R.F.B., Da, Buchholtz, E.K., Carlson, A.K., Dou, Y., … Liu, J. (2019). Telecoupling research : The first five years. *Sustainability*, *11*, 1–13.
Lane, S.N. (2001). Constructive comments on D massey 'space-time, "science" and the relationship between physical geography and human geography: Rsquo. *Transactions of the Institute of British Geographers*, *26*(2), 243–256.
Lapola, D.M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., & Priess, J.A. (2010). Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(8), 3388–3393.
Le, Q. B, Park, S. J, & Vlek, Paul L.G. (2010). Land use dynamic simulator (ludas): a multi-agent system model for simulating spatio-temporal dynamics of coupled human–landscape system. *Ecological Informatics*, *5*(3), 203–221. doi:10.1016/j.ecoinf.2010.02.001
Le, Q. B, Park, S. J, Vlek, Paul L.G, & Cremers, A. B. (2008). Land-use dynamic simulator (ludas): a multi-agent system model for simulating spatio-temporal dynamics of coupled human–landscape system. i. structure and theoretical specification. *Ecological Informatics*, *3*(2), 135–153. doi:10.1016/j.ecoinf.2008.04.003
Le, Q. B, Seidl, R, & Scholz, R. W. (2012). Feedback loops and types of adaptation in the modelling of land-use decisions in an agent-based simulation. *Environmental Modelling & Software*, *27–28 27–28 27-28*(0), 83–96. doi:10.1016/j.envsoft.2011.09.002
Liu, J. (2014). Forest sustainability in China and implications for a telecoupled world. *Asia & the Pacific Policy Studies*, *1*(1), 230–250.
Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., … Taylor, W.W. (2007). Complexity of coupled human and natural systems. *Science*, *317*(5844), 1513–1516.
Liu, J., Dou, Y., Batistella, M., Challies, E., Connor, T., Friis, C., … Sun, J. (2018). Spillover systems in a telecoupled anthropocene: Typology, methods, and governance for global sustainability. *Current Opinion in Environmental Sustainability*, *33*, 58–69.
Liu, J., Hertel, T., Nichols, S., Moran, E., & Viña, A. (2015). *Complex dynamics of telecoupled human and natural systems*. Retrieved from National Science Foundation Grant website: https://www.nsf.gov/awardsearch/showAward?AWD_ID=1518518
Liu, J., Hull, V., Batistella, M., Defries, R., Dietz, T., Fu, F., … Zhu, C. (2013). Framing sustainability in a telecoupled world. *Ecology And Society*, *18*(2(26)), 19. Retrieved from: http://www.ecologyandsociety.org/vol18/iss2/art26/ES-2013-5873.pdf
Liu, J., Mooney, H., Hull, V., Davis, S.J., Gaskell, J., Hertel, T., … Li, S. (2015). Systems integration for global sustainability. *Science*, *347*(6225), 963–973.
Luus, K.A., Robinson, D.T., & Deadman, P.J. (2011). Representing ecological processes in agent-based models of land use and cover change. *Journal of Land Use Science*, *8*(2), 175–198.
Manson, S M. (2005). Agent-based modeling and genetic programming for modeling land change in the southern yucatán peninsular region of mexico. *Agriculture, Ecosystems & Environment*, *111*(1–4), 47–62. doi:10.1016/j.agee.2005.04.024
Manson, S M. (2006). Bounded rationality in agent-based models: experiments with evolutionary programs. International Journal of Geographical Information Science, 20(9), 991–1012. Retrieved from http://dx.doi.org/10.1080/13658810600830566 *20* 267-1012 doi:10.1080/13658810600830566
Manson, Steven, & Evans, T. (2007). Agent-based modeling of deforestation in southern Yucatán, Mexico, and reforestation in the Midwest United States. Proceedings of the National Academy of Sciences of the United States of America, *104*(52), 20678–20683. Retrieved from http://www.pnas.org/content/104/52/20678.abstract
Matthews, R. (2006). The people and landscape model (palm): towards full integration of human decision-making and biophysical simulation models. *Ecological Modelling*, *194*(4), 329–343. doi:10.1016/j.ecolmodel.2005.10.032

Meyfroidt, P., & Lambin, E.F. (2009). Forest transition in Vietnam and displacement of deforestation abroad. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(38), 16139–16144.
Millington, J., Xiong, H., Peterson, S., & Woods, J. (2017). Integrating modelling approaches for understanding telecoupling: Global food trade and local land use. *Land*, *6*(3), 56.
Millington, J.D.A., Demeritt, D., & Romero-Calcerrada, R. (2011). Participatory evaluation of agent-based land-use models. *Journal of Land Use Science*, *6*(2–3), 195–210.
Murray-Rust, D., Brown, C., van Vliet, J., Alam, S.J., Robinson, D.T., Verburg, P.H., & Rounsevell, M. (2014). Combining agent functional types, capitals and services to model land use dynamics. *Environmental Modelling & Software*, *59*, 187–201.
Murungweni, C., van Wijk, M.T., Andersson, J.A., Smaling, E.M.A., Giller, K.E., Wijk, M.T.V., … Giller, K.E. (2011). Application of fuzzy cognitive mapping in livelihood vulnerability. *Ecology and Society*, *16*(4), 8.
Nepstad, D., Mcgrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., … Hess, L. (2014). Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science*, *344*(6188), 1118–1123.
Ngo, T.A., & See, L. (2012). Calibration and validation of agent-based models of land cover change. In A.J. Heppenstall, A. T. Crooks, L.M. See, & M. Batty (Eds.), *Agent-based models of geographical systems* (pp. 181–197). doi:10.1007/978-90-481-8927-4.
O'Sullivan, D., Evans, T., Manson, S., Metcalf, S., Ligmann-Zielinska, A., & Bone, C. (2015). Strategic directions for agent-based modeling: Avoiding the YAAWN syndrome. *Journal of Land Use Science*, (August), 1–11. doi:10.1080/1747423X.2015.1030463
Özesmi, U., & Özesmi, S.L. (2004). Ecological models based on people's knowledge: A multi-step fuzzy cognitive mapping approach. *Ecological Modelling*, *176*(1–2), 43–64.
Parker, D.C., Entwisle, B., Rindfuss, R.R., Vanwey, L.K., Manson, S.M., Moran, E., … Malanson, G. (2008). Case studies, cross-site comparisons, and the challenge of generalization: Comparing agent-based models of land-use change in frontier regions. *Journal of Land Use Science*, *3*(1), 41–72.
Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J., & Deadman, P. (2003). Multi-agent systems for the simulation of land-use and land-cover change: A review. *Annals of the Association of American Geographers*, *93*(2), 314–337.
Polhill, J Gary, & Parker, D. C., & Gotts, N. *M*. (2007). Effects of land markets on competition between innovators and imitators in land use : results from fearlus-elmm. In B. Edmonds, K. G. Troitzsch, & C. H. Iglesias (Eds.), Social Simulation: Technologies, Advances and New Discoveries (pp. 81–97). doi.10.4018/978-1-59904-522-1.ch007
Polhill, J.G., Sutherland, L.-A., & Gotts, N. *M*. (2010). Using qualitative evidence to enhance an agent-based modelling system for studying land use change. Journal of Artificial Societies and Social Simulation, 13(2), 10. Retrieved from http://jasss.soc.surrey.ac.uk/13/2/10.html
Reimer, J.J., Zheng, X., & Gehlhar, M.J. (2012). Export demand elasticity estimation for major U.S. crops. *Journal of Agricultural and Applied Economics*, *44*(4), 501–515. Retrieved from: http://purl.umn.edu/137120
Richards, P. (2015). What drives indirect land use change? How Brazil's agriculture sector influences frontier deforestation. *Annals of the Association of American Geographers*, *105*(5), 1026–1040.
Richards, P.D., Walker, R.T., & Arima, E.Y. (2014). Spatially complex land change: The indirect effect of Brazil's agricultural sector on land use in Amazonia. *Global Environmental Change*, *29*(November), 1–9.
Robinson, D.T., Brown, D.G., Parker, D.C., Schreinemachers, P., Janssen, M.A., Huigen, M., … Barnaud, C. (2007). Comparison of empirical methods for building agent-based models in land use science. *Journal of Land Use Science*, *2*(1), 31–55. .
Schreinemachers, P. (2005). The (Ir) relevance of the Crop Yield Gap Concept to Food Security in Developing Countries-With an Application of Multi Agent Modeling to Farming Systems in Uganda (University of Bonn Dissertation, Cuvillier Verlag Gottingen). Retrieved from https://igm.uni-hohenheim.de/cms/fileadmin/documents/ProjectDocs/OtherDocuments/Schreinemachers_2006 cuv.pdf
Schreinemachers, P., & Berger, T. (2006b). Simulating farm household poverty: from passive victims to adaptive agents. International Association of Agricultural Economists Conference, 1–22. Retrieved from http://ideas.repec.org/p/ags/iaae06/25479.html
Schreinemachers, P, & Berger, T. (2011). An agent-based simulation model of human–environment interactions in agricultural systems. *Environmental Modelling & Software*, *26*(7), 845–859. doi:10.1016/j.envsoft.2011.02.004
Seto, K.C., & Reenberg, A. (Eds.). (2014). *Rethinking global land use in an urban era*. Massachusetts, Cambridge: MIT Press.
Seto, K.C., Reenberg, A., Boone, C.G., Fragkias, M., Haase, D., Langanke, T., … Simon, D. (2012). Urban land teleconnections and sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(20), 7687–7692.
Silva, R., Batistella, M., Dou, Y., Moran, E., Torres, S., & Liu, J. (2017). The Sino-Brazilian telecoupled soybean system and cascading effects for the exporting country. *Land*, *6*(53). doi:10.3390/land6030053
Smajgl, A., Brown, D.G., Valbuena, D., & Huigen, M.G.A. (2011). Empirical characterisation of agent behaviours in socio-ecological systems. *Environmental Modelling and Software*, *26*(7), 837–844.
Sun, J., Mooney, H., Wu, W., Tang, H., Tong, Y., Xu, Z., … Liu, J. (2018). Importing food damages domestic environment: Evidence from global soybean trade. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(21), 5415–5419.

Sun, J., Tong, Y., & Liu, J. (2017). Telecoupled land-use changes in distant countries. *Journal of Integrative Agriculture*, *16*(2), 368–376.

Tong, Y., Liu, J., Li, X., Sun, J., Herzberger, A., Wei, D., … Zhang, F. (2017). Cropping system conversion led to organic carbon change in China's mollisols regions. *Scientific Reports*, *7*(1), 1–9.

Turner, B.L., II, Lambin, E.F., & Reenberg, A. (2007). The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(52), 20666–20672. Retrieved from: http://www.pnas.org/content/104/52/20666.short

Valbuena, D., Verburg, P.H., & Bregt, A.K. (2008). A method to define a typology for agent-based analysis in regional land-use research. *Agriculture, Ecosystems & Environment*, *128*(1–2), 27–36.

van Vliet, M., Kok, K., & Veldkamp, T. (2010). Linking stakeholders and modellers in scenario studies: The use of fuzzy cognitive maps as a communication and learning tool. *Futures*, *42*(1), 1–14.

Verburg, P.H., Alexander, P., Evans, T., Magliocca, N.R., Malek, Z., Rounsevell, M.D., & van Vliet, J. (2019). Beyond land cover change: Towards a new generation of land use models. *Current Opinion in Environmental Sustainability*, *38*(May), 77–85.

Verburg, P.H., Crossman, N., Ellis, E., Heinimann, A., Hostert, P., Mertz, O., … Lin, Y.-P. (2016). *Science Plan and Implementation Strategy*. Bern: GLP.

Verburg, P.H., Crossman, N., Ellis, E.C., Heinimann, A., Hostert, P., Mertz, O., … Zhen, L. (2015). Land system science and sustainable development of the earth system: A global land project perspective. *Anthropocene*, *12*, 29–41.

Villamor, G. B., & Van, Troitzsch, Noordwijk, M., K. G., & Vlek, P. L. G. (2012). Human decision making for empirical agent-based models : construction and validation. In R. Seppelt, A. A. Voinov, S. Lange, & D. Bankamp (Eds.), International Environmental Modelling and Software Society (iEMSs), 2012 International Congress on Environmental Modelling and Software. Leipzig, Germany: Sixth Biennial Meeting.

Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling & Software*, *25*(11), 1268–1281.

Wang, F., & Liu, J. (2016). Conservation planning beyond giant pandas: The need for an innovative telecoupling framework. *Science China Life Sciences*, *60*(5), 1–4.

Yang, W., Hyndman, D.W., Winkler, J.A., Viña, A., Deines, J.M., Lupi, F., … Liu, J. (2016). Urban water sustainability: Framework and application. *Ecology and Society*, *21*(4(4)), 14.

Yao, G., Hertel, T.W., & Taheripour, F. (2018). Economic drivers of telecoupling and terrestrial carbon fluxes in the global soybean complex. *Global Environmental Change*, *50*(March), 190–200.