Modeling telecoupled systems: design for simulating telecoupled soybean trade

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Abstract:

How to feed the world's population and achieve environmental sustainability of the planet earth is a global challenge. The telecoupling concept and framework are proposed for the fast-growing trend of agricultural trade and other flows between different systems and have been applied to a variety of cases. However, a comprehensive computer simulation model that can represent telecoupled human and natural systems is still lacking. Such a model can permit users to advance the understanding of telecoupling features and help decision making. Therefore, in this paper, we demonstrate the design of a TeleABM (i.e., an ABM that represents telecoupled human and natural systems) to show different components (i.e., coupled systems, flows, agents, causes, and effects) and features of telecoupled systems.

Under the framework of telecoupling, we use an ABM as the backbone to guide the construction of TeleABM, and integrate other modeling approaches (e.g., GTAP) to complement their strengths and weaknesses to tackle the challenges of modeling telecoupled systems. We use the soybean trade between China and Brazil as a demonstration of telecoupled systems, where Brazil as the sending country that exports soybeans, China as the receiving system that imports significant amount of soybeans from Brazil.

1. Introduction

How to feed the world's population and achieve environmental sustainability is a global challenge (Godfray et al., 2012). Over the past decades, useful insights to increase food security and sustainability have been gained by using the concept of coupled human and natural systems (CHANS) and its modeling applications, particularly agent-based modeling approach (An and Liu, 2010; Liu et al., 2007; Manson and Evans, 2007).

However, under the fast-growing trend of agricultural trade, many knowledge gaps need to be filled due to the increasing distant socioeconomic and environmental interactions. The telecoupling concept and framework were proposed for this purpose (Liu et al., 2013) and have been conceptually and empirically applied to a variety of cases (Liu, 2014; Seto and Reenberg, 2014; Wang and Liu, 2016; W. Yang et al., 2016). A comprehensive system model that can represent and simulate telecoupled human and natural systems, however, is still lacking.

In this paper, we present the design of a TeleABM (i.e., an agent-based model of telecoupling systems), building beyond the system models used to represent CHANS. Based on the telecoupling framework, TeleABM is a system simulation model that can capture micro-level behaviors of agents in two or more distant CHANS through the focused flows, and produce macro-level emergent phenomenon in one system or the telecoupled system. Such a model, as a computational laboratory, would allow users to reproduce the telecoupling, test various hypotheses, and simulate different scenarios, through fitting parameters and running simulations which are not applicable by other methods. With the advantages from a TeleABM, scientists can better understand the roles of agents in a telecoupled system and test alternative governance approaches to inform policy-makers.

1.1 The telecoupling framework

The coupled human-natural systems have been widely used by scientists to understand the feedbacks, dynamics, and impacts of the interactions of human and natural components (Liu et al., 2007; Turner II, 2010). However, these studies usually (1) are conducted within a single system which excludes the interactions with other systems (particularly distant systems), or (2) treat the external factors as one-directional driver instead of a reciprocal interaction. The CHANS framework and various case studies of coupled human-natural systems have established a solid ground, but are not enough to fill the gaps mentioned above. Yet these knowledge gaps are becoming profound along with the distant interactions growing in extent and frequency and call for a better framework and simulation tool for current sustainability science.

As a logical extension of the coupled system, the telecoupling framework gives a coupled human-natural system a role (i.e., sending, receiving, and spillover) by connecting these systems through flows that one is interested at (e.g., movement of commodity, information, energy) (Liu et al., 2013). Within each CHANS, there are agents that facilitate or hinder the emergence, transferring, and dissolution of flows, causes that influence the dynamics of flows, and effects as the consequences or impacts from the telecoupling. The flows between systems are the media of reciprocal interactions in a telecoupled system, which are often treated as external factors if using CHANS. However, a single CHANS is not enough to define and quantify the cause and effect associated with flows, which is one of the many challenges of using the telecoupling framework and calls for a system modeling tool.

1.2 ABM as an excellent tool to simulate CHANS and challenges for simulating telecoupled systems

Many system modeling tools and methods have been developed to represent CHANS and facilitate our understanding of CHANS (e.g., system dynamic modeling, cellular automata, network analysis, CLUE-S model, scenario matrix). They integrate information and knowledge to analyze current systems and assess alternative or future systems under different scenarios (e.g., IPCC's representative concentration pathways, organic farming instead of conventional agriculture).

Among the modeling tools, Agent-Based Models (ABM) are becoming increasingly popular. It is a computer simulation tool consisting of a number of agents interacting with a dynamic environment and with other agents through prescribed decision making rules. The major advantages of an ABM include its flexibility of incorporating any components of a system (Parker et al., 2003), the power of modeling and aggregating heterogeneous behaviors (Huang et al., 2013), and capability of representing processes, social norms and structures (An, 2012). Therefore they have been widely employed to simulate CHANS in both theoretical and empirical grounds (An, 2012; Parker et al., 2003).

Although far from being perfect, the ABM modeling community has made huge progress and contributed to the advancement of CHANS theories for the past two decades. Successful ABM applications have facilitated the discovery of several key features of CHANS, including reciprocal effects and feedback loops, nonlinearities and thresholds, legacy effects and time lags, and heterogeneity (Liu et al., 2007). However, the potential of using an ABM to represent a telecoupled system and to simulate telecoupling features has never been discussed. In fact, besides the technical challenges that an ABM is facing (e.g., scaling up, informing decision making, empirical validation), there are multiple challenges raised by the telecoupling framework that modellers need to solve (e.g., how to represent the flows).

1.3 Objective, structure, and significance of this paper

The objective of this paper is to demonstrate the design of a TeleABM (an ABM that represents telecoupled human-natural systems), to show different components of a telecoupled system (i.e., coupled systems, flows, agents, causes, and effects). We use the agent-based modeling approach as the backbone to guide the construction of a TeleABM, building on its progress and filling the gaps in this modeling approach. We present alternative approaches for constructing this TeleABM, including how to represent different CHANS and capture the flows, and provide strategies to calibrate and validate the TeleABM empirically.

In the first section of this paper, we review current progress of case studies using telecoupling framework, and propose the need to call for a system simulation model. In the second section, we review ABM applications and the gaps to represent a telecoupled system, particularly on how to represent more than one CHANS in the model and connect them through the representation of flows. We then proceed to introduce an example of telecoupled system, which is the soybean trade between China and Brazil, and point out the challenges that modellers are facing. Next, we present the structure of a TeleABM, particularly how to address the requirements raised by the framework. In the following section, we propose the design of interfaces and how several approaches could be integrated into the TeleABM (e.g., mental modeling and Global Trade Analysis Project). We conclude with a discussion of a potential path from transferring this conceptual design to an empirical context.

This paper serves as the very first attempt of modeling telecoupled systems. The purpose of this paper is not to give an explicit design of model variables and processes, rather, it is to offer a path and a way of thinking for modellers to identify proper model boundaries, challenges, useful approaches for model development, through an example of TeleABMs. With a system model such as this the theories and hypotheses of the telecoupling framework could be tested.

2. The need for a system modeling tool to represent telecoupled human and natural systems and to answer fundamental questions of telecoupling issues

Since the first publication of the framework in 2013 (Liu et al., 2013), there have been a growing number of articles and studies that use this framework (Liu, 2014; Seto and Reenberg, 2014; Sun et al., 2017; Wang and Liu, 2016; W. Yang et al., 2016). These works can be divided into three broad types, summarized as follows.

The first is that telecoupling framework being used as an umbrella concept to frame a location-based sustainability and other issues for policy implications. Several major challenges are identified to build the ambitious Belt and Road region for China using the telecoupling framework (D. Yang et al., 2016); Brondizio et al. (2016) integrated six types of telecoupling conditions (i.e., socio-demographic, economic, governance, ecological, material, and climatic-hydrological) into a framework to analyze resilience issues of small farmers in Amazon delta regions; it is also used in the energy sector (Fang et al., 2016) to enhance solar energy sustainability.

The focus of these studies is a specific system at a location or about a sector, but they are identified as sending, receiving, or spillover systems in a broader context of the telecoupled system (Figure 1). Telecoupling framework is used in this type of study to help conceptualize the flows and to seek for solutions. By systematically identifying the flows going out or coming into the system, problems and/or solutions for enhancing the sustainability of the focal system can be analyzed without limiting by the system boundary.

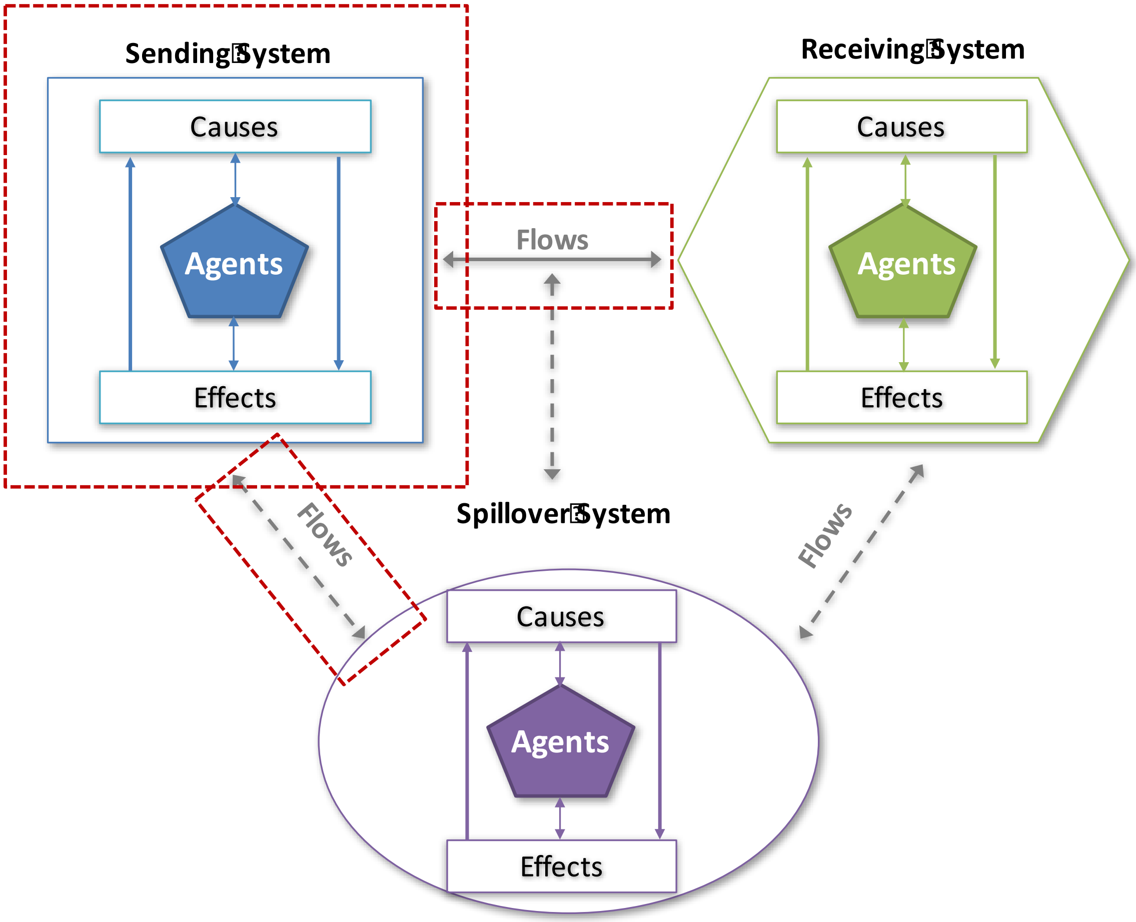

Figure 1 First type of telecoupling analysis, focusing on one system and the flows (here using sending in the illustration, but can be any system)

The second is when telecoupling framework is used to analyze the dynamics of the same item at the sending, receiving, and spillover systems in a telecoupled system (Figure 2). For example, Sun et al. (2017) compared different spatial distributions of soybean land gain and loss in Brazil as a sending system, China as a receiving system, and the United States as a spillover system using remote sensing data. It is a systematic demonstration that international food trade as the telecoupling flows has caused different spatial patterns of soybean land across these systems. However, such analysis can only present patterns in each system but not distinguish the causes for these patterns. Neither can they quantify the flows, therefore quantify the causes and effects by the flows.

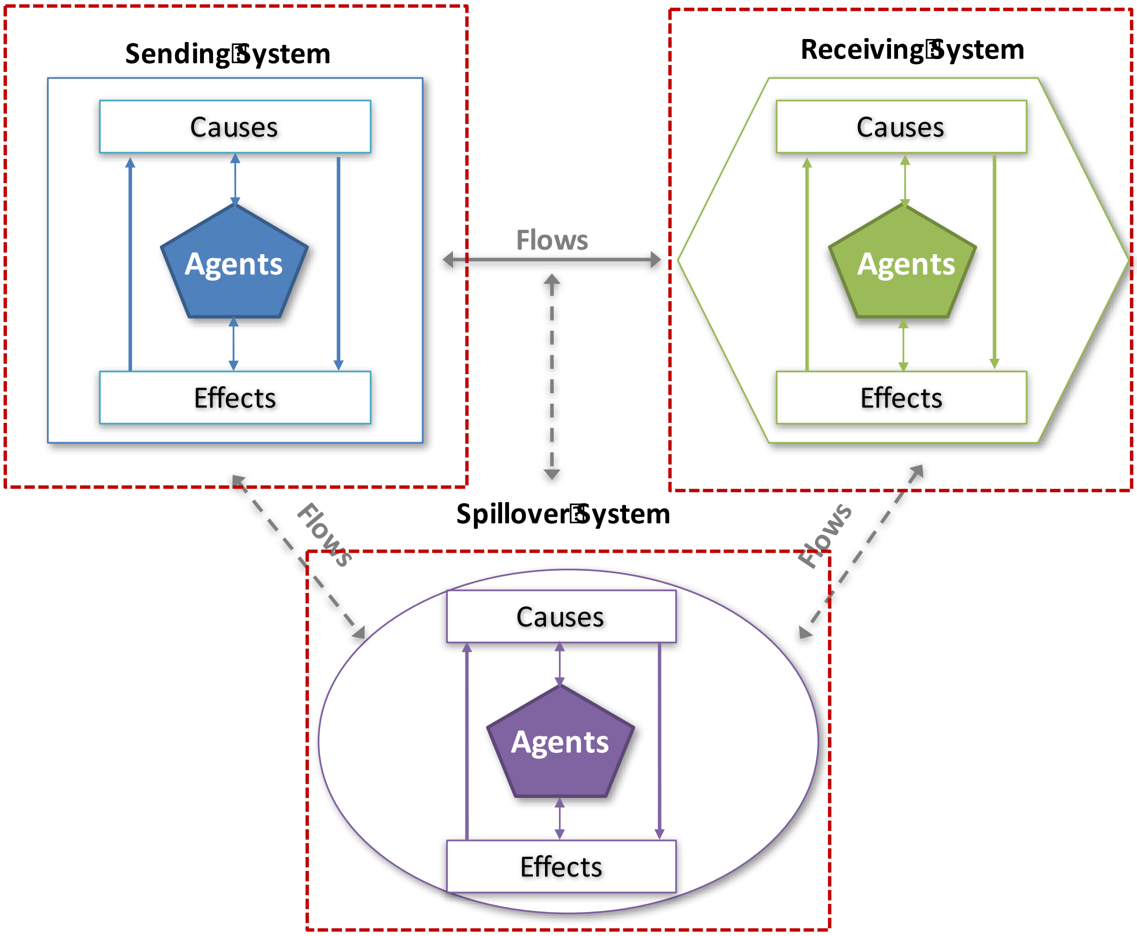

Figure 2 Second type of telecoupling analysis that demonstrate the changes in each system

The third one is flows as the main focus that being identified and quantified (Figure 3). Methods used for this analysis include accounting, and network analysis in a few current works. For example, the physical and virtual water being sent to Beijing from distant regions are accounted and the water stocks in Beijing can be assessed (Deines et al., 2015; W. Yang et al., 2016). The virtual land exchanged between different countries as agricultural products can be calculated in a hybrid form of both monetary and physical unit (Bruckner et al., 2015). However, these analysis is limited by its bookkeeping nature, which can only quantify flows but not causes, effects, and possible changes of flows.

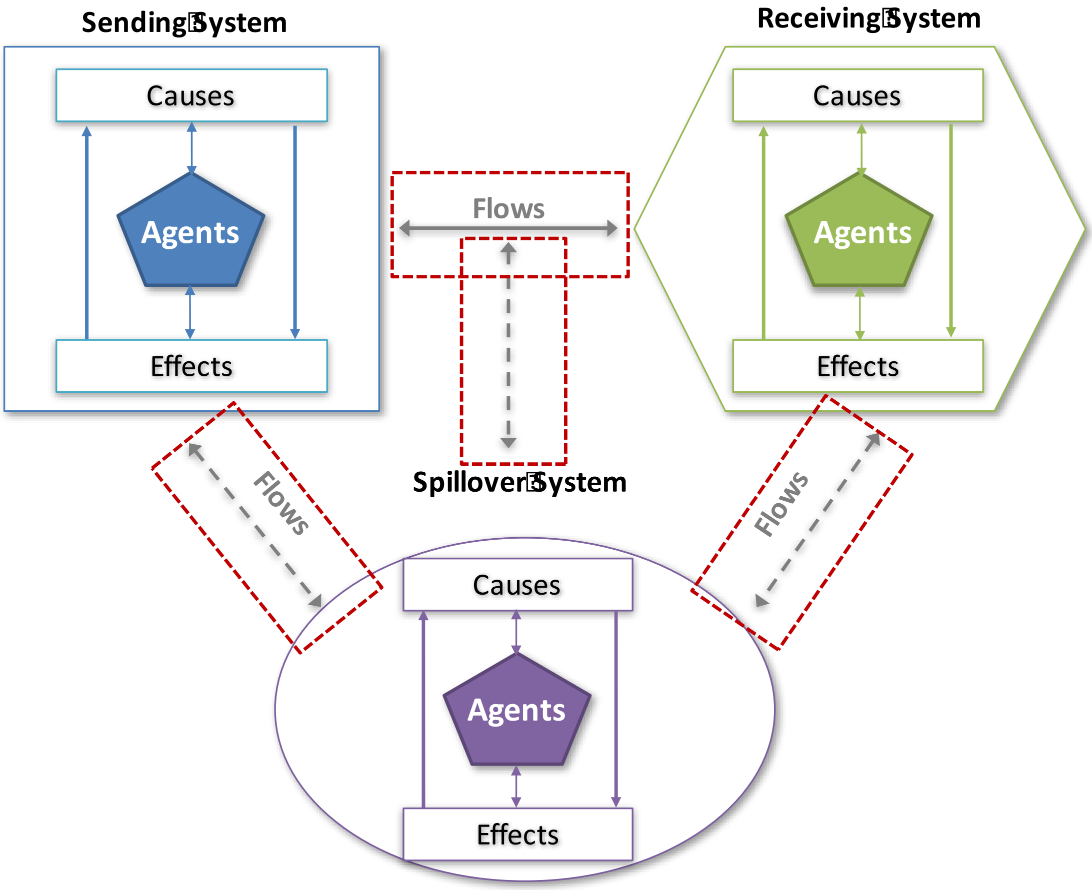

Figure 3 Third type of telecoupling analysis that account for flows

Because of its integrality and complexity, telecoupling involves "multiple flows, multiple agents, multiple causes, and multiple effects across multiple systems at multiple scales" (Liu et al., 2013, p. 25). In spite of rapid growing use of the framework, none of the three types of current telecoupling analyses can address the multiple requirements simultaneously, due to the limitation of the analytical methods. This calls for a system simulation to represent and quantify the dynamics within a system and the flows between systems (Figure 4). In the following sections, we introduce the design of a simulation tool that integrates several approaches so that both systems and their flows can be addressed to quantify telecoupling features.

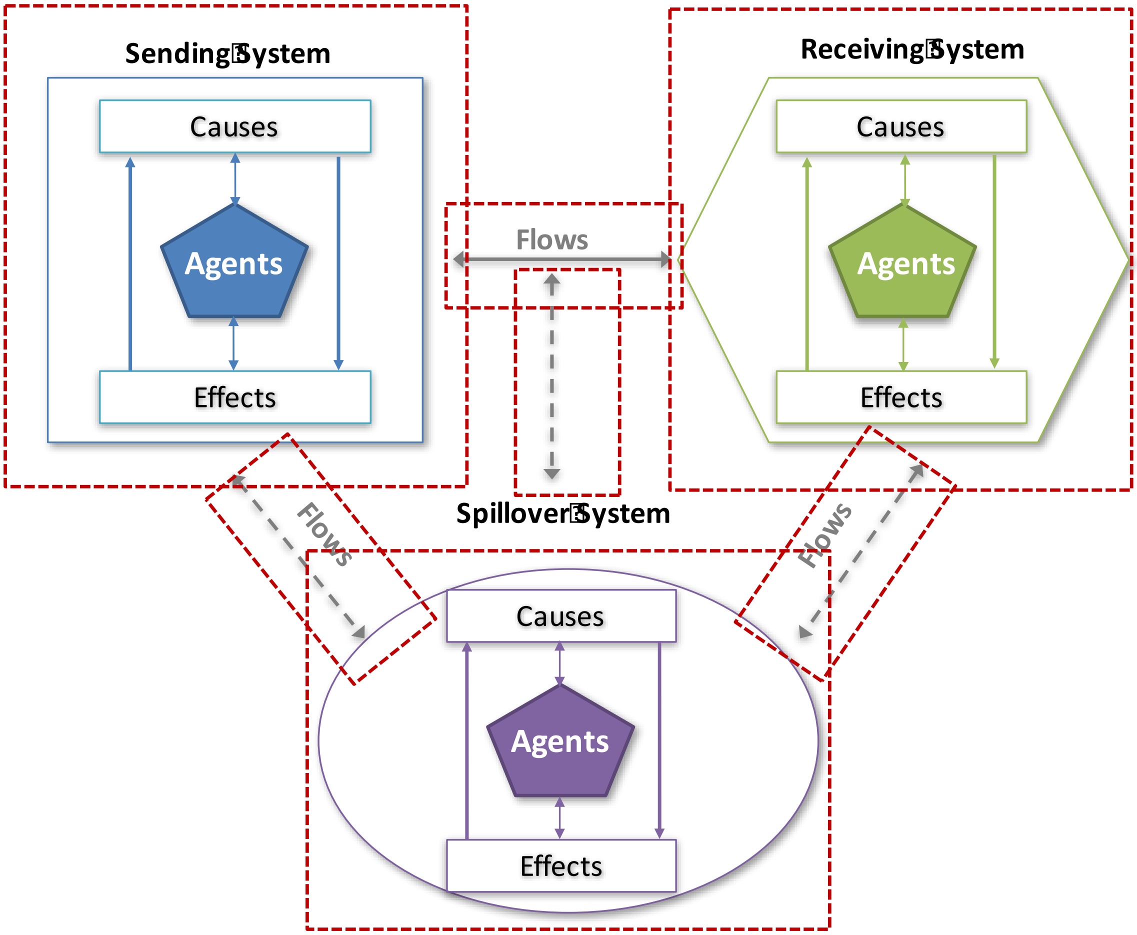

Figure 4 Proposed simulation tool should address systems and flows

3. ABMs in practice and its gaps for TeleABM

To complement the current analytical methods used to address telecoupling, we can use ABM to construct the telecoupled system. The advantages of using agent-based modeling approach to simulate CHANS, compared to other methods, have been reviewed and supported by many scholars (An and Liu, 2010; Deadman et al., 2004; Liu et al., 2007; Murray-Rust et al., 2014; Parker et al., 2003). It is a natural choice of representing the telecoupled CHANS and capturing the telecoupling features.

3.1 Adequacy and gaps in representing telecoupling systems and components using ABM

Based on the integrated framework of telecoupling, perhaps the easiest way to construct a TeleABM is to build two (or more) ABMs that represent an interrelated set of CHANS and connect them by the flows among these CHANS (Figure 5). On the one hand, the various ABM applications assist our understanding of CHANS and advance the theory development of CHANS; on the other hand, they add up to an adequate collection of developed models and techniques but gaps remain to represent telecoupled systems (Table 1).

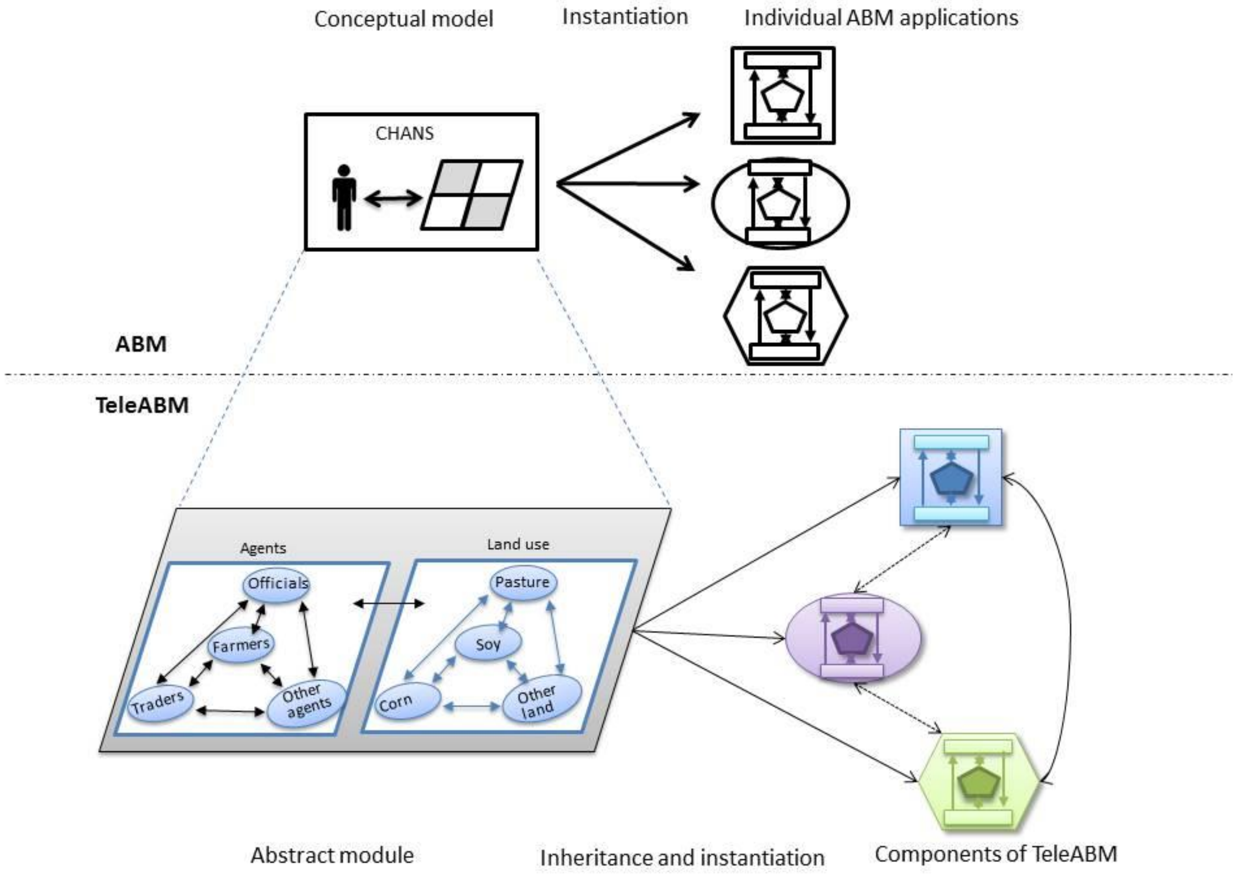

Figure 5 From the concept of coupled human-natural systems to the component of TeleABM

Currently, individual ABMs are the instantiation of a completed CHANS, each of them standing as an independent case (Table 1). Only demonstrating one CHANS, these models are not able to represent the receiving, sending, and spillover systems, as well as the flows across these systems. These models are used as a tool for scholars to identify the key drivers and how agents respond to different scenarios within each CHANS. So far, these models are not given a role as in a telecoupled system. Therefore, they are not equipped to explore the causes and effects due to telecoupling.

Furthermore, these models are not able to capture the flows between systems in a long distance. ABM represents the feedbacks between agents and between agents and environment (Le et al., 2008; Liu et al., 2007) within a system, but feedbacks occurring in a long distance and between systems are not well represented.

To fill these gaps, we reviewed how ABM are used to represent individual CHANS and propose an approach to represent more than one CHANS for a telecoupling system (i.e., individual CHANS as sending, receiving, and spillover systems). We also reviewed how current ABMs define and represent the system boundary so that flows can be added in the telecoupling system.

Table 1 Adequacy and gaps among current ABM applications for TeleABM

Principles of a TeleABM	**Adequacy**	**Gaps**
Components	one local/regional CHANS	no receiving/ sending/spillover systems, and no flows between the systems
Impacts	local causes and effects	no telecoupling causes and effects
Interactions	mostly within-scale and some cross-scale	have to have cross-scale interactions; no distant interactions
Feedbacks	only local feedbacks	no feedbacks between systems

3.2 How to represent the components in TeleABM

Most existing ABM applications are case-specific and representing a single system, but telecoupling needs more than one. There are attempts beyond one system, such as running parallel comparisons or synthesis of different ABM cases. The first comparison was made among several models that simulate land use changes in agricultural frontier areas, where Parker et al. (2008) revealed the common and unique processes in these frontier sites that are represented by ABMs. Later, an ODD protocol (Overview, Design concepts, and Details) was published to standardize the descriptions of ABMs (Grimm et al., 2010, 2006). Since then, many published ABMs have been documented using this protocol (Bert et al., 2011; Cabrera et al., 2012;

Schreinemachers and Berger, 2011; Zheng et al., 2013) which conducted to the emergence of comparative studies (An et al., 2014; Polhill et al., 2008).

The primary purposes of these comparisons or the development of comparative tools are: (i) improving model communications and increasing the likelihood of a model being reused by other scholars, (ii) formulating models more rigorously to avoid irreproducibility, and (iii) allowing generalizations of interactions and processes among different CHANS. However, these comparisons still treat each model as an individual system which neglects the potential telecoupling interactions they may have. The idea of generalization among model applications can be useful (e.g., advancing the theoretical understanding of CHANS complexities established by Liu et al., (2007), identifying common processes in all frontier agricultural regions (Parker et al., 2008)), but the development of TeleABM from these comparisons has not been attempted nor discussed.

Based on these comparative studies, ABM modellers have developed modular ABMs (Bell et al., 2015) and agent-based virtual laboratories (Magliocca et al., 2015, 2013), to represent key processes in different cases and support their use beyond the original developing team. For instance, they have established several independent modules including a crop diversity index module and a soil loss estimation tool (Bell et al., 2015) that can be used in any ABM that simulates agricultural systems. The philosophy behind the development of these modules or tools is for researchers who are troubled by the same issue to reduce the labor and time cost of re-producing the essential modules to represent core processes or attributes of the CHANS. The intention of these inventions is not regarding to TeleABM, however, it is a useful strategy to develop a model that has more than one system.

3.3 How to represent the flows among CHANS

Sending, receiving, and spillover systems in a telecoupled system depend on their contingent conditions and often exchange tangible and intangible flows (e.g., mass, energy, money, information, power). This attribute requires the model to be open in order to exchange the flows between them. However, many ABM applications represent a CHANS on which other systems have no or limited influence (Table 2).

A certain degree of “closeness” is necessary for scientists to study the mechanisms of emergent patterns and dynamics of a system (Brown, 2010, 2004). In terms of modeling, the level of “closeness” of a system is measured by the information exchanged between the system and the outside environment. If the information flow is mostly endogenous within the system, then the model is more close than models with more variables being defined exogenous. Using this, we can divide ABM applications into two broad categories: relatively closed ABMs and relatively open ABMs.

Relatively closed ABMs are those in a state of (or almost) isolation from other systems, where modellers are interested in the interactions between agents and the environment. Models that have exogenous variables are also included in this category: modellers assign values to these variables which determines the flows going into the modeled system. This type of ABMs is not designed to have a dynamic flow that can change along with the modeled system. To the contrary, relatively open ABMs are models that can capture the flows both into and out of them. Flows are represented by exogenous variables which are partially affected by the modeled system, which modellers can set the scene instead of assigning values.

One example of relatively closed ABM is the model of Wolong (An et al., 2005; An and Liu, 2010; Chen et al., 2014) (No.3 in Table 2), which describes the complex relationship between rural households in the Wolong Nature Reserve and the habitat for the endangered giant panda. It is on the close side of the closeness spectrum because the main interaction between household agents and the natural vegetation is through fuel collection within the system. There is no migration or tourism from outside Wolong area represented in the model. In the later version by Chen et al., (2014), conservation policy is included as an institutional driver that may alter household’s fuel collections. Applications of this model have successfully demonstrated the impact of family planning and compared the effectiveness of different conservation program scenarios(An and Liu, 2010; Chen et al., 2014). However, none of these applications includes any telecoupling features that can be important to the sustainability of Wolong area, such as eco-tourism (Liu et al., 2015).

Another example is the model LUCITA (Cabrera et al., 2012; Deadman et al., 2004) (No.1 in Table 2), which simulates the deforestation and land use behaviors of indigenous communities in the Brazilian Amazon region as a closed CHANS. Although many factors that link rural communities to the outside systems (e.g., multi-sited households, non-farm income, and urban-rural migration (De Janvry and Sadoulet, 2001; Padoch et al., 2008; Seto et al., 2012)) have been proved important for rural sustainability, they are not considered in this model, although being claimed by the author that could "add a further degree of realism".

Some models are influenced by external factors, examples of which include price of crops/forest products, climate variables. However, most models either set these factors as constant or determined by the modellers in an input file for the model to read. Examples include LUDAS (No. 5 in Table 2), which uses the empirical local price of crops in 2002/2003 in the decision making phase. Households convert different kinds of crops into unified monetary value in order to compare different decision options. Another example is MARIA (No. 2 in Table 2), which has input files for cash crop and subsistence crops to represent different price scenarios.

The model Cormas (No. 4 in Table 2) is a unique ABM that separates from others because it was constructed using a participatory approach (i.e., designed and validated with stakeholders). For example, villagers pointed out several important factors, including the price fluctuation for cash crop is one of the major concerns for them, while modellers built module to reflect these important factors. Although the model simulates a local CHANS in northern Thailand, the price fluctuation of their cash crops is likely to be influenced by distant markets in North America and China. However, it is difficult for an ABM simulating local CHANS to capture this global price dynamic, so often it is treated as a given exogenous input. The assumption behind this simplification is that the emergent phenomenon from the model does not have any influence on outside environments (e.g., agents are price-takers in a global economy, or carbon emission and other factors associated with land use changes from one region will not change climate patterns), which is not necessarily true under the lens of the telecoupling framework.

Models on the relative open side of the closeness specturm are rare among ABM applications. The only one we have found so far is AgriPolis (No. 6 in Table 2). In this model, the price of crops is represented by a simple price function with price elasticity and a price trend for each product in a regional market. The price is varied depending on the cumulative quantities produced by local farm agents. Different from other models, this price is affected by aggregated farmers' behaviors. This property gives modellers options to quantify this local CHANS' interactions and feedback with other systems. However, the price function in this model is not adequate to represent the complexity of flows exchanged between two systems, because it is only partially affected by local system within a regional system. We still need to develop other means to represent the flow in telecoupled ABM.

Table 2 Description of classic ABM applications

Model ID and Name	**References**	**Spectrum of closeness**	**Access to external labor/capital/work**	**Market representation**	**Networks**
1 LUCITA	Cabrera et al., 2012; Deadman et al., 2004	relatively closed	Local labor pool		no
2 MARIA	Cabrera et al., 2010	relatively close	Local labor pool and off-farming work	Exogenous, price is given	no
3 Wolong	An and Liu, 2010; Chen et al., 2014	relatively close	no	no	social norm in later version
4 CORMAS	Barnaud et al., 2008, 2007	relatively close	Short-time credit	Exogenous, but next step is to include collective system to sell all production	social statue
5 LUDAS	Le et al., 2012, 2010, 2008; Villamor et al., 2012	relatively close	Off-farm	--	Neighborhood effect
6 AgriPoliS	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	relatively open	Off-farm income	Price is influenced by amount of supply	Household groups
7 SYPIRA	Manson, 2006, 2005; Manson and Evans, 2007	relatively close	Off-farm labor	Markets are exogenous given, scenarios are set differently (e.g., historical, monotonically increasing,)	Institution and neighborhood effect (environment)
8 LUCIM	Evans and Kelley, 2008, 2004	relatively close	off-farming activities	Markets are exogenous	Neighborhood effect (of forest)
9 FEARLUS	Gotts et al., 2003; Gotts and Polhill, 2009; Polhill et al., 2010; Polhill and Parker, 2007	relatively close	no	Price is exogenous	Neighborhood effect
10 VV	Valbuena et al., 2010, 2008	relatively close	no	exogenous	no
11 PALM	Matthews, 2006	relatively close	Off-farm working	Fixed price	no

4. Design TeleABM

Besides the challenges for building an ABM, there are unique tasks for the construction of a TeleABM (Figure 6). The first task is to describe the telecoupled system that one wants to represent as a conceptual model, by (1) identifying the sending and receiving systems, (2) identifying spillover systems (if present), (3) identifying crucial or emerging flows of interest among the many possible flows between sending and receiving systems, and (4) identifying the scale, the agents, and the attributes of the flow. Once this model characterization is set, the large body of literature in ABM methods and other modeling approaches can be used to construct each of the components for a TeleABM.

In this section, we demonstrate our designed TeleABM using the soybean trade between China and Brazil as a case to develop a telecoupled system. Detailed description of this telecoupled system can be found (Liu et al., 2013), hence we skip the first step which is to introduce the conceptual model. Details from a modeling perspective will be included in the second and third steps, which are define model boundary and approach the two challenges we identified in current ABM applications earlier.

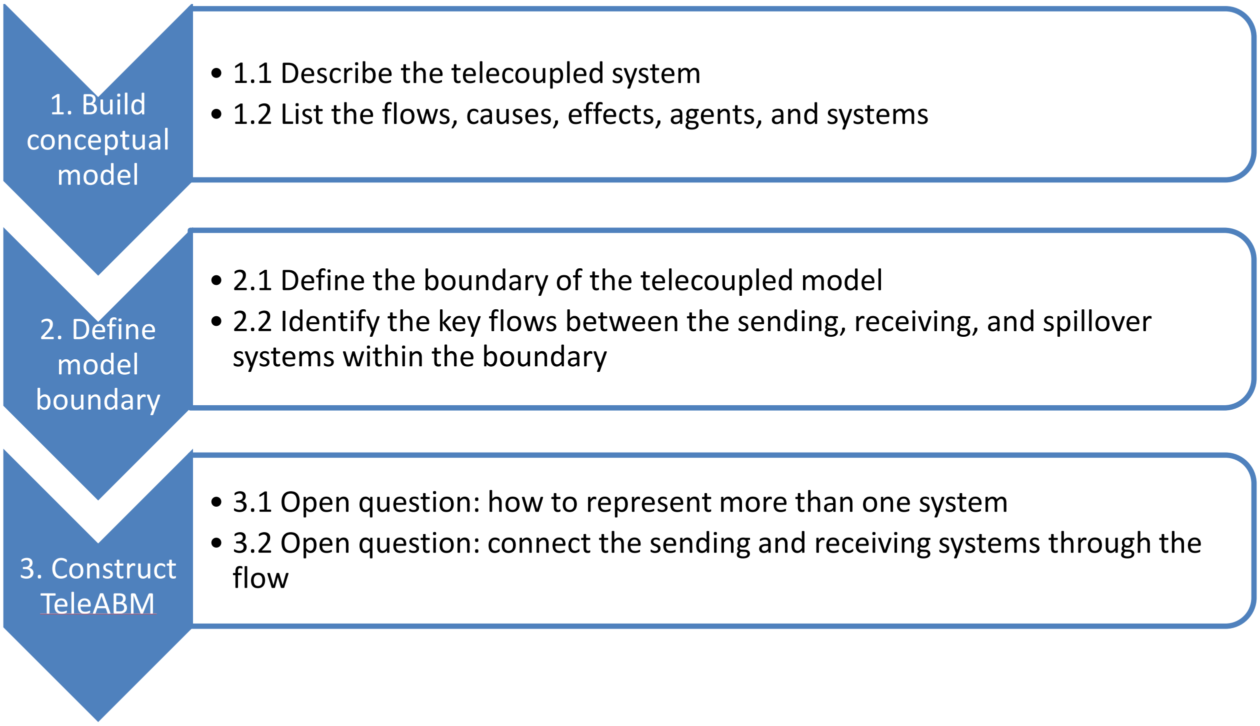

Figure 6 Tasks and steps for building a TeleABM

4.1 Define the model boundary

Soybean is one of the top traded crop commodities internationally. The majority of countries are involved in either import or export of soybean or soybean products (e.g., oil, soya curd). Many hidden linkages between spillover countries are also worth investigating. However, for the TeleABM (**Figure 7** A) we start with currently the major exporting country (Brazil as sending system) and currently the largest importing country (China as receiving system), and initially exclude spillover countries (they will be added in the future).

Modeling the whole country (i.e., setting the model boundary as country) is ideal but not necessary if taking the computational and verification cost into consideration. Scaling down from the country as the unit of international trade, we move to the main soybean production regions in both countries (**Figure 7** B and Table 3). Heilongjiang province in the northeast China and the states of Mato Grosso, Goias, and Tocantins are chosen as the focal regions in each country because these areas are the top soybean producers, exhibiting the largest soybean expansions or declines. The spatial coverage of our TeleABM will be these regions from the two countries.

Table 3 Focal regions in sending and receiving countries

	Focal regions in sending system (2014)	**Focal region in receiving system (2015)**
Boundary	Mato Grosso, Goias, Tocantins	Heilongjiang
Population (1000)	11, 244	38,120
GDP (billion USD)	92.725	2193
Area (1000 ha)	152,106	47,300
Agricultural area (1000 ha)	165,501	39,583
Arable land (1000 ha)	21,468	11,990
Forest and other natural vegetation (1000 ha)	98,694	24,430
Pasture land (1000 ha)	45,339	4,333

There are many flows associated with the soybean trade, however, our designed TeleABM uses the soybean exported from Brazil to China as the primary flow, and the money generated by this trade to complete the loop of this flow. Other flows, such as carbon emission caused by the soybean transportation, or knowledge diffusion, are not considered but can be added and analyzed in the future.

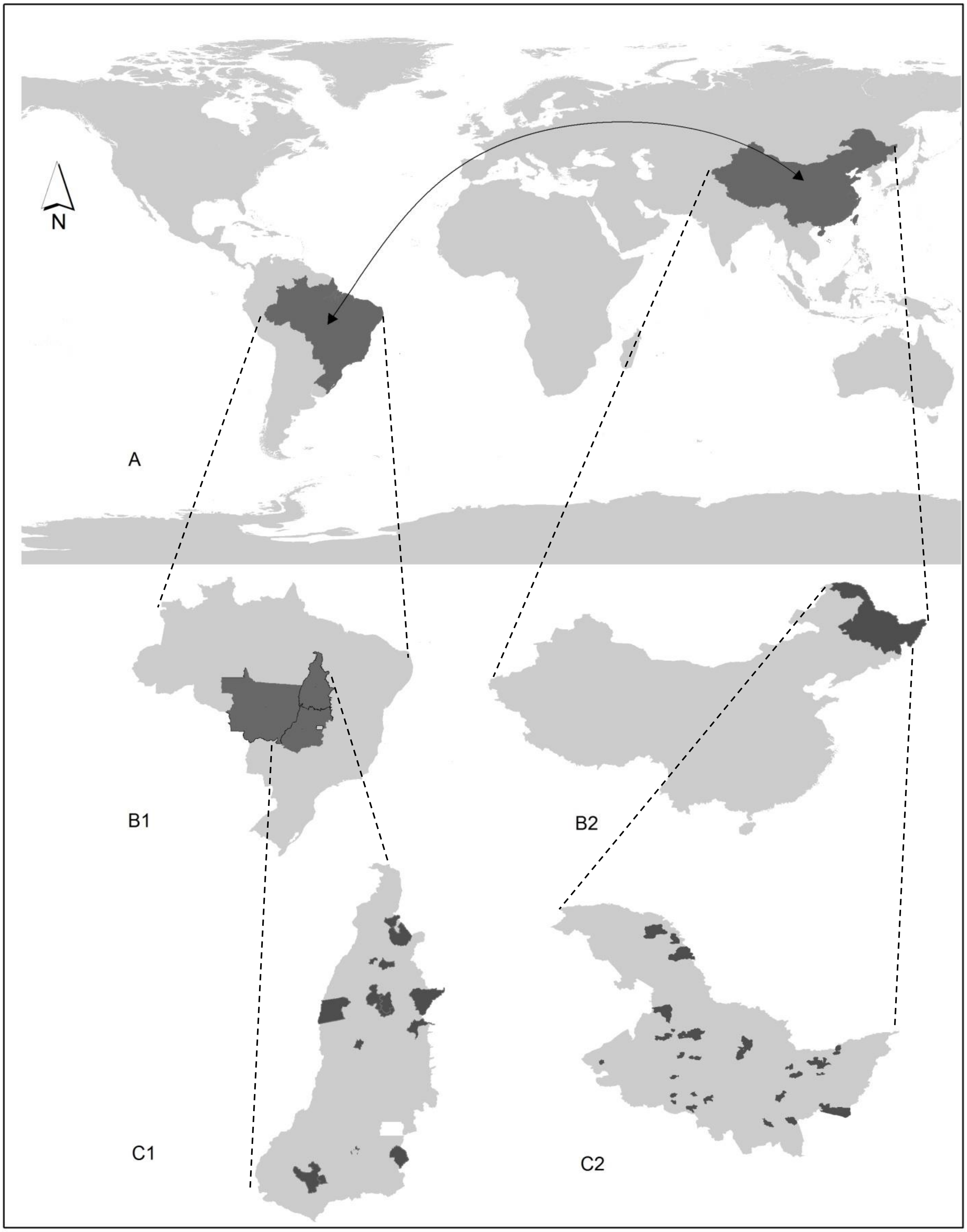
N
A
B1
B2
C1
C2

Figure 7 Telecoupling system through different scales. A: sending and receiving countries connected through flows of soybean; **B1**: Major soybean production regions in sending system; **B2**: Major soybean production region in receiving system; **C1** and **C2**: sampled households and/or farms. Note B1 and B2 are in the same scale (1: 70,000,000), so are C1 and C2 (1:20,000,000).

4.1.1 Description of the agents in receiving and sending CHANS

Agents in this telecoupled system are soybean producers, soybean traders, government officials, and others involved in the telecoupling processes (Figure 8). The interactions within one system and between the two systems include direct interactions between same type of agents, different agents in the same level, or cross scale interactions.

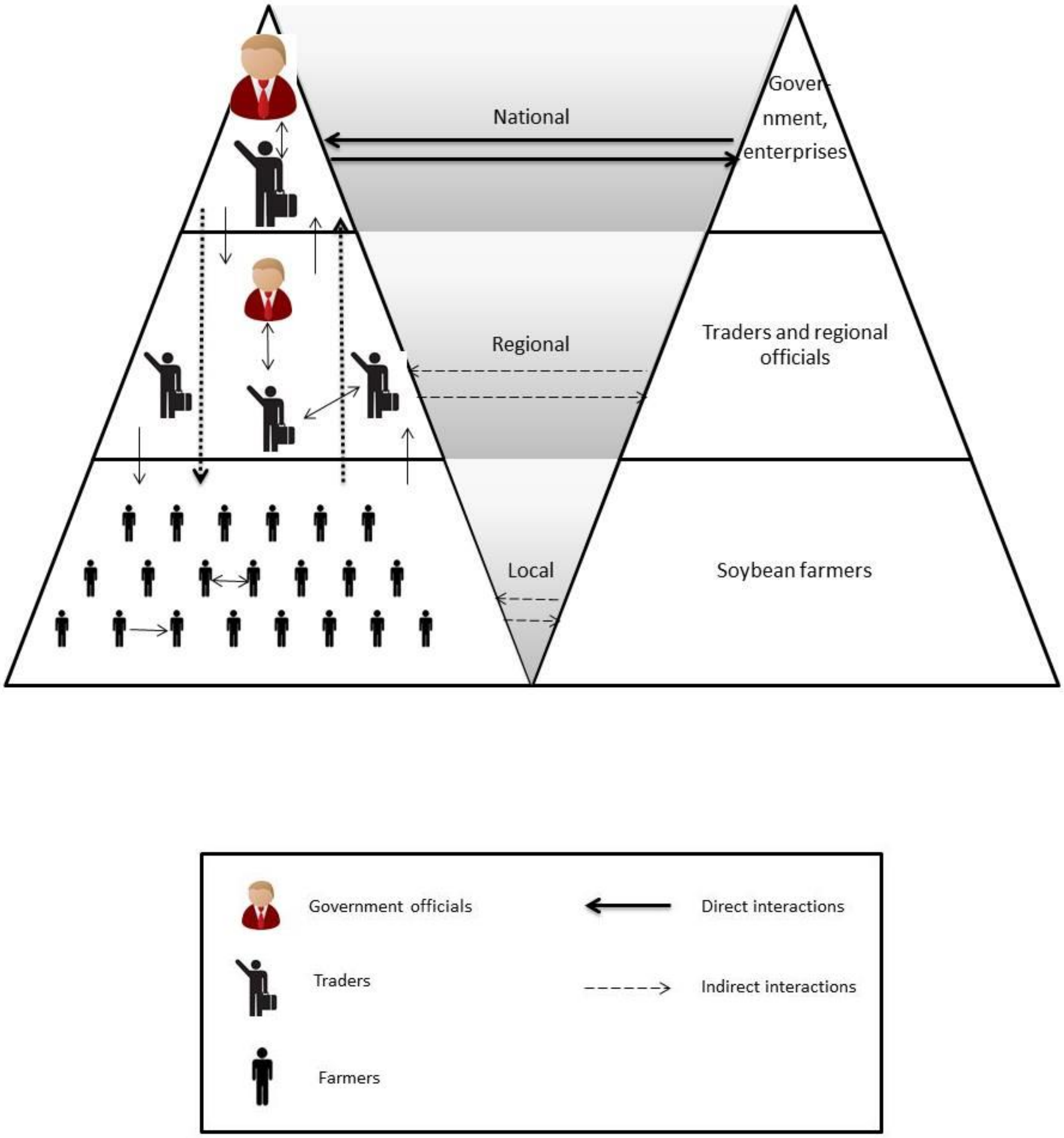

Figure 8 Different types of agents at different scales and their interactions

Agents have basic features and behaviors (Table 4 and Table 5). According to our fieldwork in June-August 2016 and data from census and statistics (Table 4), farmers in the receiving system are smallholders with an average farm size of 1.3 ha, while the size of soybean farms in the sending system ranges from 300 to 18800 ha. The agricultural input and output are also different for agents in the two systems: cost of seeds, fertilizer, and other agricultural inputs is higher in large mechanical farms in Brazil (i.e., around 700 dollars per hectare) than the cost among small households in China (i.e., around 260 dollars per hectare).

Table 4 Comparison of basic features of farming agents in the receiving and sending systems, based on data collected from fieldwork during 2016

	Sending system (Brazil)	Receiving system (China)
Farm size (ha) [min, max]	[300, 18800]	[0.30, 13]
Average farm size (ha)	5337	1.3
Soy yield (kg/ha)	~ 3000	~ 2500
Input in monetary unit (usd/ha)	~ 700	~ 260

Agents interact with their environments and with each other differently in the two systems (Table 5). In the sending system, soybean farmers often use double cropping and no-tillage technique. They can also expand new agricultural fields into the native vegetation. To the contrary, Chinese soy farmers grow single season and use tillage. The market structures are different in the sending and receiving systems, so farmers interact with market representatives (e.g., middlemen or trading companies) differently. Farmers in the sending system also collaborate with seed and fertilizer companies, while farmers in the receiving system may have less choice on what seed and fertilizer being sold to them.

Table 5 Agent behaviors and interactions in two systems

	Sending system (Brazil)	Receiving system (China)
Farmer cropping behaviors	double cropping no-till heavy use of fertilizer, pesticide, and herbicide	single cropping tillage use of fertilizer, pesticide, and herbicide
Interactions with natural component	clear native vegetation	indirect interaction through the use of fertilizer and pesticide
Farmer interacting with each other	association competition	forming farm cooperatives rent land social-norm
Farmer interacting with traders	sign multiple-year contract before planting get credit purchase seed package	sell to local middleman after harvest
Farmer interacting with	access to public rural credit	subsidy

government officials	environmental regulation road construction

4.1.2 Open question: how to represent two systems in one model

There is no case in current ABM applications for representing two systems in one model. As summarized above, the sending and receiving systems vary in agent attributes, behaviors, interactions, and market structure. We offer two alternative approaches, one from existing models and the other as our design.

(1) Approach from existing methods: using agent functional types from the CRAFTY framework (Competition for Resources between Agent Functional TYpes) (Arneth et al., 2014; Rounsevell et al., 2012). Agent functional types (AFT) are analogy of plant functional types, to support scaling agents to larger areas. Groups of AFT have different traits of roles and attributes, and compete land resources on grid-based space. It has not been widely used and the library of AFT needs further expansion. Furthermore, the tradeoff for the capacity to scale up is limited degree of heterogeneity and flexibility, which may need to be addressed if we want to represent two systems using AFT.

(2) Alternative approach: Instead of calibrating theoretical agent functional types, we draw upon empirical data and examples to identify shared features and functions of agents and environments in the telecoupled system. These shared features and functions are represented as abstract modules in the TeleABM. This approach shares the same philosophy as the comparative studies of ABM cases we reviewed earlier, the goal of which is to identify essential modules and procedures in different systems and to increase the model reuse efficiency.

The TeleABM consists of two main abstract modules (i.e., the human module and the natural module) that contain a list of shared features that appear in all sending, receiving, and spillover systems. For instance, the human module has several agent types that are involved in the soybean trade, including farmers, traders, government officials, and consumers; the natural module has climate, land cells (i.e., pixels), and landscape classes. Each class is constructed with basic features and functions, which can be implemented and parameterized to the actual system.

To explain the design here we use the soybean farmer agent as an example. Brazilian and Chinese farmers who grow soybeans differ in their attributes and decision making processes (as well as their responses to environmental and policy variables included in other modules), which are presented in Table 4 and Table 5. However, if we follow the agent typology method (Valbuena et al., 2008) that has been widely used in ABM applications, we can characterize soybean farmer agents based on their internal views, farm attributes, and external factors that affect their land use decisions. Therefore, each farmer agent in the human module can be an abstract class that contains the same attributes (e.g., agent id, 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 same external factors that we can use 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 sending and receiving systems (e.g., growing rice paddy only exists in the receiving system, while growing cotton is only feasible in the sending system). The same design philosophy applies to the natural module, with an abstract representation of the natural vegetation, land uses, soil dynamics, and the potential to include more functions (e.g., ecological model to simulate the vegetation transition).

Our reasons to use this design for TeleABM are twofold, from telecoupling theoretical aspect and modeling aspect. A telecoupled system is a set of CHANS connected through flows, where the same conceptual structure of human agents and natural systems is shared among sending, receiving, and spillover systems. The use of abstract modules of different CHANS in the telecoupled systems can help users to understand and compare the functions and effects of the same components in different roles of sending and receiving systems. From the modeling aspect, having the abstract human and natural modules provides an interface for modellers to load and run desired systems (i.e., single receiving system, sending system, or spillover system) and system combinations (e.g., the combination of sending and receiving systems, or all three systems) independently, hence gives modellers a higher level of freedom (e.g., we can initialize each system differently). These can also be easily adopted by modeling practices for other telecoupled systems.

4.2 Define the flow in the model

4.2.1 Description of the flows between the sending system and the receiving system

The area of planted soybean has increased 113 % and 1,219 % from 2000 to 2015 in the state of Goias and Tocantins respectively, along with agricultural intensification promoted by Brazilian research institutes and government. The majority of the soybean production is exported, where China is the largest destination (i.e., 83 % of the total production of Goias and 57 % of Tocantins goes to China). In China, soybeans are imported, distributed, and processed (e.g., to soybean meal and oil) by large international corporations (e.g., ADM, Bunge, Cargill, LouisDreyfus). Heilongjiang is one of the main soybean growing areas in China. However, being a main producer itself, Heilongjiang has imported 7.4 million tons of soybeans from 2002 to 2011 because of the low price of imported soybean. This caused the local soybean price to decline and many farmers have abandoned the soy-corn yearly rotation practice and switch to growing corn only (e.g., up to five years in a row, or some farmers haven't been growing soy for over 10 years). The flow in the model is the collective amount of soybeans being produced and traded between the sending and receiving systems, and the price of soy in both systems affected by the traded quantity.

4.2.2 Open question: how to represent the flows between receiving and sending systems

Most ABM applications are relatively closed and have no flows coming in and out of the models. There are two ways to represent the flow of soybeans between the sending and receiving systems:

(1) Approach from existing models: we can adopt a price function that is similar as AgriPolis. The assumption in AgriPolis is that the regional price of one commodity is affected by the aggregated production in the area that is being simulated. This assumption, however, has limitations when transfers to a telecoupled system. The flow of soybean and money exchanged between the sending and receiving system is only a small proportion of the global soy market, which is a much bigger scale than the regional scale in AgriPolis. It is also the dynamics of equilibrium of demand and supply of soybeans in the model, compared to only the supply being represented in the AgriPolis. Moreover, the price of soybean in sending and receiving systems are affected by various other

factors, such as transportation cost, government subsidy, and environmental variations, which an aggregated price function on supply side is not able to capture.

(2) Alternative approach: Using the Global Trade Analysis Project (GTAP) model and its database (particularly with its land use and land cover database, GTAP-Bio). Special review or introduction papers on this approach are available (see Hertel and Rose (2008) for GTAP-Bio). Instead of estimating the elasticity of a simple price function as AgriPolis, we can couple GTAP with TeleABM to generate a price of soybean flow between the two countries and the rest of the world that are involved with soybean trade. GTAP is a top-down equation-based economic analysis, which will be fed by the aggregated soybean production from the sending system and receiving system, as well as control for the demand of soybean from both systems. Similar global trading models (e.g., PEATSim) can also serve this purpose.

The coupling between TeleABM and GTAP can work on a year basis (Figure 9). Agents in both sending and receiving systems update their land use decisions and produce and sell soybeans to the market (at time step t_0). The aggregated soybean production from both sending and receiving systems then is sent to GTAP, as part of the global supply and demand dynamics, to simulate the regional soybean price for the sending and receiving systems respectively (at time step t_1). The soybean price, which is regional scale and can be distributed to grids within the region, is adopted by agents in the sending and receiving systems to make land use decisions for next year (t_1). However, the GTAP database and simulation has a three-year time gap and TeleABM is on a yearly basis. How to fill in the gaps of the two years needs further consideration.

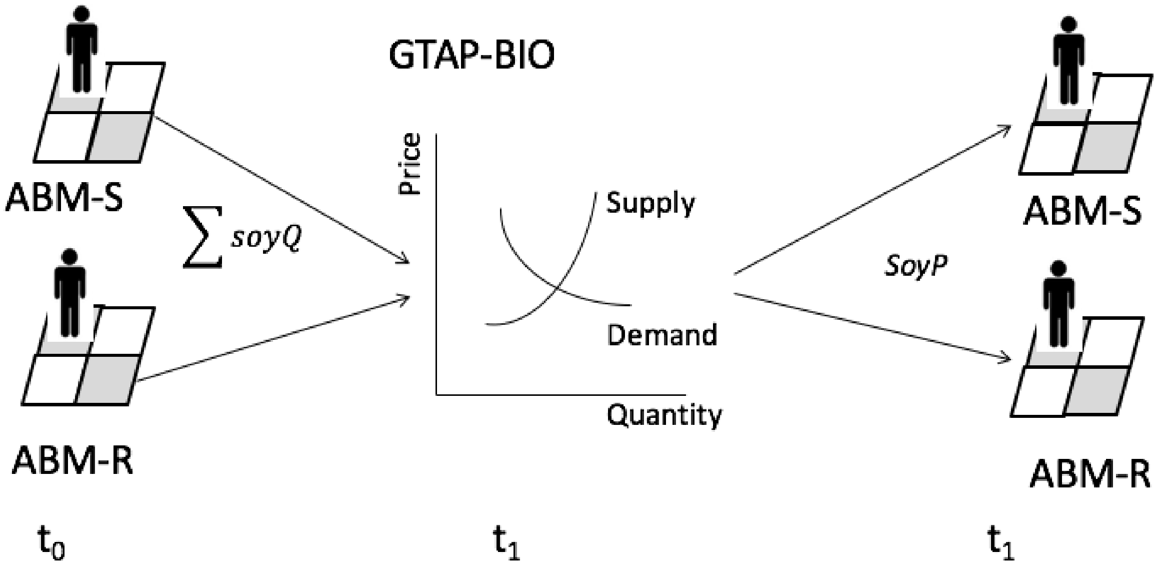

Figure 9 Procedures of coupling TeleABM and GTAP

5. Constructing an empirical TeleABM: next steps

It is always a challenge to empirically calibrate and validate an ABM. In terms of TeleABM, the challenges go beyond the conventional challenges of developing a single ABM. First, the spatial extent of TeleABM can be large and there can be great distance between the sending and receiving systems. This causes additional challenges of generating agents and their environments beyond an "empirically grounded" space. Besides these, how to calibrate and validate the dynamic flows between the two systems before the causes and effects are known also adds complexity. Here based on the existing ABMs, we summarize the main challenges and provide possible means to solve these challenges.

5.1 Ground-truth data

The empirical methods to get ground-truth data and inform agents have been reviewed systematically (Robinson et al., 2007; Smajgl et al., 2011). Several methods are highlighted here for TeleABM, and the choice of the method is based on the characteristics of the CHANS in the telecoupled system.

- 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). Behavioral information can be estimated based on data and theories generated from economy, anthropology, and phycology, or be asked as hypothetical questions during the survey. 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 and Liu, 2010; Chen et al., 2014; Huang et al., 2013) is available.
- Mental modeling: a type of participatory modelling approach that engages experts and stakeholders' knowledge and encourage the communication between stakeholders and modellers during the modeling process (Özesmi and Özesmi, 2004; van Vliet et al., 2010; Voinov and 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). For example, small farmers in the Amazon forest in Para, Brazil, were clustered based on livelihood strategies into three groups (Diniz et al., 2015). Using this approach important factors and qualitative relationships between these factors to stakeholders' decisions can be captured.
- The scopes and agent characteristics of the two CHANS in the sending and receiving systems are different. In the receiving system, the number of farming households and the average size of farmland are the opposite of those in the sending systems. Therefore, different data-acquiring methods should be used in the two focal regions. Questionnaire is more appropriate to sample large populations while mental modeling is more useful at obtaining in-depth decision making reasoning in smaller populations.

5.2 Scale up and scale out

Scaling up and scaling out are useful strategies to translate limited sample data or interviews into an empirical model that covers large scales. The former is used to aggregate model behaviors to a higher representational level while the latter is used to apply the same behavior across a larger spatial extent by increasing the input data (Rounsevell et al., 2012). Defining agent typology (Valbuena et al., 2008) based on sampled agents and using Monte Carlo or other methods (e.g., Microbial Genetic Algorithm) to apply the typologies to the population is an available procedure for scaling out (Chen et al., 2016; Smajgl et al., 2011).

In this case, the 960 households we sampled last year are carefully designed to represent the whole province (Figure 10), which has soybean gain, soybean loss, and soybean unchanged sub-regions. Agent typologies is a useful scale up and scale out approach that group human decision makers with similar characteristics and behaviors. It can be defined based on their land use behaviors during previous years and scale out to the sub-regions and counties. Sample surveys and mental models can help to parameterize and allocate different agent typologies. Monte Carlo method can be used to allocate these agents across the model space.

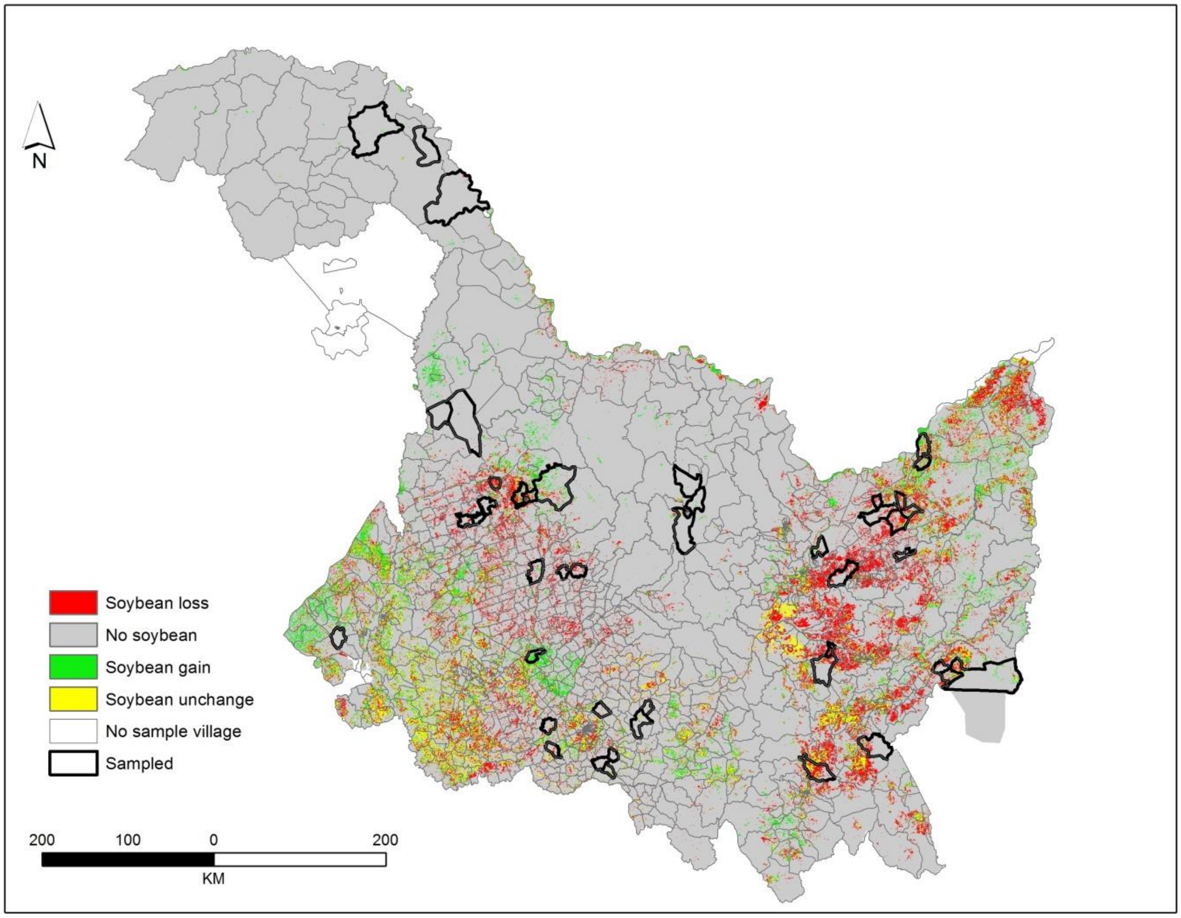

Figure 10 Soybean change from 2005 to 2010 and sampled counties in the receiving focal region (based on Sun et al, 2016).

5.3 Validation

Validation of ABMs includes two parts: the decision making process and the model outcome. The first one has no commonly agreed method, but many techniques are developed to validate the outcomes of ABMs (Evans, 2012), such as pattern-oriented validation (Castella and Verburg, 2007; Grimm et al., 2005), and ratio of variant and invariant regions (Brown et al., 2007). For instance, the quantities of soybean land use changes in each sub-region or even counties can be compared to the historical soybean land use change patterns observed from remote sensing images (Sun et al., 2017).

When it comes to TeleABM, the flow between the sending and receiving systems also requires validation. The flow between the receiving and sending systems is a fraction of international soybean supply and demand. Simulated soybean flows between sending and receiving systems can be compared to the historical transactional data between the two regions in GTAP database.

6. Conclusions

In this paper, we have outlined a conceptual design for TeleABM using the soybean trade between China and Brazil as a case telecoupled system. Our proposed model is grounded by the telecoupling framework and goes beyond typical agent-based models in at least two aspects: representing more than one coupled human-natural system in a single model and connecting the systems with an open-model feature. We present the design of a TeleABM with potential solutions which is well grounded on existing ABM applications and alternative modeling approaches, particularly the coupling with GTAP-BIO as the flow between the sending and receiving systems. We also offer methods and solutions for applying this conceptual design to an empirical model, including data collection and validation. We hope this design will be of interest to researchers seeking for a quantification using the telecoupling framework, as well as for ABM modellers that are looking for alternative frameworks for conceptual innovation.

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