A framework for modelling the complexities of food and water security under globalisation

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Abstract

We present a new framework for modelling the complexities of food and water security under globalisation. The framework sets out a method to capture regional and sectoral interdependencies and cross scale feedbacks within the global food system that contribute to emergent water use patterns. The framework integrates aspects of existing models and approaches in the fields of hydrology and Integrated Assessment Modelling. The core of the framework is a multi-agent network of city agents connected by socioeconomic and infrastructural trade networks. Agents receive socioeconomic and ecohydrological constraint information from existing models and simulate complex, socioenvironmental dynamics that operate within those constraints. The emergent changes in food and water resources are aggregated and fed back to the original models with minimal modification of the structure of those models. It is our conviction that models built according to this framework can form the basis for a new wave of tools that capture the complexities of environmental change within our globalised world. In doing so they will contribute to illuminating pathways towards a sustainable future for humans, ecosystems and the water they share.

Keywords: food and water security, globalisation, urbanization, complexity, hydrology, integrated-assessment models

1 Introduction

Ensuring food and water security in our globalised world is an urgent and complex challenge (Shiklomanov, 2000; United Nations Water, 2015). Food and water security are inextricably intertwined, with variability in agricultural production impacting water resource use and vice versa (Liu and Savenije, 2008). Trade, both international and domestic, plays a central role in determining water use in the global food system, because when we trade food, we are also trading the water embedded in the production of that food (Fader et al., 2013; Hoekstra and Chapagain, 2006; Hoekstra and Mekonnen, 2012). The global system of food production and trade is complex and drives interdependency among heterogeneous regions, meaning that socioeconomic or environmental changes in one part of the globe can have cascading impacts for food and water security throughout (Fig. 1) (D'Odorico et al., 2010; J. Liu et al., 2015; Marchand et al., 2016; Young et al., 2006). Equally, there is interdependency across sectors with the mechanisation of agriculture leading to a tighter coupling of the food, water and energy sectors in recent years, often referred as the food-water-energy nexus (Fig. 1a) (Bazilian et al., 2011). Within this interdependent system, interactions occur across spatial and temporal scales (d'Amour et al., 2016; Sivapalan and Blöschl, 2015) (Fig. 1c). For example, the combined effect of small-scale abstraction of ground and surface water to secure short-term food and water security can lead to large scale and long-term depletion of water resources, which ultimately undermines food and water security (Sivapalan and Blöschl, 2015; Sophocleous, 2012). Given the complexity of the food system, it is challenging to develop effective food and water management strategies because policies can leak across regions, sectors and scales (Eakin et al., 2009; Hejazi et al., 2015; Meyfroidt et al., 2013). Models and decision tools exist to inform policy makers on these issues (Bierkens and van Beek, 2009; Hanasaki et al., 2008a; Lotze-Campen et al., 2008; Sitch et al., 2005; Stehfest et al., 2014), however to our knowledge, regional and sectoral interdependencies and cross-scale feedbacks associated with food and water security have not been captured in a single modelling framework. As a result, existing decision tools miss important dynamics (Konar et al., 2016a; Srinivasan et al., 2017). It is urgent that we develop models and approaches that capture these complexities within a single framework to assist decision makers in navigating the increasingly complex global food system and help ensure that we stay within the natural limits of our planet's boundaries for water resources (Rockström et al., 2009; Wagener et al., 2010).

Figure 1. Complex dynamics within the global food system that lead to emergent water use patterns.

In this paper, we set out a framework to capture regional and sectoral interdependencies and cross-scale feedbacks in the global food system that contribute to emergent water use patterns. The framework builds upon and combines existing models and approaches via a multi-agent network of city agents and trade links. In our framework city agents consist of an urban agglomeration and an associated hinterland, which we define as the agricultural area economically tied to a city. We focus on cities because they are centres of food and water demand and important agents of change within the global food system, with 54% of the world's population urbanised, consuming a disproportionately large, 75% of the world's resources (United Nations, 2012; United Nations Environmental Programme, 2013). Cities play a key role in driving regional interdependency via trade. In fact, cities and trade coevolved, with demand from cities determining the location of physical trade networks that constrain our ability to extract food and water resources from the environment and redistribute them around the globe to meet demand (Barber et al., 2014; Barredo and Demicheli, 2003; Friedmann and Wolff, 1982; Fujita et

al., 2001; Rees and Wackernagel, 2008) As city populations grow, infrastructural networks continue to upgrade capacity and extend further into natural systems, increasing our ability to extract natural resources, but also increasing regional interdependence (Ibisch et al., 2016; Laurance et al., 2015). The infrastructural networks that radiate from cities, serve to link environmental resources in their hinterlands to global food markets, thus playing a key role in facilitating cross-scale socioenvironmental feedbacks within the global food system (Brenner, 1999; Güneralp et al., 2013; Harvey, 1990).

Environmental conditions in the hinterlands of cities constrain the production of food and associated water use, whilst socioeconomic conditions across different sectors of the economy constrain the ability to exploit those environmental conditions for food production (Godfray et al., 2010). Socioeconomic conditions also constrain the ability of cities to trade food on regional and global markets (FAO, 2015). Trade cannot occur directly between two cities unless the socioeconomic links exist and not at all if the infrastructural links are missing (De Benedictis and Tajoli, 2011). Of course, physical infrastructural and socioeconomic networks cannot be disentangled. Strengthening of socioeconomic ties invariably leads to strengthening of infrastructural links, whilst the cost of investment in that infrastructure serves to stabilise those socioeconomic ties (Khanna, 2016).

Capturing these different components of the global food system in a single framework is ambitious but has parallels to the discipline of climate modelling, which began with models of sub-components of the climate system. However, it became clear that these subcomponents were interdependent and it was necessary to capture these interdependencies in a single framework in order to understand the climate system (Edwards, 2011). A similar approach is urgently required to understand how cross-scale and interdependent socioenvironmental interactions impact food and water security in our globalised and urbanised world (Liu et al., 2015). In the following section 2, we present an overview of existing models and approaches to understand food and water security. We highlight some important knowledge gaps in these approaches that our framework aims to fill. In section 3 we present our framework in detail, outlining how we aim to capture regional and sectoral interdependencies and cross-scale feedbacks in a single framework. In section 4 we outline potential applications of a realised version of the framework. In section 5 we outline steps required to make this ambitious vision a reality.

2. Challenges in managing water within the global food system

Water resource use in the global food system emerges from complex, socioeconomic and environmental dynamics that are interdependent across regions, sectors and scales (Eakin et al., 2009; Hejazi et al., 2015; Meyfroidt et al., 2013). However, to our knowledge, no current decision tools capture the two-way interaction between socioeconomic and environmental processes across regions, sectors and scales within a single modelling framework. Given that many sustainability challenges are interlinked, it is urgent that we develop approaches that capture these interdependencies (Güneralp et al., 2013; Liu et al., 2015; Puma et al., 2015). In the following section, we outline the progress made in existing approaches that our framework aims to build upon as well as specific knowledge gaps that out framework aims to fill.

2.1 Regional Interdependence

As the food system becomes increasingly globalised and urbanised, trade, both domestic and international, becomes ever more important for food and water security, driving interdependency among trading regions (FAO,

2015; Sartori and Schiavo, 2015). Water footprint studies have played an important role in quantifying the volume of water used in food production and embedded in traded food, known as virtual water trade (Allan, 1998; Fader et al., 2011; Hanasaki et al., 2010; Konar et al., 2016b). These studies apply hydrological models to estimate the amount of green (recently precipitated, rapidly replenished water in the upper soil layer) or blue water (slowly replenished ground and surface water resources) used in food production (Fader et al., 2011; Hoff et al., 2010). At a global scale, 84% of food production relies on green water, which has generally less negative impacts on the environment compared with blue water. In terms of internationally traded food, 16% of traded food comes from green water resources and 6% from blue water resources (Fader et al. 2011). As a result, at a global scale, trade saves water (de Fraiture et al., 2004; Hanasaki et al., 2010; Konar et al., 2011). However, recent studies have revealed that an increasing proportion of traded food is produced from unsustainably abstracted blue water resources (Dalin et al., 2017; Wada et al., 2012, 2010). Owing to regional interdependency of the food system, these unsustainable practices threaten the future food and water security of trading regions (Gleeson et al., 2012; Wada and Bierkens, 2014) (Fig. 2a). The increase in unsustainable water abstraction is principally owing to increased demand arising from population growth, with climate change projected to exacerbate stress on food and water resources in the future (Gerten et al., 2011).

A knowledge gap in water footprint studies is that there tends to be a focus on international bilateral trade, meaning the impact of domestic trade on water resources is often neglected (Konar et al., 2016). In the developed world, almost all food reaches consumers through domestic and international trade networks whilst in the developing world, the numbers of people involved in subsistence agriculture is also decreasing, owing to rapid urbanisation trends in these regions (Chen, 2007; IFPRI, 2017; Seto and Reenberg, 2014; United Nations, 2012). The lack of studies on domestic trade is in large part owing to the lack of data. However, increasingly there are attempts to quantify virtual water flows within countries (Fig. 2b) (Dalin et al., 2014; Dang et al., 2015) and the water footprints of cities (Hoff et al., 2014). Identifying the fine-scale networks that constrain where water resources are extracted from the environment to meet remote demand is essential for managing water under globalisation. By capturing these fine scale virtual water flows, it will improve our ability to estimate how socioeconomic or environmental change in one part of the food system can be transmitted through the trade network (Karpiarz et al., 2014). This will improve our ability to diagnose the remote drivers of water resource use and how socioeconomic and environmental changes may cascade through the global trade network (Puma et al., 2015). Thus, the first knowledge gap our framework seeks to fill is to capture the fine-scale networks that constrain virtual water trade within countries and among cities. We aim to close this knowledge gap by capturing spatially explicit demand and production at the city and hinterland scale and the infrastructure that constrains the redistribution of water resources to meet this demand (d'Amour et al., 2016).

Figure 2. Water footprint studies.

2.2 Sectoral Interdependence

Owing to the increased mechanisation of agriculture and the development of more diverse energy sources, water now sits at the centre of the food, water energy nexus (Bazilian et al., 2011; Kraucunas et al., 2015; United Nations Water, 2015). Currently 30% of energy produced is used within the food sector, with fluctuations in energy costs having direct impacts on agriculture and thus water resources (Frieler et al., 2015). Next to this, the energy sector

requires considerable water resources (Bijl et al., 2016). Fossil fuel extraction such as coal mining and shale gas fracking are highly water intensive, whilst biofuel production competes with food production for land and water resources (Bonsch et al., 2016; Hejazi et al., 2015). Failure to capture sectoral interdependencies means we may fail to identify synergistic solutions, or worse still, policies in one sector may have unintended negative consequences in another. For example, investment in climate change mitigation measures such as biofuel production may lead to unsustainable water resource use (Hejazi et al., 2015).

Integrated Assessment Models (IAMs) are powerful tools to explore sectoral interdependencies (Bazilian et al., 2011). Until now, IAMs have principally been focused on projecting greenhouse gas emissions, however increasingly, the agricultural sector is being captured within IAMs (Stehfest et al., 2013; Stehfest and Bouwman, 2006; Wise et al., 2009). For example, the IMAGE IAM contains an agriculture and land module which is internally coupled with an energy supply and demand module. IMAGE calculates changes in agriculture based on two-way interactions between the agriculture and energy sectors (Stehfest et al., 2014). IMAGE has also been coupled with the MAGNET agro-economic model, a Computable General Equilibrium (CGE) model that uses information from IMAGE on land availability and suitability, labour supply, technological change to estimate international food trade, demand and supply (Stehfest et al., 2013; von Lampe et al., 2014; Woltjer et al., 2014). An integrated approach has also been applied by Bonsch et al. (2016) using MAgPIE (Lotze-Campen et al., 2008), a global land and water-use allocation model, to understand the trade-off between agricultural expansion and intensification via water abstraction to meet biofuel targets. Similarly to Hejazi et al. (2015), their integrated approach showed that changes in the energy sector can lead to competition for water resources with the food sector. The MAgPIE approach underlines the importance of capturing dynamic vegetation and hydrological processes in the same modelling framework as the two are intrinisically intertwined with changes in vegetation impacting water resources and vice versa (Fader et al., 2011; Konar et al., 2013; Lotze-Campen et al., 2008).

Although IAM approaches capture important sectoral interdependencies, they cannot provide a representation of non-linear transformative change of socioenvironmental systems and the dynamics associated with it (Filatova et al., 2013; Folke, 2006; Rockström et al., 2017). Incorporating these processes in IAMs would risk including too much complexity, possibly leading to a trade-off with transparency (van Vuuren et al., 2016). An alternative approach is to couple IAMs with models that capture these important processes, without changing the internal structure of IAMs. Some progress has already been made in this direction by coupling land use models with IAMs and aggregating the emergent fine-scale patterns at the regional scale captured in the IAM, which resulted in improved projections as land allocation models capture within-region heterogeneity (Hasegawa et al., 2017; Stehfest et al., 2013). In order to model the complexity of socioenvironmental systems, it is necessary to capture dynamics such as agency, emergence, non-linearities and feedbacks (Berger, 2001; Brown et al., 2005; Farmer and Foley, 2009; Farmer and Geanakoplos, 2009; Helbing, 2013; Sivapalan et al., 2012). However, the pathway to capturing these dynamics within global models is not obvious (Müller-Hansen et al., 2017). For example, it is not practical from a computational or data perspective to represent farmers as agents at a global scale. Thus, the second knowledge gap our framework aims to fill is to incorporate the complex dynamics associated with socioenvironmental systems within the IAM framework, without adding unwanted complexity to those models. We aim to achieve this by focusing on cities. Cities are important agents of environmental change and sit at the intersection of scales within the global food system (Brenner, 1999; United Nations Water, 2015).

2.3 Cross-scale socioenvironmental feedbacks

Cross-scale socioenvironmental feedbacks describe a broad range of processes where small-scale or short-term actions bring about large-scale or long-term emergent change (Folke, 2006; Sivapalan and Blöschl, 2015). These emergent higher-level changes may feedback at the finer scale. In terms of water resources, sociohydrological studies have played an important role in helping to understand emergent water use patterns by capturing cross-scale socioenvironmental feedbacks (Di Baldassarre et al., 2013b, 2013a; Montanari et al., 2013; Sivapalan et al., 2012; Troy et al., 2015). They have done so by explicitly considering bi-directional feedbacks between humans and the environment in hydrological basins. An example of emergent dynamics is a "pendulum swing", in communities that have alternated between water extraction for agriculture in the early stages of development, followed by subsequent efforts to mitigate or reverse the consequent degradation of the riparian ecosystems (Kandasamy et al., 2014; Liu et al., 2014). This has been explained by counteracting productive and restorative forces, mediated via technology, environmental awareness and the intervention of governance institutions (Elshafei et al., 2015; Liu et al., 2015; van Emmerik et al., 2014).

However, sociohydrological studies maintain a disciplinary focus on water and do not capture important sectoral interdependencies as IAMs do (Troy et al., 2015). Equally, they have so far assumed the systems of concern are isolated entities in space, e.g., an agricultural river basin whereas, in a globalised world, many different such entities may be linked through trade as demonstrated in water footprint studies (Konar et al., 2016a). Capturing linkages to regional and global markets is critical to understanding cross-scale feedbacks, because the more connected water resources are to markets via trade, the more sensitive they are to cross-scale feedbacks (Eakin et al., 2009; Pande and Sivapalan, 2016). For example, the 2010 drought in Russia and Kazakhstan led to a spike in the price of wheat on global markets (Nelson et al., 2014). Food producers in other wheat producing regions of the world that were well connected to global markets via physical and socioeconomic trade links were impacted by this price rise as they could sell their products to global markets at increased profit. Thus, environmental change in Russia impacted global markets which drove local water resource use in other parts of the world. There has been a recognition of the important role trade plays in facilitating cross-scale feedbacks in literature related to land use change (Geist and Lambin, 2002; Lambin and Geist, 2008). These studies have highlighted that distant market demand drives local land use change and in order to predict land use change we need to model land as an open with system with flows of resources coming in and out (Lambin and Meyfroidt, 2011). However, modelling of these issues in relation to water resources is still in its infancy (Konar et al., 2016a). Thus, the third challenge is to capture the crucial role of trade networks in facilitating cross-scale feedbacks between local water resources and regional and global markets.

3. Modelling Framework

3.1.1 City agent attributes

The core structure of our framework is a multi-agent network of city nodes and trade links (Fig. 3). In our framework, cities are agents and comprise of an urban area and associated hinterland. City agents sit at the intersection of scales between environmental resources in their hinterlands and global markets via radiating trade networks. The environmental conditions in hinterlands of city agents are determined from a grid-based ecohydrological model for natural and managed land. Socioeconomic conditions in the hinterlands of cities are determined from an IAM. Socioeconomic conditions constrain agent's ability to exploit environmental conditions

within their hinterland for food production. City agents have a common utility function: to satisfy local and market demand for food, which in turn leads to emergent water use. City agents satisfy demand via food production and trade. How each city satisfies demand differs based on the heterogeneous socioeconomic and environmental conditions within their hinterland and the socioeconomic and infrastructural networks that link them. The fine-scale interactions among cities and their environment bring about higher-level emergent patterns which provide input conditions for the next simulation step of the ecohydrological model and IAM. Thus, fine-scale interactions among heterogeneous city agents and their environment bring about emergent change which is incorporated within existing model structures with minimal change to the structure or complexity of those models.

Figure 3. City agent attributes

3.1.2 The city and its hinterland

Each city agent has an associated hinterland. The size of a hinterland depends upon food demand in the city and on the ease of transportation between the city and the agricultural area, which is determined by geographic, infrastructural and socio-political factors (Billen et al., 2009). To capture these elements, we define city hinterlands based on the hierarchical overlay of supra-sub national administrative borders and theissen polygon operation among cities based on the gravity equation of trade with mass equal to demand and distance equal to the cost-distance of trade via road, rail and inland water ways (Fig. 4) (Berthelon and Freund, 2008; Chaney, 2013). We base hinterlands on administrative borders so that the framework can capture the impact of heterogeneous policy or socioeconomic conditions at the administrative scale. For many cities, and depending on the food commodity, the effective hinterland will extend beyond these contiguous administrative regions (Billen et al., 2009; Güneralp et al., 2013). However, policy is applied at the scale of these administrative boundaries and cities operate within these policy constraints. If policies stimulate free trade between administrative regions, then the effective hinterland of a city can expand (Knox and McCarthy, 2012). Therefore, the framework allows for the exploration of the impact of policy at different scales on food and water use and virtual water flows. By also basing the size of hinterlands on the cost-distance of trade via road, rail and shipping, we capture the key role that infrastructural networks play in linking demand in cities with environmental resources. Hinterlands vary in terms of size and composition.

The hinterland of a city in Western Australia will be large, with a high proportion of natural landcover and low population density, whilst a hinterland in Eastern China will be smaller with a high proportion of agricultural and urban landcover and high population density. From a socioeconomic perspective, per capita demand will differ among hinterlands based on culture, affluence etc. derived from the IAM. Equally, the agricultural intensification of a hinterland in the Netherlands will be greater compared with a sub-Saharan African region owing to factors such as mechanisation of agriculture, access to fertilizers etc. (Stehfest et al., 2014).

Figure 4. The city and its hinterland

3.2 Food production and water use

Within our framework, city agent food production decisions are constrained by socioeconomic and environmental conditions within their hinterlands. The environmental conditions within the hinterlands of cities are determined using a process-based ecohydrological model for natural and managed land similar to the approach of Hejazi et

al. (2015) and Lotze-Campen et al. (2008). However, we recommend tight coupling between dynamic vegetation models such as Lund-Potsdam-Jena managed Land (LPJ-ML) model and a complex hydrological model that captures water fluxes between the soil layer and groundwater reservoir, which is key for computing groundwater recharge rates (Bierkens and van Beek., 2009; Bondeau et al., 2007; Hanasaki et al., 2008b). Each city hinterland has a potential yield and associated water resource usage based on these ecohydrological constraints. Socioeconomic constraints on food production are taken from the IAM based on factors such as the mechanisation of agriculture, acces to fertilizers etc. The demand for each food commodity in a city and its hinterland is equal to (per capita demand taken from IAM * population), with population based on spatially explicit grid-scale population estimates (Bijl et al., 2017; Brinkhoff, 2016; Klein Goldewijk et al., 2011; Stehfest, 2014; UN Population Division, 2015). Cities and their hinterland are either in surplus or deficit for a crop type based on (local production – local demand) (Dermody et al., 2014). Cities with predominantly urbanised hinterlands will have a net demand for food resources whilst others, with large areas of agriculture within their hinterlands, will have a net surplus in food resources (Dermody et al., 2014). Demand is also based on trade demand calculated in the trade component of the framework (Section 3.3).

Cities adapt to changes in food demand through agricultural expansion/contraction, (de)intensification or trade. Agricultural expansion and intensification potential are estimated using land use algorithms. The algorithms used to calculate agricultural expansion and intensification potential in IAMs such as IMAGE may be extended to include detailed infrastructural data as well as more complex hydrology in determining agricultural suitability (Barber et al., 2014; Wada et al., 2012; Walker et al., 2013). In our framework, cities with increasing demand, low (high) agricultural intensity potential and high (low) expansion potential are likely to expand (intensify) agriculture (Fig. 5). Cities that are constrained from expanding or intensifying agriculture will increase imports to sustain growth. The agent decision process generates land-use maps that are prescribed to the ecohydrological model (Biemans et al., 2013; Wada et al., 2012).

The method for capturing food production outlined, blends macroscale interdependencies between the agricultural and energy sector with small-scale ecohydrolgial and demographic conditions to estimate land use change, similar to the approach by (Hasegawa et al., 2017; Verstegen et al., 2016). Importantly, our approach also captures how market demand is transmitted heterogeneously within a region or country via socioeconomic and infrastructural networks (see section 3.3 for more details). This is a critical step in understanding how regional interdependence for food and water security impacts local water resource use (Konar et al., 2016a; Lambin and Meyfroidt, 2011).

Figure 5. Food production decisions.

3.3 Virtual Water Trade

The trade network that links city agents is hierarchical. The network comprises a lower-level physical infrastructural network and an upper-level network with link weights reflecting bilateral socioeconomic trade links (Fig. 6). The lower level of the trade network is defined by physical trade infrastructure of roads, rail and shipping lanes (Berthelon and Freund, 2008; Karpiarz et al., 2014; Limão and Venables, 2001). The data required to build this network, such as open street maps and database of cargo ship movements, is openly available in digital format (Brinkhoff, 2016; Haklay and Weber, 2008; Kaluza et al., 2010). Each link type has a different

transport cost. For example, the cost of bulk trade is approximately 7-times less by ship than by road (Limão and Venables, 2001). In addition, intermodal transport costs are applied for transferring goods between transport modes (Janic, 2007). Infrastructure development can be projected using infrastructure growth algorithms or manually added to explore the impacts of prospective plans such as the new trans-Eurasian Silk Road Economic Belt on virtual water trade (Ahmed et al., 2013; Arima et al., 2008; Brugier, 2014; Walker et al., 2013). Because the infrastructural network constrains where resources can be extracted from the environment and redistributed to meet demand, all resource flows travel via the lower level physical infrastructural network in a realised version of the model framework (Barber et al., 2014; Khanna, 2016). The upper level network consists of bilateral trade links among countries. Link weights among countries are calculated using a CGE model, which is coupled to certain IAMs (Stehfest et al., 2013). CGEs are constrained with historical data on bilateral trade balances, competitiveness (relative price developments) and trade policies to estimate trade patterns (Hertel et al., 2007; Hertel and Hertel, 1997; Woltjer et al., 2014). If the CGE simulates high trade volumes between two countries, then the link weight between those countries in our framework will reflect a high probability of bilateral trade.

Figure 6. Virtual Water Trade Network.

The food produced in the hinterland of cities is either consumed locally or exported to meet market demand. Cities with a demand, import from cities with a surplus based on the cost-distance among cities (Berthelon and Freund, 2008). Thus, the probability of trade among cities decays with increasing cost-distance (Karpiarz et al., 2014; Limão and Venables, 2001). City agents within the same country trade with one another based solely on supply and demand for each food commodity and the cost-distance of trade among cities. Cities in different countries are also constrained by bilateral trade probabilities of the upper-level network (Fig. 6). For example, the probability of trade between Japan and American cities will be determined by the upper level network based on CGE output. However, it is more likely that the demand will be met from hinterlands on the West Coast of the United States owing to the lower cost-distance of trade. The emergent trade patterns are aggregated at the country and region scale of the CGE and fed back into it for the next simulation year. Because city agent trade decisions are stochastic, it allows for alternate emergent trade patterns within the constraints of the same network. Thus, for given constraints there will be a range of possible solutions. The stronger (weaker) the constraints the narrower (wider) the solution space. In this way, the solution space for given environmental, socioeconomic and infrastructural constraints can be explored (An, 2012). Equally, if conditions change at the small scale, this will result in alternative emergent patterns at the large scale (Fig. 7b). In this way, agency, cross-scale processes, socioeconomic, environmental and infrastructural constraints are married with conventional general equilibrium modelling approaches. This is a novel and potentially important step in capturing non-equilibrium dynamics within pre-existing equilibrium approaches without adding unwanted complexity to CGEs or IAMs (Farmer and Geanakoplos, 2009). It also allows us to begin to uncover the role of cross-scale feedbacks which link local water resources to the dynamics of regional or global markets. By capturing these cross-scale feedbacks, we can begin to see how heterogeneous water use can bring about emergent large-scale and long-term market change, which in turn feeds back to local scale water use.

Figure 7. Modelling Framework Workflow.

4. Applications of the framework

The framework is designed to be used with IAMs, which are influential decision tools but are unable to capture non-linear, emergent change typical of socioenvironmental systems (Rockström et al., 2017; van Vuuren et al., 2016). Our approach blends agency and emergent processes captured by the multi-agent network of cities with the top-down approach captured by IAMs. Thus, a realised version of the framework has the potential to illuminate how the large scale patterns demonstrated in IAMs emerge. In terms of informing policy, this is an essential step as it allows policy makers to explore the impacts of policy changes at the different spatial and temporal scales at which policy is applied. In doing so, models based on the framework can help illuminate roadmaps, considering complex dynamics, to reach regional and long-term goals outlined in IAMs (Rockström et al., 2017). For example, it allows the exploration of how scenarios, such as the recently published Shared Socioeconomic Pathway (SSP), which outlines future environmental change according to different socioeconomic development storylines (O'Neill et al., 2015), can be implemented at finer scales and taking account of sectoral and regional interdependencies and cross-scale feedbacks. This can be a potentially important step in extending the usefulness of IAMs whilst avoiding adding unwanted complexity to those models (van Vuuren et al., 2016).

The multi-agent network of cities at the core of the framework enables the exploration of the emergent solution space for realizing food and water security requirements based on these constraints. The emergent solution space illuminates how constrained regions or sectors are based on socioeconomic, environmental and infrastructural factors to transition to sustainable and secure water use pathways (Brown et al., 2005; Garud et al., 2010). Those regions or sectors that are locked into unsustainable or vulnerable water use pathways should be prioritised for intervention (Fig. 8) (Liebowitz and Margolis, 1995; Sophocleous, 2012). Within the solution space, sustainable and secure development pathways can be explored. A common approach for exploring multi-dimensional solution space is to use optimality algorithms (Dermody et al., 2011; Konak et al., 2006; Vrugt et al., 2003). For example, optimality algorithms can be applied to find solutions that are optimal from a land saving and water saving perspective. Because the IAM captures cross-sectoral interdependencies, multi-objective optimality algorithms can be used to explore synergistically sustainable solutions across sectors. Such synergistic approaches are key to addressing the challenges set out in the UN Sustainable Development Goals (Costanza et al., 2016; Lu et al., 2015). In addition, our approach can uncover potential displacement of environmental impact of policies to other regions (Lambin and Meyfroidt, 2011). Thus, policies can be explored that are sustainable both in the administrative region where those policies are applied as well as interdependent regions.

Figure 8. The solution space illustrates how constrained regions or sectors are along their current water use pathway.

Given the importance of cross-scale feedbacks for understanding local water use, it is essential that smaller scale studies on food and water security can be linked with regional-global scale models (Pande and Sivapalan, 2016; Sivapalan and Blöschl, 2015; Verburg and Overmars, 2009). Returning to the parallels with climate modelling, small-scale studies use output from Global General Circulation Models as boundary conditions for local-regional climate studies (Douglas et al., 2009). Equally, the model framework outlined can be used to

understand how detailed changes within a city or catchment link to large-scale market or hydrological changes. Thus, models built according to our framework can contribute to, and benefit from, the rapid growth of within-city studies such as studies of urban metabolism or sociohydrological studies which focus on the catchment scale (Broto et al., 2012; Liu et al., 2014; van Emmerik et al., 2014; Zhang, 2013). In the case of urban metabolism studies, detailed analysis is done of resources flows into and out of a city. Models based on our framework can illustrate how those resource flows are linked to environmental change in other parts of the globe and the feedback of those global changes at the city scale. In the case of sociohydrological studies, the framework outlined can help illustrate how small-scale changes across multiple catchments can emergent market changes, which in turn feedback on water use within a single catchment.

5. Summary and recommendations

The complex and interdependent nature of food and water security within our globalised and urbanised world requires new models and approaches to inform policy makers. Models built using the framework outlined are ideally suited to informing policy on so-called "wicked problems" associated with water resource use within the globalized food system (Dentoni et al., 2012; Duit and Galaz, 2008; Lach et al., 2005). The framework we present builds on the existing fields of hydrology and Integrated Assessment Modelling to understand emergent water use patterns. It is our conviction that models built according to the framework outlined will represent a new wave of decision tools that can help policy makers navigate the complexity of socioenvironmental interactions within our globalised world. Much of the groundwork for the framework already exists, however extra efforts are required to achieve an operational model.

The main step required to make this framework a reality is the construction of a multi-agent network of city nodes and trade links. As outlined, cities and infrastructural trade networks play a key role in environmental change. Cities are where the majority of resource demand is, whilst infrastructural networks constrain our ability to extract resources from the environment and redistribute them around the globe to meet this demand. Thus, a multi-agent network of cities and infrastructural links will provide a platform for a wide range of research questions related to environmental change. The resources required to build this network are openly available but need to be translated to a scalable and flexible network architecture. The structure of this network should be designed in collaboration with scientists from a wide range of disciplines to ensure the relevant elements are incorporated to meet a range of research questions.

In order to facilitate collaboration in building such a multi-agent network, there is a need for interdisciplinary dialogue and collaboration. Indeed, this is essential for achieving the Sustainable Development Goals which present interdependent challenges across disciplines (Costanza et al., 2016; Lu et al., 2015). In our experience, the theories and methods associated with complexity science provide an ideal approach for tackling interdependent sustainability challenges (Liu et al., 2015). Complexity is not just a suite of theories and methods, it delivers an intuitive way of understanding interdependent systems and provides a platform for deep interdisciplinarity collaboration that is required to meet today's sustainability challenges.

Competing interests. The authors declare that they have no conflict of interest.

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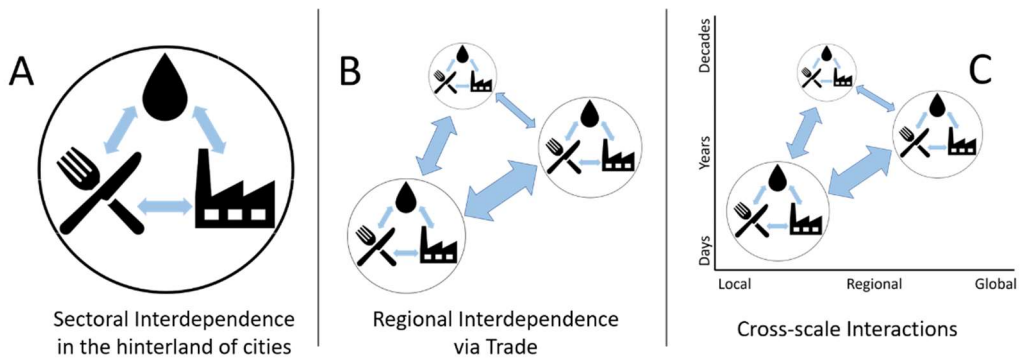
Figure 1. Complex dynamics within the global food system that lead to emergent water use patterns. (A) Sectoral interdependence in water resources within the food-water-energy nexus **(B)** Regional interdependence in water resource owing to the importance of trade for food security under globalization and urbanization **(C)** Sectoral and regional interdependencies are linked via cross-scale feedbacks. Fine-scale interactions bring about emergent change at larger spatial or longer spatial scales. Those emergent changes feedback at the fine scale (Sivapalan and Bloschl, 2016).
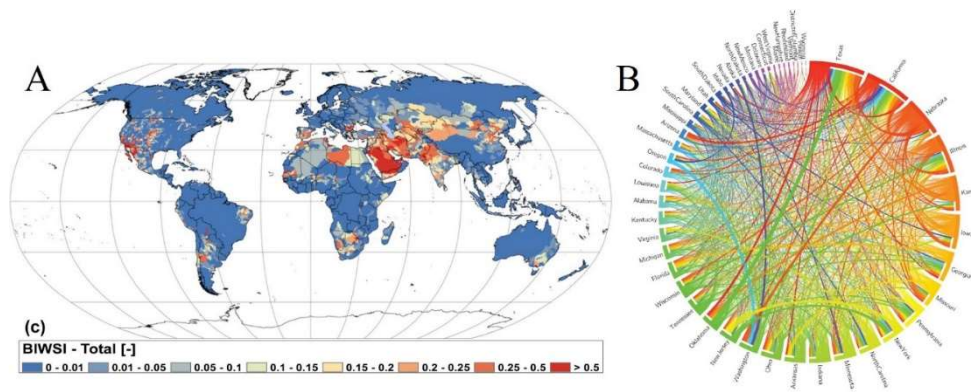
Figure 2. Water footprint studies. Water footprint studies exploit hydrological models to estimate blue and green water use in agriculture. This data is combined with data on food trade to estimate the fluxes of virtual water embedded in food trade. **A)** The unsustainable water footprint of agriculture is shown in red, where groundwater abstraction exceeds aquifer recharge (*taken from* Wada and Bierkens, 2014). **B)** Virtual water flows within the United States. U.S. States are ranked according to the total trade volume and plotted clockwise in descending order. The size of the outer bar indicates the total virtual water trade volume of each State as a percentage of total U.S. trade. Destination volume is indicated with links emanating from the outer bar of the same colour. Origin volume is indicated with a white area separating the outer bar from links of a different colour (*taken from* Dang et al., 2015).
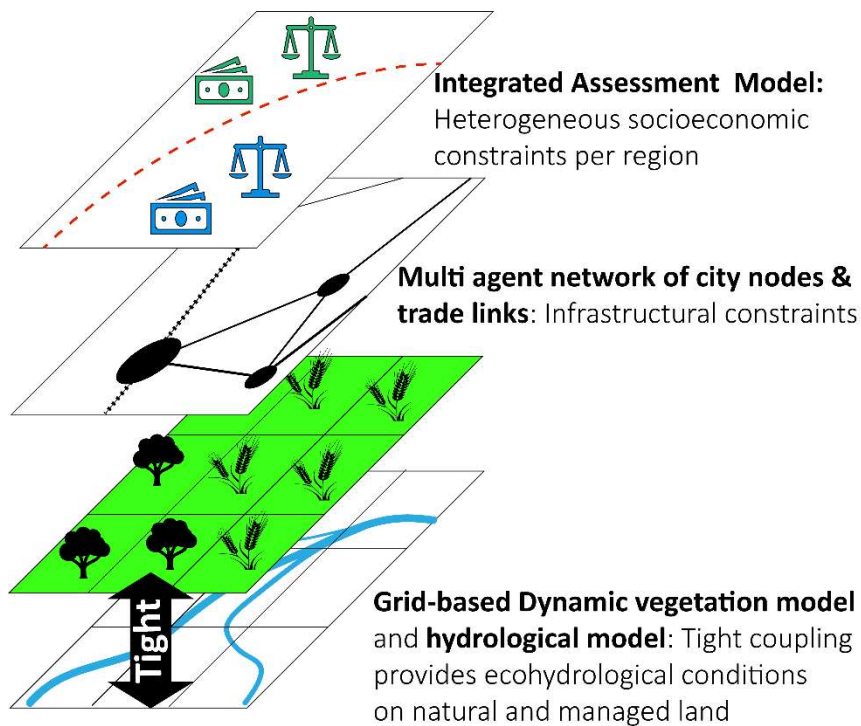
Figure 3. City agent attributes. In our framework, city agents receive environmental and socioeconomic constraints from ecohydrological and Integrated Assessment Models. Ecohydrological conditions on natural and managed land determine food production potential and associated water use. Ecohydrological conditions are computed by a tight coupling between a dynamic vegetation model and hydrological model. The IAM captures heterogeneous socioeconomic conditions that constrain the ability of cities to exploit ecohydrological conditions for food production. Apart from the multi-agent model, the other elements of the framework have already been developed. However, to our knowledge a dynamic vegetation model has yet to be coupled to a complex hydrological model that computes water exchange between soil and groundwater.
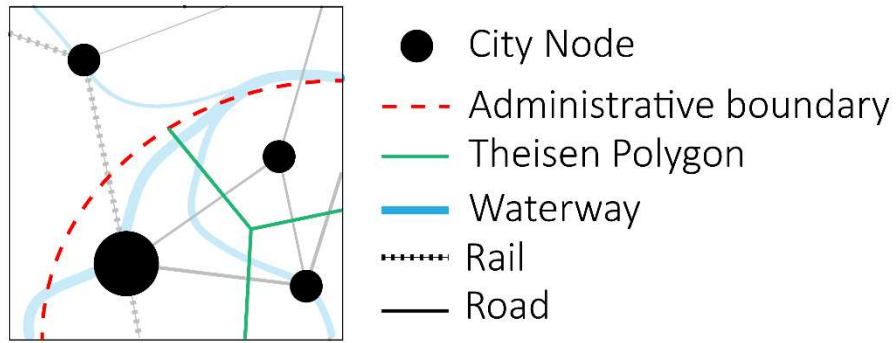
Figure 4. The city and its hinterland. City agent hinterlands are defined by a hierarchical overlay of supra-sub-national administrative boundaries and Theisen interpolation among city nodes based on the gravity equation of trade. Cities are linked by physical infrastructural network of roads, rail and shipping routes.
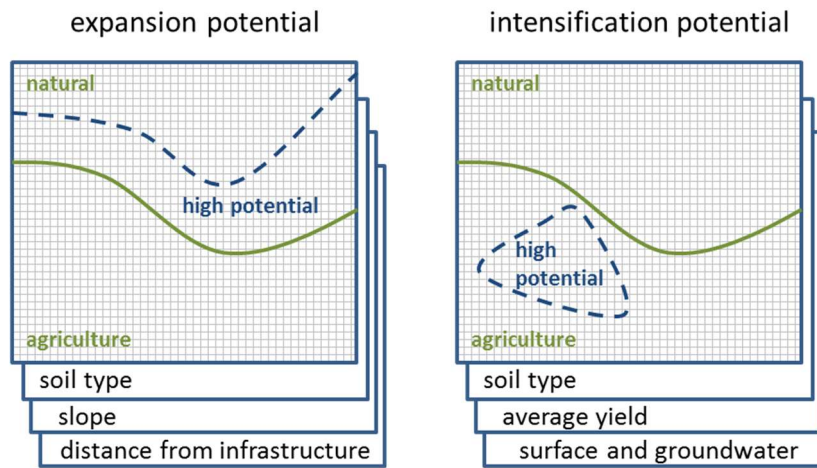
Figure 5. Food production decisions. City agents decide on agricultural expansion (left side) or intensification (right side) based on demand and spatially explicit crop production potential in their hinterlands.
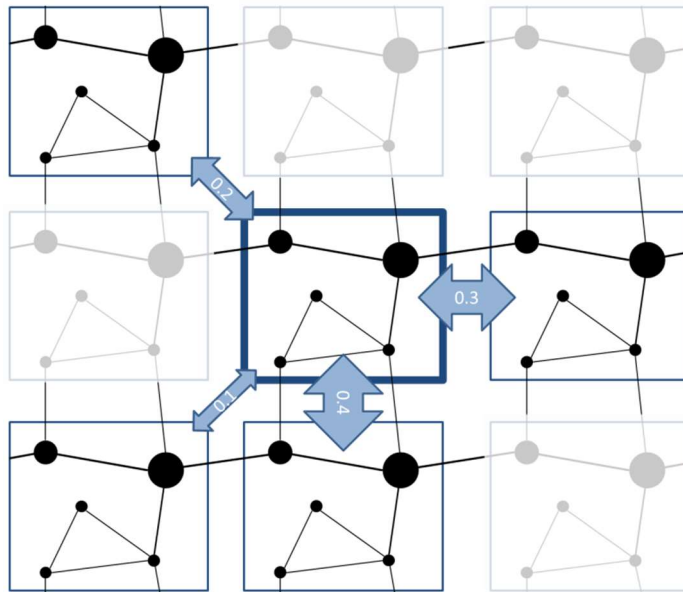
Figure 6. Virtual Water Trade Network. The trade network is hierarchical, containing an upper-level network that determines the strength of trade links among countries and a lower level physical infrastructural network which captures the network of roads, rail and shipping lanes that link cities. The link weights of the upper level network are calculated using a CGE model based on factors such as historical trade patterns, trade agreements etc. Because infrastructure constrains trade, all virtual water trade flows via the physical trade network. City agents within the same country trade with one another based solely on supply and demand for each food commodity and the cost-distance of trade among cities. Cities in different countries are also constrained by bilateral trade probabilities of upper-level network.
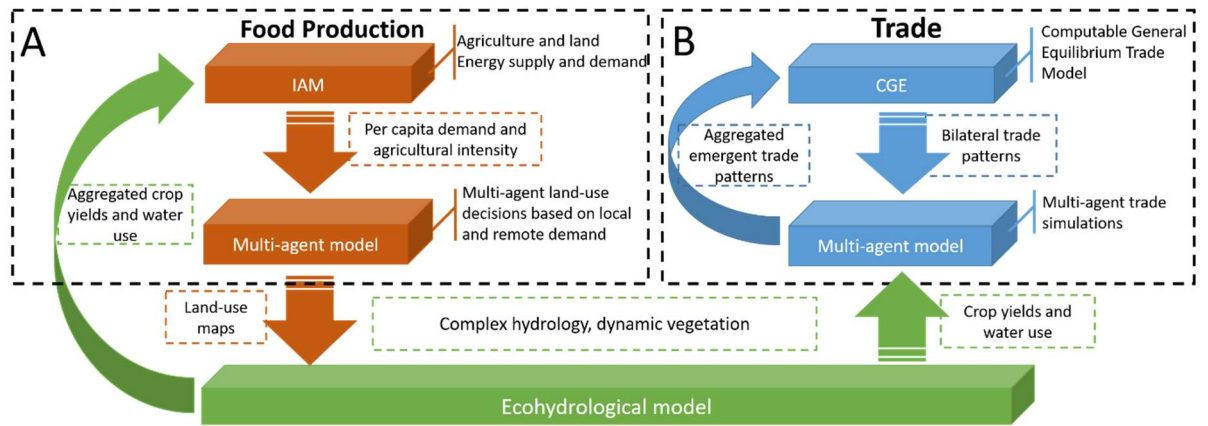
Figure 7. Modelling Framework Workflow. The multi-agent network sits at the interface between the IAM and an ecohydrological model **(A)** The IAM, calculates per capita food demand at a regional scale, which is converted into spatially explicit demand using population maps. The IAM also calculates agricultural intensity constraints. Based on agroeconomic and environmental constraints, agents make food production decisions which change ecohydrological conditions in their catchment. The emergent crop production and water use patterns are aggregated and feedback to the IAM **(B)** A CGE trade model coupled to the IAM provides link weights for the upper level network. Virtual Water Trade among cities is calculated based on supply and demand and cost-distance of trade via the multi-agent trade network. The emergent aggregated trade patterns feedback to CGE as input for the next simulation year.
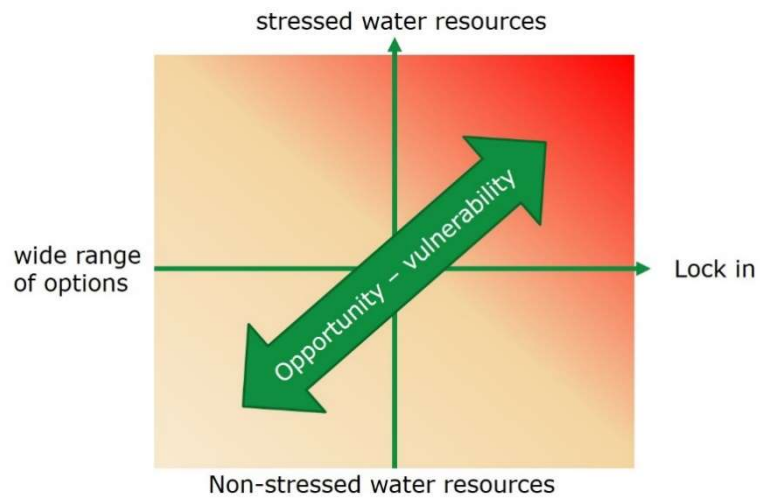
Figure 8. The solution space illustrates how constrained regions or sectors are along their current water use pathway. The solution space emerges from the multi-agent simulations and illuminates how locked-in regions or sectors are along their current water use pathway. The solution space can be explored using optimality algorithms to find pathways towards sustainable water futures, whilst taking account of regional and sectoral interdependencies and cross-scale feedbacks