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The land-network problem: ecosystem carbon balance in planning sustainable agro-food supply chains

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A B S T R A C T

Global food demand will double by 2050 and strain agro-food supply chains. The increasing relevance of non-agrarian activities within the food supply chain mandates a systemic perspective for addressing sustainability. We consider the food supply chain as an ecosystem and define more inclusive boundaries. We present a design framework that supports strategic decision-making on agriculture and food distribution issues while addressing climate stability. We describe the methodology used to construct the framework, which entails a multi-disciplinary approach. An original land-network problem merges localized and large-scaled decisions as land-use allocation and location-allocation problems in an agro-food network. A linear programming model optimizes infrastructure, agriculture, and logistics costs and also balances carbon emissions within the agro-food ecosystem. A regional potato supply chain illustrates the effectiveness of the proposed model. Findings show the interdependency between infrastructure, production, distribution, and environmental resources. Results highlight the consequences of unbalanced planning focused solely on cost efficiency. In conclusion we identify enabling conditions, drivers and metrics for the design of cost effective and carbon balanced agro-food ecosystems.

1. Introduction

Humanity is demanding more and richer food. Population growth and rising per capita consumption of animal products will double global food demand by 2050 (Koning and Van Ittersum, 2009). The rapid development of new economy countries propels demand not only in absolute quantities but also with respect to year round availability. Global food supply chains are expanding to match seasonal food production to demand (Ahumada and Villalobos, 2009; World Bank, 2011).

These trends support considering the food supply chain as a whole: not only cultivating and processing but also packaging, storing, and distributing foods as well as handling by-products and waste. These processes result in more complex supply networks, increasing distances between stages and decreasing consumer awareness of what is required to get from farm-to-fork (Manzini and Accorsi, 2013). Even the collection of by-products and waste has significant ramifications (Ruggeri et al., 2009). Food supply chain actors typically focus on economic sustainability: cost reduction. Environmental sustainability receives less attention, and environmental externalities are neither accounted for nor assigned to any actors. This negligence results in the agro-food sector contributing greatly to climate change (Desjardins et al., 2007).

Growing demand is forcing the conversation on reconciling economic growth with environmental sustainability. Tilman et al. (2002) consider the tradeoffs between intensive global food production based on economies of scale and sustainable localized, smaller farming models. Others document the diverse environmental impacts of intensive farming and production upon natural resources and ecosystems (Tukker et al., 2008), as well as the energy requirements and resultant greenhouse gas (GHG) emissions from food storage and transportation (Milà i Canals et al., 2007; Cholette and Venkat, 2009). Some studies challenge the perceived “common knowledge” about food systems (McCown, 2002a,b; Hinrichs, 2003; Nilsson, 2004; Partidario et al., 2007; Weber and Mathews, 2008; Massoud et al., 2010) and identify challenges and research agendas (Soussana, 2014) for mitigating the environmental impacts of the food sector. Sustainable agro-food systems must address food security, promote environmentally sustainable development, and balance food production with ecosystem services and biodiversity (FACCE-JPI, 2011). These ambitious challenges require holistic tools for analyzing the entire food supply

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chain, coupling cost control with natural resource management and emissions reduction (Akkerman and Van Donk, 2010; FAO, 2012; Leduc et al., 2013).

This paper builds upon extant agro-industrial ecology research on creating and maintaining equilibria within observed ecosystems (Varga and Kuehr, 2007). UNEP (2009) provides the theoretical background for the paper as follows. While agro-food ecosystems provide nourishment, they are also fundamentally connected to climate regulation by acting as either carbon sources or sinks. Canadell et al. (2007) recommend that an ecosystem's absorption of GHGs balance the ecosystem's natural emissions and any additional human induced emissions.

This paper studies the role of the agro-food ecosystem as a whole in reducing the carbon cycle imbalance. We redefine the system boundaries to be more inclusive. Fig. 1 shows how cultivation, packaging, storage and distribution become parts of the same ecosystem along with carbon sinks to mitigate resultant emissions. This original framework merges both local and global scaled strategic decisions. It breaks down the geographic boundaries of food production and distribution and accounts for both costs and environmental impacts.

Local scaled decisions include but are not limited to the following: farm design, crop allocation, adoption of equipment and infrastructure, landscape planning, and groundwater management. Such decisions greatly affect land-use and are responsible for much of human-induced emissions (Ovando and Caparros, 2009; Ponsioen and Blonk, 2012). Emissions goals at the local scale are reflected in the tradeoff between food crops and other land uses, such as forestry or biofuel production. At the agriculture level, modelling the spatially constrained system is suited for operation research techniques such as linear programming (LP). Singh (2012) provides a comprehensive survey of relevant operation research applications to agro-food system problems solved at a local scale. Singh (2012) identifies groundwater management, irrigation scheduling, crop yield enhancement, land planning, and resource and waste management as active areas of interest. Additional studies show land-use allocation (LUA) problems may consider a wide set of goals and objectives, including returns and costs (Singh and Panda, 2012), crop yields (Zeng et al., 2010), and water-management regimes (Yang et al., 2009; Dai and Li, 2013).

Global scaled decisions involve designing supply chain infrastructures, namely selecting growers/suppliers, creating multi-echelon logistics networks (Apaiah and Hendrix, 2005), and distributing appropriately (Ahumada and Villalobos, 2011). Such logistics decisions can be modeled and solved via linear programming. The classic location-allocation (LA) problem selects from a set of potential nodes and minimizes distribution costs while meeting demands (Azarmand and Neishabouri, 2009; Manzini et al., 2014). Global net emissions goals are reached through proper network design and mitigation of environmental externalities.

By representing the agro-food supply chain as an inclusive ecosystem (see Fig. 1), the proposed framework integrates local and global scaled decisions to provide sufficient food and balance net emissions. Three local scaled decisions are considered. The first locates crops, maximizing crop yields on the basis of climate, soil and water availability conditions for a given area. The second places facilities for the following operations: consolidating raw materials, processing, packaging, and storing finished food products. The third allocates renewable energy sources, solar arrays or wind farms, to power the agro-food supply chain plants and services.

The global scaled decisions concern network design and route selection for distributing food over the larger region. Since the supply chain produces emissions through cultivation, packaging, storage and transport processes, a more inclusive agro-food ecosystem should offset these emissions. To this purpose, the framework includes a land use for sequestering carbon. The economic and environmental trade-offs associated with ecosystem-based carbon mitigation strategies are embedded in the land-network (LN) problem. The LN problem models the agro-food supply chain as a closed ecosystem comprised of integrated networks of lands allocated to multiple uses and services: crops, facilities, energy sources. The agro-food ecosystem must manage the available land and energy resources to satisfy food demand and reduce net emissions. From a modeling perspective, the LN problem integrates LUA and LA problems and balances food costs with climate stability goals.

The proposed framework contributes to the literature by considering the agro-food supply chain as a whole ecosystem. This holistic approach integrates strategic long-term decisions on production, and distribution processes, exposing the underlying interdependencies between agriculture and logistics in sustainable agro-food ecosystems. Furthermore, the model incorporates environmental externalities by constraining the food supply chain activities in accordance with climate stability and ecosystem conservation goals. To this purpose, the framework involves alternative land uses, carbon plantings and renewable energy fields, not commonly included in supply chain analyses but necessary to guarantee that demand is fulfilled efficiently in presence of climate stability constraints.

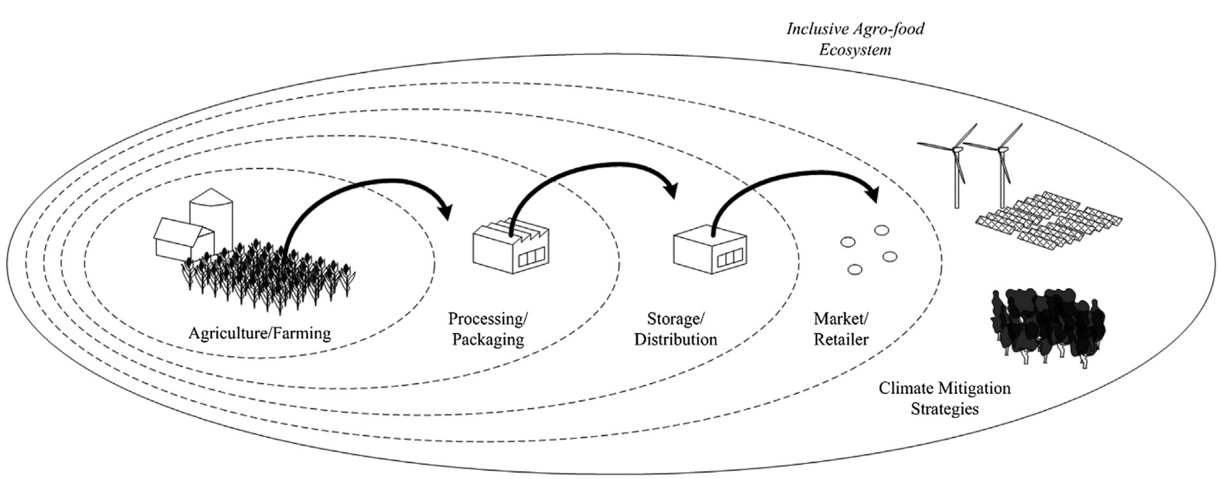

Fig. 1. An inclusive definition of the agro-food ecosystem: agro-food system processes across the food supply chain and climate mitigation strategies.

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