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Towards an Agro-Industrial Ecology: A review of nutrient flow modelling and assessment tools in agro-food systems at the local scale

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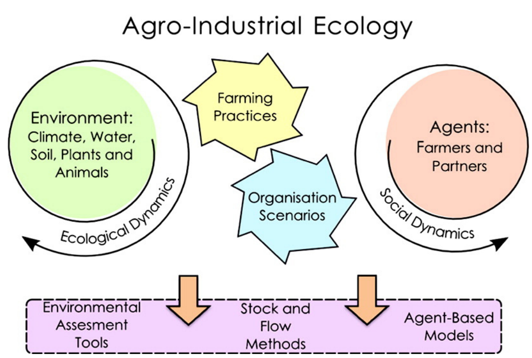
HIGHLIGHTS

- An Agro-Industrial Ecology perspective is essential to model local agro-food systems.
- We provide a classification of nutrient (N, P) models, methods and assessment tools.
- We distinguished Environmental Assessment, Stock and flow and Agent-based approaches.
- The pros and cons of these nutrient cycle models, methods and tools are discussed.
- Their combination is promising to address nutrient issues in agro-food social-ecological systems.

GRAPHICAL ABSTRACT



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ABSTRACT

Improvement in nutrient recycling in agriculture is essential to maintain food production while minimising nutrient pollution of the environment. For this purpose, understanding and modelling nutrient cycles in food and related agro-industrial systems is a crucial task. Although nutrient management has been addressed at the plot and farm scales for many years now in the agricultural sciences, there is a need to upscale these approaches to capture the additional drivers of nutrient cycles that may occur at the local, i.e. district, scale. Industrial ecology principles provide sound bases to analyse nutrient cycling in complex systems. However, since agro-food social-ecological systems have specific ecological and social dimensions, we argue that a new field, referred to as "Agro-Industrial Ecology", is needed to study these systems. In this paper, we review the literature on nutrient cycling in complex social-ecological systems that can provide a basis for Agro-Industrial Ecology. We identify and describe three major approaches: Environmental Assessment tools, Stock and Flow Analysis methods and Agent-based models. We then discuss their advantages and drawbacks for assessing and modelling nutrient cycles in agro-food systems in terms of their purpose and scope, object representation and time-spatial dynamics. We finally argue that combining stock-flow methods with both agent-based models and environmental impact assessment tools is a promising way to analyse the role of economic agents on nutrient flows and losses and to explore scenarios that better close the nutrient cycles at the local scale.

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Contents

1. Introduction

The demand for agricultural and natural resources is continually increasing due to global population growth and overall diet transition to higher meat consumption. Meeting society's growing food needs while simultaneously reducing the environmental impact of agriculture is, undoubtedly, one of the greatest challenges of the century (Foley et al., 2011; Godfray et al., 2010; Makowski et al., 2014). Nutrients such as nitrogen and phosphorus play a critical role in food production and global food security (Erisman et al., 2008; Wetzel and Likens, 2000) and have been widely used as fertilisers to sustain high agricultural yields for decades (Tilman et al., 2002). However, the massive use of fertilisers during the last decades has resulted in dramatic changes in global nutrient cycles. In particular, large nutrient losses from agricultural soils to the environment have resulted in natural ecosystem pollution and the loss of services provided by these ecosystems. For example, the massive use of mineral nitrogen fertilisers has led to dramatic changes in the atmospheric, aquatic and terrestrial pools of the global nitrogen cycle as well as to increased transfers between compartments, compared to pre-industrial times (Gruber and Galloway, 2008). This has caused serious ecosystem disturbances, including water eutrophication, soil acidification and greenhouse gas emissions (Conley et al., 2009; Galloway et al., 2008; Sharpley et al., 1994). Similarly, the widespread use of mineral phosphorus fertilisers derived from phosphate rock in industrial agriculture is increasing the risk of depletion of this non-renewable and highly geopolitically-sensitive resource (Cordell et al., 2009). Phosphorus transfers from agricultural lands to water bodies are also known to trigger algae bloom and eutrophication in freshwater ecosystems (Conley et al., 2009). There is therefore an urgent need for a drastic increase in use efficiency and recycling of these nutrients, in particular, in areas where food production has been highly intensified.

Large efforts have been made to improve nutrient management in agriculture over the last decades (Gerber et al., 2014). In the past, this generally involved understanding and modelling nutrient dynamics in the soil-plant system and designing decision tools for fertilisation at the field and farm scale (Gruhn et al., 2000; Havlin et al., 2005; Nesme et al., 2005). These tools helped to correct improper management of fertilisers and manure by farmers and to better adjust fertiliser supply to crop requirements at these small spatial scales. However, these approaches were inherently limited since they did not consider some key segments of the nutrient cycles that occur at larger scales, such as material flows (e.g., grain, straw and manure) between farms and their upstream and downstream economic partners (e.g., feed and fertiliser suppliers, grain and livestock product collectors and processors, waste producers, etc.). Such upscaling is in fact needed to improve our understanding of how nutrients flow in and out of farms and, ultimately, into the environment, and to promote more efficient recycling loops in agriculture (Nowak et al., 2015).

Industrial ecology emerged during the last decades as a scientific field focused on the interactions between industrial societies and their environment, considering industrial societies as systems (Allenby and Graedel, 1993). Developing a circular economy that protects finite natural resources by better closure of materials and energy cycles is at the core of its principles (Ayres and Ayres, 2002; Socolow, 1997). For that purpose, industrial ecology encompasses a range of approaches ranging from ecology and industrial management to economy and sociology (Andrews, 2000; Boons and Howard-Grenville, 2009; Seuring, 2004). Numerous approaches have been developed to design recycling loops and to explore circular economy options in industrial social-ecological systems. They include Substance Flow Analysis (Brunner and Ma, 2009), Industrial Symbiosis analysis (Chertow, 2007) and regional Life Cycle Assessment (Frischknecht, 2006). However, these approaches strongly differ in terms of purpose, scope and framework, making the assessment of their advantages and drawbacks to design recycling loops extremely difficult.

Our aim in this paper is to review the different approaches that were designed to analyse, assess and simulate nutrient flows and to explore nutrient recycling scenarios in complex social-ecological systems. We focused our analysis on agro-food systems at the local scale where economic agents may exchange agricultural inputs, products, by-products and waste. We defined the local scale as regions or districts in which economic partners are spatially close enough to be connected within exchange networks, while sharing the same natural environment. We excluded long upstream and downstream chains such as global food markets from our analysis (Fig. 1).

We argue that agro-food systems have several specificities compared to purely industrial social-ecological systems. These specificities are related to: (i) the strong interactions between farming production processes and the natural environment; (ii) the predominance of diffuse vs. point source pollution in farming operations; (iii) the highly scattered nature of farming enterprises within landscapes; and (iv) the high diversity of farming practices and interactions over time and space. For these reasons, we paid specific attention to environmental assessment approaches that account for diffuse nutrient losses to the environment, and to agent-based models that account for social interactions within complex social systems. We consider this extended set of approaches to be better suited to the analysis of nutrient flows within agro-food chains and to the design of efficient recycling loops in agriculture. In that perspective, we propose to define Agro-Industrial Ecology as the specific application of industrial ecology to farming system analysis.

We explored the scientific literature in search of approaches that would help to assess, analyse or model nutrient flows (as food,