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Modelling nutrient flows in a simplified local food-energy-water system

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ABSTRACT

Sustainable use and management of nutrients is an important issue for food, energy and water systems. The close connections between the three systems, reflected by the "nexus" concept, warrant an integrated approach to nutrients management across the nexus. In this paper, dynamic modelling of nutrient flows in a local food-energy-water system is presented and applied to a simplified case study. The model was used to simulate several scenarios affecting nitrogen flows and stocks to assess the impact of a) the level of local wheat production, b) the selection of energy generation technology, and c) the management of available nutrient resources (digestate and straws). The simulation results showed that varying the proportion of locally produced wheat significantly affects the surface runoff and the nitrogen content in a local water body, with the latter increasing by nearly 70% in 50 years if about half of the wheat consumed is produced locally as opposed to being 100% imported. The introduction of anaerobic digestion as an energy generation option helps to supply more electricity, reduce the imported fertiliser, and also significantly reduce the landfilled nitrogen nutrient by up to 60 times, due to the reuse of the anaerobic digestate. On the other hand, a balanced consideration should be given between using the straw as fertiliser and as feedstock for energy generation. This work offers a first analysis of the food-energy-water nexus with a focus on nutrient flows and stocks. The modelling approach has the potential to inform holistic decision making with respect to nutrient usage, efficiency and the related environmental impact in the design of a local system for meeting the demand for food, energy and water.

1. Introduction

One of the greatest challenges faced by our society today is the increasing demand for energy, food and water within a context of climate change and scarcity of resources (FAO, 2014). Food, energy and water are the three most essential needs for humans, and their natural availability and supply infrastructures can be intimately related in complex ways forming a nexus. The food-energy-water (FEW) nexus is a concept that is gaining attention to inform sustainable development strategies of a country or region, as it can potentially affect the extent to which food, energy and water security objectives are simultaneously achieved (Hoff, 2011). To tackle the complexity of the nexus, it is essential to quantify the interactions between the subsystems of the nexus and between the nexus and its environment (Chang et al., 2016). This allows for the identification of key interactions that can be manipulated to balance negative impacts currently affecting nexus resources and their provisioning systems, so that sustainable solutions can be devised (Martinez-Hernandez et al., 2017a). To-date, nexus studies have considered the global scale (Machell et al., 2015), while regional and local scale nexus studies are also needed because the impacts of nexus decisions on populations, ecosystems and activities are often localised in the first place; opportunities of making improvements also more directly call for regional and local actions (Martinez-Hernandez et al., 2017b).

As an initial step towards sustainable solutions, quantitative modelling and assessment of the nexus are required (Bazilian et al., 2011). Improving resource efficiency and environmental sustainability through (i) the integration of industrial processes and (ii) due considerations on the interactions between human activities and ecosystems has long been the central theme of industrial ecology (Allenby, 1992). Recently, assessment of the capacity of local ecosystems to meet industrial demand for ecosystem services was conducted by Gopalakrishnan et al. (2016), where synergistic techno-ecological systems operating within ecological constraints were proposed. There have been several other advances to understand and manage interactions within the FEW nexus with a focus on how to best couple the three subsystems using input-output analyses (White et al., 2018), network models (Vora et al., 2017), life cycle assessment (Irabien and Darton, 2016), mathematical modelling (Karnib, 2017) and optimisation (Leung Pah Hang et al., 2016), insight-based methods (Leung Pah Hang

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et al., 2017) and other process systems engineering approaches (Garcia and You, 2016; Al-Ansari et al., 2017). A nexus simulation tool has also been developed to support the analysis of interactions between FEW components and the ecosystem at a local scale (Martinez-Hernandez et al., 2017a).

While managing nutrient flows has widely been considered in areas such as industrial ecology (e.g. in the well-known example of Kalundborg, described in Jacobsen (2006)) and environmental protection in coastal regions (Townsend, 1998; Howarth and Paerl, 2008), existing work on the FEW nexus has presented rather limited studies that feature an explicit analysis of nutrient flows and associated environmental impacts. Nutrients play a major role in the interconnection between food, energy, water nexus, especially affecting food and energy crop yields and also the quality of water resources (Davidson et al., 2016). In particular, the extensive use of synthetic nitrogen fertilisers has been vital for increasing the food productivity, much needed by the growing world population. However, only about half of the nitrogen fertilisers applied to farms is taken up by the crops, while the rest remains as stock in the soil or enters other parts of the environment. The latter is known to cause eutrophication of water bodies and air pollution due to the losses through surface runoff, soil leaching and volatilisation (Mortensen et al., 2016). Therefore, it is important to holistically analyse and predict nitrogen flows, which can be carried out through mathematical modelling, as demonstrated by the recent work of Singh et al. (2017) for Illinois with a focus on 3 agricultural commodities. In the context of FEW nexus, appropriate models that capture the inter-coupling between the three sectors are needed to assess different design choices, so that opportunities across the three sectors to increase resource efficiency and to reduce adverse environmental impacts can be revealed, ultimately contributing to the closed-loop management of resources (Mo and Zhang, 2013; Davis et al., 2016).

In this paper, an approach for the dynamic modelling of nutrients flows and stocks in the FEW nexus is presented via a case study based on the settings of an eco-town in the UK. The objective of the model is to simulate several scenarios which are different in the level of local wheat production, the technical options for energy generation, and the management of available nutrient resources. The simulation results are used to analyse the impact of these scenarios on imported fertiliser flows, energy production flows, nitrogen flows to landfill and air emissions, as well as the impact on water quality in terms of nitrogen concentration in a local water body. This work adopts the generic modelling approach previously proposed for local production systems (Martinez-Hernandez et al., 2017b), and has been carried out in parallel with the development of a general-purpose simulator for local food-energy-water systems (Martinez-Hernandez et al., 2017a). The unique contribution of this work lies in the detailed modelling of nutrient stocks and flows and using the model to analyse the impact of various decisions on nutrient efficiency and associated environmental aspects, including particularly those some of which could arise from the inter-coupling between the three sectors of food, energy and water. This work adopts the same case study locale as in earlier work on optimal design of local FEW systems (Leung Pah Hang et al., 2016, 2017), where cumulative exergy consumption was used as the optimisation objective. While both the exergy cost for fertilizer supply and that for reducing nutrients in wastewater to acceptable levels were considered in the optimal design work, the mathematical model used in optimisation was for steady states, therefore no system dynamics was captured. In principle, the dynamic model developed in this work can be used to support more detailed studies of the schemes recommended by optimal design, with a focus on the perspective of nutrient flows and stocks, to further inform the integrated management of local FEW systems.

2. Overall approach

The analysis of interactions between food-energy-water systems and their effects on nutrients flows and stocks in an overall local system requires a mathematical model that can capture all the important connections and dynamics. The approach followed in this work comprises the following steps:

(i) developing a conceptual description of individual subsystems and their interactions;
(ii) building mathematical models of individual subsystems;
(iii) simulating and analysing individual systems if desirable;
(iv) integration of subsystem models based on the connectivity identified in step (i);
(v) assessing the resulting nexus system through simulation studies of various scenarios of interest.

As an overview of the proposed approach, principles for developing a conceptual description (step i) and mathematical models (steps ii and iv) are presented; a detailed illustration of these steps and of the more case-specific steps for simulation and analysis (i.e. steps iii and iv) will be given through a case study in Sections 3 and 4.

2.1. Conceptual structures

A conceptual structure of a system shows the key components and connections between them. In particular, a "*source-sink*" mapping diagram can help to represent a system by showing the matches between sources and sinks. In the case of nutrient flow analysis, "sources" refer to the nutrients or material flows containing the nutrients relevant to the goals of a given study; and "sinks" refer to the processes that change or transform a nutrient flow, or the point of termination of a nutrient flow. The direction of flows, and the introduction, consumption and disposal of nutrients within or external to the system are also shown as part of the source-sink mapping diagram. The structure of a complete FEW system can be obtained by connecting the structures of individual subsystems through resource flows.

2.2. Mathematical models and implementation

From a conceptual description of a local food-energy-water system, nutrients can be identified either in *flows* between various processes such as food manufacturing, energy production and waste water treatment, or as being cumulated in soil and a water body, in the form of nutrient *stock*. The stock-flow framework enables mathematical construction of each subsystem's model. In this framework, the temporal variation of nutrient stocks is captured by differential equations that link the change in stock "levels" due to incoming and outgoing flows. These flows are determined in different ways, depending on their nature:

- For a flow representing an internal demand (e.g. bread consumption), it is typically pre-specified as part of a scenario to be studied.
- An output from an internal stock (associated with a system component) (e.g. nutrient runoff from land), which may become input to an internal process, stock or the external environment, is typically determined by solving a differential equation representing the conservation of the physical quantity that corresponds to the stock (e.g. nitrogen level).
- An output from an internal industrial process (e.g. digestate from anaerobic digestion), which may become input to another internal process or stock, can be estimated by an algebraic function of the input of the process, ignoring any internal accumulation within the industrial process.
- Exchange of resources and products with the external environment (e.g. import or chemical fertilizer), which is determined based on supply-demand balances.

Once the model equations are developed, implementation in a