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Including nature in the food-energy-water nexus can improve sustainability across multiple ecosystem services

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ABSTRACT

Activities in the food-energy-water nexus require ecosystem services to maintain productivity and prevent ecological degradation. This work applies techno-ecological synergy concepts in an optimization formulation to design a system for co-producing food and energy under constraints on ecological sustainability. The system includes land use activities and biomass conversion processes for the production of energy carriers, as well as supporting ecosystems that increase the supply of key ecosystem services. The co-production system was linearized and reduced to a mixed-integer linear program, which was optimized for single objectives under a variety of production and sustainability constraints. Results indicate that for the system considered to achieve high food and energy co-production, land use options should be balanced between food-producing crops and electricity-producing wind turbines and solar panels. Results also show that ecological sustainability can be achieved for this system with relatively small changes in land use patterns. The inclusion of nature in the design enables the system as a whole to achieve ecological sustainability for multiple ecosystem services with moderate sacrifices of food and energy productivity.

1. Introduction

The food-energy-water (FEW) nexus is a set of linkages and trade-offs between food production, energy production, and water provisioning and quality (Hellegers et al., 2008). Links between the nexus components are many and varied. Some links are physical flows: water and other ecosystem services are critical inputs to both food and energy production (in this work the focus is on renewable energy production), energy is likewise a critical input to water purification and supply and food production, and both food and energy production lead to degraded water quality through fertilizer runoff (Khan and Hanjra, 2009). Other links are causal and create trade-offs between the three nexus components: finite land availability means that food and energy production are frequently in competition, and as water is used for one type of production it becomes less available for the other and less available to non-nexus activities.

To a certain extent, these trade-offs are unavoidable. Food can only be produced via agricultural activities that require large areas of arable land and suitable climate conditions. Renewable energy production is somewhat more flexible, as technologies including on and offshore wind turbines and hydropower require significantly less land than other options such as biofuels produced from food or energy crops. However, regardless of how food or energy is produced, the production still requires water as an input and, more generally, creates ecosystem service demand which is all but guaranteed to be in excess of the capacity of supporting ecosystems to supply those services. Reducing production to reduce demand for water provisioning and other ecosystem services is not a feasible option, as human demand for both food and energy continues to grow, but continuing to overburden supporting ecosystems will in the long term lead to ecological degradation and a reduction in the amount of food and energy that can be produced.

It is essential for long-term sustainability that the ecosystem service demands of human activities, including food and energy production, not be greater than what can be supplied by supporting ecosystems. This work designs a food and energy co-production system for ecological sustainability by applying the techno-ecological synergy (TES) concept of balancing ecosystem service demand with supply (Bakshi et al., 2015). The co-production system uses land for agriculture, for technological energy-producing activities and for engineered ecosystems that increase the available ecosystem service supply. Results show that balancing land use between food production, energy production and ecosystem service supply enables the co-production system to

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achieve ecological sustainability and food and energy productivity, but at the expense of economic feasibility. Applying TES concepts to the design of food and energy co-production systems allows not only water provisioning and water quality impacts to be mitigated, but also applies to a variety of ecosystem services that are essential to maintaining productive land and reducing or eliminating the environmental impacts of human activities.

That ecosystem services are critical to successfully addressing FEW nexus issues has been well established in the literature. The International Institute for Sustainable Development has recommended treating ecosystem goods and services as the foundation of FEW nexus issues (Bizikova et al., 2013). One case study for the U.S. state of California examined interdependencies between food and energy production life cycles and drivers of climate change, finding that ecosystem service degradation caused by climate change had a negative impact on food and energy production (Liu, 2016). The study concluded that changes in the way production systems are managed are essential to reducing ecosystem service degradation and maintaining productivity. Similar conclusions were reached from an analysis on the Hindu Kush Himalayan region of South Asia, which emphasized the importance of focusing equally on ecosystem services provisioning and on the more anthropocentric objectives of food and energy production (Rasul, 2012, 2014).

Studies from outside the FEW nexus field have also shown the environmental and other benefits of maintaining and increasing ecosystem service provisioning. Gopalakrishnan et al. (2016) quantified the potential for mitigating ecosystem service demand created by industrial facilities throughout the U.S. via strategic management of the land surrounding each facility. Li et al. (2018) analyzed the impacts of regional land use change on ecosystem service provisioning in the area surrounding Chengdu, China, concluding that due to the land management practices being used, the value of the total ecosystem services provided by the land was increasing over time. However, the analysis did not quantify the impacts on specific ecosystem services, and it is therefore possible that some services (such as food provisioning from agriculture) were increasing while others (climate regulation, erosion control, and many others) were decreasing. Several studies have demonstrated that land use, with the appropriate management practices, has the potential to provide significant climate regulation and a variety of other ecosystem services (Rose et al., 2012), and can also help to mitigate or resolve completely trade-offs between different ecosystem services (Zheng et al., 2016).

The present work expands on these previously published analyses by taking an optimization approach to addressing issues in the FEW nexus. Food production, energy production, and system economics are taken as objectives, while the net supply (supply minus demand) of key ecosystem services are used to constrain a co-production system to different degrees of ecological sustainability, defined for this work as having an ecosystem service supply greater than or equal to demand for the services considered. This work moves beyond identifying opportunities and obstacles to provide a framework for making sustainable decisions around food and energy production, including how to manage various land use types, which crops to grow, which energy products to produce, and others.

FEW nexus components, including relevant physical flows, interdependencies and causal linkages, can be quantified and studied at almost any spatial scale. In particular, different ecosystem services are relevant at different scales; climate regulation is relevant at the global scale – a tree grown in Australia can offset carbon emissions in the U.S. – while water quality regulation and provisioning is relevant at the watershed (regional) scale, and other services such as pollination are only relevant at the local scale. At the small household (Urban and Bakshi, 2013; Wa'el et al., 2017) or community scale (Perrone et al., 2011; Martire et al., 2015; Guo et al., 2017), highly detailed data may be available and decisions can be relatively easily quantified and implemented, but the smaller scale systems are heavily dependent on inputs from other systems which are outside of the smaller system's control. Quantifying large scale ecosystem services, such as climate regulation supply and demand, for small scale systems may also prove problematic, as local scale ecosystems alone may not be able to offset the ecosystem service demand. Regional scale systems are less dependent on outside inputs, and are at a sufficiently large scale that balancing ecosystem service demand and supply may be possible (Rasul and Sharma, 2016; Wang et al., 2017; White et al., 2017). At the national, multi-national and larger scales, modeling and analysis tends to be complicated by the heavy interdependencies among sub-systems and by the lack of detail in available data sets (Bazilian et al., 2011; Ibarrola-Rivas et al., 2017). Large scale decisions may be analyzed, but it is unlikely that all the benefits and disbenefits of those decisions can be known with certainty. The lack of detailed data also complicates the modeling of any ecosystem service that is relevant at smaller scales, although it is ideally suited to modeling climate regulation and other global scale services.

The food and energy co-production system optimized in this work is modeled at multiple scales as described in Section 2. Land use activities are modeled at the regional scale (approximately the scale of a U.S. county), while biomass conversion processes that produce energy production from biomass are modeled at the local scale. The national scale life cycle of activities modeled at the smaller scales is also included, to capture ecosystem service demand created upstream in the supply chains of activity inputs. This multi-scale approach provides a reasonable balance of comprehensiveness and detail, and enables ecosystem service modeling at appropriate scales.

Because land use activities are modeled at the regional rather than the local scale, the co-production system model in this work cannot be used for landscape planning on a particular piece of land. The model, optimization formulation and results are intended to demonstrate how supporting ecosystems and techno-ecological synergies may be incorporated into the FEW nexus, and quantify any benefits or disbenefits of doing so within an example of a food and energy co-production system.

The remainder of the paper is organized as follows. Section 2 discusses the co-production system model and optimization formulation used to obtain system designs. Results are presented and discussed in Section 3, and conclusions are drawn in Section 4.

2. Methods

In this work TES is applied to address FEW nexus issues by selecting land use types for energy production, food production, and ecosystem services provisioning within 10,000 acres of central Ohio farmland. Previous efforts used TES to design a multi-use landscape for energy production and two ecosystem services, climate regulation and air quality regulation (Hanes et al., 2017). In the previous work, single-objective optimization was used to select a set of land use options – including agriculture, wind turbines and solar panels, and several options for reforestation – and a set of energy conversion pathways to produce electricity or biofuels; the system was optimized for both low energy production and high energy production. Each optimal design was assessed according to the system NPV, the net amount of energy produced, and the sustainability indexes for both climate regulation and air quality regulation. This work expands on previous efforts by designing a similar system for food and energy co-production, rather than energy production alone. An additional land use option, an engineered wetland that treats runoff from agricultural fields, is added to the co-production system model, as is an additional ecosystem service, water quality regulation. The system is optimized under energy production, food production and net present value (NPV) objective functions, while constraints are imposed on the net ecosystem service supplies to restrict optimal designs to various levels of ecological sustainability. Finally, food and energy production is constrained simultaneously, to ensure that all optimal designs obtained represent co-