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Spatial optimization of the food, energy, and water nexus: A life cycle assessment-based approach

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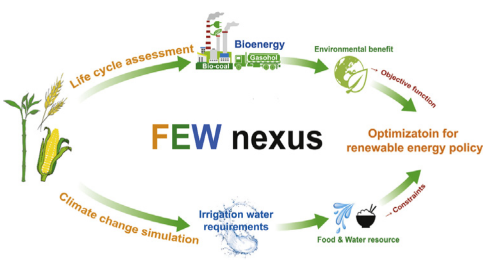
GRAPHICAL ABSTRACT



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ABSTRACT

Since the Bonn 2011 Conference, the Food-Energy-Water (FEW) nexus has become one of the most popular global research topics. Understanding and addressing the complex interactions between the FEW components is essential for sustainable development. This study proposes an environmental impact minimization model, which considers the FEW nexus under four climate change scenarios, to optimize the spatial distribution of three energy crops (rice, corn, and sugarcane). Life cycle assessment (LCA), linear programming, and a climate change simulation model are integrated to analyze appropriate bioenergy production rates while comparing the benefits of bioenergy with the current renewable energy policy in Taiwan. The major findings of LCA in this study indicate that electricity generation using bio-coal produced from rice straw is very beneficial to the environment. Considering the spatial characteristics of Taiwan, simulations from the spatial optimization model suggested that (a) the rice and corn cultivation areas should be increased in southern Taiwan for bio-coal and bioethanol production, in accordance with the "food and feed priority policy"; and (b) the rice cultivation area should be decreased across Taiwan, based on the "water conservation policy". In addition, compared to solar power, the development of bioenergy can simultaneously enhance food and energy self-sufficiency.

1. Introduction

As population growth and major socioeconomic changes lead to growing demand for vital services and resources, energy, food, and water security are becoming increasingly important (FAO, 2009; IEA, 2015; Mountford, 2011). However, the absence of systematic management of water, energy, and food makes it more difficult to balance the rising demand for these resources. To improve resource efficiency, the concept of the food, energy, and water (FEW) nexus has gained significant attention, as it is important for the well-being of mankind and the environment (Ringler et al., 2013).

A few researches have been undertaken on the food-energy linkage (Alfonso et al., 2009; Hatirli et al., 2006; Pahlavan et al., 2012; Pishgar-Komleh et al., 2011; Safa and Samarasinghe, 2011), the food-water

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linkage (Chiang et al., 2015; Holland et al., 2015; Motoshita et al., 2014; Pfister et al., 2011; Tuong et al., 2005; Wu et al., 2012), and the water-energy linkage (Brennan and Owende, 2010; Gerbens-Leenes et al., 2009; Hagman et al., 2013; Hermann et al., 2012; Mo et al., 2014; Siddiqi and Anadon, 2011). In order to comprehensively integrate the assessment of these linkages, Al-Ansari (2016) proposed a systematic tool which combines industrial ecology and life cycle assessment (LCA), to quantify material flows and energy consumption, and identify environmental pressures within the FEW nexus. Al-Ansari et al. (2014) characterized the relationship between each part of the FEW nexus, introducing a renewable energy generation system, which uses biomass as the feedstock, to enhance environmental performance. Bazilian et al. (2011) identified the inter-relationship between food, energy, and water security, highlighting the importance of biofuel production and irrigation water within the nexus. Steubing et al. (2012) proposed an optimization approach to assess food, bioenergy, and water resource use efficiency.

Electricity generated from bioenergy can be a practical option to achieve short-term greenhouse gas (GHG) emission reductions, where the technology allowing for co-firing of biomass with coal in existing coal-fired plants is sufficiently advanced (OECD and IEA, 2015). Biofuel plays an important role in enhancing energy security and reducing GHG emissions in the transport sector (IEA, 2011). The use of bioenergy from biomass can not only mitigate the stress of fossil-energy requirements but also decrease life cycle GHG emissions. Murphy and McDonnell (2017) indicated that indigenous sources of biomass for co-firing systems have lower GHG emission profiles than imported biomass, highlighting the importance of further research on biomass sources in the agricultural and food sectors.

In addition, the integration of LCA and geographic information system (GIS) can allow for comprehensive evaluation for sustainable bioenergy planning (Hiloidhari et al., 2017). Both Monforti et al. (2013) and Haase et al. (2016) estimated the potential of agro-residues for bioenergy production in the European Union using GIS. Considering the environmental characteristics, availability, and distribution of agro-residues, GIS aids in analyzing the spatiotemporal database to source and collect raw materials effectively and to allocate the benefits of bioenergy (Long et al., 2013). Selection of agricultural residues for bioenergy production can prevent competition with food production over land resources, thus aligning with sustainable development (EU, 2009). Bioenergy production from food waste and residual biomass could supply an enormous part of the energy demand of the food system, eventually becoming a development target.

One critical challenge faced by renewable energy is that its production is influenced by unmanageable weather conditions and noticeable climate change (Wang et al., 2016). For instance, weather patterns affect wind power and solar energy generation systems, while long-term climate change influences bioenergy production. Previous studies have discussed the impacts of climate change on water resources and food production (Tung et al., 2013), although little emphasis was placed on the energy part of the nexus. Criqui and Mima (2012) emphasized the consequences of climate change from the energy dimension, based on different degrees of GHG emission constraints and European climate policy. They indicated that stringent environmental policies might benefit the development of a more climate-friendly energy model, thus reducing the vulnerability of the energy market to potential price or supply fluctuations.

This study proposes a spatial optimization model for the FEW nexus analyzing the tradeoffs between food production, bioenergy generation, and environmental impacts, thus providing a better perspective on renewable energy development. The environmental impacts from components of the FEW nexus were examined through LCA, with a special focus on comparing bioenergy and traditional energy sources for generating electricity. The proposed optimization model addresses food, energy, and water security, while simultaneously considering climate factors under the Intergovernmental Panel on Climate Change (IPCC) climate change scenarios. In addition, we analyzed Taiwan's current renewable energy policies and the problems associated with farmland-based solar power systems. Based on this analysis, our study establishes a useful FEW assessment framework for selecting appropriate food, energy, and water policies to satisfy domestic demand while simultaneously mitigating environmental impacts. A case study of rice, corn, and sugarcane, the most common bioenergy crops in Taiwan (Chen et al., 2011a, 2011b; Tsai, 2014), was used to determine the optimal spatial distribution of crop cultivation areas based on different scenarios. Our results can inform bioenergy development strategies as well as food policy while considering the influence of climate change from an environmental perspective.

2. Methods

2.1. Assessment framework

In this study, two bioenergy products incorporating three agricultural residue feedstocks were selected as the assessment targets for analysis under two FEW nexus policies. The bioenergy products were bio-coal produced from rice straw via torrefaction and cellulosic ethanol produced from corn stover and sugarcane bagasse. The proposed optimization model consists of two main components, as shown in Fig. 1: (1) the objective functions and (2) the constraints. The coefficients of the objective functions were determined by evaluating the environmental impact reduction using LCA. The constraints on the optimization model included analysis of government policies and available water resources simulated from climate change model. The optimal spatial distribution of arable lands for the three crops is displayed in digital maps.

Multiple methods are integrated into this assessment framework. LCA (ISO14040, 2006; ISO14044, 2006) is the preferred method to quantify the environmental impacts, as it has been commonly applied to the agricultural sector worldwide. The influence of climate change on water resources is also considered in the current study through the irrigation water requirements. Although previous studies have focused on the importance of crop production and environmental impacts (Lin et al., 2013), cost-benefit analysis in the bioenergy sector (Rasheed et al., 2016), and the impact of climate change on agriculture (Chang et al., 2012; Chen et al., 2011a, 2011b), much less attention has been paid to identifying optimal strategies for bioenergy production coupled with crop distribution. The proposed optimization model integrates LCA and climate change simulations by comparing alternatives according to national or regional development policies, which can be used to optimize trade-offs between bioenergy production, food supply, and environmental benefits.

2.2. Life cycle assessment (LCA) of bioenergy production

Life cycle assessment is a systematic set of procedures for compiling and examining the inputs and outputs of raw materials and energy associated with environmental impacts through production, usage, and disposal (ISO14040, 2006). In this study, LCA is regarded as a quantitative tool to measure the environmental benefits of energy alternatives by comparing fossil energy production with bioenergy production. Subsequently, the environmental impact reduction resulting from alternative energy use rather than traditional energy sources serve as the decision variables of the objective function in the proposed optimization model. Impact 2002 +, an impact assessment methodology originally developed at the Swiss Federal Institute of Technology (Jolliet et al., 2003), was selected for life cycle impact assessment (LCIA), owing to the advantages offered by the Eco-indicator 99, CML 2001, and Cumulative Energy Demand components. Both mid-point and end-point assessments are incorporated in this methodology.

The assessment boundary for bio-coal generated from rice straw via torrefaction included: (1) rice cultivation; (2) in-situ collection; (3) bio-