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Implementing land-use and ecosystem service effects into an integrated bioenergy value chain optimisation framework

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ABSTRACT

This study presents a multi-objective optimisation model that is configured to account for a range of interrelated or conflicting questions with regard to the introduction of bioenergy systems. A spatial-temporal mixed integer linear programming model ETI-BVCM (Energy Technologies Institute – Bioenergy Value Chain Model) (ETI, 2015b; Newton-Cross, 2015; Samsatli et al., 2015) was adopted and extended to incorporate resource-competing systems and effects on ecosystem services brought about by the land-use transitions in response to increasing bioenergy penetration over five decades. The extended model functionality allows exploration of the effects of constraining ecosystem services impacts on other system-wide performance measures such as cost or greenhouse gas emissions. The users can therefore constrain the overall model by metric indicators which quantify the changes of ecosystem services due to land use transitions. The model provides a decision-making tool for optimal design of bioenergy value chains supporting an economically and land-use efficient and environmentally sustainable UK energy system while still delivering multiple ecosystem services.

1. Introduction

A transition from the current fossil-based to a future bio-based carbon economy is expected to evolve progressively in the coming decades (Marquardt et al., 2010). Currently fossil fuels dominate world primary energy supply, meeting 80% of global energy demand (IEA, 2013). With projections that global energy demand will increase by 40% by 2035 (IEA, 2013) a pressing question is how this demand can be met while achieving an environmentally sustainable low carbon future. The energy sector is responsible for over 80% of the total greenhouse gas (GHG) emissions in the EU-28 (EEA, 2014) and approximately 83% of the UK GHG emissions in 2012 (DECC, 2014a). Bioenergy has been widely recognised as a strategic component for mitigating climate change (DECC, 2010; DECC et al., 2012) although the extent to which it is available in the future can vary depending on modelling assumption (Ekins et al., 2013; Helmut et al., 2013). This has triggered ambitious national/regional policy targets mandating the role of bioenergy within the overall energy portfolio with an increasing focus on feedstock coming from non-food crops e.g. 2020 targets set in EU Renewable Energy Directive (RED) and EU new proposals (European Parliament, 2015; European Union, 2009). However, bioenergy is a complex system, which involves many interrelated or conflicting issues e.g. economic development vs. environmental and social sustainability, interaction between energy and non-energy sectors relying on the same resources and potentially the same productive lands (Cobuloglu and Buyuktahtakin, 2015; Čuček et al., 2012; van der Horst and Vermeylen, 2011). For the full potential of bioenergy to be exploited, a thorough understanding of the whole system and involved issues and opportunities must be developed for the environmental, social and economic consequences of key decisions enabling the identification of optimal pathways.

Landscapes generate a wide range of ecosystem services (ES) that provide benefits to human society (Mace et al., 2012; Millennium Ecosystem Assessment, 2005). These services fall into four broad categories that include – provisioning services such as food, animal feed, materials and energy; regulating and supporting services such as climate and water regulation and waste recycling; and cultural services such as recreational value and symbolic meaning. While the need to incorporate such ES into policy decisions at international, national and local scales is increasingly

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recognised (Daily and Matson, 2008; Gómez-Baggethun and Ruiz-Pérez, 2011), their value is often overlooked in real world land-use planning applications (Bateman et al., 2013). Land use transitions arising from increased production of bioenergy over coming decades have the potential to influence the provision of ES in both positive and negative ways (Holland et al., 2015; Milner et al., 2015). Such change will occur against a backdrop of ongoing global degradation of ecosystem services as highlighted by the Millennium Ecosystem Assessment (2005). Given their importance for human-wellbeing, their economic value and policy relevance, ES provide a useful framework to examine systems such as bioenergy (Gasparatos et al., 2011) and the associated environmental, social and economic implications of deployment strategies. The type, magnitude, and relative mix of services provided by ecosystems can vary with management interventions, where the ES trade-offs could occur at spatial and temporal scales (Rodriguez et al., 2006). A good example is the spatial-scale provisioning and regulating ES trade-offs arising from the land competition of bioenergy with the livestock sector, which has been recognised not only from a climate change (climate regulation ES) perspective but also in terms of agricultural household income source (food or energy provisioning ES) (Thornton and Gerber, 2010). The current study therefore sits at the nexus of a changing energy-food system over the coming decades and increased understanding of the importance of incorporating ecosystem services into land-use decisions.

There has been increasing research interests in modelling and optimisation of process industry supply chains since early 2000s as well as on bioenergy supply chains (Čuček et al., 2014; Elia and Floudas, 2014). Comprehensive reviews on biomass and bioenergy supply chain (SC) optimisation can be found in recent studies by De Meyer et al. (2014), Čuček et al. (2014), Yue et al. (2014) and Samsatli et al. (2015). As pointed out by Čuček et al. (2014), most of the studies conducted on biorefinery SC focus on specific biofuel or limited production routes and are modelled as static without considering dynamic behaviour. Recently, a comprehensive and flexible bioenergy pathway model ETI-BVCM addressed the research gap and considered multiple energy vectors and the future bioenergy mix and transition (ETI, 2015b; Newton-Cross, 2015; Samsatli et al., 2015). At the same time, the optimisation studies in the field predominantly focus on economic feasibility or trade-offs between economic performance and GHGs for bioenergy SC design (Carnbero and Sowlati, 2014) although recent developments seek to incorporate a wider sustainability criteria. Zamboni et al. (2009) developed a multi-echelon corn-bioethanol SC optimisation model to simultaneously minimise well-to-tank GHG and economic cost. Mele et al. (2011) adopted a life cycle assessment (LCA) approach, combined with multi-objective optimisation model to consider the economic and environmental issues (e.g. global warming potential (GWP)) addressed from both mid-point and end-point perspectives. Čuček et al. (2012) introduced several environmental and social footprint indicators including a food-to-energy indicator measuring the mass-flow rate of food-intended crops converted into energy. El-Halwagi et al. (2013) demonstrated a new approach to incorporate a safety matrix into the biorefinery optimisation framework. Gong and You (2014) presented a life cycle optimisation framework to simultaneously optimise the LCA functional unit based cost and GWP. Liu et al. (2014) developed a LCA-based biofuel SC optimisation model accounting for economic and two environmental objectives (fossil energy depletion and GWP). The review conducted by Yue et al. (2014) discussed four layers (i.e. ecosystem, supply chain, process and molecule) concerned in bioenergy SC optimisation and highlighted the research needs to identify sustainable solutions to minimise adverse environmental impacts and maximise societal benefits. The lack of environmental and social sustainability concerns in bioenergy SC optimisation research was confirmed by De Meyer et al. (2014), who reviewed studies between 1997 and 2012 with a focus on their modelling approach and objectives addressed. A comparatively few studies considered bioenergy deployment options while simultaneously incorporating system interaction or non-energy production into optimisation such as interaction of bioenergy with petroleum supply chains (Yue et al., 2014) and competition of food and biofuel supply chains (Cobuloglu and Buyuktahtakin, 2015; Čuček et al., 2014). The inclusion of such factors begins to explicitly acknowledge the value of ecosystem services e.g. food provisioning and the influence that they may exert on desirability of specific energy pathways.

The decision making should be supported by holistic and quantitative optimisation tools designed to consider conflicting objectives simultaneously and assessing the environmental and economic performance of bioenergy systems, considering the entire supply chain over the long-term. This study aims to bring ES into the multi-objective optimisation framework supporting bioenergy SC design and optimal land use for multiple systems (energy and non-energy use). Provisioning ES relating to food, livestock and energy production from dedicated and competing sources are considered quantitatively, as is the regulating service of stored carbon. A semi-quantitative approach to other ES is introduced (Holland et al., 2015; Milner et al., 2015) (ES categories given in Supplementary Information SI1). To our best knowledge, no publically available study has incorporated land-competing issues between bioenergy and non-energy (food) systems over time at different land types and ecosystem services impacts due to land use transitions into such a spatially-explicit optimisation model.

2. Methodology

2.1. Problem statement

The underpinning concept is to integrate the effects of bioenergy penetration on ES and resource-competing systems (bioenergy vs. non-energy) within a comprehensive optimisation framework. This has been implemented by adopting and extending a spatial-temporal mixed integer linear programming (MILP) model – ETI-BVCM (ETI, 2015b; Newton-Cross, 2015; Samsatli et al., 2015). MILP represents an effective mathematical modelling approach to solve complex optimisation tasks and identify the potential trade-offs between conflicting objectives, which can provide a better understanding of bioenergy systems and support decision-makers developing sustainable pathways towards bioenergy targets.

The ETI-BVCM model development was commissioned and funded by the UK's Energy Technologies Institute (ETI). This study is based on ETI-BVCM version 4.1.7. ETI-BVCM is a comprehensive and flexible toolkit for the whole-system optimisation of UK-based bioenergy value chains over the next five decades, supporting analysis and decision-making on optimal land use, biomass utilisation and different pathways for bioenergy production (ETI, 2015b). A model overview and a summary of the headline insights the ETI-BVCM model has generated to date have been addressed in details in the associated ETI papers (ETI, 2015b; Newton-Cross, 2015; Newton-Cross and Evans, 2016). Mathematical formulations for ETI-BVCM can be found in Samsatli et al. (2015).

The ETI-BVCM toolkit encompasses bioenergy systems considering biomass from diverse resources including domestic food crops, bioenergy crops, forest, organic and inorganic waste and imported biomass. It considers various pre-treatment and conversion technologies via biochemical, thermochemical and mechanical routes and uses inputs of yield models from feedstock resolved spatially for the UK (Hastings et al., 2014; Tallis et al., 2013). It is capable of analysing UK bioenergy supply chains at a grid resolution of 50 km × 50 km and identifying the potential trade-off between GHG targets and cost optimal solutions for bioenergy value chain design over five decades (2010s–2050s). In this study, two terms for