Land Use Policy 68 (2017) 141–151

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Where to implement local biotech innovations? A framework for multi-scale socio-economic and environmental impact assessment of Green Bio-Refineries

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ARTICLE INFO

Keywords:
Grass-based protein feed
Greenhouse gas (GHG) emissions
Interregional macroeconomic modelling
Local technical change
Multi-scale effects
Nitrogen leaching

ABSTRACT

Green Bio-Refineries (GBRs) have economic and environmental potentials through changing land use from cereals to grass production and provision of grass-based protein feed for livestock production and other valuable byproducts. However, the potentials are dependent on local conditions of the GBRs, such as land productivity, environmental sensitivity and transport distances for feedstock as well as the regional economy which GBRs are a part of. In this paper, we compare the total (direct, indirect and induced) effects of different location choices of GBRs in Denmark at different (municipal, regional, national) scales − a key step for decisions about development of GBRs from both investors' and authorities' perspectives. We integrate a local life-cycle assessment (LCA), a geographic information system (GIS) analysis and an economic-environmental input-output (EEIO) based model (LINE) into a common framework (GIS-LCA-EEIO). We show that locating GBRs in Western Denmark, where the soils are primarily sandy and livestock densities are high, generates higher socio-economic gains than in Eastern Denmark, where the soils are primarily loamy and the concentrations of livestock are lower. We conclude by sketching out priority areas for developing GBRs and discuss the policy implications of the results within the context of development of a bio-based economy.

1. Introduction

Technological innovation provides potential solutions to environmental challenges while sustaining economic growth (Smithers and Blay-Palmer, 2001). One important environmental challenge faced by agriculture, and Danish agriculture in particular, is nitrogen leaching caused by intensive farming and livestock production, and the concomitant eutrophication of fresh water and marine systems (Kronvang et al., 2008). The current agricultural production system also leads to significant greenhouse gas (GHG) emissions (Dalgaard et al., 2011) and therefore significant system changes are required to meet climate policy targets set out in the Paris agreement (COP21). Furthermore, Danish pig farming, in particular, is highly dependent on imported soya protein for feed, creating environmental and social concerns. These include deforestation (Godar et al., 2015), social tension (Weinhold et al., 2013) and threats to security of feed supply (Willems et al., 2016).

A possible alternative is to use protein feed from grass, which can be produced in green bio-refineries (GBRs), to substitute part of cereals and soya in pig feed (Kamm et al., 2010). Cultivation of grass for GBRs instead of cereals can reduce nitrogen leaching and pesticide application (Jørgensen et al., 2013; Termansen et al., 2016), as well as long-distance transportation of soya, while GBRs can produce valuable co-products, e.g. fibres and biogas (Kromus et al., 2004).

It has been shown that investments of GBRs could be technically and economically feasible under certain conditions (O'Keeffe et al., 2011). Cong and Termansen (2016) have conducted a life-cycle assessment (LCA) and a cost-benefit assessment (CBA) for the direct (economic and environmental) effects of introducing GBRs to Danish agriculture at the micro level. However, very few studies have investigated how to implement GBRs on a larger scale (e.g. where to locate GBRs) and the macro socio-economic and environmental effects. There is, therefore, a lack of knowledge to aid authorities' differentiated regional planning and policy design for GBRs development in a spatial context.

Previous Danish studies suggest that the (net) economic and

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http://dx.doi.org/10.1016/j.landusepol.2017.07.036
Received 6 May 2017; Received in revised form 4 July 2017; Accepted 19 July 2017
Available online 17 August 2017
0264-8377/

environmental benefits of introducing GBRs are significantly dependent on the soil conditions, as an important determinant of agricultural productivity and environmental benefits (Cong and Termansen, 2016). The geographical soil fertility gradient in Denmark (Adhikari et al., 2014) is therefore an important factor for GBR location selections. In addition, transportation costs affect GBRs' profitability, while location decisions could affect the average transportation distance of feedstock (grass) because of differences in land-use patterns and physical infrastructure. Thus, it is important to investigate the GBRs' locations in a spatial context, e.g. by utilizing a geographical information system (GIS).

Large-scale implementation of GBRs could have economy-wide consequences because they affect the regional and national socio-economic systems through the sector and inter- municipal/regional linkages (Madsen, 2008; Tarancón Morán and del Río González, 2007; Zhang et al., 2011). Although the economic inequality is relatively low in Denmark, there are still some variations in economic productivity and structure at the municipal and regional levels (Bhattacharjee et al., 2009; Zhang et al., 2007). Such variations imply that the socio-economic and environmental impacts of a large-scale GBR implementation could depend on the geographical locations of GBR plants.

In this paper we employ interregional Economic-Environmental Input-Output (EEIO) analysis combined with life-cycle assessment (LCA) and geographical information system (GIS) to examine the location effects of GBRs on the regional/national socio-economy and environment, and their spatial diffusion patterns (Madsen, 2008; Zhang and Anadon, 2014). Specifically, we study the direct, indirect (due to changes in intermediate demand) and induced (attributable to the ensuing change in employees' incomes) effects of three GBR location scenarios at different spatial (municipal, regional and national) scales. The potential contributions of this study are to illustrate an integrated modelling framework that can be used to: 1) upscale the micro-level effects of bio-tech innovations to the macro level, which involves both the direct and derived effects on both the agricultural sector and other sectors as well as effects of both the GBR locations and their spillovers on the municipalities without GBRs; 2) help stakeholders understand the implications of location decisions; and 3) improve land-use policy design, e.g. for promoting transitions of cereals production at certain areas into grass production. Our analysis is ex-ante since there are only a few pilot GBRs in Denmark. However, the analysis provides important inputs to decision-making for both entrepreneurs and authorities.

The remaining parts of the paper are structured as follows: Section 2 gives a brief review of existing GBR literature with LCA, GIS modelling and EEIO analysis. Section 3 introduces the GIS-LCA-EEIO modelling framework and the data sources used in the study. We present the results in Section 4 and discuss the policy implications in Section 5. Section 6 concludes.

2. Evaluating GBR investments at multiple scales–a review of the literature

2.1. Economic assessments of GBR

The idea of using grass to substitute cereals in pig feed is not new (Patterson and Walker, 1979). However, the application in practice has been limited due to grass's low digestibility for monogastric animals (Ogle, 2006). The concept “Green BioRefinery (GBR)" was firstly defined in 1997 (Kamm et al., 1998). With a GBR the grass can be separated into protein-rich press juice (PJ), fibre-rich press cake (PC) and residues. PJ can substitute part of cereals and soya in pig feed. PC can be used for production of insulation/gardening materials, cattle feed, etc. The residues can be digested to produce biogas and then fed back to soil to substitute chemical fertilizer (Kamm and Kamm, 2004). Current studies about GBR mainly focus on technical perspectives, e.g. chemical composition of products (Andersen and Kiel, 2000), technical details (Novalin and Zweckmair, 2009), and energy and mass balance (O'Keeffe et al., 2011). Relatively few papers discuss the economics of GBR. Among them, O'Keeffe et al. (2012) made a complete economic assessment for GBRs in Ireland. Cong and Termansen (2016) linked the decentralized GBRs with the pig feeding system to assess the whole supply chain from both economic and environmental perspectives. They showed that the (net) economic and environmental benefits of GBRs could be context specific, e.g. they are dependent on the soil condition of the farms which supply the feedstock, and the transportation distance from farms to GBR plants. An empirical comparison of GBRs on different sites is still lacking although it is important to understand the conditions under which (decentralized) GBRs are viable.

2.2. GIS modelling of biorefinery location

GIS have been applied to modelling location of biorefineries for biofuel production (Wilson et al., 2011). Regarding GBRs, soil condition affects not only feedstock (grass) availability but also average transportation distance (the average distance to collect grass from infertile land could be longer than fertile land, given the same grass biomass requirement), which affects both economic and environmental benefits of GBRs. Furthermore, the spatial pattern of pig productions will also affect the demand for produced protein feed. Studies about location selection for GBRs with GIS are currently missing.

2.3. Interregional EEIO analysis combined with LCA

In principle, there are three types of methods to conduct LCA of new technology: 1) traditional process-based LCA (process type LCA), which is a process assessment to study impacts throughout a product's life (i.e. cradle to grave) (Cong et al., 2017; Rebitzer et al., 2004); 2) input-output based life cycle assessment (IO type LCA) (Hendrickson et al., 2006) which takes an aggregate view of relevant sections in the economy while ignoring details at the micro level; 3) the hybrid IO-LCA, which combines the broad perspective of a IO type LCA with specific information from a process type LCA (Virtanen et al., 2011). It is generally believed that both process type and IO type LCAs have strengths and weaknesses (Suh and Huppes, 2005). Main weaknesses of IO type LCA include 1) low level of detail; 2) poor timeliness of data; 3) usually based on monetary units; 4) ignoring (or not explicitly considering) the end of life phase, etc., which are however strengths of a process type LCA. However, the detailed data requirement of a process type LCA often implies considerable time and resource commitment. The hydrid approach, which links process- and IO-type LCAs, combines the strengths of the two types of approaches.

Up till now there have been numerous studies applying the IO-LCA to investigate the effects of technical development (Mattila et al., 2010; Williams, 2004). However, IO-LCA studies analyzing technologies utilizing bio-based resources, GBR being an example, and therefore closely linked to land use are rare in the literature. Linking a GIS to the IO-LCA methodology is particularly relevant for analysis of bio-based resources due to the importance of geographical land-use patterns and spatial infrastructure. This paper aims to fill this gap and link LCA, IO analysis and GIS modelling to compare the socio-economic and environmental effects of different location selections of GBRs at municipal, regional and national scales.

3. Methodology and data

Firstly, we introduce the (process type) LCA combined with CBA for calculating the (direct) economic and environmental effects at the local (plant) level; secondly, we show the potential location selections for GBRs based on GIS modelling; finally, we integrate the LCA results and GIS information into an interregional macroeconomic model for Danish municipalities − LINE (Madsen and Jensen-Butler, 1999, 2004). The overall modelling framework (GIS- LCA-EEIO) is shown in Fig. 1.

Note: Based on Cong and Termansen (2016), Jensen-Butler and