Environmental Modelling & Software 82 (2016) 128–141

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

Regional or global? The question of low-emission food sourcing addressed with spatial optimization modelling

Ulrich Kreidenweis [a], [b], [*], Sven Lautenbach [c], Thomas Koellner [a]

[a] Professorship of Ecological Services, Faculty of Biology, Chemistry and Earth Sciences, BayCEER, University of Bayreuth, Bayreuth, Germany
[b] Potsdam Institute for Climate Impact Research, Potsdam, Germany
[c] Professorship for Land Use Modelling and Ecosystem Services, Agricultural Faculty, University of Bonn, Bonn, Germany

ARTICLE INFO

Article history:
Received 15 September 2015
Received in revised form
1 April 2016
Accepted 22 April 2016

Keywords:
Local food
Food miles
Staple crops
Optimization modelling
Life cycle assessment
Greenhouse gases

ABSTRACT

Does producing staple food locally cause fewer greenhouse gas emissions than food sourced through imports from another continent? To address this question we used a spatial optimization approach that minimized greenhouse gas emissions from production and transport of five food commodities (barley, maize, oil, sugar and wheat) and compared this to a setting of local production where distances between production and consumption were minimized. We focused on the example of two countries – Brazil and Germany – in order to allow modelling at high spatial resolution. In the model, a minimization of greenhouse gas emissions led to an allocation of large shares of production to locations abroad. In contrast, the local production case, optimized on distance only, resulted in higher greenhouse gas emissions. Our findings show that despite additional transport needs for imports, specialization of countries on the production of specified crops can represent a low climate impact strategy.

1. Introduction

In the 1990s, reducing food miles was presented as one strategy to lower carbon emissions (Ballingall and Winchester, 2008) and hence promoted the consumption of local food. The concept of food miles describes the distance food travels from producer to consumer (Paxton, 1994) which with its introduction raised awareness of emissions caused during the transport of food items. The idea, that fewer food miles means lower environmental impact, seems to have found its way to the general public. Nowadays, a clear majority of consumers agree that local food is a positive choice for the environment (PSPC, 2013) and that long distance transport is one of the most pressing environmental problems in food production (forsa, 2013). Furthermore, a majority also state that they would buy regionally or locally produced food in part for environmental reasons (A.T. Kearney, 2013; IGD, 2005). It is therefore not surprising that the question whether domestic production has a lower environmental impact than an import, has been addressed by a number of more recent studies (Avetisyan et al., 2014; Edwards-Jones, 2010; Webb et al., 2013). Others have assessed the ability of local self-provisioning and motivated this with greenhouse gas emissions from transport (Porter et al., 2014; Pradhan et al., 2014; Zumkehr and Campbell, 2015).

In general food production is an important source of greenhouse gas (GHG) emissions, making it a potential field of significant climate change mitigation. It is estimated that agriculture accounts for about 10–12% of global anthropogenic greenhouse gas emissions (Smith et al., 2007), or between 17 and 32% if land-use change is also taken into account (Bellarby et al., 2008). A study found that the food system in the UK, including manufacturing, transport, retailing, consumption and waste, accounts for 19% of the country's GHG emissions (Garnett, 2008). It was estimated that food related transport accounts for 28% of total road transport in the UK and creates external costs of £2.35 billion yr^{-1}, compared to external costs of £1.51 billion yr^{-1} for the production up to farm gate (Pretty et al., 2005).

The concept of food miles has however been criticized as an inappropriate method to describe the environmental impact and that it should not be used as a proxy for greenhouse gas emissions

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[*] Corresponding author. Potsdam Institute for Climate Impact Research, P.O. Box 601203, D-14412 Potsdam, Germany.
E-mail address: kreidenweis@pik-potsdam.de (U. Kreidenweis).

http://dx.doi.org/10.1016/j.envsoft.2016.04.020
1364-8152/

due to food production. A study in the US found that of the 8.1 t CO_2-equivalent (CO_2e) emissions of an average household for food consumption, only 4% were associated with delivery from producer to retailer (Weber and Matthews, 2008), i.e. the food miles. In 2005 a study for DEFRA had already concluded that “a single indicator based on total food kilometres is an inadequate indicator of sustainability” (Smith et al., 2005). It neglects the importance of the mode of transport, energy required for cooling of out of season produce and differences in the production between two locations. Edwards-Jones et al. (2008) argue that if at all possible, only spatially explicit life cycle assessments could account for specific production and transportation practices and therefore reveal whether “local food” is the better choice with respect to GHG emissions.

Life cycle assessments (LCA) have been offered as one way to overcome the shortcomings of the food miles concept. Several studies have compared domestic production to sourcing from further afield, e.g. tomatoes: (Smith et al., 2005; Theurl et al., 2013), lettuce: (Hospido et al., 2009; Milà i Canals et al., 2008; Reinhardt et al., 2009), livestock feed: (Baumgartner et al., 2008; Lehuger et al., 2009). A prominent, well studied and yet controversial example is the production of apples within the European Union compared to an import from New Zealand (Blanke and Burdick, 2005; Jones, 2002; Milà i Canals et al., 2007; Reinhardt et al., 2009; Saunders et al., 2006; Webb et al., 2013). Consequential life cycle assessments consider economic factors and are therefore potentially suitable to show the consequences of consumption changes. They connect LCAs to economic Partial Equilibrium (PE) or Computable General Equilibrium (GCE) models. Kløverpris et al. (2010), for instance, showed how an increased demand for wheat leads to agricultural land expansion, intensification and the displacement of other crops. However, the economic models used by such studies usually lack an explicit representation of land-use and are therefore less suitable to study land-use competition.

Land-use competition and the finiteness of land were insufficiently covered by previous research that compared greenhouse gas emissions of local production to an import from further away. This is especially problematic for staple crops that cover the largest shares of arable land today. Life cycle assessments have in general insufficiently covered questions of land-use and location (Koellner et al., 2013). They do usually not consider whether production at the studied location could be increased without displacing the production of other goods. The environmental advantage of one of several products compared in a LCA is therefore only valid for a marginal change in consumption. Coley et al. (2011), in a study on the correlation between CO_2 emissions and food miles, conclude that “because of the higher CO_2 intensity of road freight in comparison to sea, […] sourcing from regions closest to shipping ports (thus minimising road transport) would result in the lowest emissions.” This statement does not consider whether there is enough space close to the shipping port or whether another produce, in turn, would have to be produced further away. It is therefore unclear whether sourcing close to shipping ports would reduce overall emissions. Spatially differing production conditions, influencing the production emissions, can also lead to comparative advantages between different locations. Under limited availability of land it might reduce emissions to export one good just to be able to import another with improved carbon balance (see Fig. A1). It is therefore imperative to take a system perspective considering several crops at a time.

The aim of our study was to assess how local production of staple crops compares to an optimally allocated production in terms of greenhouse gas emissions if finiteness of land is taken into account. We introduce a concept where life cycle assessment data is used in a spatially explicit optimization model to test whether local production is a good strategy resulting in low greenhouse gas emissions from cultivation and transport of staple crops. Spatially explicit optimization modelling has so far been applied to questions of land-use (Aerts et al., 2003; Haque and Asami, 2014; Johnson et al., 2014; Liu et al., 2015; Stewart and Janssen, 2014; Tong and Murray, 2012) and watershed management (Darradi et al., 2012; Klein et al., 2013; Meyer et al., 2009; Rabotyagov et al., 2014, 2010a, 2010b, 2010c; Rodriguez et al., 2011; Seppelt and Lautenbach, 2010; Seppelt and Voinov, 2002, 2003; Whittaker, 2005), biodiversity management (Holzkämper and Seppelt, 2007; Polasky et al., 2008) and tradeoff analysis in ecosystem service assessments (Ausseil et al., 2013; Groot et al., 2007; Lautenbach et al., 2014, 2013). Linear programming and integer based programming have been used along with evolutionary algorithms such as genetic algorithms or particle swarm optimizers. The application of these approaches has so far focussed on the local to regional scale and has not tackled the problem in question. The only other study known to the authors, that explicitly applied optimization modelling in order to answer the question, ‘If land is limited, which foods should be grown locally?’ is of Peters et al. (2011). That study, however, maximized net returns from agricultural land-use within New York State and did not consider greenhouse gas emissions.

2. Materials and methods

A grid based linear programming model was created that spatially allocated the production of five important food commodities for exogenous food demand and yield levels. The model was run with two different optimization objectives. In the first scenario the sum of greenhouse gas emissions from production and transport was minimized (*CO₂e optimization*), to show the spatial crop allocation of a production with lowest possible emissions. This result was compared to a second scenario of local food production (*distance optimization*).

This study simplified the complex trade relationships of food transport by focusing on the idealized example of a world consisting of only two countries: Brazil and Germany. Two countries were sufficient to study the evolving crop distribution, while this at the same time reduced model complexity and allowed for a high spatial resolution. The countries have strongly differing natural preconditions and therefore different crop suitability. While Germany is located in the temperate zone, most of Brazil has tropical climate (Kottek et al., 2006). Trade between them requires long-distance overseas transport, which allows the analysis of different modes of transport relevant for staple food delivery (road and ship) and the influence of distance. Furthermore, a relatively high number of agricultural life cycle assessments have been conducted in the two countries (Ruviaro et al., 2012).

Geographical input data was mainly prepared with ArcMap 10.0 (ESRI, 2010) and GRASS GIS 6.4.3 (GRASS Development Team Version 6.4.3, 2012). Life cycle data was manipulated and analysed in SimaPro 7.3.2 (PRé Consultants, 2011). Optimizations were performed with Gurobi Optimizer 5.5 (Gurobi Optimization, 2013) on a PC with 2.5 Ghz and 16 GB RAM. Computer memory was the main factor limiting the number of variables and thereby spatial resolution.

In the following, the model setup is described. For a more detailed mathematical description, additional information on the parameterization and emission factors we refer to S1 Information.