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

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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 17-32% 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 due to food production. A study in the US found that of the 8.1 t CO₂-equivalent (CO₂e) 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 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 CO₂ emissions and food miles, conclude that “because of the higher CO₂ 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 trade-off analysis in ecosystem service assessments (Ausseil et al., 2013; Groot et al., 2007; Lautenbach et al., 2014, 2015). 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 (CO$_2$e 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.

2.1 Demand by consumption centres

The demand in the model was determined by the amount of food actually available per person in each of the two countries in the year 2009. Per capita domestic supply quantities (Domestic Supply = Production – Export + Import ± Stock variation) of five important food commodities were derived from FAOSTAT (2013). These quantities include the supply for food use, but also the use as animal feed and for bioenergy production. The three crops with the largest harvested area were in Brazil: soybean, maize and sugar cane, and in Germany: wheat, barley and rapeseed, respectively. In this study, oil from soybean and rapeseed, and sugar from sugarcane and sugar beet were treated as perfect substitutes, and only the demand for their processed goods (oil and sugar) was considered. Conversion from raw to processed goods was performed according to factors from the ecoinvent database (Jungbluth et al., 2007).

Following the approach by Peters et al. (2011, 2009), demand for food was represented by a limited number of consumption centres. Data on the location and number of inhabitants of municipalities
were acquired from the statistical offices of Germany and Brazil (DESTATIS, 2013; IBGE, 2013a, 2013b). Only cities with more than 100,000 inhabitants were included in the model. It was assumed that cities have to exceed a certain size to fulfil the function of a central place, where e.g. processing of agricultural crops takes place, and where products are sold in supermarkets. To decrease model size and thus computational effort, only the biggest one was kept as a consumption centre, whenever there was more than one city with more than 100,000 inhabitants within a radius of 25 km. This approach led to a list of 169 centres for Brazil, and 55 for Germany. These centres covered 40% and 26% of the inhabitants, respectively. The inhabitants in the remaining municipalities were spatially joined to the closest consumption centre, so that in the end all inhabitants were considered. Out of 16,817 populated municipalities 224 consumption centres were created (see Fig. A2). The food demand of each consumption centre was determined by the number of consumers (inhabitants of city and surrounding), and the average per capita domestic supply quantity of the five food commodities.

2.2 Production

Production was based on data of potential production capacity (t/ha), provided by Global Agro-Ecological Zones (GAEZ v3.0) (IIASA/FAO, 2012). Data for rain-fed conditions, high-level inputs/advanced management, and for currently cultivated land were used (Fig. 1). In the figure it is clearly visible that potential production capacities differ between and within the two countries. Additionally there is a strong difference in potential yield levels reached by the different food commodities. GAEZ dry weight values were recalculated to FAOSTAT harvest weights (see S1 Information). In the model, production was only allocated to areas currently used to grow crops. High resolution land cover data (10 arc-seconds) for the year 2009 (GlobCover (ESA/UCLouvain, 2010)) was used to determine the fraction of cropland per grid cell. The area of arable land according to this method slightly overestimated the amount reported by FAOSTAT (2013) for Germany (13.1 versus 11.9 million ha), but strongly overestimated it for Brazil (70.4 versus 164.7 million ha). A correction factor was applied to account for this and for the fact that in reality more than seven crops are grown on the available area. The correction factor was calculated for each country as the ratio between the agricultural area, as derived from the GlobCover, and the harvested area of the seven crops according to FAOSTAT values. The search space of the model was thereby restricted to the share of land currently devoted to the production of these crops. So wherever there was cropland, and production was suitable according to edaphic and climatic conditions the model could produce barley, maize, soybean, sugarcane and wheat in Brazil and barley, maize, rapeseed, sugar beet and wheat in Germany.
2.3 Calculation of CO2e raster datasets

Greenhouse gas emissions in the model were calculated from the share of the cells used to produce the food commodities and datasets containing emission values for the production of individual commodities. These emission raster datasets were precalculated for all possible combinations of the 5 food commodities and transportation to the 224 consumption centres. For the CO2e optimization this data was also used as an input to the optimizer, while for the distance optimization it was only used to calculate emissions after the optimization had taken place.
The CO₂e emissions included emissions from cultivation and harvest, transport from field to factory, processing, transport from farm or factory to city and port, the transport from port to port and the transport from port to city. Indirect land-use change effects were not taken into account since cultivation was assumed to take place only on existing farmland areas. Fig. 2 exemplarily illustrates the maximal production chain of sugar and oil as considered in the model. After the on field production raw products were assumed to be transported by lorry to the closest plant, where they were processed, and then further transported as refined sugar or oil to the harbour for international shipping. After their journey on an oceanic freighter goods were finally delivered to the consumption centres. For barley, maize and wheat no processing and related transport was considered. In the cases where production and consumption took place in the same country, no overseas transport was necessary and foodstuff was assumed to be directly transported from field or factory to the consumption centre.

Fig. 2. Steps of transport and processing considered in the model. Example of sugar and oil production in Brazil and consumption in Germany.

In the following paragraphs the computation of CO₂e values from the different production and transport steps is described in more detail.

**Cultivation and harvest:** Greenhouse gas emissions caused by on field production were calculated by multiplying cultivated land area by a crop specific emission factor based on the ecoinvent v2.2 database of life cycle processes (ecoinvent Centre, 2007) (see details in S1 Information). These data comprises CO₂ emissions from agricultural machine usage and fertilizer transport, and NH₃, N₂O, and NOₓ emissions from fertilization. The global warming potential in kg CO₂e per kg crop, computed by the IPCC 2007 GWP 100a method in SimaPro 7.3, was recalculated to per hectare values. This was done since the initial data had mostly been based on per ha requirements of fertilizers, pesticides, seeds and machine usage (Jungbluth et al., 2007; Nemecek and Kägi, 2007). For barley, maize and wheat the same per hectare emission values were assumed for both countries. The dataset for soybean originally comprised an estimate of carbon emissions from soil after deforestation of tropical rainforest (Jungbluth et al., 2007). Since the optimization only allocated crop production on currently
cultivated land, no deforestation could be caused directly, and these emissions have therefore been excluded from the calculations. For sugar and oil crops an economic allocation (see details in S1 Information) was applied that accounted for the fact that besides refined sugar and vegetable oil, by-products like rapeseed or soybean meal are also created from the same crops. These by-products are also of value, and can be associated with a certain share of the overall emissions. Emissions from on-field production were therefore split according to the economic values of the end products (e.g. soybean oil versus soybean meal), and only the fraction for the production of oil and sugar was considered.

**Transport from field to factory (only sugar and oil):** Sugarcane, sugar beet, rapeseed and soybean were assumed to be transported to the closest factory. CO₂e emissions were calculated as the product of the crop yield, the road transport distance and an emission factor. The addresses of sugar refineries and oil mills were acquired from the websites of producer associations (ABIOVE, 2013; Nordzucker, 2013; OVID, 2013; Pfeifer & Langen, 2013; Südzucker, 2013; Suiker Unie, 2013; UFOP, 2013a, 2013b; unica, 2013). These addresses were transferred to geographic coordinates with the web service GPS Visualizer (2013) (see Fig. A3 for their location). Transport distances are the product of the geodesic distance and a circuity factor to correct for real travel distances. Country specific road circuity factors were taken from Ballou et al. (2002). Emissions for one ton-kilometre of transport were taken from the ecoinvent database for a lorry with more than 16 tons.

**Processing (only sugar and oil):** The ecoinvent database provides greenhouse gas emission values per kg of processed good. Yields were therefore first recalculated to processed quantities and then multiplied with the emission factor. For instance, one ton of soybean produces about 182 kg of oil after extraction (Jungbluth et al., 2007). An economic allocation was also deployed for the emissions caused during processing, following the same principles as described above.

**Transport from farm or factory to city or port:** After leaving the factory, sugar and oil were, now in processed quantities, transported to the cities. No processing was considered in the model for barley, maize and wheat under the assumption that they were directly transported from the fields to the consumption centres. CO₂e emissions were therefore determined by the approximated road distance from field or factory to the city of consumption or the harbour city in the case of international transport.

**Transport from port to port (only if produced abroad):** If the country of production differed from that of consumption, goods were assumed to be transported by an oceanic freighter. Only the oversea transport connection between the most important port cities was considered, Hamburg in Germany and Santos in Brazil, to ensure that model complexity and memory use remained manageable. The distance between the ports was taken from the distance calculator of www.searates.com. Global warming potential of the transport by a transoceanic freight ship was taken from ecoinvent (ecoinvent Centre, 2007).

**Transport from port to city (only if produced abroad):** The last step for international products was the transport from port city to the consumption centre by lorry, using the same assumptions as described previously for domestic transport.
2.4 Optimization

The linear programming solver minimized the total costs of production under the constraints that the demand of all consumption centres for all goods had to be fulfilled (equation 3) and that the cropland of one cell was only used up to 100% (equation 2). The linear decision variable $x_{c,l,xy}$ represents the fraction of land that is used to produce one crop $l$ for one consumption centre $c$ in cell $xy$. The costs $c_{c,l,xy}$ were defined depending on the goal of the optimization (see below).

Objective function:

$$\min \sum_{c} \sum_{l} \sum_{xy} (c_{c,l,xy} \cdot x_{c,l,xy})$$  \hspace{1cm} (1)

$c_{c,l,xy}$ costs of the production of one crop $l$ in one cell $xy$ and transport to one consumption centre $c$

$x_{c,l,xy}$ decision variable for the occupation of cell $xy$ with crop $l$ for consumption centre $c$

Indices:

$c$ consumption centres (224)

$l$ land-use options (5 crops)

$xy$ grid cells in xy-coordinates

Cropland constraint:

$$\sum_{c} \sum_{l} x_{c,l,xy} \leq 1 \text{ for all cells } xy$$  \hspace{1cm} (2)

The cropland constraint allowed for the allocation of more than one crop to one grid cell, but assured that the sum of land used for the different crops did not exceed the available area.

Demand constraint:

$$\sum_{xy} p_{l,xy} \cdot x_{c,l,xy} \geq d_{c,l} \text{ for all consumption centres } c \text{ and crops } l$$  \hspace{1cm} (3)

$d_{c,l}$ demand of one consumption centre $c$ for one crop $l$

$p_{l,xy}$ yield of crop $l$ produced in cell $xy$ (processed quantities for sugar and oil)

The demand constraint ensured that the demand from each consumption centre was met.

**CO₂e optimization**: In order to derive the optimal distribution of crops, with respect to the global warming potential, total CO₂e emissions were minimized. The cost variable $c_{c,l,xy}$ in the objective function (equation 1) was therefore set to the sum of all emissions produced per cell. This incorporates all emissions during cultivation, processing and transport as described in the section “Calculation of CO₂e raster datasets”.

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**Distance optimization (local production):** For the local production scenario distances between production and consumption were minimized. The cost variable was specified as the product of the distance between the place of production and consumption and the quantity of goods that would have to be transported. In the case of sugar and oil processed quantities were used for the calculation of these transportation charges (in tonne-kilometres).

**Sensitivity analysis**

To test the influence of different input parameters several parameters were manipulated in a local sensitivity analysis of the CO$_2$e optimization. For a detailed description of the parameters modified and how they influenced the results see S2 Information. Specifically we looked at the effect of:

- the transport of whole oil crops instead of oil to the consumption centres
- replacing parts of transport by lorries with barges and trains
- an increased availability of cropland per cell
- calculating emissions from cultivation and harvest based on crop yield instead of cultivated area
- an increased demand
- optimization for single food commodities.

A special focus was placed on the influence of different strengths of land-use competition, since this was expected to strongly influence results. This effect was tested for the case of CO$_2$e optimization using a model set up that only considered the demand of one consumption centre (Berlin). Results were compared to the standard CO$_2$e optimization where the demand of all 224 cities was considered.

**3 Results**

**3.1 CO2e optimization**

Under CO$_2$e optimization no sugar and oil were produced within Germany (see Fig. 3). In addition, maize was allocated to less than 100,000 ha in Germany, which was only about 2% of the area available to the model in this country. Wheat and barley, in turn, were mainly produced in Germany, with a clear concentration in the North. Small quantities of barley and wheat were also allocated to the very South of Brazil, at the border to Uruguay, so that 13.6 % of the Brazilian demand for barley and wheat came from domestic sources. This was done on less than 2% of the land dedicated to the production of the seven crops in Brazil.
Fig. 3. Result maps of CO₂e and distance optimization. Left column shows the dominant crop of each cell. Right column shows the distance between production and consumption of these crops. Upper row depicts the results of the CO₂e optimization, lower row the distance optimization. Oil refers to rapeseed in Germany and soybean in Brazil, sugar to sugar beet and sugarcane respectively. Maps are projected in Lambert Azimuthal equal-area centred to each country.

The CO₂e optimization model in general allocated the production of specific crops to larger continuous and homogeneous regions. The distribution of barley and wheat formed an exception of this trend. The reason for this could lie in the spatial yield patterns, which were very similar (see Fig. 1), so that the same regions were equally preferable for both crops. The production of sugar exclusively took place in Brazil, close to the agglomeration of São Paulo and the port city Santos. Its allocation seems to be mainly determined by the location of processing plants (see sugar refineries in
For maize, where no transport to factories was implemented, the resulting production pattern strongly correlated to attainable yields (see Fig. 1).

The German production of wheat and barley for Brazil and the reverse trade relationship for oil, sugar and maize explains the distribution of distance classes. Large shares of North-Eastern Germany were used for export, while the other German areas were mainly used for local production with distances of less than 100 km. Very large distances within the country are of course not possible, due to the size of Germany. In both countries the areas close to the ports were utilized for export production.

3.2 Distance optimization

The result of the distance optimization differed strongly from the CO$_2$e optimization in the area occupied, the distribution of crops and in total greenhouse gas emissions. The purpose of this model setting was to serve as an example of local production. The results show that all crops were produced within the country of consumption in this model run. In total, more than 90% of all barley, maize and sugar were produced within 250 km of the place of consumption (see also Fig. 3). Only small quantities of wheat and barley would have to be transported for more than 1000 km.

For this local production scenario the product of distance between production and consumption multiplied with the amount of crops to be transported was minimized. This resulted in concentric zones dedicated to the production of one specific crop around the consumption centres. In Brazil this pattern was particularly observable. In areas where the production of all crops was possible, they were placed in the following order: sugar cane, maize, wheat/barley and finally soybean. The order corresponded to the order of crop yields in the area (see Fig. 1). Sugar cane, even in its refined form, had the highest per hectare yields and was therefore produced closest to the cities, while oil crops were produced relatively far away. The order can be seen for example in the production for the harbour city of Santos where 95% of the sugar was grown within a radius of 100 km. Maize holds the largest share produced within a range of 100 to 250 km. 97% of the wheat and all of the barley and oil were sourced from more than 250, but less than 1000 km away.

3.3 Greenhouse gas emissions and country of production

The total CO$_2$e emissions caused in the distance optimization were with 109 million tons 86% higher than those of the CO$_2$e optimization with 59 million tons (see table 1). In both cases, roughly one third of the overall emissions were caused by the production and transport for Germany. Fig. 4a shows the CO$_2$e emissions caused per crop and step of the production chain. Not only were overall emissions lower in the greenhouse gas optimized case, but also for every single food commodity.
Table 1. Results of the optimization for distance and CO2e

<table>
<thead>
<tr>
<th>Food commodity</th>
<th>sum CO2e [10^12 g]</th>
<th>sum area [km²]</th>
<th>average distance [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO2e optimization</td>
<td>distance optimization</td>
<td>CO2e optimization</td>
</tr>
<tr>
<td>Barley</td>
<td>6.0</td>
<td>7.9</td>
<td>14,630</td>
</tr>
<tr>
<td>Maize</td>
<td>26.8</td>
<td>41.7</td>
<td>42,959</td>
</tr>
<tr>
<td>Oil</td>
<td>5.3</td>
<td>11.8</td>
<td>93,054</td>
</tr>
<tr>
<td>Sugar</td>
<td>3.8</td>
<td>13.5</td>
<td>10,750</td>
</tr>
<tr>
<td>Wheat</td>
<td>16.7</td>
<td>33.9</td>
<td>31,815</td>
</tr>
<tr>
<td>total</td>
<td>58.5</td>
<td>108.9</td>
<td>193,209</td>
</tr>
</tbody>
</table>

* weighted by the amount of production

Fig. 4. Comparison of CO2e emissions and area of production for distance optimization and CO2e optimization:  a) CO2e emissions from the production of the five food commodities for all steps of the production chain and b) area of production per country and food commodity.

For barley the local scenario produced only 32% higher CO2e emissions compared to the CO2e optimization. This is due to the fact that 86% of the demand for barley came from German cities. In the distance optimization, all barley was produced domestically and also in the CO2e optimization all German consumption centres derived their barley from within the country. The difference in emissions results from small location changes within Germany, and from changing barley supply for Brazil. Emissions from maize were increased by 56%, for oil and wheat they were more than twice as
high, and for sugar even 3.6 times higher when produced locally. The reasons for these higher values differ. For barley, maize and wheat higher emissions from cultivation and harvest were mainly responsible for the weaker performance of local production. Since the same per hectare emissions were assumed for both countries, higher emissions were the consequence of larger area requirements due to a production on fields with lower productivity. Fig. 4b illustrates that in particular these three crops covered more area in the local production scenario. The explanation for the higher emissions from oil production is more complex. As for barley, maize and wheat, changes in the emissions from field production explained the differences between the model settings. But for oil the area demand was slightly lower in the distance optimization. The effect was caused by the different crops used in the two countries to produce oil. In the local production scenario, oil crops, in form of rapeseed, were grown in Germany. Rapeseed has higher per hectare yields and its use therefore led to decreased occupation of land, but with higher per kg CO\textsubscript{2}e emissions. For sugar mainly the higher emissions from transport to the factory explained the differences between the scenarios. When geographic distances between field of production and place of consumption were minimized, the distances between field and factory increased. This effect, together with higher emissions from sugar beet production within Germany, explained the large increase in emissions for sugar in the distance optimization. In general, however, transport emissions played a minor role: in the distance optimized case transport emissions made up only 2 or 3% of the total greenhouse gas emissions. Only for oil and sugar transport emissions represented a significant share with 8 and 70% respectively. Under CO\textsubscript{2}e optimization the transport share in emissions grew to 10% for barley and about 20% for maize, oil and wheat. For sugar it was reduced to 56%.

Higher emissions in the local scenario were thereby only partly a consequence of selecting few cells with very high CO\textsubscript{2}e emissions. The minimization of distances between production and consumption led for most crops to a selection of cells with a wide range of per kg CO\textsubscript{2}e emissions values (see Fig. A4).

A clear specialization of the two countries in the production of the food commodities became visible in the CO\textsubscript{2}e optimization (see Fig. 4b), whereas in the distance optimization the distribution of production areas between the two countries reflected demand. For instance, 88% of the demand for maize came from Brazil, and 87% of the area used to produce maize was located in Brazil, when distances were minimized. For barley and wheat, whose productivity was comparatively low throughout Brazil, the share in area was somewhat higher than the share in demand; for sugar it was the other way round. In the CO\textsubscript{2}e optimization in contrast, almost all maize, oil and sugar was produced in Brazil, while barley and wheat were mostly originated in Germany. This emphasizes the importance of trade between the two countries, if CO\textsubscript{2}e emissions are to be minimized. Fig. 4b also shows that local production required significantly more land area across all crops. In the CO\textsubscript{2}e optimization the model had a direct incentive to reduce area, to avoid emissions from cultivation and harvest. Production was therefore concentrated in the most productive areas. This incentive was missing in the distance optimization, where in total about 50% more land was used.
3.4 Sensitivity analysis

Only very small changes to the standard CO₂e optimization were observed for the pseudo-inclusion of whole oil crops and when on-shore transport was assumed to be partly by rail and barge (also see S2 Information). When all cropland within the cells was made available to the model, crop production centred on the most productive areas and cropland area was reduced by 5.5%. Increasing demand increased cropland disproportionately. Small changes in crop allocation were observed but in total the crop production pattern remained relatively stable compared to the CO₂e optimization. Changing emissions from cultivation and harvest from a per area calculation to a per yield calculation resulted in a crop allocation that more resembled the distribution of the distances optimization. In this case yields did not influence emissions anymore and transport emissions became the only factor influencing the allocation. When the competition between cities was neglected by including Berlin as the only consumption centre, slight differences in crop allocation were visible (Fig. 5). While in the standard model run, the production of wheat and barley was more clustered around Berlin, the production was more greatly distributed when only Berlin demanded resources. In contrast, the cultivation of maize and soybean in Brazil was more distributed in the optimization for all cities, than in the singular optimization for Berlin. However, the overall differences between these two approaches were rather small. In both cases, Berlin sourced all of its sugar and oil from Brazil, and all barley and wheat were produced within a distance of 250 km. The biggest difference emerged for maize. Under competitive conditions, if demand of all cities had to be fulfilled, all maize for Berlin was produced in Brazil. Without this competition, 71% of the maize was produced domestically.

![Food sourcing of the city of Berlin](image)

Fig. 5. Food sourcing of the city of Berlin. a) standard optimization: minimization of CO₂e for all cities, results shown only for Berlin. b) optimization performed with Berlin as the only city in the model.

4 Discussion

It seems plausible, at first glance, that producing crops locally would cause fewer emissions since they would have to be transported over shorter distances. However, for staple crops emissions from transport usually make up only a small percentage of the total greenhouse gas emissions. It can
therefore be environmentally favourable to transport goods with a favourable carbon balance in production over longer distances.

The study presented here addressed this question with a spatial optimization model based on potential yield distributions, and greenhouse gas emissions from a life cycle assessment database. This way we were able to include the spatial dimension that is needed to assess effects of land-use competition, while taking advantage of the details in LCA data. We thereby followed a rather theoretical approach, asking how the optimal crop allocation would look like with respect to greenhouse gas emissions from production and transport, irrespective of how this could be achieved. This is in contrast to earlier studies (e.g. Avetisyan et al., 2014), who assessed in an economic model how a tax induced substitution of domestic for imported food would change emissions. Our model was based on a simplified two country problem, since a representation of global food production and trade patterns was infeasible. The questions addressed here could also have been studied in a fictive landscape, but a decision to employ real world data was made for illustrative purposes and because real data represents real properties best.

Of course, there are other reasons aside from minimizing greenhouse gas emissions that can justify local production. Many consumers are motivated to buy locally by their desire to support local farmers and their perceived better knowledge of production (IGD, 2005). A diversification of local crop production can reduce susceptibility to extreme weather events. Finally, a high rate of domestic self-supply can also be a policy target due to security considerations.

4.1 Local production for low emissions?

The results of this study show that a merely local or regional production is suboptimal with respect to the reduction of greenhouse gas emissions in the agricultural sector. Minimizing greenhouse gas emissions from production and transport led to a pattern where large shares of crop production were not coming from regional sources, even though a domestic production would have been possible. The majority of the wheat and barley was produced in Germany, and most of the sugar, oil and maize was allocated to Brazil. The comparison with a simplified scenario of local production also showed that greenhouse gas emissions in the CO₂-e optimized case were much smaller.

International trade lowered overall greenhouse gas emissions, also because in general emissions from cultivation and harvest were substantially higher than those caused by transport. The low transport share in total emissions found in our study is in line with earlier studies. Lehuger et al. (2009) found that imported soybean meal had a lower global warming potential in French dairy farming than a diet based on domestic rapeseed, also because the transatlantic shipping contributed only 3% to the overall impact. Baumgartner et al. (2008), on the contrary, reported lower emissions for feeding German pigs with European grain legumes than for the use of soy imported from Argentina and Brazil. However, it were not the higher emissions from transport that explained this – transport emissions were also comparably low – but the assumed land transformations for the production of soy in Brazil. This indicates the importance of land-use change emissions and also explains how similar studies can come to different results. In our study we restricted the allocation of production to current cropland areas and therefore neglected land-use change. Both studies of Lehuger et al. (2009) and
Baumgartner et al. (2008) did not consider the question of land-use competition that we addressed in our approach. The reduction of on-field emissions by an intelligent, spatial allocation of crop production is important because other options to reduce these emissions are limited. For our study we relied on emission factors from a life-cycle-assessment database (ecoinvent Centre, 2007). This data considers emissions caused by the production up to farm gate from a number of sub-processes, like N₂O emissions from fertilization and CO₂ emissions from machine usage. It also comprises emissions caused further down in the production chain, for instance for the creation of tractors or energy use for the production of fertilizers. The single most important source of greenhouse gas emissions was for most crops the nitrogen fertilization. For wheat and barley, the application of an ammonium nitrate fertilizer accounted, for instance, for about 35% of the overall CO₂e emissions. Soybean forms an exception, as it is a nitrogen fixing crop, and does not require the application of an N fertilizer. For sugarcane, whose production caused relatively low emissions in total, farm level transport played a larger role.

Mitigation measures exist to help reduce GHG emissions associated to most of these aspects of agricultural management. Agricultural machinery could for instance use biofuels, but it has been questioned whether this really decreases emissions (Searchinger et al., 2008). Emissions from nitrogen fertilization could be reduced by lower fertilization rates, more frequent but smaller doses, or with nitrogen inhibitors (Bell et al., 2015). However, the effects on yields and the additional emissions for more tractors usage have to be taken into account as well. It is therefore unlikely that emissions from cultivation and harvest of staple crops get lower than those from transport in the near future, so that trading crops will remain to lead to a reduction of emissions.

4.2 Land-use competition

One basic assumption of our study was that competition for land plays an important role in deciding where crops are optimally allocated to minimize greenhouse gas emissions. The results, however, provided only limited evidence for the importance of this effect given our model parameterization. The two model modifications intended to test the influence of this competition effect - optimization for single crops and optimization using only one single city - showed only minor differences compared to the standard model with all seven crops and 224 cities. The sensitivity of the model towards the availability of land within one grid cell was also relatively low: if more cropland was made available to the model this did not greatly change the overall distribution of crop production (see S2 Information). In any case, the crop allocation was strongly influenced by the spatial distribution of potential yields.

A slightly more pronounced effect was seen if the parameters were changed towards more intensified land-use competition. When the overall demand level was increased, this partly led to a production of wheat in areas where under lower demand oil was produced. The already low production of maize in Germany was reduced to zero, and the share in production of barley and wheat slightly shifted to Brazil. While these effects were still of minor importance for the overall carbon footprint of food production, they indicate that the ratio between yields and demand might have been too high to lead to a strong competition effect. Yields in the model were potential production capacities from GAEZ
(IIASA/FAO, 2012), and observed yields are commonly lower than potential ones; a so-called yield gap exists between them. Nevertheless, we had to rely on these potential yields, since no actual crop yield information is available for crops where they are currently not produced. Furthermore, the demand in the model was determined by the amount of agricultural products currently available for consumption in the two countries. Since in reality trade relationships with other countries exist, this demand can be smaller than the actual amount currently produced within the two countries. In 2009, for example, Brazil exported about 50% of the 57.3 million tonnes of its soybean production. Germany, in the same year, imported only 3.2 million tonnes of soy. So for soybeans the amount that the model needed to produce was much smaller than the present production on Brazil’s agricultural areas.

For our study we cannot finally answer whether it was the specific example of Germany and Brazil with the yield, city and factory distribution that we used, or a too low demand to yield level that led to a seemingly low land-use competition. Further research should therefore study competitive effects for different combinations of countries.

4.3 Limitations

A number of simplifying assumptions had to be made during the construction of the model. For several aspects a sensitivity analysis was performed, for others their influence on the model results is less clear. In general, however, it should be kept in mind that it was neither the aim to produce completely realistic land-use patterns with the model, nor to represent the agricultural sector in a perfect way. We decided to model a two country world with Germany and Brazil. Further simplifications were needed to compute the model on a relatively high geographic resolution, e.g. only one transport connection between the two countries (Santos - Hamburg) could be implemented. And while the transportation network was represented with a high level of detail we are aware that the model simplified reality. Goods for instance are often transported to distribution centres before reaching the consumer. For oil we assumed that extraction takes place at the closest factory, while in reality soybeans may be shipped from South America to the Netherlands where oil is produced and then subsequently transported to other European countries (Kastner et al., 2011). Furthermore, our analysis was based on the current, static distribution of factories. An altered distribution of crop production would likely also cause a reallocation of factories, which would in turn lead to a reduction of transport emissions. However, we believe that the simplified representation of the transportation network is not a major concern for the results presented here.

Potentially the biggest known uncertainties came from the life cycle assessment input data and the way it was used. Such data is usually prepared based on data from a small study region. Here it was extrapolated to whole countries, even though its representativeness at this scale could be questioned. For instance, the process of sugar beet production used here assumes green manure before the beets are produced (Nemecek and Kägi, 2007), while in Germany, this is only performed on 38% of the area (BISZ, 2013). For sugar cane 20% mechanical and 80% manual harvest are assumed, while legislation requires 100% mechanical harvesting by 2021 in the State of São Paulo (Jungbluth et al., 2007). Also the heterogeneity in farming practices, soils and climatic conditions could lead to strong regional differences in emissions. The sensitivity analysis (see S2 Information) has revealed that the way this data was fed into the model is of major importance. In our model we assumed emissions from
cultivation and harvest to be independent of crop yields. When in the sensitivity analysis emissions were instead defined as a function of crop yields, results differed strongly. The reality will probably be somewhere in between these two extremes. Emissions from field preparation and seeding operations should be predominantly a function of farmed area. The amount of fertilizer needed, however, will be higher if more nutrients are removed with the harvest on high yielding fields. The precise relationship between different climatic and edaphic conditions, yields and the emissions caused by cultivation and harvest remains unknown. Charles et al. (2006) studied the greenhouse gas emissions of wheat production under different fertilization intensities and found that high rates caused lower emissions if they were normalized to the same wheat quality. Nemecek et al. (2012, 2011a, 2011b) performed a geographical extrapolation of LCA data and found an increase in global warming potential per hectare with increasing yields as a result of higher farming intensity. In contrast to these studies we explicitly wanted to exclude yield differences resulting from different management intensity and assumed the same management in all regions in calculating emissions. Potentially the biggest improvement in our emission estimates could be made if N₂O and NO emissions were calculated cell-wise based on adaptive fertilizer application rates, soil and climate conditions as done by Bouwman et al. (2002). In general, however, we believe that places with more favourable climatic and edaphic conditions will in any case produce higher yields irrespective of fertilizer inputs, so that our general results remain valid.

The other main limitations of the optimization model presented in this study were a consequence of the boundary conditions. For this study we have decided to focus on five important food commodities in each of the countries. While this is better than looking only at one crop at a time, it is far removed from a full coverage of the agricultural sector. It was for instance beyond the scope of this study to consider the by-products of sugar and oil production. Soybean and rapeseed meal are important animal feed, but their modelling is complicated by the need to adapt complete feed rations if they are to be substituted (LiF, 2012). Additionally, the allocation of crops in our model was limited to the current cropland area. This means that no direct land-use transformations from forest to cropland could occur. It would, however, be naive to assume the absence of indirect land-use effects, although this is strongly influenced by policy (Nepstad et al., 2014). There is one aspect that lessens this problem in our model, namely that the area needed for production was reduced when CO₂e emissions were minimized. If the then unused cropland were covered by vegetation with a higher carbon content, such as forest, that would further reduce the emissions from the CO₂e optimized scenario compared to the local production strategy.

Given all the uncertainties discussed, we still believe the main outcomes remain valid and shed light on the problem of producing food commodities regionally or globally. Due to the relatively low share of transport in the overall emissions, production should be placed at locations that lead to low emissions on field.

5 Conclusion

Deep emission cuts are urgently needed – not least in the agricultural sector - to mitigate ongoing climate change. This could partly be achieved with an intelligent allocation of agricultural production. Our study presents an optimization approach, where spatial optimization modelling was used in
conjunction with agricultural life cycle assessment data. This approach can be used to identify a more optimal production allocation under limited availability of land, and shows which agricultural products should be traded to reduce greenhouse gas emission from production and transport. However, such modelling is strongly restricted by data availability and uncertainty on the one hand, and computational resources on the other. In order to be able to extend this approach to larger geographical areas, future research will need to identify which level of model detail is needed to capture most important real world properties.

Counting food miles has been criticized as being too simplistic to assess the climate impact of food production. This study adds new evidence that for staple crops local production is not always a way to lower greenhouse gas emissions. We have shown that in order to minimize emissions from production and transport, it can be beneficial to source some food commodities from further away, even from another continent. In the example of the two countries studied here, Brazil and Germany, this result held true even when land-use competition was accounted for, and if the demand of the exporting country had to be fulfilled as well. The advantage of non-local production is thereby explained by the minor importance of transport emissions compared to those caused by the production up to farm gate. On field emissions are influenced by yield differences which are in turn a consequence of soil and climate conditions. They can vary even stronger between different regions if different crops are used to produce the same commodity, as has been shown for the example of sugarcane and sugar beet cultivation for the production of sugar.

When buying locally, consumers have so far mainly focused on fresh products like fruit and vegetables; less attention has been placed on staple crops (IGD, 2005). Our study suggests that this should remain the same. Food commodities like sugar, oil and wheat should rather be produced where the crops grow best, and then be traded internationally in order to cause fewer greenhouse gas emissions.
Appendix

Fig. A1. Emissions from agricultural production as a classical example of comparative advantages.

Example of two port cities (A and B) in two countries that need to be supplied with two different crops (β and γ). These crops can be produced on two fields in each country. While the production of γ leads to three emission units (EUs) in both countries, the production of β leads to two EUs in country A and five EUs in country B. a) domestic production results in 13 EUs in total. b) international trade of both products decreases the amount of emissions (10 EUs). Emissions are lower even if we assume that international transport caused 2 EUs. We would not see any advantage of trading γ, if we only look at the emissions of γ. Would we only look at the demand of city A we would also not see an advantage of trade. Lastly, we would think it would be best to produce all of β and its own demand for γ in country A, if we would not know that area is limited and only two fields are available for production. To be able to capture these effects requires a spatially explicit model with several products and demand centres.

Fig. A2 Location of municipalities (grey dots) and consumption centres (blue symbols)
Fig. A3 Location of sugar refineries and oil mills

Fig. A4 Distribution of emissions values of all cells used for production. Solid lines indicate the median of the distribution. Dotted lines represent the median of all cells theoretically available for the production of one food commodity.
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