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Urban food systems: how regionalization can contribute to climate change mitigation

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Abstract

Cities will play a key role in the grand challenge of nourishing a growing global population, because, due to their population density, they set the demand. To ensure that food systems are sustainable as well as nourishing, one solution often suggested is to shorten their supply chains towards a regional rather than a global basis. Whilst such regional systems may have a range of costs and benefits, we investigate the mitigation potential of regionalized urban food systems by examining the greenhouse gas emissions associated with food transport. Using data on food consumption for 7,108 urban administrative units (UAUs), we simulate total transport emissions for both regionalized and globalized supply chains. In regionalized systems, the UAUs' demands are fulfilled by peripheral food production, whereas to simulate global supply chains, food demand is met from an international pool (where the origin can be any location globally).

We estimate that regionalized systems could reduce current emissions from food transport. However, because longer supply chains benefit from maximizing comparative advantage, this emission reduction would require closing yield gaps, reducing food waste, shifting towards diversified farming, and consuming seasonal produce. Regionalization of food systems will be an essential component to limit global warming to well below 2 °C in the future.

Introduction

Cities are vital for sustainable consumption due to their extreme densities of consumers of goods and services and the consequent concentration of production of externalities, such as greenhouse gas (GHG) emissions.[1] Cities are hubs for innovations and development of solutions[2] and exist at a scale that allows for grassroots interventions of policy and significant potential impact, compared with central or community governance.[3] As the urban population will grow up to 66% of the total by 2050,[4,5] it is somewhat likely that urban food transport will play an increasing role in urban mitigation efforts.[6] Therefore, choices made about how to nourish growing urban populations will have significant consequences for global sustainability.

With globalization, diets are becoming homogeneous worldwide,[7] underpinned by the production of a handful of crops at huge volumes. Whether globalized food systems can provide sustainable food security under climate change is contested. On the one hand, current food trade provides nutrient access to some poorer countries,[8] and liberalized trade maximizes countries' comparative advantages and could buffer agriculture losses due to climate change.[9] On the other hand, globalization might make food systems more sensitive to climate-related disruptions[10,11] and might exacerbate environmental impacts associated with food production (e.g., tropical deforestation[12] and nutrient pollution[13,14]). Based on more local production, regionalized food systems could be an alternative to globalized ones, with multiple potential benefits. These benefits are reduction of food transport emissions, recycling of nutrients, resilience to trade interruptions, integration between producers and consumers, assurance of quality food, and supporting regional rural economies.[15] In 2010, urban and peri-urban agriculture could nourish around 30% of the global urban population.[6]

Food systems have emitted 21–37% (10.8–19.1 Gt CO_2e/yr) of the total anthropogenic GHGs during the period 2007–2016.[16,17] Within food systems, 2.6—5.2 Gt CO_2e/yr come from beyond farm gate, including manufacturing of fertilizers, food processing, transport and retail, and food consumption. Fulfilling the urban calorie demand requires transporting food over long distances.[18] Based on the life cycle assessment, Poore and Nemecek[19] estimated the global food transport emissions of 0.8 Gt CO_2e/yr in 2010 (i.e., 6% of the global food system emissions of 13.7 Gt CO_2e/yr). Until transport systems rely on fossil fuel, reducing global transport emissions will be a challenge. Additionally, the demand to move people and goods around the world is growing under current business models.[20] However, rapid decarbonization towards net-zero GHG emissions by 2050 is a prerequisite for limiting global warming well below 2 °C.[21] Therefore, we need to explore and identify all option space to mitigate GHG emissions from all sectors.[22]

The concept of regionalizing food systems is becoming popular in many major urban centers and debated in the academic literature. However, systematic investigation of their capability to sustainably ensure food security is limited.[23] We analyze the emissions reduction potential from food transport for 7,108 urban administrative units (UAUs) worldwide (covering around 50% of the global population in 2010) by sourcing food to meet the city needs as regionally as possible. For each UAU, we simulate a *foodshed* that is defined as the area required for producing enough food to nourish its population and feed to raise its livestock. We compare UAU foodsheds under *regionalized* and *globalized* food systems.

Materials and Methods

We assume that the nearest possible surroundings fulfill urban food and feed demand in *regionalized* food systems, analogous to von Thünen rings.[24] To nourish an isolated city, von Thünen considered concentric rings of agricultural activity depending on yield, market distance, and cost of production, transport, and land rent. In *globalized* food systems, the demand for each UAU is sampled, at random, from the global pool of producer areas, independent of comparative advantages and transport costs. We explore the potential differences in emissions if foodsheds were assembled at random from global producers or constrained to be as local as possible. While both scenarios are hypothetical, the contrast illustrates the potential for transport emissions to be reduced or increased. Our assumptions for the globalized food systems reflect a more end of globalization, rather than the current situation. The data and the applied methods for this analysis are described in detail in the following sections and the Supporting Information (see Texts S1–S3).

Urban Administrative Unit (UAU)

We consider 7,108 Urban Administrative Units (UAUs) worldwide, covering around 50% of the global population in 2010, by using the data on world cities,[25] the global administrative areas (GADM),[26] and the gridded population of the world (GPWv4).[27] A UAU of a city is considered as the administrative area with a population close to the city population provided by the world cities database (see Text S1 for details). For this, we only account for cities with at least 50,000 people. The world cities database contains information on the city name, the country name, the city population (as in 2006), latitude, and longitude.[25] The GADM database provides the location of the administrative boundaries within the countries. GPWv4 consists of raster data on the UN-adjusted world population at 30 arcs second resolution. A UAU may also consist of urban and peri-urban agriculture together with human settlements.

Urban Foodshed

We simulate urban foodsheds as either *regionalized* or *globalized* food systems. We identify urban food miles and emissions for both systems due to food transport into UAUs for the years 2010 and 2050 (see Texts S2 and S3).

Regionalized Food Systems

In regionalized food systems, we start by simulating the foodshed of the UAUs for each city worldwide at the same time. Figure 1 provides a simple schematic diagram of the applied methodology. For all the UAUs, we check whether the produced crop and animal calories within the UAU are enough to meet its food and feed demand based on gridded data on food and feed consumption,[28,29] and production of the crop and animal calories at five arc minute resolution[28,30] (see Text S2 for details on data). When this is the case, we consider the UAU itself as its foodshed. Otherwise, we simultaneously create a buffer of ten kilometers around the rest of the UAUs. To avoid overlapping, the grid cells (now forward mention as "cells") that do not belong to another UAU or its buffer, are only assigned as the buffer of a single UAU. The buffers are initially expanded within the national territory, reflecting a country's typical priority to source food from within the country, all things being equal. We identify the buffer as the foodshed of a UAU when the produced calories within the buffer and UAU equals or exceeds its demand. Otherwise, we simultaneously keep expanding the buffer in ten-kilometer steps. This expansion is halted when the food and feed demand is met, or the buffers take all country's territory.

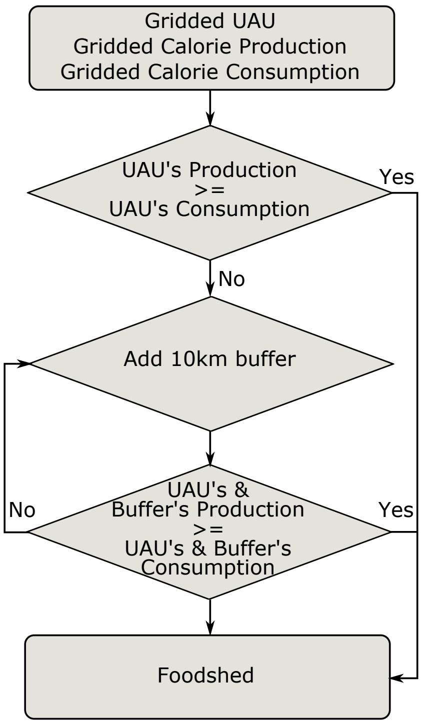

Figure 1: A simple schematic diagram shows the applied method to simulate foodsheds of Urban Administrative Units (UAUs) in a regionalized food system.

For the UAUs in which food and feed demand are not fulfilled within the national territories, we simultaneously restart the process to identify the foodshed from the very beginning by creating a buffer of ten kilometers around the UAUs. This time international territories are included in the buffers. As mentioned above, we assign the buffer as the foodshed when the produced calories within the buffer and UAU is enough to satisfy its food and feed demand. That means we consider foodsheds as food self-sufficient regions where food demand of both its urban and rural populations are met.

Globalized Food Systems

To approximate the foodsheds of globalized food systems, we start by randomly selecting a UAU, extracting its geographic location, and estimate its total food and feed demand. The latter value corresponds to the total calorie demand that needs to be supplied. Subsequently, we accumulate randomly selected cells containing the total calorie production amount until the total calorie demand of the UAU is fulfilled. These cells are considered as the foodshed of the UAU, and the amount of calories used are no longer available for other UAUs. The above procedure is repeated to identify the foodshed of the remaining UAUs. We carry out this analysis 1,000 times and estimate the average food miles and emission due to the food transport of the UAUs.

Food Miles

Food miles of a UAU is defined as the distance calories are transported by land or sea to meet its food and feed demand, excluding food transport within UAUs. We multiply the calories supplied by each cell of the foodshed and the respective Euclidean distance of the cell to the UAU (see Text S4). The product of the calories and the distance reflects the contribution of individual cells to the UAU food miles. We add up all the products to estimate the food miles.

These methods estimate the total distance traveled by food (the food miles) to meet the current needs of the UAUs under regionalized and globalized supply chains. In regionalized food systems, some buffer cells could also be net calorie consumers. In this case, the calorie demand of these net consumers also needs to be supplied by the foodshed, but the respective food miles are not accounted for the total food miles of the UAUs.

Emissions due to Food Transport (EFT)

A UAU's emissions due to food transport (EFT) depends on the distance food is transported (the food miles) and the mode of transport, which defines its emission factor of transportation (whether by land or sea: 119.7 g CO_2/t-km by road and 12.1 g CO_2/t-km by sea[31]). We consider the global emission factor of transportation for land and sea because data on country-specify emission factors for agriculture transport is limited up-to our knowledge (see Text S4).

Land and sea food miles estimated from the foodshed based on data in 2010 are calculated by summing up the products of the supplied calories and the transport distance via land and sea, respectively. Traditionally, transport emission factors are provided in grams CO_2 per tonne-kilometers (g CO_2/t-km), while we estimate the food miles in calories-kilometers (kcal-km). To convert food miles in "kcal-km" to "t-km", we derive a ratio of the total food availability in tonnes and calories for a country.[29] EFT is estimated as the multiple of the sum of land and sea food miles by the emission factors for road or maritime, respectively. We assume all food is transported by land or sea, not air, and do not differentiate between bulk or containers for maritime transport. For land, we consider food transport via road because of broader geographic coverage of the road network than the rail network (around 47 times larger in length). Depending on countries, the share of food transport via road and rail can vary a lot. For example, more than 95% of agriculture commodities are transported by train in Poland but around only 30%, in Ukraine in 2018[32]. Thus, this assumption would overestimate EFT because rail transport has a lower emission factor than the road. However, not considering air transport would underestimate EFT. Similarly, we provide a conservative estimate of transport emissions by not accounting for retailing in our study since the food transported within UAU is excluded in our definition of food miles. Transport and retailing contribute to 6% and 3% of the global food system emissions in 2010.[19]

Additionally, we compare our estimated EFT with the food transport emissions reported by Poore and Nemecek[19], i.e., the global food transport emissions of 0.8 Gt CO_2e/yr in 2010. Given that around 50% of the global population are urban inhabitants (in 2007),[33] we derive the current urban food transport emissions of $\approx$0.40 Gt CO_2e/yr (i.e., 50% of the global food transport emissions). This estimate is conservative because the food transport emissions are equally divided between urban and rural inhabitants. Many rural inhabitants have shorter supply chains than cities around the world.

Scenario analysis

Scenario analysis is used to understand the sensitivity of ETF to alternative socio-economic and technological developments for the years 2010 and 2050 (see Tables 1 and 2). For these scenarios, we consider variations in demand and production of food and feed under both regionalized and globalized food systems. Initially, we simulate the *baseline* accounting for the 2010 demand and production of food and feed (see Text S2.1). Since the baseline considers the existing food production patterns for 2010, the GHG emissions from food production remain unchanged.

It is argued that global trade enhances comparative advantage and efficiently boosts production, and a regionalized food system is likely to be less productive. To explore the extent of this argument, we model two scenarios for 2010: one where the food waste, i.e., food discarded by consumers, is halved (see Text S2.2). Currently, food demand is 1.2 times of that required, with 20% of calories being wasted.[34] In practice, we assume demand can be locally cut to ≈1.1 times of that required. However, food loss, i.e., reduced edible food during production, post-harvest, and processing, is not accounted for in this study.

Another scenario we model is if, through technology and innovations,[35] yield gaps were closed to 75% of their local potential (see Text S2.3). Currently, most countries in Sub-Saharan Africa, Eastern Europe, and South Asia have achieved less than 40% of their local potential calorie production.[36] Closing the yield gaps can also alter GHG emissions associated with food production. However, these emissions are beyond the scope of our study. We investigate the effects of halving food waste (*food waste*) and closing yield gaps (*yield gap*) individually and in combination (*food waste and yield gap*) for the year 2010 (see Text S2.4). Moving beyond total calories, we analyze foodsheds separating the demand and production of the eight *food groups* in 2010, namely: animal products, fruits and vegetables, cereals, oil and oil crops, pulses, roots and tubers, sugar and sweeteners, and stimulants (see Text S2.5).

For 2050, we consider the following factors for designing the scenarios: demographic growth, dietary changes, feed conversion efficiency, food waste reduction, and crop yield under climate change. In these scenarios, the emission factor of transportation is kept constant as for 2010 to limit the considered factors while designing the scenarios. Potentially, a large number of scenarios can be developed using these factors (Figure S1). However, we simulate six scenarios, including the lower and the upper bounds, which can capture a multitude of futures (see Table 2 and Text S3 for details).

Scenario I is the lower bound, which accounts for population growth from the Shared Socioeconomic Pathway II (SSP2),[37] potential crop yields under the Representative Concentration Pathway

(RCP) 2.6 with the CO_2 fertilization effect (i.e., closing yield gap by 100%),[30] and per capita food demand of the year 2010[29] (Text S3). SSPs are a set of narratives, describing alternative socio-economic developments, indicating a range of challenges for climate change mitigation and adaptation.[38] Among SSPs, we choose SSP2 that is considered the middle of the road scenario, because it describes a future that follows the historical trends. The RCPs are a set of scenarios representing different levels of climate change based on a wide range of radiative forcing that arises from different levels of atmospheric concentrations of GHGs.[39] RCP 2.6 assumes peaking of global annual GHG emissions between 2010—2020, resulting in global mean temperature change of 0.9–2.3 °C.[40] We consider that yield gaps are closed by 2050, in line with increases in agriculture productivity of smallholder farmers as envisioned by Sustainable Development Goals (SDGs).[41]

Scenario II additionally accounts for the reported shifts towards rich diets building on Scenario I.[28,42] We design Scenario III, considering an improvement in livestock feed conversion efficiency[43] as an add-on to Scenario II. Scenario IV accounts for 75% reduction of the food waste besides the considerations of Scenario III. We consider the 75% reduction by 2050, assuming that food waste would be halved by 2030 as targeted by SDGs. Scenario V separates the CO_2 fertilization effect on crop yields from Scenario II. Scenario V is the upper bound that investigates high-end impacts of climate change on the urban foodshed by accounting for the crop yields under RCP 8.5 without the CO_2 fertilization effect. The RCP 8.5 assumes a continuous increase in global radiative forcing throughout the 21st century, resulting in global mean temperature changes of 3.2–5.4 °C compared to pre-industrial levels.[40]

Results

In 2010, the UAUs contributed to around 26% of the global calorie production but consumed around 43% of the produced calories. Whilst many urban centers, in regionalized food systems, would have foodsheds of radius <100 km, some UAUs would still require >5,000 km (Figure 2).

In total, ≈80% of the consumed calories are transported 500 km or less. Under globalized food systems, the average distance is up to 9,000 km to meet the calorie demand of 80% of the UAUs. This variation in distances highlights the substantial underlying differences in urban foodsheds between the two explored systems. The following sections focus on the critical variations of food miles and EFT associated with these two systems for the years 2010 and 2050.

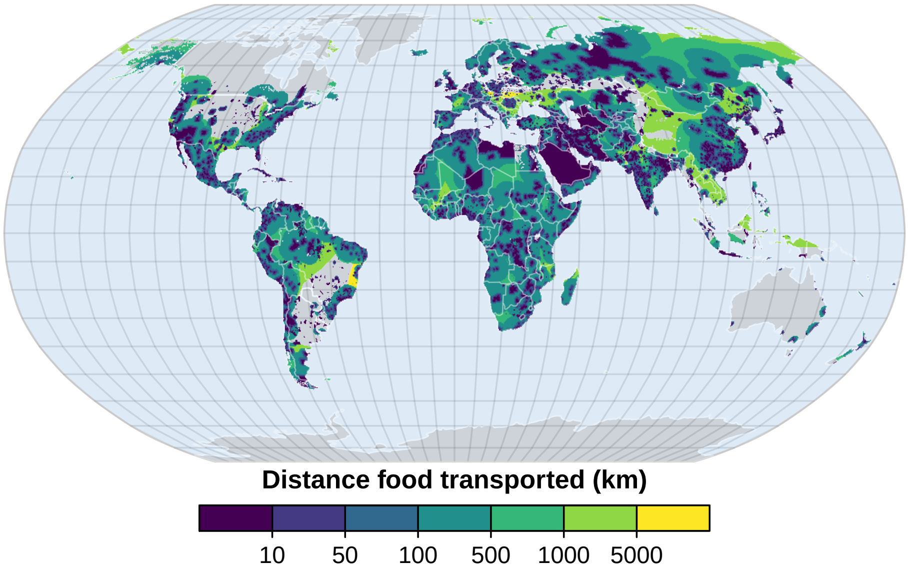

Figure 2: The distance that food produced in each cell needs to be transported to meet the urban administrative units' demand under regionalized food systems (the year 2010). Blue colors represent shorter transport distances, yellow colors longer ones.

Regionalized vs. Globalized Food Systems

In 2010 baseline, the food miles vary significantly between <10 and $>10^{10}$ million kcal km/year among UAUs when modeled assuming regionalized system (Figure 3). If UAUs regionalized their food systems, those in the food-producing subcontinents (e.g., North America, Europe, South Asia, and South East Asia) would have relatively lower accumulated food miles ($<10^6$ million kcal km/year) because of their potential to meet the demand regionally. Since we consider production and consumption of total calories for the baseline, for regionalization to occur, the present food system would need to be restructured both from the production and consumption sides. In particular, this restructuring requires diversifying cropping to produce a variety of products and shifting diets towards more regional and season products. Despite these changes, the regionalized production of some particular crops (e.g., mango, avocados) cannot be feasible due to specific agro-climatic requirements. These requirements indicate the existence of clear limits to the regionalization potential of food systems.

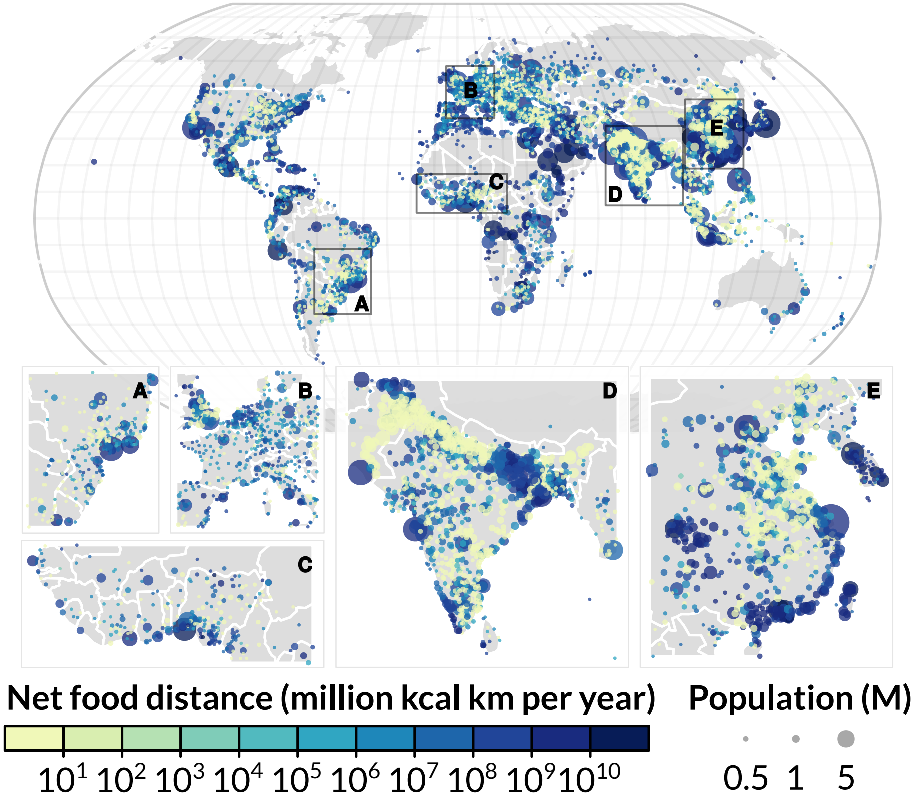

Figure 3: Under regionalized food systems, the food miles associated with urban administrative units varies considerably across the world. The circle size represents the population in millions (M). The color scale is logarithmic and represents food miles of a regionalized food system that would fulfill the calorie demand of urban administrative units in the year 2010.

UAUs with regionalized food systems in the subcontinents with higher population densities or more limited agricultural production capacities (e.g., East Asia and Middle, North, and West Africa) would have cases with total food miles larger than 10^8 million kcal km/year (Figure 3 and Tables S1–S2). Such UAUs necessarily depend on international trade for their food. Under globalized food systems, the total food miles for UAUs converge to large values ($>10^8$ million kcal km/year) regardless of socioeconomic and geophysical characteristics as the demand is met randomly from the global market (Figures S2-S3 and Tables S1-S2).

Our results indicate that an essential benefit of regionalized food systems would be to cut the current total EFT for urban inhabitants by more than half (Table 1). Conversely, under globalized systems, the emissions are more than four times (1.87 Gt CO_2/yr) the current emissions. In summary, regionalization has the potential to reduce total and per capita urban EFT in all subcontinents (Tables S3–S4), and increasing globalization has the risk of increasing transport emissions considerably.

Table 1: The total emissions due to food transport (EFT) to UAUs in Gt CO_2/yr under regionalized and globalized food systems in 2010 considering: i) demand and production of total calories (Baseline), ii) halving food waste (Food waste), iii) closing yield gaps by 75% of potential yields (Yield gap), iv) combination of ii) and iii) (Food waste & Yield gap), v) demand and production of the eight major food product categories (Food groups: animal products, cereals, fruits and vegetables, oil crops and products, pulses, roots and tubers, sugar crops and products, and stimulants). Under regionalized food systems, EFT is more significant in the scenario accounting for food groups than in the baseline because of larger foodsheds while considering different food groups beyond the total calories. However, the opposite is the case under globalized food systems. This scenario deals with a small amount of calories for different food groups than large total value.

Food systems	Baseline	Food waste	Yield gap	Food waste & Yield gap	Food groups
Regionalized	0.15	0.10	0.09	0.06	0.29
Globalized	1.87	1.75	1.87	1.75	1.74

Food Waste

Halving food waste, and therefore reducing the demand for agricultural products and their transport, also has a positive effect in reducing food miles and, in turn, associated transport emissions. Reducing food waste has a more significant effect under regionalized rather than globalized food systems, i.e., 30% and 6% emission reduction compared to the baseline, respectively (Table 1). A substantial reduction effect under regionalized food systems can be traced to a relatively low EFT under the baseline. In absolute terms, halving food waste decreases EFT by 0.05 and 0.12 Gt CO_2/yr from the baseline under regionalized and globalized food systems, respectively.

As might be expected, this transport emission reduction potential by saving food varies across the world (Tables S1–S4). The potential is lower for UAUs in subcontinents with higher food self-sufficiency (e.g., 20%–30% compared to baseline under regionalized systems in North America, West Europe, and North Europe). In contrast, UAUs in subcontinents with lower food self-sufficiency would benefit mainly by halving the food waste. Reducing food waste would decrease their food miles and associated transport emissions (e.g., $>50\%$ of emission reduction compared to baseline under regionalized systems in East Asia, West Africa, and South Africa). Additionally, saving food also contributes to mitigate GHG emissions from the agriculture sector and to enhance local and regional food security.[34,44,45] In return, the regionalization of food systems can reduce food loss during transport due to shorter supply chains.

Yield Gaps

Closing crop yield gaps is a more effective strategy to reduce transport demand, and thus food miles and transport emissions under regionalized rather than globalized food systems (Table 1). Subcontinents with larger yield gaps (e.g., Africa and Asia) would benefit more through decreased transport distance and emissions (Tables S1–S4). The current total urban EFT could be reduced to 0.06 Gt CO_2/yr under regionalized systems by halving food waste and closing yield gaps to 75% of potential yields (Table 1). All subcontinents would reduce their urban EFTs by incorporating both demand and supply management, regardless of their socioeconomic and geophysical characteristics (Tables S1–S4).

Food Groups

When food groups are distinguished in the regionalized food systems, the total urban EFT almost double (0.29 Gt CO_2/yr) compared to the analysis considering the total calorie (baseline). However, they are nevertheless $\approx$17% of the globalized systems' emissions (Table 1 and Figure 4). Still, the regionalized food systems contribute to reducing the current EFT by 25%. Under assumptions of globalized food systems, cereals create more than 30% of the emissions (Figure 4 and Tables S5-S8). This figure might be reduced to half under regionalized food systems, assuming that the production efficiency remains the same. In 2010, cereals provided 45% of the global average calorie supply.[29]

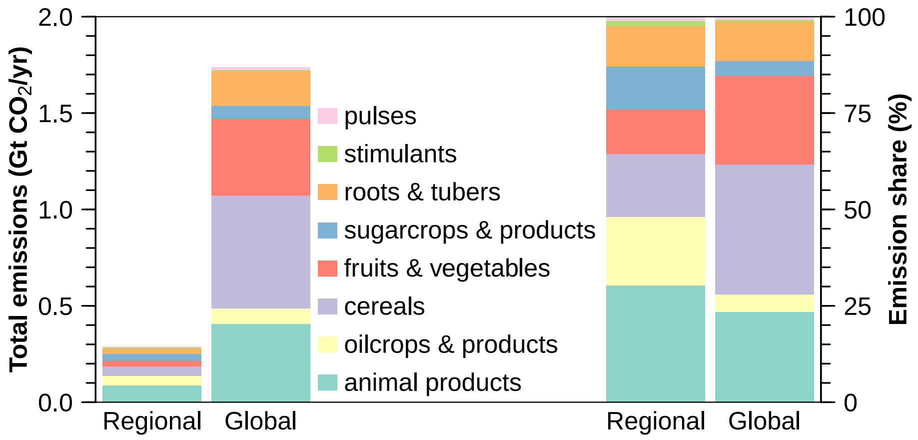

Figure 4: The total emissions due to food transport into UAUs and their shares for the eight food groups, based on demand in 2010, vary between modeled regionalized (Regional) and globalized (Global) food systems.

Animal products contribute the largest share of the emissions (30%) in regionalized food systems, even though only 18% of the average calorie supply comes from animal sources. The transport emissions from oil crops and products (0.051 Gt CO_2/yr) that provide 12% of the average calorie supply are slightly larger than cereals (0.047 Gt CO_2/yr), the major calorie contributor in human diets, under regionalized food systems. That is mainly due to the increasing trade in oil crops used as livestock feed, e.g., soybean.[29] Although fruits and vegetables contribute only 6% of the average calorie supply,[29] they are responsible for 11% and 22% of the total urban EFT under regionalized and globalized food systems, respectively. The transport emissions of these food groups could be reduced by diversification of crop and animal products under regionalized food systems to meet the local demand. Nevertheless, the emissions of the food groups that are mainly produced in special geographical regions (e.g., stimulants like tea and coffee) are comparable under both systems.

Option Space for Regionalization

Globalized and regionalized food systems have different balances of risks and rewards. For globalized, EFT may be higher, but so might production efficiency and exposure to risks of climate impacts. How best to balance these costs and benefits in a context-dependent and holistic way is an important research question. Indeed, given the size of EFT, it suggests the need to internalize the carbon costs of transport into food markets fully. By 2050, the total urban EFT may increase to 0.25–0.92 Gt CO_2/yr and 2.20–3.00 Gt CO_2/yr under regionalized and globalized food systems, respectively (Tables 2, S9–S10).

Table 2: The total emissions due to food transport into UAUs in Gt CO_2/yr in 2050 considering: demographic growth (POP) under SSP2, dietary changes (DC), feed conversion efficiency (FE), food waste reduction (FW), and crop yields under climate change (RCP 2.6 and RCP 8.5) with and without CO_2 fertilization effects (CO_2). The scenarios assume potential crop yields and no agricultural expansion (Figure S1). *May require agricultural expansion to feed the urban population.

	Demand	Supply	Regionalized (R)	Globalized (G)	Ratio (G/R)
Scenario I	POP	RCP2.6 +CO2	0.250	2.203	8.8
Scenario II	POP, DC	RCP2.6 +CO2	0.919	2.999	3.3
Scenario III	POP, DC, FE	RCP2.6 +CO2	0.585	2.771	4.7
Scenario IV	POP, DC, FE, FW	RCP2.6 +CO2	0.441	2.413	5.5
Scenario V	POP, DC	RCP2.6	0.760*	2.999	3.9
Scenario VI	POP, DC	RCP8.5	0.636*	3.002	4.7

Transport emissions are higher under scenarios that only consider an increase in food consumption (Scenarios II, V, and VI), compared to ones that account for food demand management (Scenarios III, and IV). Shifts toward resource-intensive diets with economic development (Scenario II), may result in more than three times the transport emissions than the scenario considering only demographic growth under regionalized food systems (Scenario I). This situation worsens when considering global warming above 2 °C or no positive CO_2 fertilization effects (Scenarios V, and VI). The increments in food miles and related EFT would mainly occur in those subcontinents where diet shifts might be prominent in the future (e.g., Africa, Asia, South America). This diet shits are due to increasing income with development (Tables S9–S10). However, the transport emissions could be lowered by reducing the overall food demand that can be achieved by limiting food waste to 25% and improving livestock feed conversion efficiency (scenarios III and IV).

Discussion

Our discussion focuses on several key findings this study presents on the interplay between urban foodshed, food miles, and food transport emissions. We simulate foodsheds for 7,108 UAUs, representing 50% of the global population. Most of the existing studies on urban foodshed are limited to some cities or countries.[46,47] Our study identifies that 80% of the food demand of the UAUs and their foodsheds, in 2010 could have been provided within 500 km distance (i.e., under our regionalized food systems). However, total food transport distance increases significantly under the globalized food systems scenario.

We highlight the role of local, regional, and seasonal food for climate change mitigation by reducing food miles. In globalized food systems, under the agriculture production and food consumption patterns of 2010, the urban EFT can be more than ten times higher than in regionalized ones. As derived from the recent literature, the current urban EFT of 0.40 Gt CO_2/yr[19] (see Method section for details) can be reduced down to 0.06 Gt CO_2/yr by the regionalization of the urban food systems together with closing yield gaps and reducing food waste. Additionally, for achieving this regionalization, a transformation of the current food system is needed based on shifting towards diversified farming and consuming regional and seasonal products (though some of these may increase emissions in other ways).

Our finding on this emission reduction potential is in agreement with other studies at the country scale. For example, Michalskỳ and Hooda[48] highlights the UK's emission saving potential of 86.7 kt CO_{2eq}/yr by 75% reduction on imports of selected fruits and vegetables by increasing their local production. Whilst consumption of regional and seasonal food can save transport emissions, embodied emissions of non-seasonal regional food can be larger than the same food imported from some regions. These higher emissions can be due to, for example, from additional energy requirement for preserving or growing non-seasonal food.[49] Therefore, we emphasize that the reduction of transport emissions from local and regional food is mainly beneficial when consumption patterns are also changed in favor of seasonal food. The IPCC Special Report on Climate Change and Land highlights that consumption of local foods can reduce emissions when grown efficiently.

However, imported foods may also have low carbon footprints due to lower emission intensities in some cases.[16]

Our study additionally presents the importance of regionalized food systems to reduce the risk of rising EFT in the future. Although many studies show that consumers increasingly prefer local and regional food,[50] the food trade in terms of calories has grown by five times between 1961 and 2011.[29] This growing food trade indicates the rapid globalization of food systems and an increase in the EFT in the future. By 2050, the urban EFT would grow up to ≈3 Gt CO_2/yr under a globalized food system. Such a scenario would comprise 60% of the estimated annual emission budget in 2050 to keep climate change well below 2 °C.[21] Under regionalized food systems, this increase in transport emission can be limited to ≈1 Gt CO_2/yr (Scenario II).

We highlight the importance of reducing food waste and closing yield gaps to nourish the growing population, which also supports the finding of many other studies.[23,34,45,51] However, we supplement the literature by additionally showing the role of supply and demand management to reduce transport emissions. The effect on emission reduction is more prominent in regionalized food systems (30% less than the baseline) than in globalized ones (6% less than the baseline). Thus, strategies for reducing food waste and closing yield gaps need also to incorporate regionalization aspects to maximize emission saving. Otherwise, there is a risk of a rebound effect, mainly an increase in food miles of produced or saved food due to exports.

Our findings, of course, have some limitations. The results presented are based on yield projections from one crop model.[30] We leave the analysis of other crop models for future work. We based our study on data on crop yields from IIASA/FAO[30] because the data is provided at the finer resolution of five arc minutes. In contrast, most of the global crop models have coarser resolutions.

We apply global emission factors to estimate food transport emissions. These factors could be updated by finer-scale data on transport modes, once they are available. We acknowledge the simplicity of using a global emissions factor versus country-specific ones. On the other hand, obtaining country-specific emission factors will always imply the adoption of further assumption, given that detailed information is not available for all countries. This subject is for further study in itself. Similarly, assuming that all food transport by land is done by road probably leads to an over-estimate of transport emissions in some countries. This over-estimate would lower the emission reduction potential of the regionalized food system. Nevertheless, we still provide a conservative estimate by not accounting for other emission-intensive transport modes, e.g., food transported via air.

We also acknowledge the simplification of not changing emissions intensities in the future projection. Nevertheless, this simplification is justified in the light of the recent IPCC report.[52] Electrification is expected to be a powerful measure to decarbonize short-distance passenger travel (e.g., cars, two-wheelers, rails), mainly by changing the fuel mix. In road freight transport, the systemic improvements in supply chains, logistics, and routing (aspects that are mirrored in our regionalized scenario) would be the most effective measures in conjunction with vehicles' efficiency improvement. Furthermore, for the case of High Duty Vehicles (HDV's), the backbone of road transport, it is anticipated that by 2050 bio-fuels will make up 85% of fuel use.[53] This further reinforces the limited scope for a change of intensity factors in freight transport. Additionally, further studies can also consider changes in the potential transport fuel mix in the future since technologies are evolving to utilize renewable energy in freight activities.

On the methods side, we provide the lowest estimates of transport mitigation potentials of regionalized food systems. We consider the Euclidean distance between production and consumption, not accounting for emissions due to food transported via air and energy use during the storage of the transported food. However, when measuring distances between pairs of points in a two-dimensional space, the Euclidian distance is a commonly used metric.[54] Additionally, for regions with dense transport infrastructure, the use of Euclidian distance as an approximation to the correct physical distance can be justified.[55] Nevertheless, our approach can be extended by incorporating the transport infrastructure in the future.

Our study only considers transport emissions but not overall emissions embodied in food. Due to variation in emission intensities of agriculture products across the world,[29] regionalized food systems may suffer from rebound effects by increasing production in countries with high emission intensities. This rebound may result in a more significant amount of emissions than emission saving from a short supply chain.[56] However, these countries can also lower their emission intensities while closing their yield gaps. Under regionalized food systems, efficient distribution systems and improvement in emission intensities are required to lower the overall embodied emissions.[57]

Limiting global warming to well below 2 °C, as agreed in Paris in 2015, requires significantly increasing efforts. Specifically, it requires an unprecedented decrease in global emissions from fossil fuel and industry to 5 Gt CO_2/yr by 2050.[21] For achieving this, unprecedented changes are required, and countries need to cut emissions in every possible sector. Regionalized food systems can represent a significant contribution, which have the potential to reduce food transport emissions. However, agro-climatic conditions can constrain some crops' local production, which is a potential setback for regionalized food systems. Nevertheless, increasing globalization would increase food transport emissions considerably. Although international food trade has a crucial role in nourishing the growing population,[23] trade dependency will be higher in globalized food systems than in regionalized ones.

Moreover, regionalized food systems should have a positive effect on decreasing the total emissions footprint of the agriculture sector instead of increasing the emissions due to food production in regions with high emission intensities to meet regional demands. How to achieve a low total emissions footprint of regionalized food systems is a question for further research. Sustainable agricultural intensification would be required to materialize the regionalization. Sustainable intensification would reduce emissions by improving emission intensities and fertilizer use efficiencies of developing countries[58,59] and limiting agricultural expansion that would avoid emissions from land use and land cover changes. Regionalized food systems would also largely contribute to sustainably nourishing the growing population by fostering mutual consumer and producer feedbacks, leading to responsible food production and consumption and closure of nutrient cycles.[50] Additionally, a shift in consumer demand towards seasonal produce plays a crucial role in translating transport emission reductions achieved in the regionalized food systems into lowering overall agricultural emissions

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Supporting Information Available

The supporting information consists of details on Materials and Methods (Texts S1–S4), and additional figures (Figures S1–S3) and tables (Tables S1-S10).

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Graphical TOC Entry