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Local food crop production can fulfil demand for less than one-third of population

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Abstract

The distance between the origin and endpoint of food supply, and the 'localness' of food systems, are key considerations of many narratives associated with sustainability. Yet, information on the minimum distance to food crops is still scarce at the global level. Using an optimisation model based on 'foodsheds' (i.e. self-sufficient areas with internal dependencies), we calculate the potential minimum distance between food production and consumption for six crop types around the world. We show that only 11-28% of the global population can fulfil their demand for specific crops within a 100 km-radius, with substantial variation between different regions and crops. For 26-64% of the population, that distance is greater than 1000 km. Even if transnational foodsheds were in place, large parts of the globe would still depend on trade to feed themselves. While yield gap closure and food loss reductions could favour more local food systems, particularly in Africa and Asia, global supply chains would still be needed to ensure adequate and stable food supply.

Main

Globalization has significantly transformed food production systems[1]. Increasing trade linkages have enabled countries to rely on imports rather than producing commodities themselves[2], thereby overcoming their own production constraints[3] while saving resources globally through more efficient production systems[4]. Further, international food trade has the potential to increase nutritious and diverse food supply[5], and thus increase resilience to local shocks[6]. At the same time, however, global trade has partly led to decreased diversity in local food production landscapes[7], increased vulnerability to market shocks[8], and the decoupling of food production and consumption (potentially associated with losses of cultural values and traditions)[9].

The negative impacts of globalization and food trade have strengthened local food movements[10,11] and food sovereignty discourses[12] preconizing small-scale farming and local markets as a means to reduce dependence on globalized value chains and value individual food producers[10,11,13]. This emphasis often stems from the ambition of restructuring the decision-making landscape to transfer power from large agricultural companies and global markets to local actors[11,13]. According to these narratives, localizing value chains may also decrease greenhouse gas (GHG) emissions from transportation, although agricultural production is a larger contributor to total food-related GHG emissions[14,15].

Direct measurements of the distance to food at global level, with subnational resolution, are still scarce. There remains a clear need to understand the physical constraints posed by food transportation systems to the reorganization of food flows. Existing literature has examined the 'localness' of food systems from several perspectives. The capacity for self-sufficiency has been explored in global[16], regional[17] and city-specific analyses[18]. Life-cycle assessments have addressed the distance to consumption as a factor controlling energy consumption and transportation-related GHG emissions[14,19,20]. More recently, Kriewald et al.[21] estimated the food travel distance for cities with over 100,000 inhabitants. Gravity modelling, in turn, has shown that despite considerably improved transportation networks[16], distance between trading partners has a substantial effect on bilateral trade[17].

The objective here is to calculate the potential minimum distance needed for satisfying food demand with local food resources. Using an optimization model, we determine a hypothetical food distribution set-up which minimises global food miles in order to measure the minimum achievable crop-specific distance between food production and consumption. Using four different food supply scenarios (one representing baseline conditions and three simulating different levels of yield gap closure and/or food loss reduction), we also illustrate how changes in food supply and demand affect the potential to use more local food resources. Six crop types were considered: temperate cereals (wheat, barley, rye), rice, maize, tropical cereals (millet, sorghum), tropical roots (cassava) and pulses.

In quantifying how local current food consumption could be, we utilise the concept of "foodsheds" (see e.g. Peters et al.[22]) in a global context, as a natural unit of analysis, to illustrate the areas emerging as self-sufficient if distance between food consumption and production were minimised (see definition and calculations in Methods). Foodsheds illustrate the effect of flow paths of food and how they may be influenced by e.g. the transport infrastructure.

Results

Minimum distance to consumption

In several regions, locally produced crops are insufficient to satisfy the local demand, rendering food flows necessary to balance surplus and deficit areas (Fig. 1). Globally, 22-28% of the population could satisfy its demand for temperate cereals, rice, tropical cereals, and pulses within 100 km of its location. In contrast, for tropical roots and maize, only around 11-16% of the population could meet its demand within 100 km. The geographic distribution of food self-sufficiency is quite similar for most of the crops analysed, the transport distances needed to satisfy the rest of the demand are both crop and region-specific (Figs. 2, 3).

For temperate cereals (Fig. 2a), the distances are strongly controlled by climatic conditions suitable for cultivation; based on our simulations, the population-weighted average minimum distance is ca. 3800 km. Half of the global population could satisfy its demand within a 900 km, whereas the last 25% of global population would require a distance greater than 5,200 km (Fig. 3a). Most areas in North America and Europe could satisfy their demand within 500 km from the production region, but this distance would be up to 5,000 km nearly everywhere in Sub-Saharan Africa (Fig. 2).

For rice, global demand for 50% of the population could be satisfied within 650 km (Fig. 3c). This distance increases rapidly for the remaining 50%, resulting in a population-weighted average distance of 2,700 km globally (Fig. 2c). The transport distances for maize (Fig. 2e) are considerably different compared to other crops examined. The Americas, Europe and Asia have substantial maize surplus areas, which provide abundant food supply sources at short distances (Fig. 3e) when considering only production intended for human population (see Methods). The global population-weighted average distance to satisfy maize demand is 1,300 km. Three quarters of the global population could satisfy its maize demand within a 1,000 km radius, and for the 90th percentile the distance would be slightly over 2,400 km. The average distance across the six crops is around 2,200 km, weighted by population and crop-specific shares of the total usage of the six crops in each cell. The weighted mean distance is dominated by temperate cereals and rice, given their major share of the food supply globally (Fig. 2).

The comparison between the baseline scenario and the food supply scenario that assumes halved yield gap and food losses (see Methods for detailed scenario description) shows that with temperate cereals (Fig. 2b), the largest changes in minimum achievable distance occurs in South America as well as in eastern and north-western Africa. For rice (Fig. 2d), Sub-Saharan Africa shows substantial decreases in minimum achievable distance. These changes result mainly from halving the yield gap, especially in Africa and South America. The absolute changes in distance for maize (Fig. 2f) are relatively small, as the distances are already considerably lower than for other crops in the baseline scenario (Fig. 2e). While all the scenarios increase food availability, a few places show increased distances that are due to altered consumption and production patterns, resulting in different optimum transport linkages.

The impact of each food supply scenario differs substantially across regions. In places such as Europe (Supplementary Fig. 4b) or Oceania (Supplementary Fig. 4d), the different scenarios do not cause substantial changes to the relationship between population and distance. Other regions show larger spread between the scenarios; halving the yield gap has a major impact on the distance, particularly in Africa and Asia. Interestingly, although halving food loss has substantial impact on distance in e.g. Africa (Supplementary Fig. 4c) and South America (Supplementary Fig. 4f), the difference in distance needed to satisfy a given population between the HalfLoss + HalfYieldGap and only HalfYieldGap scenarios is very small, on the order of 100-200 km.

Mapping foodsheds

Consumption preferences and food supply patterns bring together local, regional, and global food supply systems through food trade. Food flows from surplus areas to deficit areas connect different regions through resources (supply and demand) as well as infrastructure.

Building on an existing definition of foodsheds[22], we take them here as potentially self-sufficient areas in terms of food, but also connected to the "supply chain" through trade (see Methods). Each crop produces a distinct set of foodsheds depending on consumption and production patterns and the availability of transport networks. Beyond their size, foodsheds offer a visualisation of the connectedness between regions under each scenario considered.

The total number of foodsheds ranges between 448 (tropical roots) and 1,209 (maize). For temperate cereals (Fig. 4a), a major foodshed connects large parts of North and South America with Africa, Europe and Asia. The larger foodsheds surround several smaller ones in e.g. South America and in Asia, whereas the United States are clearly divided into a large foodshed in the east and several smaller foodsheds in the west.

Similar to temperate cereal basins, rice foodsheds show a large connected area covering the majority of Africa, Europe, and parts of South and North America (Fig. 4b). However, they differ for example in northern parts of South America, where rice is fragmented into smaller foodsheds, in contrast to those for temperate cereals. Globally more dispersed production patterns for maize enable more localized access to supply, resulting in a much more fragmented foodshed structure, with a large number of small foodsheds (Fig. 4c). It is notable that the small foodsheds (≤25,000 km^2) make up a large proportion of the total number of foodsheds for all the crops (Supplementary Fig. 5).

We explored combined foodsheds in two different ways: a) by looking at flows of aggregated crop production and demand (Supplementary Fig. 8a), which implies that total energy demand for the analysed crops may be satisfied by any combination of the six crops that minimises the distance; and b) by combining the gridded flows of all six crop types (Supplementary Fig. 8c). In the first case, the flows form one large foodshed accompanied by several smaller foodsheds, rather similar to the temperate cereals and maize foodsheds (Supplementary Fig. 8a). On the other hand, combining the flows of the six crops yields one global foodshed (Supplementary Fig. 8c), implying that while the supply systems for single crops in certain areas might be really local (Fig. 4), the diversity in diets results in a very interconnected world with a single global food supply system – already when considering only six crops.

Multiple factors impacting food flows

We illustrate in Fig. 5 the potential impact of infrastructure on food trade flow by first minimizing only distance and secondly accounting also for transport infrastructure (roads, trains, shipping) and travel time (see Methods). In our optimisations, minimizing only distance causes food flows to take the shape of wide, spatially uniform patterns, with many connections over oceans, where the distance is sufficiently short (Fig. 5a,c,d,f). After accounting for transport infrastructure, the flows concentrate into relatively few preferential pathways carrying sizable food flows. This concentration of flows is highly visible with temperate cereals and rice (Fig. 5b,d) whereas maize flows (Fig. 5e) have substantially lower volumes. While the importance of a given pathway might change between the crops, the different friction surfaces highlight the importance of trade infrastructure and transportation technology in shaping market accessibility, and hence food availability[23,24].

In addition to supply and demand, the size and direction of the trade flows and food systems are affected by a multitude of factors, such as access to markets[23], infrastructure[25] , or trade agreements[26]. This is visible when comparing our optimised minimum distance trade flow patterns with the actual reported trade flows (Fig. 6). For the comparison, we combined the reported bilateral trade flows averaged over 2006-2010 for the six crops analysed here and aggregated them to regional level (Fig. 6b). We also aggregated our optimisation results to that same spatial scale (Fig. 6a). The flow patterns for Northern America remain mainly similar between the modelled flows and FAOSTAT statistics, as Northern America is in both cases the largest food net exporter for most regions. However, particularly for Africa, Asia and Europe the flow sources are somewhat less distributed for the optimised flows (Fig. 6a) compared to the FAOSTAT statistics (Fig. 6b).

Discussion

Satisfying food demand with local production is not achievable with current production and consumption patterns. The distance between food production and consumption is a function of flows of food, and the concept of foodsheds provides a way of investigating self-sufficient areas and interpreting food flows in terms of their interconnectivity. While 11-28% of global population could fulfil their crop-specific energy demand with production not further than 100 km (Fig. 2), there are a number of large foodsheds where food flows connect regions from several continents. While this same variation has been shown for foodsheds of cities[21], our results indicate that accounting for also rural areas as well as transport networks results in more globally connected foodsheds. In addition, focusing only on distance and not the actual routing and travel time cost has substantial effects on food flow patterns, possibly neglecting potential logistic bottlenecks or vulnerabilities.

Changes in current production and consumption patterns might facilitate the transition towards more local food consumption, but holistic approaches are needed as the food system incorporates many factors and perspectives. For example, favouring efficiently grown local food has potential for decreasing food loss and GHG emissions, simultaneously supporting food security and energy efficiency[27]. On the other hand, increasing local production around extremely densely populated areas or regions which already face sustainability challenges could further increase the pressures placed on the environment, such as water pollution, loss of biodiversity and overuse of local water resources[28]. Moreover, shifting towards more self-sufficiency-oriented policies may induce trade-offs for the food supply, such as increased vulnerability to local disruptions like mass migrations[29], loss of harvests[30–32], or challenges for the food supply to meet nutritional needs[33]. Therefore, resilient food systems would need flexibility to deal with a range of scenarios and potential shocks. There is a fine balance between benefiting from trade, while avoiding becoming overly reliant on it.

Systemic transitions such as minimizing food loss and waste and closing yield gaps can provide opportunities to improve food availability[28,34,35] while decreasing environmental impact[36]. However, the potential magnitude of these changes is highly region-specific (Supplementary Fig. 4). For instance, the potential to decrease the minimum achievable distance in Africa is much higher than in Europe. Our results show that optimisations with different friction surfaces and the combined foodsheds, as well as the way we represent accessibility and diets, have substantial influence on which flow paths – and consequently foodsheds – emerge. While only six crop types were included in the analysis, results suggest that including additional crops will also have a compounding effect, which would still lead to a globally connected system, even if transport networks were optimised and food was sourced as locally as possible (Supplementary Fig. 8c). The precise flow paths are strongly tied to geographical characteristics such as transport infrastructure, emphasizing the importance of the local context in understanding what "local" means.

This study has several limitations that are worth exploring in future work. The six crop types included here cover a varying share of the national dietary energy, e.g. over 70% in Afghanistan, Lesotho and Bangladesh, but less than 20% in countries such as Belgium or Iceland. Animal products and feed are also crucial elements to include given their importance for diets (~40% of dietary protein[37]) and trade (~25% of global value[38]), respectively. A more comprehensive representation of diets would allow us to quantify their impacts on distance to food and how they change over time. In addition, quality requirements differ a lot depending on the intended use of crops, e.g. cereals used in bakeries, breweries or as livestock fodder. These quality requirements may further diversify patterns in production, demand and trade. Further, the areas producing food quality crops might also change from year to year depending on e.g. the weather conditions during the growing season. Lack of global data has made it impossible to account for these factors in the present study.

Although we deliberately focus on physical constraints affecting food transportation, future research might look at constraints limiting practical feasibility. This includes trade networks and agreements[39], as well as economic costs of food production, consumption, and logistics beyond distance and time. Within local and global value chains, intermediate steps involving storage or processing are also important to capture, both in terms of transportation to facilities and potential for degradation or losses during storage, transport and processing[40]. A more detailed representation of transportation networks would enable us to look at the vulnerability of trade routes and how that could impact the regional or global trade network[41], or even the magnitude of benefits gained from improving infrastructure[24].

More fundamentally, further work is needed to integrate the evaluation of minimum achievable distances to food within broader food security analyses. This study has highlighted how distance to food relates to a broader set of issues, e.g. geopolitical dependencies, capital investment including infrastructure, technology, and resource use. These relationships could be investigated in much more detail in future studies, in addition to tackling issues not yet raised, such as access to adequate and nutritious food as well as fairness of equal food distribution[42]. Although here we assume food supply to match the current food demand of every world region as reported by FAOSTAT, in reality not everybody has the means to satisfy their food demand due to e.g. insufficient income or limited access to food.

Global approaches such as the one we present are clearly not intended to provide granular local results for policy decisions, but rather an overview – and a starting point – for understanding the complexity within common discourses. Although food trade should not be seen as a panacea for resource management and food security, the local food discourse has also been prone to the "local trap", in which local food production is promoted as the best option and inherently more sustainable compared to global food supply systems[10,43]. All the above-mentioned factors intertwine local and global food systems into complex systems, where there is most likely no single operation framework that fits in all situations or spaces. Food, food production and food systems in general should not be considered only as a source of energy for the people but rather a complicated mix of utility, desires, culture, tradition, socio-economic status and livelihood[44]. Exploring minimum achievable distance to food, however, provides one key building block in understanding the complex linkages within the local food-narratives.

Methods

Data

The analysis uses gridded data on dietary energy supply from crops and dietary energy demand of the human population. The local energy supply from crops was defined by three factors: crop production, crop energy content, and losses, namely post-harvesting losses and losses in processing and packaging. For crop production we used data from the global gridded vegetation model LPJmL[45], as calibrated and evaluated by Heino et al.[46] (see Supplementary Fig. 10 and Supplementary Fig. 11). We use LPJmL to simulate production for 13 Crop Functional Types (CFTs). Of these 13 CFTs, we selected six (i.e. temperate cereals, maize, rice, tropical cereals, tropical roots, and pulses) for further analysis, as these crops account for approximately 47% of globally traded calories[38].

We adjusted the LPJmL simulated CFT specific production by a country specific factor to match FAOSTAT Food Balance Sheet (FBS) statistics[37] on a country level, averaged over the years 2006-2010, as some countries had substantial differences between simulated production and reported production. The production values for each country were multiplied by the ratio between FAOSTAT country production and the LPJmL values, aggregated to country level. For major temperate cereal producers such as China, United States or France, the adjustment varied between 0.98-1.27. However, there were some larger outliers, for example India (1.58) and Australia (1.59). For rice, the multiplication factor for the top producers varied 0.95 (China) to 1.9 (Myanmar). For some countries with smaller production the adjustment considerably larger, for example the multiplication factor for temperate cereals varied between 0.02 (Montenegro) and 9.5 (Ethiopia). This discrepancy notably arises due to the lack of multiple cropping practices in LPJmL simulations, temporal variation and other possible sources of error. For countries without FBS production data, the simulated CFT production values were not scaled. To handle countries without FBS data on crop energy content, diet composition and crop specific demand, we applied regional averages based on eight geographically distinctive areas (see Supplementary Fig. 1). To account for supply-side losses, the energy supply was scaled downwards according to region-specific waste percentages[47].

In addition to food, crops are used also as feed and biofuel. On average, around 75% of the global maize production between the years 2006-2010 was used for feed and other uses such as biofuel, whereas for temperate cereals and rice the combined share of feed and other uses was only 29% and 10%, respectively[37]. Thus, we constrained crop production so that in each country only a certain fraction of the crop production was intended for direct human consumption. The crop production was divided into country and crop specific food, feed and non-food fractions[48], each varying between 0 and 1 and summing up to one for each country. The different fractions are built from values averaged between 1997 and 2003 - relying on available data[48], thus introducing an inconsistency between timeframes of different data sources. The food fractions were therefore increased by globally uniform but crop specific multipliers, to match the global crop production intended for human use and demand for each crop. The food fractions were increased between 5% (tropical roots) and 81% (temperate cereals). For pulses, the production with initial food fraction was sufficient to satisfy the global demand. The food fractions for each country were capped at one, assuring that total crop production is not increased. For countries without data, it was assumed that 100% of the crop production was used as food.

The energy demand for each cell was calculated using gridded population[49], country and crop specific food demand from FAOSTAT statistics[37] averaged over the years 2006-2010, and percentage of total food energy supply contributed by each crop[37] (see Supplementary material Note S1). The demand was scaled upwards by a region-specific fraction to account for waste and losses in distribution and consumption according to Gustavsson et al.[47]. For the combined food demand, the individual food consumption was summed across crops.

For the aggregation of FAOSTAT, bilateral trade statistics were averaged over years 2006 to 2010 and the product specific values were transformed to primary crop equivalents in kilograms using conversion factors i.e. percentage share of the primary crop in a given product[50]. The primary crop equivalents were then converted into kilocalories and aggregated over all of the six crops. Lastly, the obtained country-to-country trade values were aggregated into regions according to FAO classifications.

The reliability of FAO trade statistics creates some uncertainty in our comparison to actual trade flows, as we only use data from reporting countries. In some cases, the reports from the exporter and importer countries differ substantially[38]. This can create variation especially within countries that do not have reliable accounting of import and export flows. In addition, our model tracks the food flows only between adjacent countries; thus, some flows may be registered also for the intermediary country.

Scenarios

In addition to our baseline of years 2006-2010, we used three scenarios to estimate how increases in food availability would affect the simulated minimum achievable distance. We considered two different changes to food availability: decreasing food losses and reducing the global yield gaps. The impact of these changes was assessed both separately and together. The crop and region-specific food loss percentages[47] were cut in half in every phase of the supply chain, thus increasing the supply (less is wasted in production and processing) and decreasing the demand i.e. less is wasted in distribution and consumption. In the yield gap scenarios, the difference between maximum attainable yield and the initial yields were halved. Both yield estimates were obtained from LPJmL[45] simulations.

Optimisation framework

The optimisation framework consists of two phases. First, we created a linear programming matrix where we minimize the total distance or travel time that food must travel to fulfil the energy demand in a given cell (see Supplementary materials Note S1). Given that the aim of our analysis was to emphasize consumption of local food, we assumed that local production is consumed preferentially, satisfying as much of the demand as possible within the cell before any imports or exports occur. Here, imports and exports refer to optimised flows between adjacent cells considering eight surrounding cells (and not actual country-to-country trade flows). When the local production cannot fulfil the energy demand of a given cell, imports from adjacent cells are needed to fulfil the energy deficit of a specific crop (see Supplementary Fig. 12). For each cell in a raster grid, we optimised the food flows from and to its adjacent cells that were part of a transport network (see section "Friction surfaces" for transportation network analysis). Cells that have surplus production act as source cells from which food is exported initially.

In the second phase of the optimisation, we calculated the average distance across multiple flow steps for each grid cell (see Note S1 for mathematical formulation). For example, consider a flow step from point A to B (see Supplementary Fig. 12). The total food miles depend on the average food miles to reach cell A, the distance between cell A and B, and the size of the flow. We assumed that once food is imported to a cell, it is completely mixed with other imports and potential surplus from that cell (implying that the original source cannot be traced). As an example, if a cell imports 100 billion kcal, it is mixed with its own surplus of 50 billion kcal, adding up to 150 billion kcal. Similarly, the potentially exported food from a cell is a uniform mix of imported and locally produced surplus food. Equations can therefore be formulated where the average food miles from cell A is calculated by dividing the total food miles by the sum of local production and all imported food flows. If 150 billion kcal of food are transported via this same cell, the transit trade exported from that cell is considered a mix of both imported transit (100 billion kcal) and surplus (50 billion kcal) food. Thus, the food that the cell exports results either from surplus local production, or from food transit through that cell. In the resulting system of equations, the only unknown variable is the total food miles for each grid cell, which is then calculated by matrix algebra. After solving for the food miles, we can also calculate the average distance between food production and consumption for each of the grid cells.

Friction surfaces

We constructed two friction surfaces with different sets of weights to assess the impact of transport networks, and therefore accessibility. The first friction surface was constructed using only the great circle distance between cell centroids. The second friction surface captures transport travel time cost between cells. In addition to distance, we also accounted for the global coverage and speed of different transportation methods as well as the relative costs of each transportation method. The resolution for the friction surfaces was 30-arcmin, as used by our input data from the LPJmL model. We acknowledge that performing the optimisation at 30-arcmin resolution adds several uncertainties. The aggregation of demand points may induce errors in, for example, distance calculations[51] through underestimation of road meandering or overestimation of the transport network coverage, especially in more remote areas. Hence, to diminish the effect of these factors, the transport travel time cost friction surface was initially constructed at 5-arcmin resolution and then aggregated into 30-arcmin resolution.

The friction surface was constructed using a cost-surface approach, i.e. where travelling through each raster cell was assigned a cost based on the friction surface. The value for each raster cell was classified as the lowest travel cost across the available transport methods within that cell. To define adjacent cells, we used queen adjacency where all eight surrounding raster cells are considered as adjacent to any given raster cell. To define the travel time cost between adjacent 30-arcmin grid cells, we first divided each 30-arcmin grid cell into 36 cells with a resolution of 5-arcmin. Within adjacent 30-arcmin cells, we then searched for the optimal minimum cost path between each combination of the resulting 36 source and 36 target cells using the *shortest path* -function in MATLAB®. Lastly, the travel time cost was averaged between all the 5-arcmin combinations for the overlying 30-arcmin grid cells. All the distance calculations were performed using great circle distance between centroids of raster cells.

The shipping[52] and railroad[53] datasets which were in feature vector format were initially converted to raster grids with 5-arcmin resolution. For roads, we used the Global Roads Inventory Project (GRIP)[54] dataset which is a raster set with 5-arcmin resolution depicting road density per square kilometre. The road dataset was divided into four groups based on their classification in the original dataset and given a representative speed in all cells that had density larger than zero. In the absence of more precise information, highways and primary roads were assigned representative traveling speeds of 100 and 80 km/h, respectively. Secondary roads were assigned the speed 60 km/h and tertiary roads were combined with roads with unknown type and assigned 20 km/h traveling speed. Cells along a railroad network were assigned a traveling speed of 24 km/h[55]. Our transport dataset does not necessarily include the entire global road network, and thus to guarantee that all cells could be connected, we assign a minimum travel speed of 5 km/h for all land areas.

Transporting through the oceans was modelled as port-to-port connections where all the ports were free to ship to any other port. As some of the islands in our dataset did not have a port, they were assigned one as close as possible to an existing port to keep the optimisation problem feasible. As these points were not actual ports, they were connected to only the ten closest actual ports. The friction between ports was divided into two categories. Speed within major shipping lanes was assumed to be 19 km/h[55]. All open ocean areas (areas outside major shipping lanes) were assigned a minimum traveling speed of 10 km/h.

Cost of transport influences decisions on where and how to transport goods. As such, it has an important role in global trade network. Each of the transport methods was scaled to account for differences in freight costs per ton-mile, with factors of 1, 3 and 25 for shipping, railroads and roads, respectively[56]. Technically, this means that the optimisation minimizes the cost of travel time with a friction surface expressed in ship-equivalent kilometres/hour/tonne. All of these assumptions can change the flows obtained by the optimisation. Key results of our analysis are robust, however, with transport networks leading to preferential flow paths, and some large foodsheds emerging. If global demand and production are relatively close, substantial trade is needed for all demand to be met, and the resulting flows have a good chance of connecting large parts of the globe unless production is widely distributed (as for maize).

We also assigned a constant 24-hour friction to country borders to depict the friction of border crossings, such as customs checks. As domestically produced items are usually preferred over international[57], the friction at country borders also tries to capture the mental barrier of acquiring food from abroad. While this is not an accurate estimate, it can be refined as appropriate data becomes available. We did not consider any capacity constraints for the transportation network and therefore a theoretical maximum speed was assumed in each cell. In reality, capacity depends on the availability of the transport vehicles as well as capacity of the transport infrastructure and trade systems. Modelling such detailed particularities of the global transport systems was outside the scope of our study.

Foodsheds

To assess the connectedness of different regions globally, we adopted the concept of foodsheds. We defined foodsheds as areas that are linked together through movement and consumption of food (see Supplementary Fig. 12). The distance between adjacent cells was calculated using great circle distance (distance-function) between cell centroids with the WGS84 reference ellipsoid in MATLAB. The areas for the foodsheds were calculated using the area-function from the raster-package[58] in R. The foodsheds are divided by “ridge-cells”: cells which are source cells without any incoming flows connecting two or more foodsheds. They act similarly to mountain tops which divide rainwater into separate natural river basins. Adjacent cells which have food flows between them belong to the same foodshed. Individual foodsheds are crop-specific and there are no interactions between foodsheds of different crops. However, we do consider also aggregate foodsheds which are formed by combining the separate food flows before creating the foodsheds. The formation of foodsheds from food flows provides a natural unit of analysis to reflect on food production and the interconnectedness between regions within a seemingly simple narrative, "as local as possible".

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Data and materials availability: Key outcome data is available at *address of the repository will be added in proof stage*. All the scripts are available from the corresponding authors.

Figure captions

Fig. 1: **Food supply and demand for baseline scenario.** Food supply in calories (left panels) for temperate cereals (**a**), rice (**c**), maize (**e**) and combined supply of all six crop types including additionally tropical roots, tropical cereals and pulses **(g)**. Food demand (right panels) for temperate cereals (**b**), rice (**d**), maize (**f**) and combined supply of all six crop types **(h)**. All panels are based on a 30 arc-min grid (~50 km x 50 km at the equator). See Supplementary Fig. 2 for crop-specific maps of tropical roots, tropical cereals and pulses.

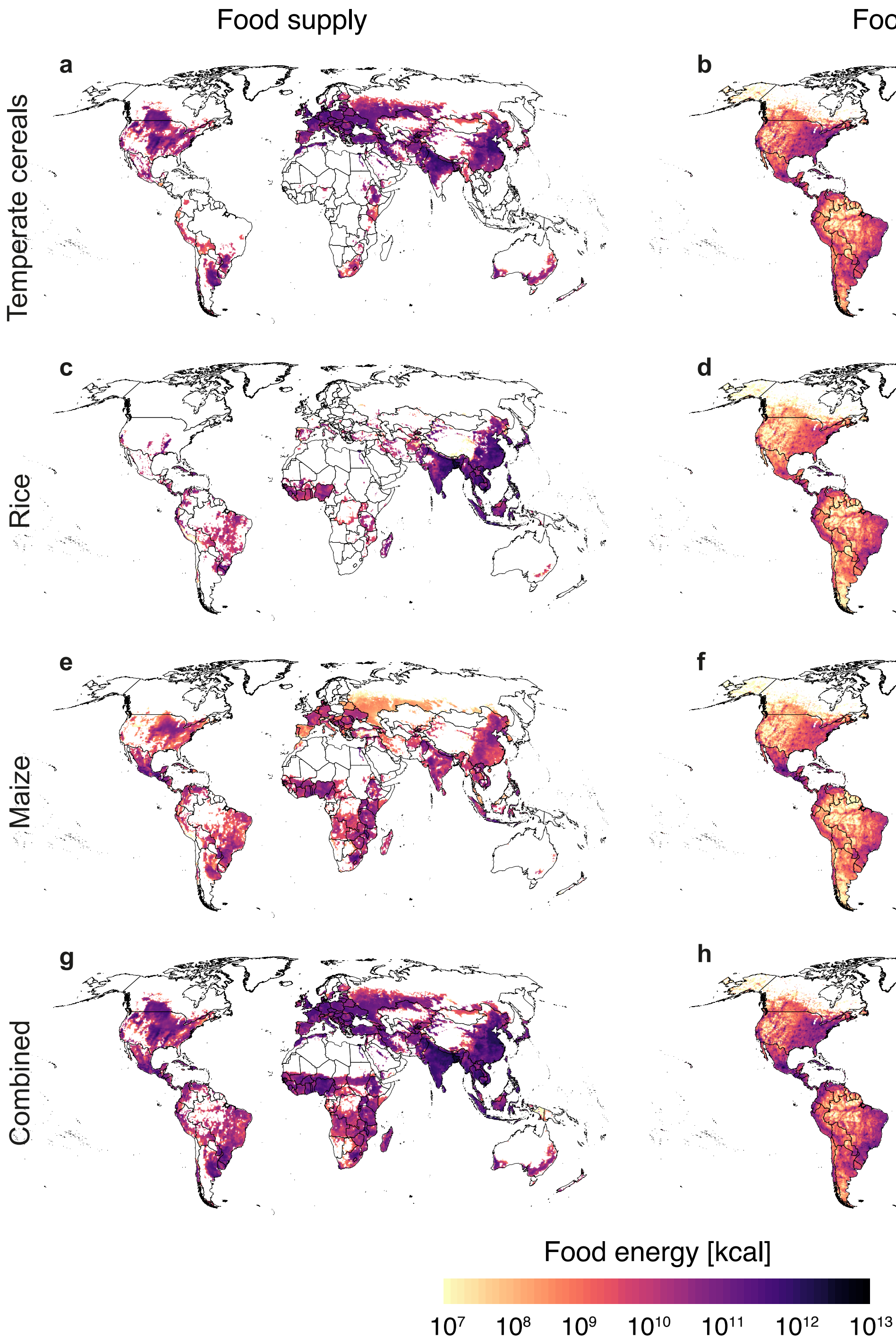
Fig. 2: **Optimised simulated distance from food production to consumption.** Panels on the left show the distance under baseline conditions and panels on the right show the change in distance when the HalfLoss + HalfYieldGap scenario is considered. Distances needed to satisfy food demand for temperate cereals (**a**), rice (**c**), maize (**e**), and the mean distance of all six crops weighted by their individual shares of their total usage in each cell (**g**). Change in distance relative to the baseline scenario for temperate cereals (**b**), rice (**d**), maize (**f**), and their weighted mean (**h**). Food flows are determined by minimizing a friction surface capturing transport travel time costs. See Supplementary Fig. 3 for crop-specific maps of tropical roots, tropical cereals and pulses.

Fig. 3: **Cumulative population distributions for six crops and the crop mix weighted mean.** Population distributions for temperate cereals (**a**), rice (**b**), maize (**c**), pulses (**d**), tropical cereals (**e**), tropical roots **(f)** and the mean distance weighted by the share of each crop of the total supply of the six crops included in the analysis (**g**). The distributions are aggregated globally and over eight regions (see region aggregation in Supplementary Fig. 1). The scenario results are shown in Supplementary Fig. 4.

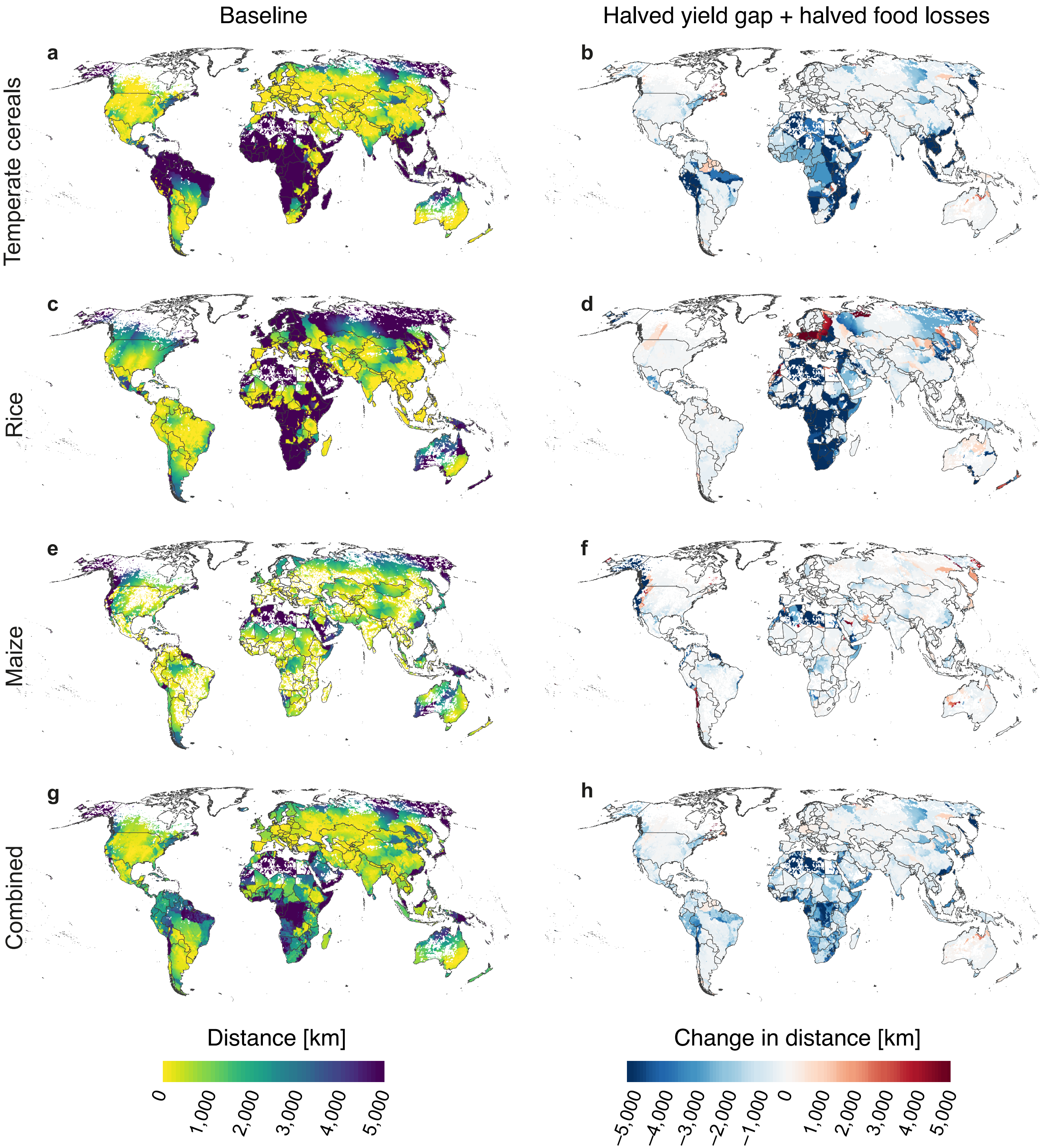
Fig. 4: **Foodsheds for temperate cereals, rice and maize.** For each crop, all areas with the same colour belong to the same foodshed. All foodsheds smaller than 25,000 km^2 are shown in grey. 'Ridge cells' are surplus production cells that have no incoming flows and connect to two or more foodsheds. 'Unconnected single cells' (in pink) are food self-sufficient and have no connection to other cells. Foodsheds also include non-production demand-only areas. Food flows were determined by minimizing a friction surface capturing transport travel time costs. The foodsheds for all the crops as well as yield gap closure and food loss reductions scenarios are shown in Supplementary Fig. 6 and Supplementary Fig. 7, while foodsheds for combined crop demand is shown in Supplementary Fig. 8.

Fig. 5: **The impact of friction surfaces on optimised food flows.** Flow routes using cell centroid distance as friction surface in the optimisation (left panels) for temperate cereals (**a**), rice (**c**), maize (**e**), and combined supply (**g**). Flow routes when using transport travel time cost (see Methods) as a friction surface in the optimisation (right panels) for temperate cereals (**b**), rice (**d**), maize (**f**), and combined supply (**h**). The optimisation is done on a 30 arc-min grid (~50 km x 50 km at the equator). See Supplementary Fig. 9 for other crop types.

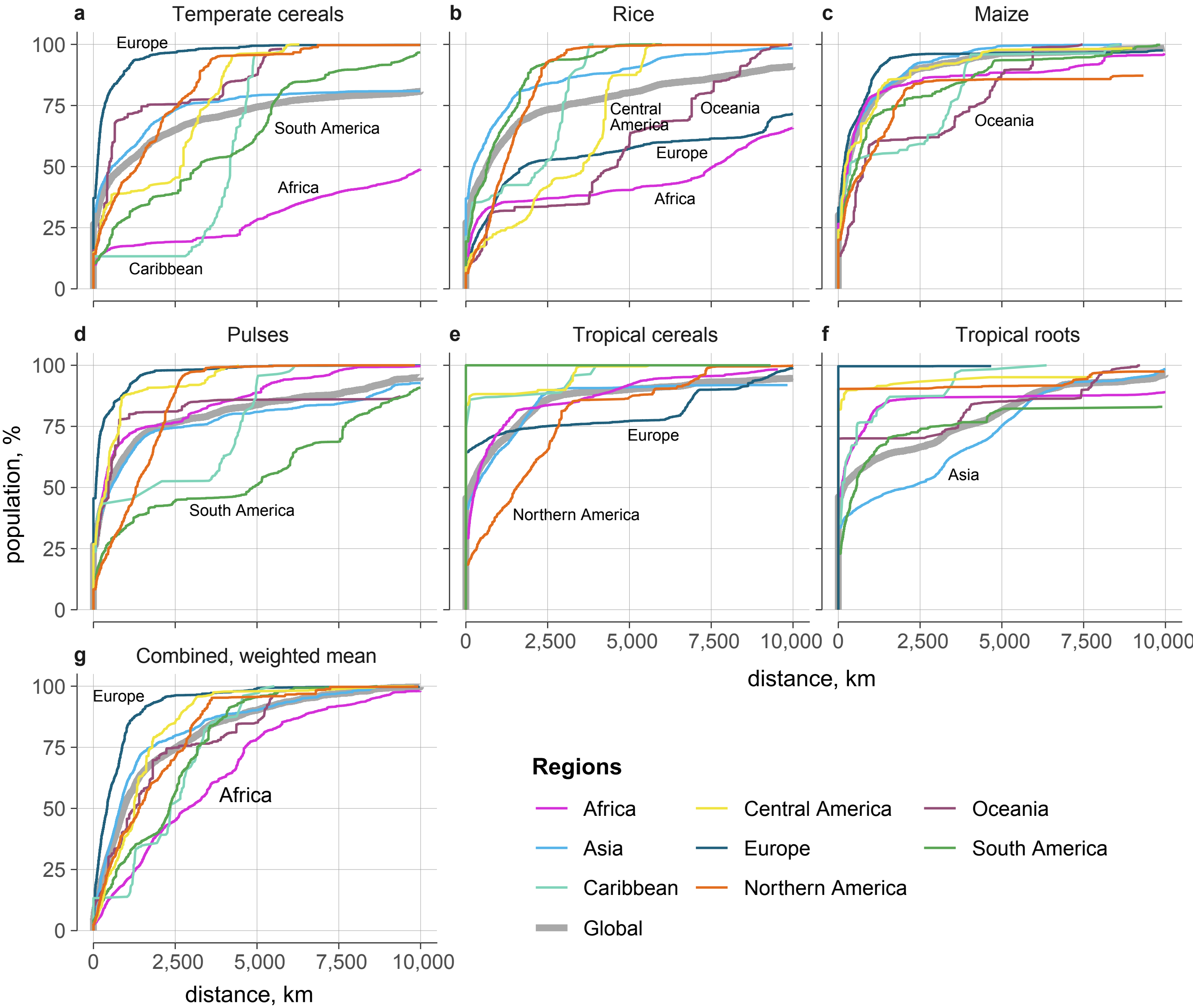
Fig. 6: **Comparison of modelled net food flows (a) and FAOSTAT bilateral net trade between regions (b).** The flows of all the crops have been measured in kcal and then combined. The arrows show the relative size of the total flows between the regions (see region delineation in Supplementary Fig. 1).

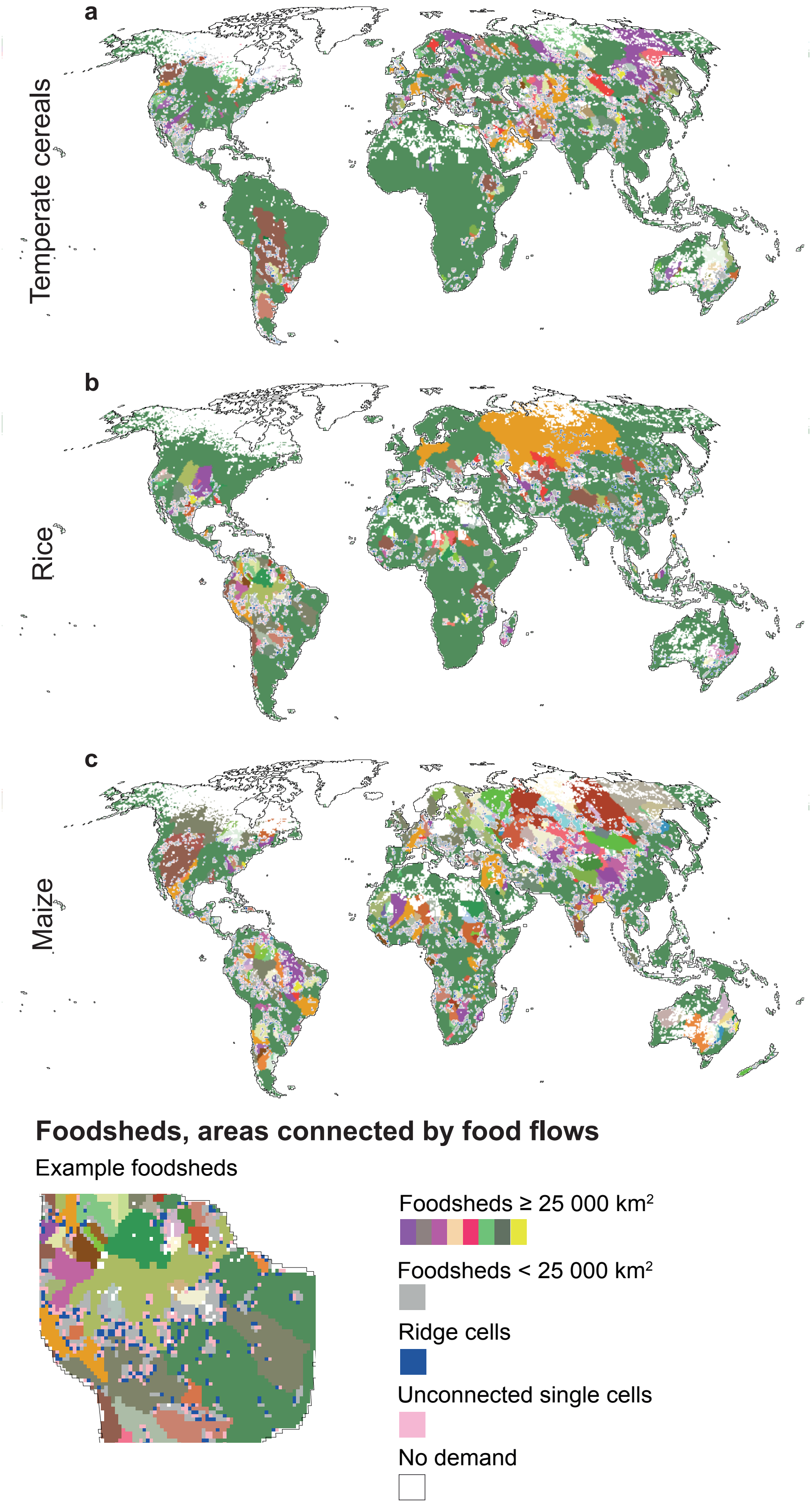


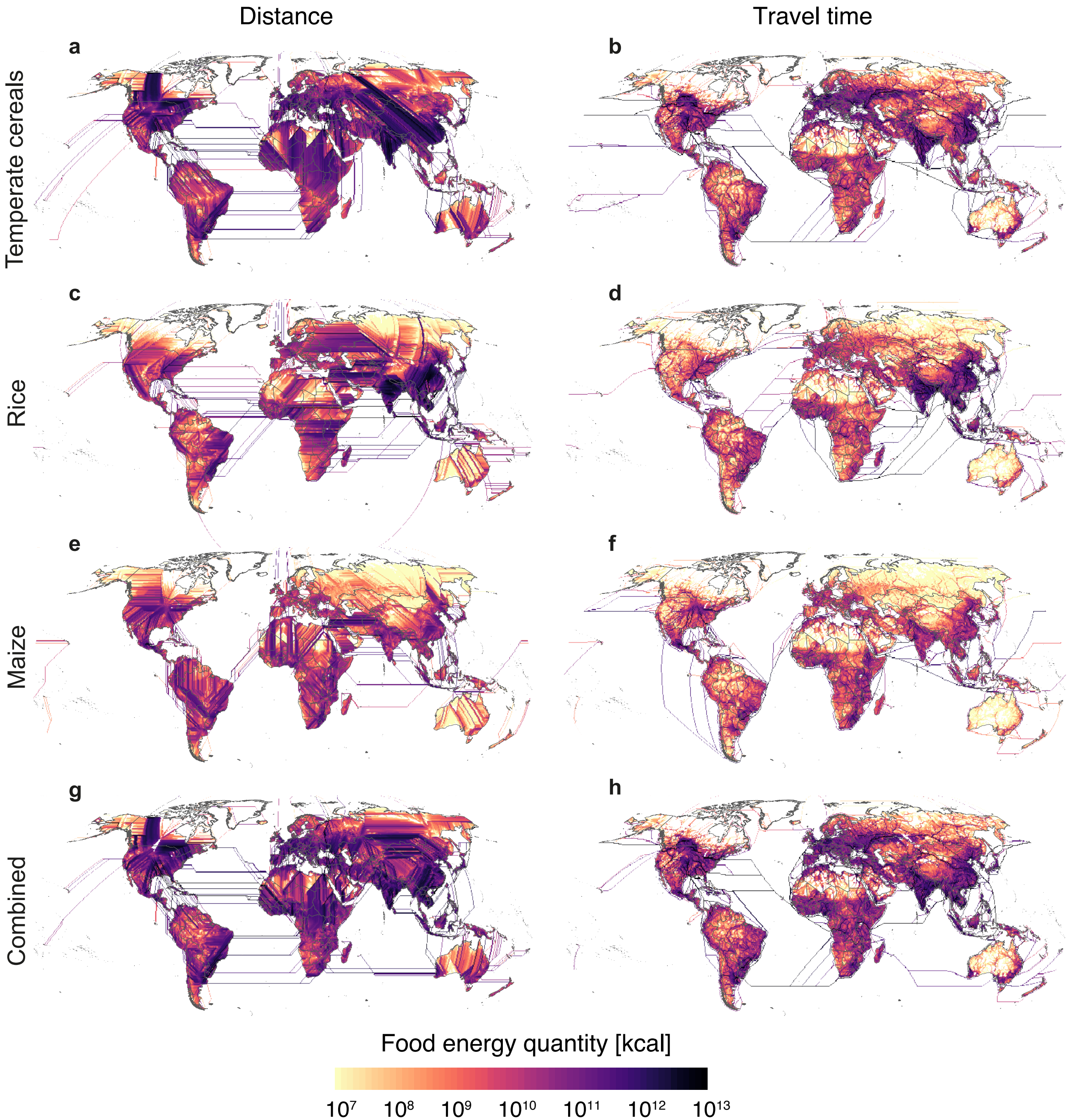
Food supply
Food demand
a
b
c
d
e
f
g
h
Temperate cereals
Rice
Maize
Combined
Food energy [kcal]
10^7
10^8
10^9
10^10
10^11
10^12
10^13



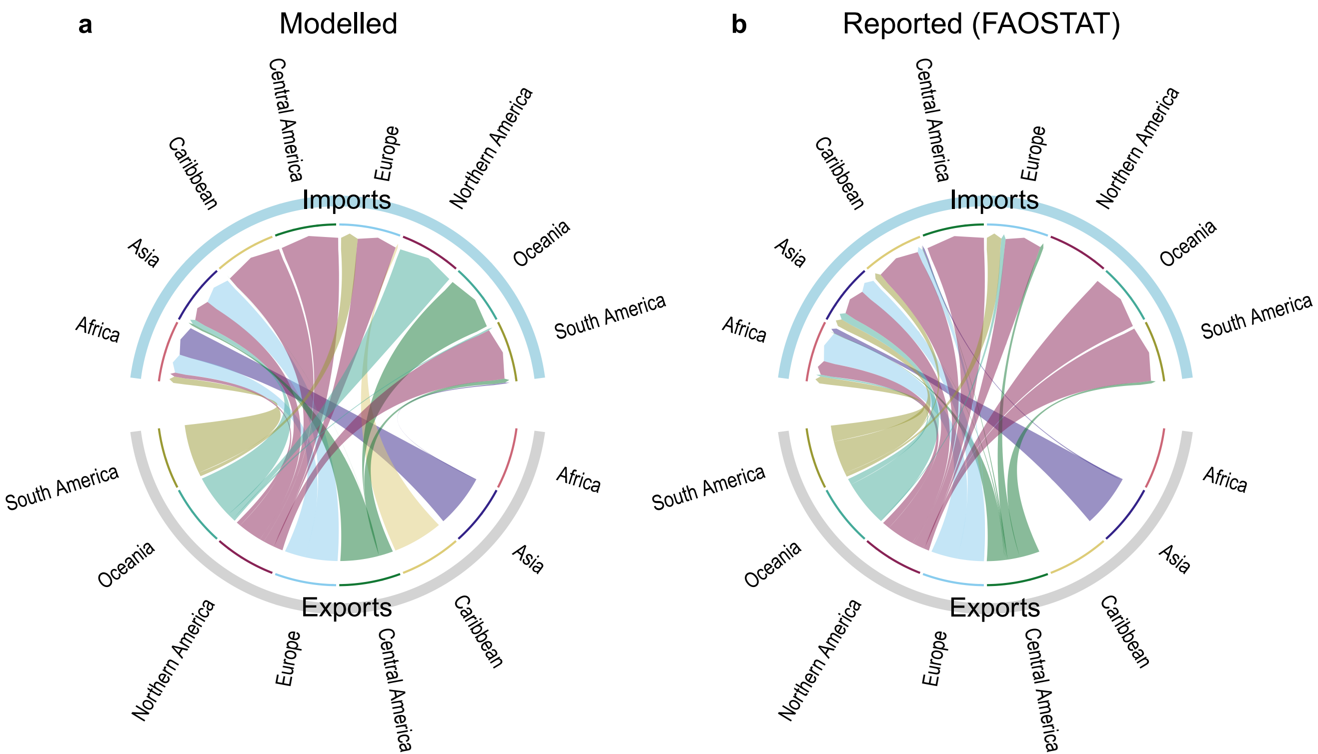
Baseline
Halved yield gap + halved food losses
a
b
Temperate cereals
c
d
Rice
e
f
Maize
g
h
Combined
Distance [km]
0
1,000
2,000
3,000
4,000
5,000
Change in distance [km]
−5,000
−4,000
−3,000
−2,000
−1,000
0
1,000
2,000
3,000
4,000
5,000


a
Temperate cereals
Europe
South America
Africa
Caribbean
b
Rice
Central America
Oceania
Europe
Africa
c
Maize
Oceania
d
Pulses
South America
e
Tropical cereals
Europe
Northern America
f
Tropical roots
Asia
g
Combined, weighted mean
Europe
Africa
population, %
distance, km
Regions
Africa
Asia
Caribbean
Global
Central America
Europe
Northern America
Oceania
South America


a
Temperate cereals
b
Rice
c
Maize
Foodsheds, areas connected by food flows
Example foodsheds
Foodsheds ≥ 25 000 km²
Foodsheds < 25 000 km²
Ridge cells
Unconnected single cells
No demand



Distance
Travel time
a
b
Temperate cereals
c
d
Rice
e
f
Maize
g
h
Combined
Food energy quantity [kcal]
10^7
10^8
10^9
10^10
10^11
10^12
10^13


a
Modelled
Imports
Exports
Caribbean
Central America
Europe
Northern America
Oceania
South America
Asia
Africa
South America
Oceania
Northern America
Europe
Central America
Caribbean
Asia
Africa
b
Reported (FAOSTAT)
Imports
Exports
Caribbean
Central America
Europe
Northern America
Oceania
South America
Asia
Africa
South America
Oceania
Northern America
Europe
Central America
Caribbean
Asia
Africa