nature food

ARTICLES

https://doi.org/10.1038/s43016-020-0060-7

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

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The distance between the origin and end-point of food supply chains, 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 optimization model based on 'foodsheds' (that is, 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 1,000 km. Even if transnational foodsheds were in place, large parts of the globe would still depend on trade to feed themselves. Although 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 an adequate and stable food supply.

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]. International food trade also has the potential to provide a more 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] that preconize 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 the global level, with subnational resolution, are still scarce. There remains a clear need to understand the physical constraints posed by food transportation systems on 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], the distance between trading partners has a substantial effect on bilateral trade[17].

The objective here is to calculate the potential minimum distance needed to satisfy food demand. Using an optimization model, we determine a hypothetical food distribution set-up that minimizes global food miles to measure the minimum achievable crop-specific distance between food production and consumption. Applying four different food supply scenarios, we also illustrate how changes in food supply and demand affect the potential to use more local food resources. One scenario represents baseline conditions, and the other three simulate halving global yield gaps (HalfYieldGap), halving food losses (HalfLoss) and their combination (HalfLoss + HalfYieldGap). 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 use the concept of foodsheds (for example, Peters et al.[22]) in a global context as a natural unit of analysis, to illustrate the areas that emerge as self-sufficient if the distance between food consumption and production is minimized (see definition and calculations in the Methods). Foodsheds illustrate the effect of flow paths of food and how they may be influenced by the transport infrastructure, for example.

Results

Minimum distance to consumption. In several regions, locally produced crops are insufficient to satisfy the local demand, rendering food flows necessary to balance areas of surplus and deficit (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. For tropical roots and maize, however, only around

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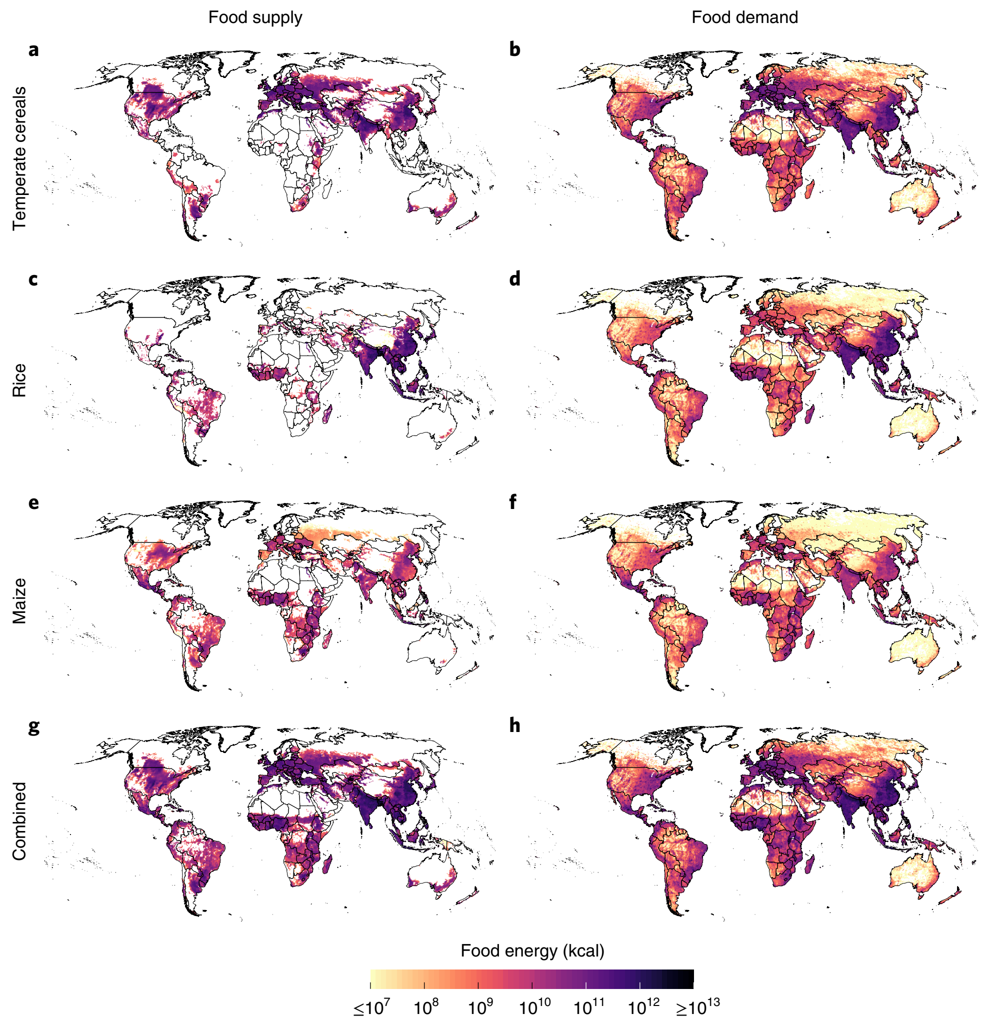

Fig. 1 | Food supply and demand for the baseline scenario. a,c,e,g, Food supply for temperate cereals (**a**), rice (**c**) and maize (**e**), and the combined supply of all six crop types (**g**). **b,d,f,h**, Food demand for temperate cereals (**b**), rice (**d**) and maize (**f**), and the combined supply of all six crop types (**h**). All panels are based on a 30 arcmin grid (~50 km × 50 km at the Equator). See Supplementary Fig. 2 for the crop-specific maps for tropical roots, tropical cereals and pulses.

11–16% of the population could meet its demand within 100 km. The geographic distribution of food self-sufficiency is 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 and 3).

For temperate cereals (Fig. 2a), the distances are strongly controlled by the climatic conditions suitable for cultivation; on the basis of our simulations, the population-weighted average minimum distance is approximately 3,800 km. Half of the global population could satisfy its demand within 900 km, whereas the last 25% of the global population would require a distance greater than 5,200 km (Fig. 3a). Most areas in Northern 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, demand for 50% of the global 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 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 the 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 gaps and food losses (see the Methods for a detailed scenario description) shows that with temperate cereals (Fig. 2b), the largest changes in minimum achievable distance occur in South America and in eastern and northwestern Africa. For rice (Fig. 2d), Sub-Saharan Africa shows substantial decreases in minimum achievable distances. 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 shorter than for other crops in the baseline scenario (Fig. 2e). All of the scenarios increase food availability, but 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

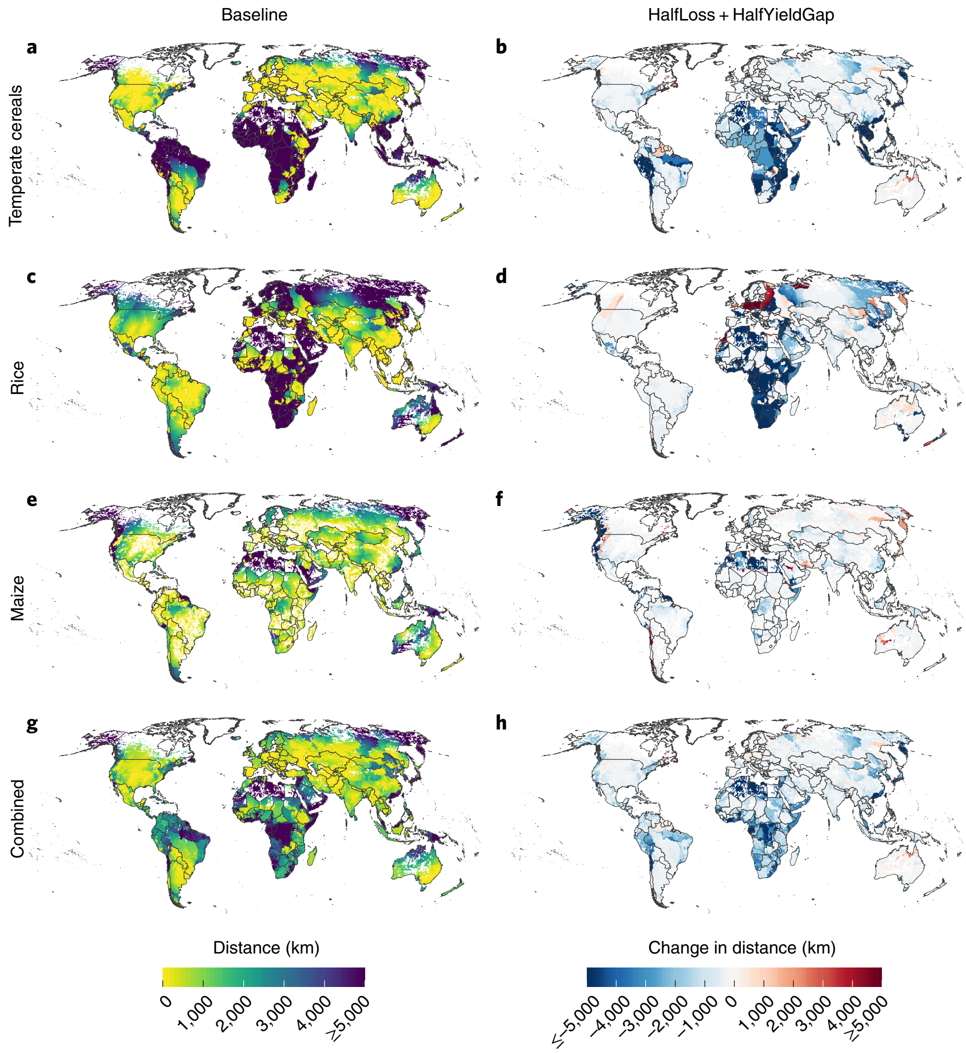

Fig. 2 | Optimized simulated distance from food production to consumption. a,**c**,**e**,**g**, Distances needed to satisfy food demand under baseline conditions for temperate cereals (**a**), rice (**c**) and maize (**e**), and the mean distance of all six crops weighted by their individual shares of their total usage in each cell (**g**). **b**,**d**,**f**,**h**, Changes in distances relative to the baseline under the HalfLoss + HalfYieldGap scenario for temperate cereals (**b**), rice (**d**) and maize (**f**), and their weighted mean (**h**). Food flows are determined by minimizing a friction surface that captures transport travel time costs. See Supplementary Fig. 3 for the crop-specific maps for tropical roots, tropical cereals and pulses.

cause substantial changes in the 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. Although halving food loss has substantial impact on distance in, for example, 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 visualization of the connectedness between regions under each scenario considered.

The total number of foodsheds ranges between 515 (tropical cereals) and 1,377 (pulses). For temperate cereals (Fig. 4a), a major foodshed connects large parts of Northern and South America with Africa, Europe and Asia. The larger foodsheds surround several smaller ones in South America and in Asia, for example, whereas the United States is 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 Northern America (Fig. 4b). However, they differ in northern parts of South America, for example, where rice is fragmented into smaller foodsheds, in contrast to those for temperate cereals. More dispersed global 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 of the crops (Supplementary Fig. 5).

We explored combined foodsheds in two different ways: (1) by looking at flows of aggregated crop production and demand (Supplementary Fig. 8a), which implies that total energy demand

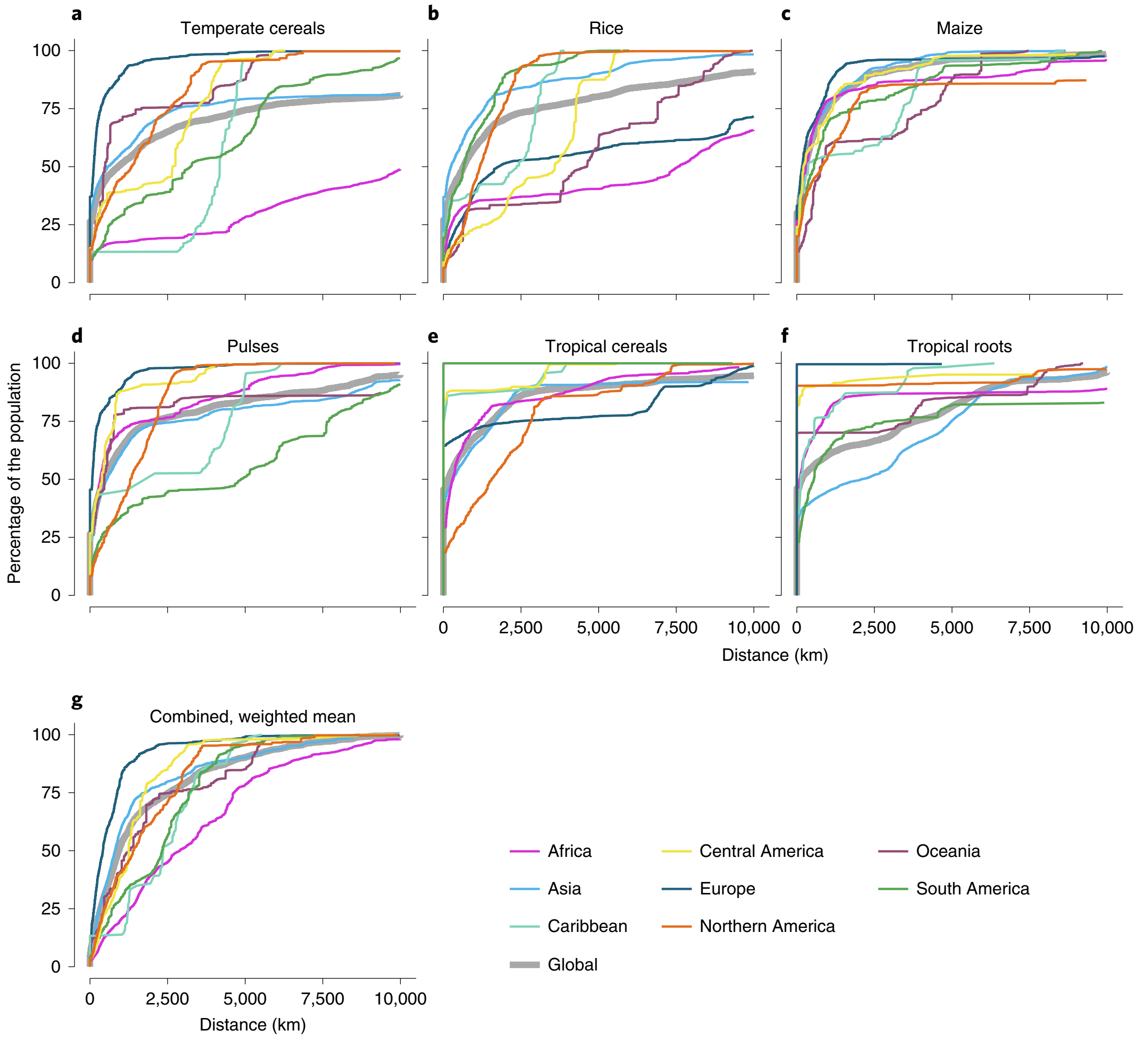

Fig. 3 | Cumulative population distributions for six crops and the crop mix weighted mean. a–g, Population distributions for temperate cereals (**a**), rice (**b**), maize (**c**), pulses (**d**), tropical cereals (**e**), tropical roots (**f**) and the mean distance weighted by the share of each crop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

for the analysed crops may be satisfied by any combination of the six crops that minimizes the distance; and (2) 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, 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—even when considering only six crops.

Multiple factors impacting food flows. We illustrate in Fig. 5 the potential impact of infrastructure on food trade flows by first minimizing only distance, and secondly accounting also for transport infrastructure (roads, trains, shipping) and travel time (see Methods). In our optimizations, 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. The importance of a given pathway might change between the crops, but 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 optimized 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 the regional level (Fig. 6b). We also aggregated our optimization results to that same spatial scale (Fig. 6a). The flow patterns for Northern America remain similar between the modelled flows and FAOSTAT statistics, as Northern America is in both cases the largest net exporter of food for most regions. However, particularly for Africa, Asia and Europe, the flow sources are less widely distributed for the optimized flows (Fig. 6a) compared with the FAOSTAT statistics (Fig. 6b).

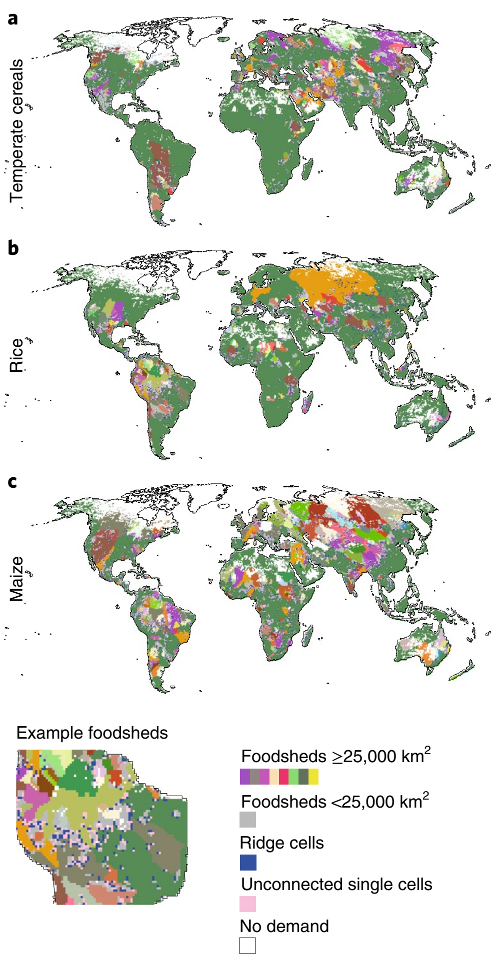

Fig. 4 | Foodsheds for temperate cereals, rice and maize. a, Temperate cereals. **b**, Rice. **c**, Maize. For each crop, all areas with the same colour belong to the same foodshed, and the colour scheme distinguishes individual basins. All foodsheds smaller than 25,000 km^2 are shown in grey. Ridge cells are surplus production cells that have no incoming flows and connect to two or more foodsheds. Unconnected single cells are food self-sufficient and have no connection to other cells. The example foodsheds map illustrates the fine-scale spatial variation of the basin and the location of the ridge and unconnected single cells that are not visible on global maps **a**–**c**. Foodsheds also include non-production, demand-only areas. Food flows were determined by minimizing a friction surface that captures 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 Figs. 6 and 7, whereas foodsheds for combined crop demand are shown in Supplementary Fig. 8.

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. Although 11–28% of the global population could fulfil their crop-specific energy demand with production not further than 100 km away (Fig. 2), there are a number of large foodsheds where food flows connect regions from several continents. This same variation has been shown for foodsheds of cities[21], and our results indicate that accounting for 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, meaning potential logistic bottlenecks or vulnerabilities may be unaccounted for.

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 the potential to decrease 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 that 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 in the food supply, such as increased vulnerability to local disruptions like mass migrations[29], loss of harvests[30–32] or challenges in meeting 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 optimizations with different friction surfaces and the combined foodsheds, as well as differences in the way we represent accessibility and diets, have substantial influence on which flow paths—and consequently foodsheds—emerge. Although 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 optimized 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: 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 greatly depending on the intended use of crops, for example, for cereals to be used in bakeries, breweries or as livestock fodder. These quality requirements may further diversify patterns in production, demand and trade. Furthermore, the areas producing food quality crops might also change from year to year depending on the weather conditions during the growing season, for example. The lack of global data has made it impossible to account for these factors in the present study.

Although we deliberately focus on the physical constraints affecting food transportation, future research might look at the constraints limiting practical feasibility. This includes trade networks and agreements[39], as well as the economic costs of food production, consumption and logistics beyond distance and time. Within local and global value chains, it is also important to capture intermediate steps involving storage or processing, 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

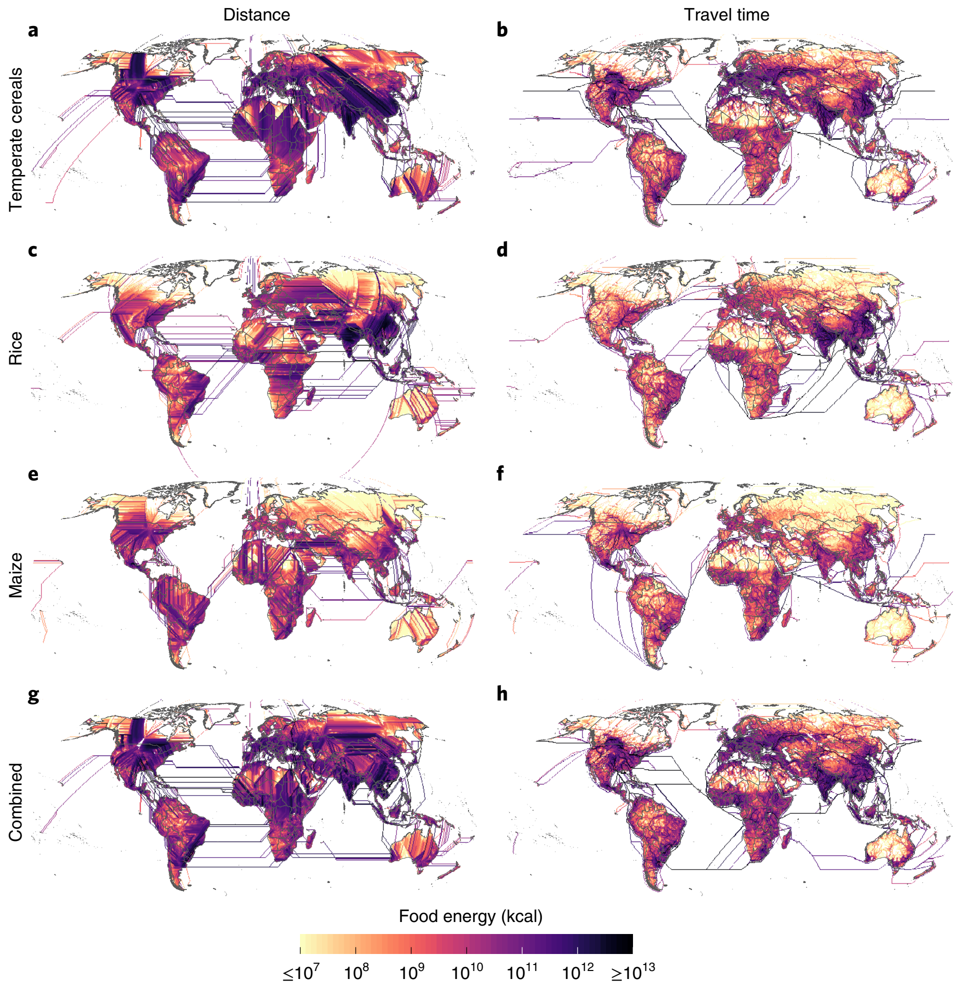

Fig. 5 | The impact of friction surfaces on optimized food flows. a,c,e,g, Flow routes using cell centroid distance as the friction surface in the optimization for temperate cereals (**a**), rice (**c**) and maize (**e**), and the combined supply (**g**). **b,d,f,h**, Flow routes using transport travel time cost (see Methods) as a friction surface in the optimization for temperate cereals (**b**), rice (**d**) and maize (**f**), and the combined supply (**h**). The optimization is done on a 30 arcmin grid (~50 km × 50 km at the Equator). See Supplementary Fig. 9 for other crop types.

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 such as geopolitical dependencies and capital investment including infrastructure, technology and resource use. These relationships could be investigated in much more detail in future studies, in addition to 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 that food supply matches 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, for example, 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—towards 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 than global food supply systems[10,43]. All the above-mentioned factors intertwine local and global food systems into complex systems, where there is most probably no single operation framework that fits 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 as a complicated mix of utility, desires, culture, tradition, socio-economic status and livelihood[44]. Exploring minimum achievable distances 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 the 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 Figs. 10 and 11). We use LPJmL to simulate production for 13 crop functional types (CFTs). Of these 13 CFTs, we selected 6 (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 simulated CFT-specific production in LPJmL 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, the United States or France,

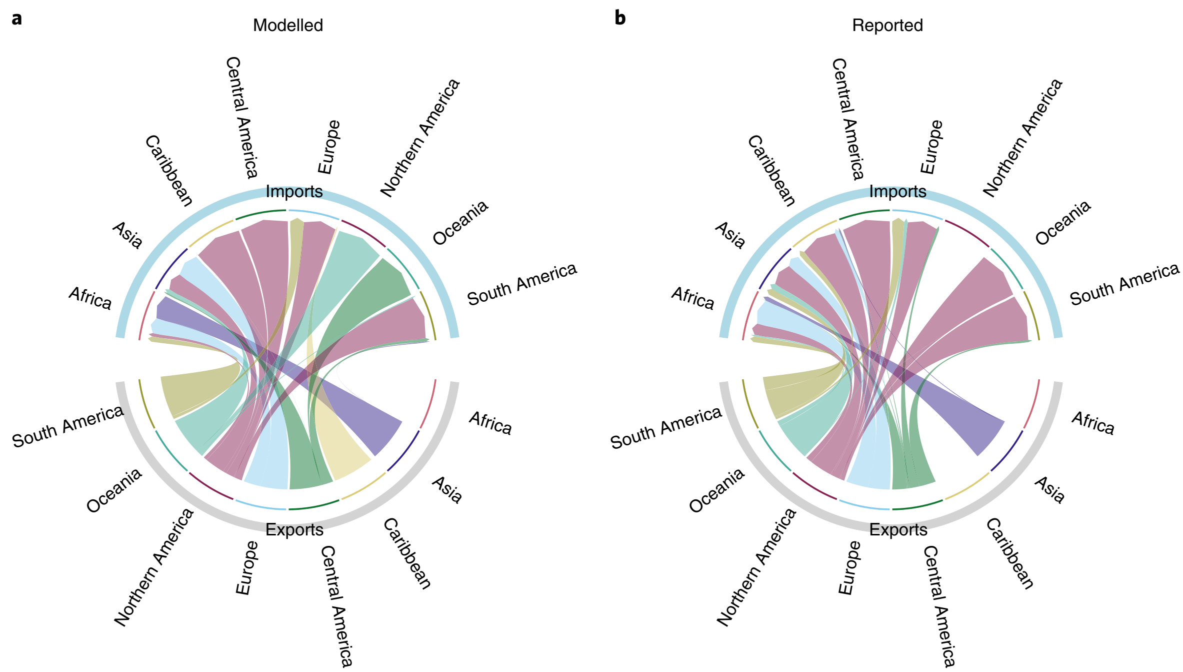

Fig. 6 | Comparison of modelled and reported net food flows. a, Optimized minimum-distance trade flows. **b**, FAOSTAT bilateral net trade between regions. The flows of all the crops have been measured in kilocalories and then combined. The bars show the relative size of the total flows between the regions (see the region delineation in Supplementary Fig. 1).

the adjustment varied between 0.98 and 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 from 0.95 (China) to 1.9 (Myanmar). For some countries with smaller production, the adjustment was considerably larger; for example, the multiplication factor for temperate cereals varied between 0.02 (Montenegro) and 9.5 (Ethiopia). This discrepancy arises due to the lack of multiple cropping practices in LPJmL simulations, temporal variation and other possible sources of error. The simulated CFT production values were not scaled for countries without FBS production data. 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 and 2010 was used for feed and other uses such as biofuel, whereas for temperate cereals and rice the combined shares of feed and other uses were 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 1 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 by 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 the gridded population[49] and country- and crop-specific food demand from FAOSTAT statistics[37] averaged over the years 2006–2010, and the percentage of total food energy supply contributed by each crop[37] (see Supplementary Note 1). 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 data, bilateral trade statistics were averaged over the years 2006 to 2010 and the product-specific values were transformed to primary crop equivalents in kilograms using conversion factors (the per cent 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. 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 with 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 only tracks the food flows between adjacent countries; thus, some flows may also be registered 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 that is 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.

Optimization framework. The optimization 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 Note 1). 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 optimized flows between adjacent cells considering eight surrounding cells (and not actual country-to-country trade flows). When 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 optimized the food flows from and to its adjacent cells that were part of a transport network (see the Friction surfaces section for the transportation network analysis). Cells that have surplus production act as source cells from which food is exported initially.

In the second phase of the optimization, we calculated the average distance across multiple flow steps for each grid cell (see Supplementary Note 1 for the 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 cells 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 potential exported food from a cell is a uniform mix of imported and locally produced surplus food. Equations can therefore be formulated in which 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 to be 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 of the friction surfaces was 30 arcmin, as used by our input data from the LPJmL model. We acknowledge that performing the optimization 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: travelling through each raster cell was assigned a cost on the basis of the friction surface. The value for each raster cell was classified as the lowest travel cost across the available transport methods within that cell. We used queen adjacency to define adjacent cells, 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[52]. Lastly, the travel time cost was averaged between all 5 arcmin combinations for the overlying 30 arcmin grid cells. All of the distance calculations were performed using great circle distances between the centroids of raster cells.

The shipping[53] and railroad[54] datasets were in feature vector format, and were thus initially converted to raster grids with 5 arcmin resolution. For roads, we used the Global Roads Inventory Project (GRIP)[55] dataset, which is a raster set with 5 arcmin resolution depicting road density per square kilometre. The road dataset was divided into four groups on the basis of their classifications in the original dataset and given a representative speed in all cells that had a density larger than zero. In the absence of more precise information, highways and primary roads were assigned representative travelling speeds of 100 and 80 km h^{-1}, respectively. Secondary roads were assigned a speed of 60 km h^{-1} and tertiary roads were combined with roads of unknown type and assigned a 20 km h^{-1} travelling speed. Cells along a railroad network were assigned a travelling speed of 24 km h^{-1} (ref. [56]). 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^{-1} 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 optimization 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^{-1} (ref. [56]). All open ocean areas (areas outside major shipping lanes) were assigned a minimum travelling speed of 10 km h^{-1}.

The cost of transport influences decisions on where and how to transport goods. As such, it has an important role in global trade networks. 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[57]. Technically, this means that the optimization minimizes the cost of travel time with a friction surface expressed in ship-equivalent kilometres per hour per tonne. All of these assumptions can change the flows obtained by the optimization. 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 h friction to country borders to depict the friction of border crossings, such as customs checks. As domestically produced items are usually preferred over international items[58], the friction at country borders also tries to capture the mental barrier of acquiring food from abroad. Although this is not an accurate estimate, it can be refined as appropriate data become 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. We adopted the concept of foodsheds to assess the connectedness of different regions globally. 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[59] in R. The foodsheds are divided by ridge cells: cells that 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 that 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 also consider 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 for food production and the interconnectedness between regions within a seemingly simple narrative: 'as local as possible'.

Data availability

Key outcome data is available at https://doi.org/10.5281/zenodo.3725646.

Code availability

All scripts for the optimization and calculations of the minimum achievable distance are available from the corresponding authors.

Received: 17 September 2019; Accepted: 16 March 2020;
Published online: 17 April 2020

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Acknowledgements

The authors thank their colleagues from the Water and Development research group for their comments and support. P.K. and M.T. received funding from *Maa- ja vesitekniikan tuki ry*. through its Majakka project. M.J.P. was supported in whole or in part by the Army Research Office/Army Research Laboratory under award no. W911NF1810267 (Multi-University Research Initiative). The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies either expressed or implied of the Army Research Office or the US Government. M.J. received funding from *Maa- ja vesitekniikan tuki ry*. M.K. received financial support from the Academy of Finland project WASCO (grant no. 305471), the Academy of Finland SRC project 'Winland', the Emil Aaltonen foundation project 'eat-less-water' and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement no. 819202). J.H.A.G. received support from WASCO and 'eat-less-water'. P.D. was funded by the USDA Hatch Multistate project no. W4190 capacity fund.

Author contributions

M.K., P.K. and J.H.A.G. conceptualized the study. P.K. and J.H.A.G coded the numerical analyses. P.K., J.H.A.G., M.T. and M.K. analysed the data and made the visualizations in consultation with P.D., S.S., M.J.P. and M.J. P.K. drafted the manuscript. P.K., J.H.A.G., M.T., P.D., S.S., M.J.P. and M.K. wrote and edited the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s43016-020-0060-7.

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