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Graphical abstract

Highlights

- 3.7 B people live in countries without enough land to source a planetary health diet
- Food-system interventions allow for 7.2 billion people to live in such countries
- The impact of diet and food waste changes are far larger than crop yield increases

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In brief

A globalized food network delivers efficient supply chains, but these are susceptible to disruptions (e.g., the war in Ukraine and COVID-19). These disruptions can cause overproduction in some regions while others encounter food shortages. Navarre et al. explore the potential for each nation to follow a planetary health diet based on domestic production within their agricultural land. These strategies can provide nations with additional food system resilience in case of supply chain breakdowns, ensuring food supply to their populations.

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Interventions for sourcing EAT-*Lancet* diets within national agricultural areas: A global analysis

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SCIENCE FOR SOCIETY Recently, the global trade-based food system has undergone historic shocks due to the COVID-19 pandemic and war in Ukraine, creating extreme spikes in food waste and massive food shortages around the world. At the same time there are calls for the world to adopt a planetary health diet to overcome malnutrition and the environmental impacts inflicted by the current food system. Shorter, national-scale supply chains could mitigate food shock while improving the food security of import-dependent nations, but it remains unclear whether a planetary health diet such as that proposed by the EAT-*Lancet* can be achieved through nationally sourced foods. Our analysis of 204 nations has found that 86 nations representing 51% of the global population are able to secure a nationally sourced EAT-*Lancet* diet from a land-availability perspective. Furthermore, implementation of appropriate consumption and production interventions would allow a further 113 countries to achieve self-sufficient food systems.

SUMMARY

Trade has helped the global food system drastically reduce world hunger. However, it has also left nations vulnerable to food-trade shocks that can lead to local food shortages. National food resilience may be increased by exploring the feasibility of adapting healthy diets to local production and sourcing. The EAT-*Lancet* diet has been proposed as a healthy and environmentally friendly diet, but the feasibility of sourcing it nationally remains unknown. Using FAOSTAT production data and EAT-*Lancet* Commission guidelines, we create a unique EAT-*Lancet* diet for each nation. We compare the agricultural land required for each country to supply this diet to their available agricultural land. For nations that did not have sufficient agricultural land, interventions to reduce land use were elaborated by adjusting production and consumption efficiencies of all modeled diets, revealing that 95% of the global population live in countries with a potential pathway toward food self-sufficiency.

INTRODUCTION

Currently, humankind faces the challenge of developing a robust and resilient food system that provides a sustainable and healthy diet for a growing world population. That is, a food system that provides a sufficient amount of nutritious food to all, regardless of unforeseen disturbances.[1] Today however, despite enormous food production, 77% of nations suffer from a calorie deficit[2] and 2 billion people exhibit a micronutrient deficiency, while an additional 2.2 billion people are considered overweight or obese.[3] Concomitantly, the current food production system is estimated to occupy 50% of global ice-free land,[4] has been linked to 34% of global greenhouse gas emissions,[5] and is driving the unprecedented decrease in global biodiversity.[6] The global food system thus inadequately distributes food and exerts a heavy burden on the environment.

The EAT-*Lancet* diet was proposed as a healthy diet that also ensures the environmental objectives presented in the Paris Agreement and Rio Conventions.[7] The EAT-*Lancet* diet also addresses Sustainable Development Goals (SDGs) by minimizing the food system's environmental impacts and allowing regional and cultural dietary differences.[7] This diet promotes better global nourishment (SDG2, zero hunger), while addressing other SDGs (e.g., SDG12 responsible consumption and production, SDG13 climate action, SDG14 life below water, and SDG15 life on land). In addition to these health and environmental objectives, however, achieving a resilient global food system that addresses zero hunger must reverse the increasing inequality engrained in

Table 1. Global daily food intake under nationally sourced EAT-*Lancet* diets and business-as-usual (BAU) production

Food group	Commission range (grams per day)	Model EAT intake (grams per day)	BAU intake (grams per day)
Added fats	20–80 (51.8)	43	54
Added sugars	0–31 (31)	41	597
All fruit	100–300 (200)	206	131
Beef, lamb, and pork	0–28 (14)	11	58
Chicken and other poultry	0–58 (29)	45	35
Dairy foods	0–500 (250)	77	249
Eggs	0–25 (13)	12	23
Fish	0–100 (28)	25	42
Legumes	0–100 (75)	103	132
Nuts	0–75 (50)	77	17
Potatoes and cassava	0–100 (50)	24	131
Vegetables	200–600 (300)	309	173
Whole grains	232 (232)	240	684
Total	1,324	1,213	2,326

Gram per day values inside the EAT-*Lancet* Commission recommended range are highlighted in green, while values outside the range are highlighted in red.

global food trade that hampers universal access to this healthy diet.[8]

The global food trade allows for production in better suited locations to grow food, thus increasing production specialization, efficiency, and comparative advantages.[9] Trade has also helped diversify food supply in many countries.[10] It also provides a buffer for nations susceptible to local limitations, particularly in times of uncertainty.[10] Global trade also has the potential to mitigate local food shocks such as pest outbreaks and extreme weather events as imports can facilitate a steady supply of food regardless of local conditions.[11,12] In certain countries, crop production for exports has become a core component of their economic output, making the global market an important source of local revenue.[13] For low-income countries in particular, trade taxes may be an important source of revenue.[14] Overall, trade has helped improved food stability, availability, access, and utilization, while also promoting economic growth.[15]

However, trade also creates dependencies on imports for many low- and middle-income nations. These countries are vulnerable to food system perturbations, such as pandemics or war occurring in major exporting nations.[11,16] Such shocks cause price spikes, local food shortages, and severe undernourishment.[11] Despite increasing food supply diversity in many nations, the global food trade has also led to a substantial decrease in local food production diversity, instead favoring monoculture crops that tend to have low resilience when subjected to shocks.[17] In certain regions, global food trade can increase the price of food items, rendering them inaccessible to the local population.[18] This price action, in addition to income, marketing, and consumer behavior, among other factors,[19] has contributed to the loss of local dietary culture and food traditions as more affordable but less nutritious globalized diets have eclipsed local diets.[20] Trade also spurs a global nutrient imbalance, by spatially separating food production from consumption.[21,22] These negative impacts are amplified in times of crises,[23] highlighting the need to explore alternative models of national food production that can provide local food system resilience despite global fragility.

This study specifically examines the feasibility and required food-system interventions of sourcing locally tailored EAT-*Lancet* diets within a nation's agricultural land, defined as the sum of arable land, cropland, and pastureland, thus allowing it to couple production and consumption at the national scale without incorporating international food trade.[24] By exploring these interventions at national levels, tailored solutions to regional food system inefficiencies emerge that can create a more resilient global food system that could withstand severe shocks to global food trade. We find that 86 countries currently have the capacity to supply their populations with a nationlly sourced EAT-*Lancet* diet. A further 113 countries have potential pathways to self-sufficient food systems from a land use perspective, if proper consumption and production interventions are implemented. Although a fully self-sufficient system cannot be implemented in the near-term due to the dependence of many countries on trade, understanding a countries' potential to become more self-reliant is an important strategic policy consideration to navigate growing global uncertainty.[25,26]

RESULTS AND DISCUSSION

Global food consumption patterns

Of the 204 nations who reported FAOSTAT production data, 155 can supply an EAT-*Lancet* diet that includes food items from all food groups, while 49 do not produced food items from one or more food groups (see Data S1.csv at https://doi.org/10.5281/zenodo.7405302).

From the 155 nations producing all required food groups, a globally averaged EAT-*Lancet* diet provides 2,810 calories, 97 g of protein, 104 g of fat for consumption per capita per day, and it comprises circa 66 (range: 32–131) food items (see Data S1.csv at https://doi.org/10.5281/zenodo.7405302). At 104 g, fat accounts for 34% of the calories provided by the whole diet, falling within the recommended range of 25%–35% needed to maintain general fitness.[27] The intake of 2,809 calories and 97 g of protein is also sufficient to satisfy the demands of a generally active and healthy adult exercising three times per week for 30–40 min per day.

The modeled EAT-*Lancet* diets were largely able to shift consumptions patterns to within the commission recommendations, with the exception of added sugar, legume, and nut consumption slightly exceeding the maximum intake recommendations by weight (Table 1). This small discrepancy arises from scaling the diets to the caloric food group ratios rather than the mass-based ones. When compared with business-as-usual (BAU) consumption, the modeled EAT-*Lancet* diet dramatically reduces the consumption of added sugars, animal products, potatoes and cassava, and whole grains, while notably increasing the consumption of fruits, vegetables, and nuts. Our modeled EAT-*Lancet* diet still provides 170 g/day of animal products,

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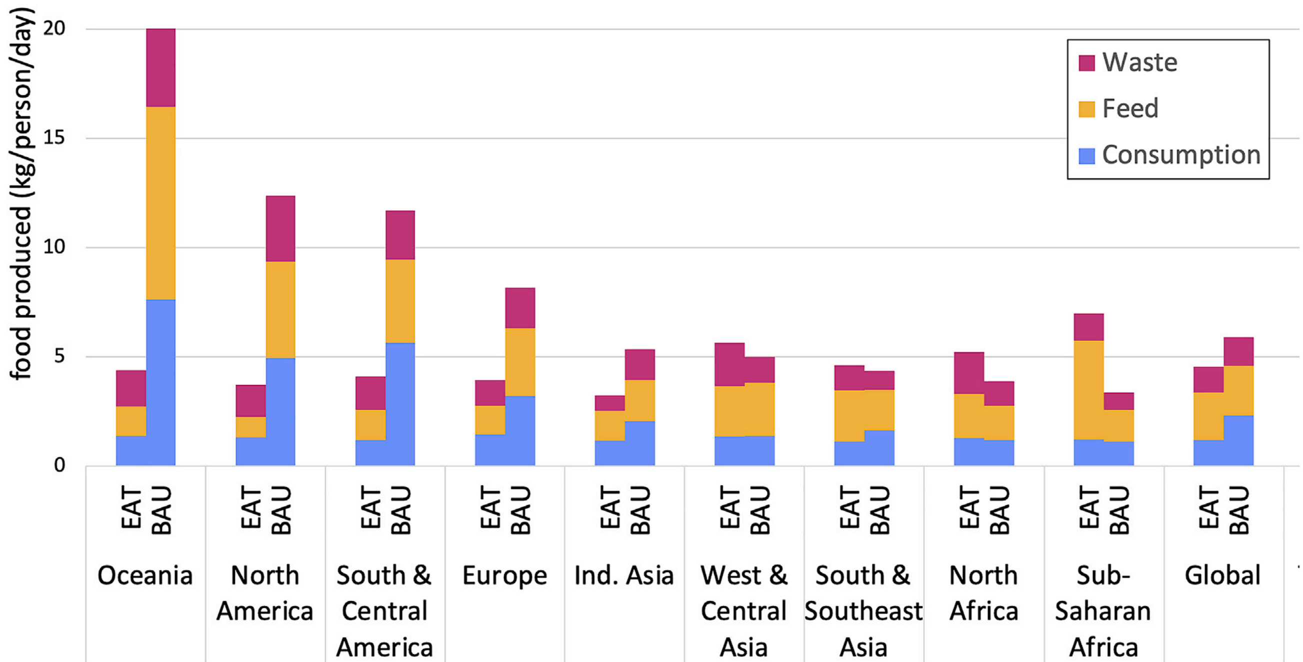

Figure 1. Global per capita daily production of food for consumption, feed, and lost as waste under EAT-*Lancet* and business-as-usual (BAU) conditions

including 45 g/capita/day of chicken or other poultry, exceeding the global BAU consumption of 35 g/capita/day. In total, we estimate the modeled EAT-*Lancet* diets provide 1.2 kg of food/capita/day compared with 2.3 kg food/capita/day under BAU condition, indicating that the current large-scale production of carbohydrate crops (sugars, potatoes and cassava, and whole grains) can be reduced without affecting the intake of key macronutrients.[7]

Global food production patterns

Despite the significant reduction in food produced for consumption from 2.3 to 1.2 kg of food/capita/day, global feed production does not decrease so drastically, only from 2.26 to 2.17 kg of feed/capita/day (Figure 1). This is largely due to the shift of food production from nations with high-yielding livestock, primarily in Oceania, the Americas, and Europe, to nations in South and Southeast Asia, North Africa, and sub-Saharan Africa with lower yielding feed and livestock (see Data S1.csv at https://doi.org/10.5281/zenodo.7405302).[28] For example, we find that nations in sub-Saharan Africa need to produce 3.4 times more feed on average than nations in Europe to supply a similar EAT-*Lancet* diet (Figure 1). This is largely a result of the lower livestock yields found in these regions and the increased production quantities required to satisfy domestic demand.

The amount of food lost to waste also decreases significantly less than food consumption. The modest decrease from 1.32 to 1.19 kg food/capita/day is the product of the global shift of food production away from low-waste systems to higher waste ones and the increased production of high-waste food types. Regions with higher waste profiles throughout their entire supply chain see an increase in total food production (North Africa, sub-Saharan Africa, South and Southeast Asia), while regions with lower waste profiles see a decrease in production (Oceania, North America, Europe, Industrialized Asia). Furthermore, the added production of high-waste fruits and vegetables stipulated by the EAT-*Lancet* committee and the decreased production of low-waste food types such as meats, cereals, and dairy prevent food waste from decreasing in accordance with lower food consumption. On the contrary, the combination of producing higher waste food items in higher waste food supply chains leads to a relative increase in food waste. Despite these added inefficiencies, global food production for consumption, feed, and food lost to waste are all reduced under domestically produced EAT-*Lancet* diet conditions while providing proper nutrition.

The impact of restructuring global food production also results in a significant reallocation of agricultural land use globally. Nations in North America, Europe, Industrialized Asia, and South and Central America would decrease their overall land demand by a combined 838 million hectares (Mha), from 1,689 Mha to 851 Mha (Table 2, full dataset available in Table S1). Nations in South and Southeast Asia together with West and Central Asia will also see a modest increase in agricultural land use from 1,475 Mha to 1,495 Mha. Nations in North Africa would be required to expand their agricultural land use from 77 Mha to 104 Mha. In sub-Saharan Africa, agricultural land use would have to double, from 497 Mha to 996 Mha, highlighting this region's current heavy dependence on food imports.[21,22] Globally, total agricultural land use would decrease by 9%, from 3,798 Mha to 3,469 Mha, a small reduction compared with the 48% reduction in total food for consumption.

Global agricultural land requirements

Of the 155 nations that can supply an EAT-*Lancet* diet by including food items from all food groups, 86 have sufficient

Table 2. Global agricultural land use change from BAU diet production to the diets modeled from EAT-*Lancet* caloric ratios production

	Agricultural land use (Mha)		
Region	EAT-*Lancet*	BAU	Available land
Europe	231.3	422.9	554.7
Industrialized Asia	350.8	483.2	628.8
Oceania	13.3	55.9	386.9
Other	9.7	5.2	3.6
North America	68.0	305.1	509.1
North Africa	104.2	76.6	86.2
South and Central America	201.0	477.4	477.4
South and Southeast Asia	1,321.3	1,275.6	1,275.6
Sub-Saharan Africa	995.9	497.3	1,037.0
West and Central Asia	173.4	198.9	669.9
Global	3,468.8	3,798.1	5,629.2

agricultural land to feasibly source a domestically sourced EAT-*Lancet* diet, accounting for 3.81 billion people (Figure 2). The remaining 69 nations, accounting for 3.72 billion people, do not have sufficient agricultural land to produce enough food for their population's consumption demand under EAT-*Lancet* dietary conditions and would require interventions (see below) to their domestic food system. The regions of South and Southeast Asia and Africa (both North and sub-Saharan) host the majority of nations incapable of domestically sourcing EAT-*Lancet* diets, accounting for 37 of these nations. Countries in South and Central America account for 11 such nations, while Europe hosts 10, and nations in Industrialized Asia and West and Central Asia account for the remaining 9. The two remaining nations without sufficient agricultural land are the Solomon Islands in Oceania and North Korea. Finally, the remaining 49 nations cannot produce food from all food groups, and thus are unable to provide a diversified diet. These nations are largely represented by small island nations, city states, and countries with arid climates.

Interventions to reduce agricultural land requirements

Following the patterns observed in our initial results, we explore four major interventions (see experimental procedures) to identify pathways for the 69 nations incapable of producing nationally sourced EAT-*Lancet* diets under baseline conditions to achieve sufficient production capacity within their agricultural land.

Under national production, the EAT-*Lancet* diet's reduced consumption of animal products does not result in a significant reduction of global feed production (Figure 1). As a result, we explore two interventions addressing this issue: (1) further increasing plant-based protein consumption and (2) improving livestock and feed yields. In addition to interventions addressing the need for feed production, we also explore two further interventions: (3) improving non-feed crop yields and (4) reducing food waste across the entire supply chain.

Increasing plant-based proteins

As protein production from animals requires significantly more land compared with production of plant-based proteins,[29] further dietary adjustments within the EAT-*Lancet* constraints are possible to reduce the land demand of animal products. To investigate the potential of further increasing plant-based proteins, we reduced the daily consumption of beef, lamb and pork, poultry, and eggs to 50% of their original EAT-*Lancet* levels (from 30, 62, and 19 calories to 15, 31, and 9.5 calories, respectively) while proportionally allocating these calories to plant-based proteins (nuts, legumes).

The resulting diet provides 2,860 calories, 97 g of protein, and 103 g of fat, macronutrient metrics that are largely consistent with the baseline EAT-*Lancet* diet. This variant of the EAT-*Lancet* diet would allow 11 additional nations to satisfy their food demand domestically (Figure 3A) and would be particularly effective in Europe, where six nations could potentially become capable of domestically sourcing low-animal protein EAT-*Lancet* diets. Furthermore, two nations in South and Southeast Asia and sub-Saharan Africa and Panama in South and Central America could also successfully adopt this strategy. Overall, this intervention would grant domestically sourced EAT-*Lancet* diets to an additional 156 million people.

This intervention, however, would require drastic changes in the global trend of increasing meat consumption.[7] Under the explored low-meat EAT-*Lancet* diet, daily animal product consumption (excluding fish) would decrease from 365 to 121 g of animal products/capita/day. Although such low levels of animal consumptions may be considered unfeasible in many countries, these consumption rates are still expected to be sufficient to satisfy a healthy daily intake.[7]

Improving livestock and feed yields

In most nations, the reduction in animal consumption under the EAT-*Lancet* diet causes a large reduction in per capita feed production. Notable exceptions include nations in North Africa where per capita feed production maintains current levels, nations in South and Southeast Asia where a marginal decrease is observed, and nations in sub-Saharan Africa where per capita feed production nearly doubles. For the nations composing the latter two regions, low livestock and feed crop yields limit the benefits of reducing the overall share of animal products as prescribed by the EAT-*Lancet* diet. In particular, low livestock yields significantly impact the need to produce additional feed, as more animals are required to compensate for lower livestock yields.[30] We explore the impact of raising feed and livestock yields of the least efficient nations in South and Southeast Asia and sub-Saharan Africa to their respective Food and Agriculture Organization of the United Nations (FAO) regional group average levels as a means to address this problem.

This intervention would be less effective than reducing animal protein consumption, only allowing one extra nation across sub-Saharan Africa and South and Southeast Asia (Bhutan) to feasibly implement a domestically sourced EAT-*Lancet* diet (Figure 3B). However, by increasing the feed and livestock yields of the nations in these regions were increased to globally average yields, seven nations in sub-Saharan Africa and two nations in South and Southeast Asia (an additional 324 million people) could save enough agricultural land to implement domestically sourced EAT-*Lancet* diets (Figure S1). We find that average global feed crop yields are 1.43 times higher than those found in South and Southeast Asia and 1.76 times higher than those found in sub-Saharan Africa. This lack of access to varied and nutritious feed also limits the potential production output for livestock farmers in these regions, resulting in global livestock yields

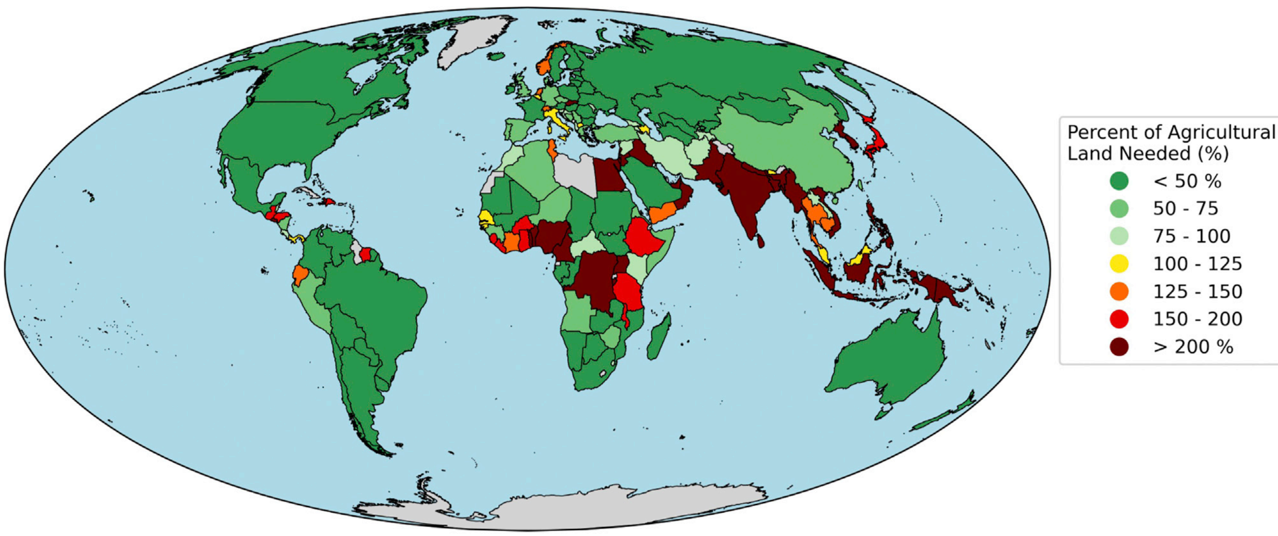

Figure 2. Fraction of total agricultural land use needed to satisfy a domestically sourced EAT-*Lancet* diet food production demand
The results are normalized to 100%, with values less than 100% indicating nations that require less than the totality of their agricultural land. Values above 100% indicate nations that require more than their available agricultural land. Countries without sufficiently diversified food production are presented in gray.

being up to 1.81 times higher than those found in South and Southeast Asia and up to 1.42 times higher than those found in sub-Saharan Africa.

Livestock yields in sub-Saharan Africa and South and Southeast Asia have stagnated over the past 40 years, limiting the potential for food self-sufficiency in these regions.[28] However, the implementation of shorter national food supply chains may improve accessibility to nutritious feed,[31] and in combination with educational programs addressing the importance of providing balanced feeds,[32] regional livestock yields could begin to increase in these regions under a nationally sourced food system.[33] Increasing yields by such factors is a daunting task nonetheless, and it requires careful attention to potential impacts caused by increased nutrient loading and water usage in these regions.[34]

Improving crop yields

Next, we explore the impact of improving crop yields (excluding all feed and livestock yields) as they comprise 44% of the total food weight produced in an EAT-*Lancet* diet. We evaluated an intervention in which nations in sub-Saharan Africa and South and Southeast Asia increase the yield of each crop item to their regional averages. The effect of this intervention was also only minimal, as it enabled only Bhutan in South and Southeast Asia, and no nation in sub-Saharan Africa, to self-satisfy their domestic food demand (Figure 3C). Further analyses show that if nations in these regions increase their crop yields to globally average levels, three additional nations in sub-Saharan Africa and one in South and Southeast Asia could potentially source domestic EAT-*Lancet* diets (Figure S1).

Improving both the yields of crops for feed and for human consumption can be addressed through various facets. Many nations in sub-Saharan Africa suffer from poor pest and weed management, severely limiting their potential yields.[35,36] Therefore promoting and incentivizing farmer eduction and access to technological innovations and crop management strategies are paramount for the realization of such interventions.[37] Soil constraints due to insufficient nutrient availability or water capacity are also significant barriers to improving yields across all regions. These soil constraints can be overcome through soil management techniques; however, they may be costly and impractical to implement.[38] Alternatively, introducing high-yielding hybrid crop variants can be effective in helping nations achieve regional, and even global, crop yields.[39]

Reducing of food loss and waste

In addition to the highfeed quantities required under national EAT-*Lancet* diet production, we find that food waste does not decrease in accordance with the reduction in food production (Figure 1). Instead, we find that the global food system waste rate would increase under nationally sourced diets despite maintaining the food loss and waste rates as currently reported.

Under nationally sourced EAT-*Lancet* diets, two factors, in addition to percentage waste rates, play a critical role in increasing the quantity of lost or wasted food. First is the decentralization of food production away from nations with low-food-waste supply chains to nations with higher waste supply chains. The current high-export, low-waste food production systems found in the high-income countries of Oceania, North America, Europe, and Industrialized Asia would drastically reduce their food production. Concurrently, low- and middle-income countries with higher waste in their food production systems (e.g., in Africa and Asia) would drastically increase their food production. The shift in food production away from high-income countries to low- and middle-income countries would therefore increase the food waste fraction of the global food system under self-sufficient conditions (Figure 1).

Secondly, an EAT-*Lancet* diet stipulates an increased share of plant-based proteins, fruits, and vegetables (Table 1). These are food groups with high production losses and consumption waste fractions, while meats, which are less consumed under

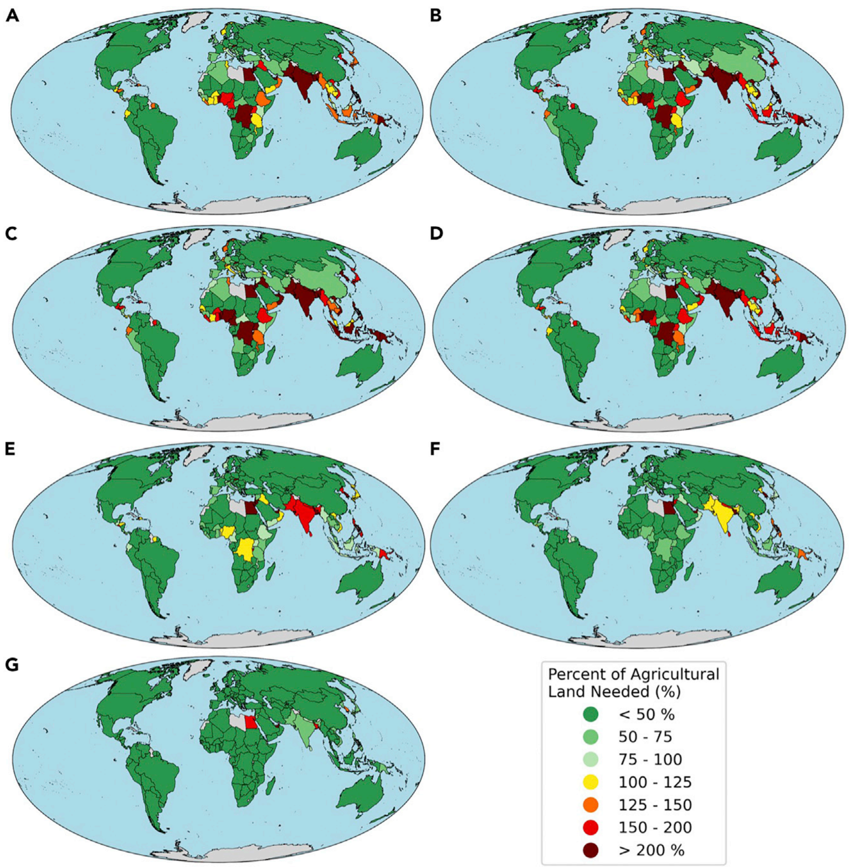

Figure 3. EAT-*Lancet* diet national agricultural land use of (A) reducing animal meat and eggs consumption by 50%, (B) improving livestock yields and feed yields to regional averages in sub-Saharan Africa and South and Southeast Asia, (C) improving crop yields to regional averages in sub-Saharan Africa and South and Southeast Asia, (D) reducing each regional food category's loss rate to the lowest globally observed value, (E) combining interventions (A)–(D) simultaneously, (F) intervention (E) and expanded yield improvements to globally average levels and to nations outside of sub-Saharan Africa and South and Southeast Asia, and (G) intervention (F) with the adoption of a pescatarian diet.

EAT-*Lancet* conditions, generally have a lower loss and waste fraction (Table S2).[16]

As a result of this increased global rate of food waste, we explore the effects of a low-waste intervention. Our intervention reduces the waste rate of each food category at each supply chain stage to the lowest currently observed values. For example, the lowest loss rate of cereals in agricultural production is found to be 2% in multiple regions. North Africa has a 6% loss rate for this food group at the agricultural production stage. At the consumption stage, however, sub-Saharan Africa has a waste rate of 5% fruits and vegetables, while North America has a rate of 28% (full breakdown in Table S2). This approach, instead of a broad 50% reduction as found in the EAT-*Lancet* Commission report,[7] was chosen as it provides tangible objectives for each country to emulate waste rates already observed elsewhere.

This intervention would be very effective in Europe, where seven nations would save sufficient agricultural land to domestically source EAT-*Lancet* diets (Figure 3D). In South and Southeast Asia and sub-Saharan Africa, two nations would sufficiently reduce agricultural land use, as would one additional nation in North Africa.

Although addressing food waste at the global scale is a daunting task, minimizing food loss throughout the supply chain may be more easily achieved under shorter, national supply chains, where reduced inefficiencies lead to improved food surplus management.[40] In low-income countries, addressing issues related to infrastructure such as storage facilities, transportation, refrigeration, and packaging are paramount to reduce food losses early in the supply chain.[4] In high-income countries, the current high rates of food losses at the consumption stage reflect the over-consumption of food items under our current production patterns. With production quantities shifted to more appropriate consumption levels under EAT-*Lancet* conditions, waste rates occurring in the late stages of high-income country supply chains may decrease as a result of improved consumption planning.[4] Currently, overproduction to satisfy trade quality requirements or product takeback obligations represent a significant portion of production losses.[41] Limited trade the food system could also remove these burdens, reducing the need for overproduction and the food waste it generates.

*Toward a robust EAT-*Lancet *diet for every nation*

The EAT-*Lancet* Commission originally estimated that shifting the composition of global food consumption toward their vision of a planetary health diet would not have a significant impact on cropland use.[7] Our results, which project a similar food consumption vision, support this conclusion, despite analyzing the global food system under self-sufficient conditions. However, our analysis reveals that 118 nations cannot, under current production practices, develop a national food production system based on the EAT-*Lancet* diet. Of these countries, 49 lack the production of major food groups to provide a fully nutritious diet. These countries are primarily island nations, micro-states, and countries largely located within the arid Köppen climate classification. For the 62 million people who live in such countries (<1% of the global population), trade seems an essential and irreplaceable instrument to provide a nutritious diet as their land resources do not allow for a self-reliant food system.

The remaining 69 countries produce food from all needed food categories, but do not possess sufficient agricultural land to satisfy their domestic food demand. Although no single intervention can accommodate nationally sourced diets for all nations, we find that further increasing the share of plant-based proteins

(11 countries) and reducing food waste (seven countries) would be the most effective interventions in helping nations overcome their land use limitations. On the other hand, improving livestock and feed yields (one country) and crop yields (one country) in sub-Saharan Africa and South and Southeast Asia would be far less effective, highlighting the immense yield gap that has developed in these regions.[28] Nevertheless, if all the issues are addressed concurrently, the four interventions presented in the current work provide 32 additional nations sufficient agricultural land, leaving 37 countries with no clear path to efficient enough land use (Figure 3E).

For these 37 remaining countries, more extreme interventions will be required to raise their production efficiency to levels at which they could consider relying exclusively on domestic food production. If these countries can raise their crop and livestock yields to globally average rates, an additional 13 nations would have sufficient agricultural land to consider domestic food production (Figure 3F). Another 19 nations of the remaining 24 would achieve the same result if they also adopted a pescatarian diet (caloric breakdown available in Table S3; Figure 3G). The final five nations are South Korea, Bangladesh, Egypt, Grenada, and the United Arab Emirates. In these countries, very high population densities ranging from 12.9 to 26.0 people per hectare of agricultural land (global average: 1.48 people per hectare of agricultural land), prevent these already vast interventions from sufficiently reducing their agricultural land demand to levels within their available agricultural land resources.

The challenges ahead

The ideas we present in this paper potentially have far reaching ramifications in estimating the quantity, composition, and land use constraints of nationally sourced EAT-*Lancet* diets. However, both production-side interventions as well as consumer-side interventions likely require more work to address some other important unknowns. Production-side interventions (yield increase and less production loss) are likely to affect nutrient and water demand, especially in impoverished agricultural soils, which we did not evaluate in this study.[37] Moreover, our work assumes the simultaneous production of all food items; however rotated crop production could significantly reduce the agricultural land use required to satisfy the domestic food demand of many countries. Furthermore, our analysis does not differentiate between cropland and pastureland, the latter of which is not always suitable for the former. Nevertheless, historically, a significant fraction of pastureland has been developed from woodlands or that would have alternatively been suitable for croplands.[42] From this, and the net reduction of land use globally, we do not expect the differentiation to significantly alter the results found in our model. Consumer-side interventions (lower waste and diets with higher plant-based proteins) must address public reception and willingness, together with effective policies that can facilitate such transitions. The economic impacts of restructuring the food system away from importing nations to exporting nations is also likely to have many ramifications both intended and unintended.[10] Further studies must address how to enact adequate governance that ensures an appropriate implementation of these interventions to achieve zero hunger at a global scale and avoid social justice issues, such as affordability and worker rights.[43–46] As certain nations, particularly in sub-Saharan Africa, would be required to drastically expand their agricultural land use, optimizing cropland locations will be crucial to maintain local biodiversity and minimize water impacts. Further analysis is also required to determine the infrastructural needs and economic consequences of such a shift in production.[47]

Although our results indicate many nations would not be limited by agricultural land, the issue of self-sufficient food systems is deeply nuanced and should consider many more dimensions. Removing trade would risk increasing the risk of local disruptions in food production due to local economic, political, or environmental shocks.[11,12] Such shocks would be difficult to overcome without the possibility of relying on trade to mitigate their impacts. Economically, certain countries spent the final decades of the 20th century optimizing their agricultural production toward crops for export.[13,48] Drastically and rapidly reversing the product of these policies would therefore have serious economic consequences on such countries and their trade partners. Due to these risks, adopting self-sufficient food systems is unlikely to be a beneficial solution in the near-term, particularly given the existing dependence on food imports many countries rely on.[25]

Nevertheless, countries operate their national food system somewhere on a continuum ranging from total autarky to complete dependence on imports.[11] Historically, countries have moved across this continuum, sometimes from one extreme to the other, through the implementation of policies.[25] For example, during the 1980s, many countries in Africa shifted away from seeking food self-sufficiency and move toward integrating trade as a fundamental source of food.[13] Therefore, understanding how far across this continuum a nation's food system can be shifted over time in order to maintain and improve resilience is strategically important in a world potentially facing more frequent global shocks.[49]

Conclusions

Our study expands upon the work of the EAT-*Lancet* Commission by assessing the feasibility of domestically sourcing an EAT-*Lancet* diet within the agricultural constraints of each nation. Although the commission does not intend, nor discuss, shifting food production toward self-sufficient systems, understanding the potential for a country to domestically supply a planetary health diet to their population is relevant for countries attempting to improve local food system resilience in times of uncertain global food supply chains. We find that 50% of the global population live in countries where this feat could already be accomplished. Further, we estimate that up to 95% of the global population live in countries that have enough agricultural land to develop a self-sufficient EAT-*Lancet*-based food system by successfully implementing a combination of production and consumption-based interventions. The potential for domestic food systems from an agricultural land perspective does not necessarily imply the potential for domestic food security, however, which integrates additional factors including food availability, accessibility, utilization, and stability.[50]

Furthermore, we find that shifting to self-sufficient food systems supplying planetary health diets would require a significant increase in food production for most low- and middle-income countries, while many high-income countries would drastically decrease food production. As predicted by the EAT-*Lancet* Commission and others, shifting the global production in such a way resulted in an increase in the global food waste rate.[7,16] In addition, increasing food production in certain countries may cause negative impacts on biodiversity and water-use, among other considerations. Further research is required to evaluate how such a food system may affect these aspects of the food system.

Nevertheless, these results indicate that agricultural land is unlikely to be a limiting factor for countries that seek to strengthen their local food system resilience by further integrating domestic food production. Although the food system in different regions responded uniquely to these proposed interventions, our results highlight that the investigated changes in diet and reductions in food waste had a far bigger impact when compared to increases in food and feed crop yields. Tackling these issues will require major investment in locally tailored agricultural systems. Nonetheless, they may become more necessary as growing disparities in food trade, growing populations, and increasing susceptibility of crops to climate change are leading to a decreasing global food system resiliency.[51]

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Nicolas Navarre (n.h.navarre@cml.leidenuniv.nl).

Materials availability

This study did not generate new unique materials.

Data and code availability

All original code and datasets have been deposited at Zenodo under https://doi.org/10.5281/zenodo.7405302.

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

Constructing national business-as-usual diets

First, we approximate contemporary national diets by averaging domestic food production reported by FAOSAT Production[52] from 2015 to 2019. By relying on national production data, we ensure that all food items considered are available for production within a nation, while imported food items are not considered. All food items reported for production within a nation were assigned to their respective EAT-*Lancet* diet food group (see Data S1.csv at https://doi.org/10.5281/zenodo.7405302).[7] To approximate consumption patterns from the production data, we applied regional-scale FAO loss rates at the food group level throughout the supply chain to determine the quantity of each food item ultimately available for consumption.[16] The food item quantities calculated after factoring in food losses and waste provide the dietary composition of a nation based on its domestic production data, hereinafter referred to as the BAU diet.

Constructing national EAT-*Lancet* diets

To develop an EAT-*Lancet* counterpart to the BAU diets, the food item composition of each food group gathered from the BAU diets was maintained, but the quantity consumed of each food group was fixed to match the caloric ratios established by the EAT-*Lancet* Commission (Table S3).

The total food production of a national EAT-*Lancet* diet was scaled to nation-specific protein demand. Protein demand was selected as the scaling factor instead of caloric demand, because it provides a reasonable estimate of required food intake and is considered an essential nutritional component to maintain critical body functions.[53] This study considers 1.6 g_p/kg_{bw}/day an appropriate amount for adults with general fitness.[27,54,55] The generally used benchmark of 0.8 g_p/kg_{bw}/day was not used as this is only sufficient to maintain minimum nitrogen balance, does not account for any physical activity, and is insufficient for children and elderly people.[27,53,55] Fat and caloric intake were used as secondary indicators to ensure that more than one macronutrient was sufficiently consumed. For these macronutrients, a target consumption of at least 35 kcal/kg_{bw}/day and 1.0–1.5 g_{fat}/kg_{bw}/day was considered a nutritious diet.[54] A target weight for all nations was determined assuming a body mass index of (BMI) of 22, considered a healthy BMI objective for both men and women.[56] The BMI to national target weight conversion was calculated as follows:

$$Weight_{avg,kg} = Height^2_{avg,m} * 22 \qquad \text{(Equation 1)}$$

where national average height data in meters was collected from the World Population Review.[57] Average national height was calculated using the average height of men and women assuming a 1:1 ratio of each gender. National height was considered the most appropriate scaling factor to combine with BMI as it is an easily collected indicator and BMI is frequently used to identify healthy weight objectives.[56] Each nation's modeled target weight was then used to determine its total protein demand (Table S4). The food consumption quantities of the modeled EAT-*Lancet* diets were scaled to match the total protein demand by determining the protein density (in grams of protein per gram of food) of each nation's modeled diet. The nutritional value of all food items was calculated from FAO datasets via protein, caloric, and fat content. Missing protein and caloric information was estimated based on nitrogen to protein conversion factors[22] and caloric food group averages, respectively.

After establishing the consumption quantity of each food item, national scale consumption was modeled using 2018 FAOSTAT population data.[58] The regional-level FAO food loss rates throughout the supply chain were applied at a food group resolution to estimate the total amount of additional food production required to satisfy the new national-scale food consumption demand for each nation.

Calculating land use

The average national food item yields as reported by FAOSAT[52] from 2015 to 2019 were used to convert total domestic food production to land use. In the case of livestock-based food items, land use and feed requirements, including grass from grazing, of each livestock group were approximated using region-specific livestock systems (industrial, mixed, and pasture) as reported by the Global Livestock Environmental Assessment Model (GLEAM).[59] In the case of extensive farming systems, the stocking rates of livestock were estimated from FAO livestock units, while intensive system stocking rates were estimated from FAO and other literature sources.[30,59,60] The feed production necessary for each livestock system and type was quantified based on the feed compositions and quantities reported in the literature and FAO's GLEAM.[30,59] In the case of dairy products, yields were constrained by feed conversion ratios to account for nation-specific feed composition and quantities.[61,62] We excluded land use required for fish production as this data was only reported by 22 nations.[24] This is unlikely to significantly alter national agricultural land use as aquaculture requires an order of magnitude less feed than terrestrial animals and relies on wild-caught forage fish to supply key nutrients.[63] Furthermore, a large portion of fish production remains sourced from oceans.[63]

The land use required to achieve each nation's necessary food production was then compared with their available agricultural land. The agriculture land areas available for each nation as reported by FAOSTAT were used as the maximum limit.[24]

Interventions

We explore four major interventions to increase the robustness of local food systems:

1) Increasing plant-based proteins within the EAT-*Lancet* diet by reducing the caloric ratios of beef, lamb and pork, poultry, and eggs to 50% of their original EAT-*Lancet* levels (from 30, 62, and 19 calories to 15, 31, and 9.5 calories) while allocating these proportionally to nuts (from 284 calories to 311.4) and legumes (from 290 calories to 319.1; Table S3). For this intervention, we analyze the impact on both macronutrient intake and land use.
2) Raising feed and livestock yields for nations in sub-Saharan Africa and Southeast Asia to their FAO regional group average. In this intervention, the regional average yield of livestock and each feed crop was calculated from the nations composing sub-Saharan Africa and South and

Southeast Asia. If nations within these regions had livestock or feed crop yields below their region's calculated average, the national yield value was raised to the regional average.

3) Increasing (non-feed) crop yields for nations in sub-Saharan Africa and Southeast Asia to their FAO regional group average. This intervention follows the same approach as intervention 2, but the yields of all crops not dedicated to feed were adjusted to the regional average.
4) Reducing food waste of every FAO region to the lowest waste percentage observed for a specific food type throughout each specific portion of the food supply chain. Each food category has a reported food loss value for each supply chain stage (production, post-harvest, processing, distribution, consumption) and for each FAO region. In this intervention, the loss value for each combination of food group and supply chain stage was set to the minimum value reported by each FAO region (Table S2).

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.12.002.

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AUTHOR CONTRIBUTIONS

N.N.: conceptualization, experimental procedures, data curation, writing – original draft. C.D-V.: conceptualization, experimental procedures, data curation. M.S.: conceptualization, writing – review & editing. J.M.: conceptualization, writing – review & editing, validation.

DECLARATION OF INTERESTS

The authors declare no conflict of interests.

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