Trading Responsibility: navigating national burdens in a globalized world

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Chapter 2

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

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Abstract

The overdependence on trade increases the vulnerability of many nations to food-trade shocks that can lead to local food shortages. These issues can be alleviated by exploring scenarios of healthy and sustainable food production at national scales, especially for low-income nations. The EAT-Lancet diet has been proposed as a healthy and environmentally friendly diet, but the feasibility of sourcing it nationally has yet to be explored. Using FAOSTAT production data for 204 nations and the EAT-Lancet Commission guidelines, the baseline EAT-Lancet diet that each nation can produce within their agricultural land area was calculated. For nations that did not have sufficient agricultural land, interventions were elaborated by adjusting production and consumption efficiencies of all modeled national diets, revealing that 95% of the global population lives in countries that are not limited by land availability to source these diets.

Keywords

EAT-Lancet diet; National food production; Agricultural land-use; Food waste; Crop yields

2.1 Introduction

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 (Tendall et al., 2015). Today however, despite enormous food production, 77% of nations suffer from a calorie deficit (Davis et al., 2014), over 2 billion people face food insecurity (FAO, 2021b), 2 billion people exhibit a micronutrient deficiency, and 2 billion people are considered overweight or obese (Development initiative Ltd, 2021). Concomitantly, the current food production system is estimated to occupy 50% of global ice-free land (IPCC, 2019), has been linked to 34% of global greenhouse gas emissions (Crippa et al., 2021), and is driving the unprecedented decrease in global biodiversity (Dudley & Alexander, 2017). 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 while also ensuring the environmental objectives presented in the Paris Agreement and Rio Conventions objectives could be met (Willett et al., 2019b). The EAT-Lancet diet also addresses Sustainable Development Goals (SDGs) by minimizing the food systems' environmental impacts and allowing regional and cultural dietary differences (Willett et al., 2019b). 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 ingrained in global food trade that hampers universal access to this healthy diet (Tu et al., 2019).

The global food trade allows for production in better suited locations to grow food, thus increasing production specialization, efficiency, and comparative advantages (Bureau & Swinnen, 2018). It also provides a buffer to nations in need of support to overcome local limitations, particularly in times of uncertainty (Kummu et al., 2020b). In addition, trade taxes can be an important source of revenue, particularly in low-income countries (Barlow et al., 2021). However, it also creates dependence of many low- and middle-income nations (Gustavsson et al.,

2011) on imports, making them vulnerable to food system perturbations, such as pandemics or war, in countries that typically export large quantities of food (Clapp, 2017a). Such shocks cause price spikes, local food shortages, and severe undernourishment (Clapp, 2017a). 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 (Puma et al., 2015). Despite decreasing production diversity, trade has helped diversify food supply in many countries (Kummu et al., 2020b), however in certain regions, global food trade can increase the price of food items, rendering them inaccessible to the local population (Pace & Gephart, 2017). This price action, in addition to income, marketing, and consumer behavior, among other factors (Kearney, 2010). has contributed to the loss of local dietary culture and food traditions as more affordable but less nutritious globalized diets have eclipsed local diets (Morgan et al., 2006). Trade also spurs a global nutrient imbalance, by spatially separating food production from consumption (Lassaletta et al., 2014; Nesme et al., 2018). Some countries with high agricultural productivity create high levels of nutrient agricultural runoff making their downstream aquatic zones susceptible to eutrophication and dead zones (Nesme et al., 2018). In contrast, other less-productive countries may experience ongoing agricultural land degradation (UNCCD, 2014). These negative impacts are amplified in times of crises (Gobal Network Against Food Crisis, 2021), highlighting the need to explore alternative models of food production that minimize the increasing divide between production and consumption within a general healthy dietary framework.

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 (FAO, 2018b). 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.

2.2 Materials and methods

2.2.1 Constructing national Business-as-Usual diets

First, we approximate contemporary national diets by analyzing domestic food production as reported by averaging FAOSAT Production from 2015 to 2019 (FAO, 2018a). 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* food group and EAT-*Lancet* diet functional group (Appendix A; Table A1) (Willett et al., 2019b) To approximate consumption patterns from the production data, we applied regional-scale FAO loss rates at the functional group level throughout the supply chain to determine the quantity of each food item ultimately available for consumption (Gustavsson et al., 2011). The resulting food item quantities provide the dietary composition of the nation based on their domestic production data, hereinafter referred to as the business-as-usual (BAU) diet.

2.2.2 Constructing national EAT-Lancet diets

To develop an EAT-*Lancet* counterpart to the BAU diets, the food item composition of each functional group gathered from the BAU diets was maintained, however, the quantity consumed of each functional group was fixed to match the caloric ratios established by the EAT-*Lancet* Commission (Appendix A; Table A4).

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 (G. Wu, 2016). This study considers 1.6 g_p/kg_{bw}/day an appropriate amount for adults with general fitness (Kerksick et al., 2018a; Lonnie et al., 2018). 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 (Lonnie et al., 2018; G. Wu, 2016). Fat and caloric intake were used as secondary indicators to ensure that more than one macro-nutrient was sufficiently consumed. For these macronutrients, a target consumption

of at least 35 kcal/kg_{bw}/day and 1.0-1.5 g_f/kg_{bw}/day was considered a nutritious diet (Kerksick et al., 2018a). A target weight for all nations was determined assuming a body mass index (BMI) of 22; considered a healthy BMI objective for both men and women (CDC, 2022), using the following conversion:

$$Weight_{avg,kg} = Height^2_{avg,m} * 22 \quad (2.1)$$

where national average height data in meters was collected from the World Population Review (WPR, 2021). 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 (CDC, 2022). Each nation's modeled target weight objective was then used to determine its total protein demand (Appendix A; Table A5). 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 were estimated based on nitrogen to protein conversion factors (Lassaletta et al., 2014) 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 (FAO, 2022). The regional-level FAO food loss rates throughout the supply chain were applied at a functional group resolution to estimate the total amount of additional food production required to satisfy the new national scale food consumption demand for each nation.

2.2.3 Calculating national agricultural land-use

The average national food item yields as reported by FAOSAT (FAO, 2018a) from 2015 to 2019 were used to convert the total domestic food production to land-use. In the case of livestock-based food items, the 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 GLEAM (FAO, 2018c). 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 (FAO, 2018c, 2021a; Mottet et al., 2017). 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 model (FAO, 2018c; Mottet et al., 2017). In the case of dairy products, yields were constrained by feed conversion ratios to account for nation-specific feed composition and quantities (Arndt et al., 2015; de Oliveira et al., 2014). We excluded land use required for fish production as this data is only reported by 22 nations (FAO, 2018b). This is unlikely to significantly alter the national 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 (Froehlich et al., 2018). Furthermore, a large portion of fish production remains sourced from oceans (Froehlich et al., 2018).

The land-use required to achieve each nation's necessary food production was then compared to their available agricultural land. The agricultural land areas available for each nation as reported by FAOSTAT were used as the maximum limit (FAO, 2018b).

2.2.4 Developing food system interventions

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

Fist, increasing plant-based proteins within the EAT-*Lancet* diet by modifying the Commission's food group caloric ratios to reduce 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; Appendix A; Table A4). For this intervention, we analyze the impact on both macronutrient intake and land-use.

Secondly, 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.

Thirdly, 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 method as Intervention 2, however the yields of all crops not dedicated to feed were adjusted to the regional average.

Finally, 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 (Appendix A; Table A3).

2.3 Results

2.3.1 Global food consumption patterns

Of the 204 nations who reported FAOSTAT production data, 155 can supply an EAT-*Lancet* diet by including food items from all food groups, and 49 do not produce food items from one, or more, food groups (Appendix A; Table A1).

From the 155 nations producing food from all food groups, a globally averaged EAT-Lancet diet provides 2810 calories, 97 grams of protein, 104 grams of fat for consumption per capita per day, and comprises circa 66 (range: 32-131) food items (Appendix A; Table A1). At 104 grams, 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. The intake of 2809 calories and 97 grams of protein is also sufficient to satisfy the demands of a generally active and healthy adult exercising 3 times per week for 30-40 minutes per day (Kerksick et al., 2018b).

The modeled EAT-*Lancet* diets were largely able to shift consumption 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 2.1). This small discrepancy arises from scaling the diets to the caloric food group ratios rather than the mass-based ones. When compared to BAU consumption, the modeled EAT-*Lancet* diet dramatically reduces the consumption of added sugars, animal products, potatoes and cassava, and whole grains, while sharply increasing the consumption of fruits, vegetables, and nuts. Our modeled EAT-*Lancet* Diet still provides 170 grams/day of animal products, including 45 grams/capita/day of chicken or other poultry, exceeding the global BAU consumption of 35 grams/capita/day. In total, we estimate the modeled EAT-*Lancet* diets provide 1.2 kg of food/capita/day compared to 2.3 kg food/capita/day under BAU conditions, 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 (Willett et al., 2019b).

Table 2.1 Global daily food intake under nationally sourced EAT-Lancet diets and business as usual (BAU) production. Gram per day values inside the EAT-Lancet Commission recommended range are highlighted in green while values outside the range are highlighted in red.

Food Group	Commission Range (g/d)	Model EAT intake (g/d)	BAU intake (g/d)
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	1324	1213	2326

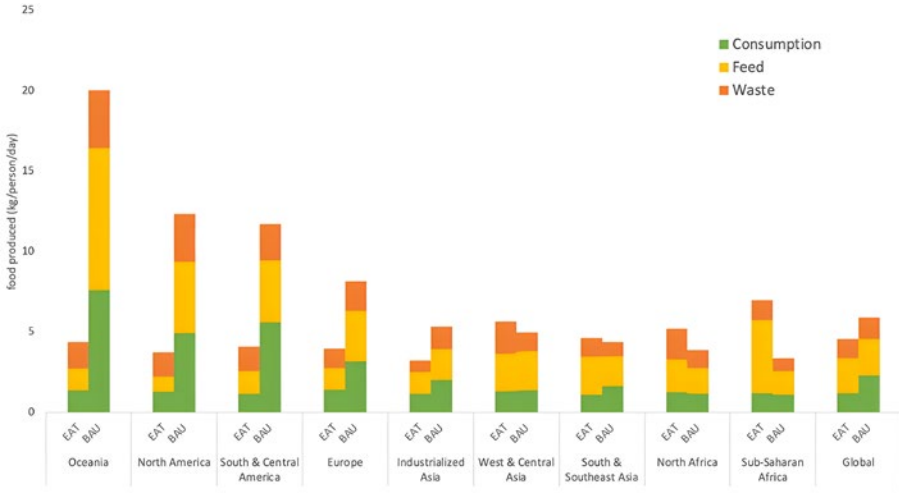

Figure 2.1 Global per capita daily production of food for consumption, feed, and lost as waste under EAT-Lancet and Business-as-usual (BAU) conditions.

2.3.2 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 2.1). 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 & Southeast Asia, North Africa, and sub-Saharan Africa with lower yielding feed and livestock (Appendix A; Table A1; Enahoro et al., 2019). 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 2.1). 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 food consumption. As a result, 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), reducing their estimated agricultural land use from 1,689 Mha to 851 Mha (Table 2.2, full dataset available in Appendix A; Table A2). Nations in South & Southeast Asia together with West & Central Asia will also see a modest increase in agricultural land use from 1475 Mha to 1495 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 the region's current heavy dependence on food imports (Lassaletta et al., 2014; Nesme et al., 2018). Globally, total agricultural land-use would decrease by 9%, from 3798 Mha to 3469 Mha; a small reduction compared to the 48% reduction in total food for consumption.

Table 2.2 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	1321.3	1275.6	1203.5
Sub-Saharan Africa	995.9	497.3	1037.0
West and Central Asia	173.4	198.9	669.9
Global	3468.8	3798.0	5079.4

2.3.3 Global agricultural land requirements

Of the 155 nations that can supply an EAT-*Lancet* diet by including food items from all functional food groups, 86 have sufficient agricultural land to feasibly source a domestically sourced EAT-*Lancet* diet, accounting for 3.81 billion people (Figure 2.2). 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 are the ones that do not produce food from all functional food groups. These nations, which cannot supply a sufficiently diversified, diet account for 0.0618 billion people and are largely represented by small island nations, city-states, and countries with arid climates.

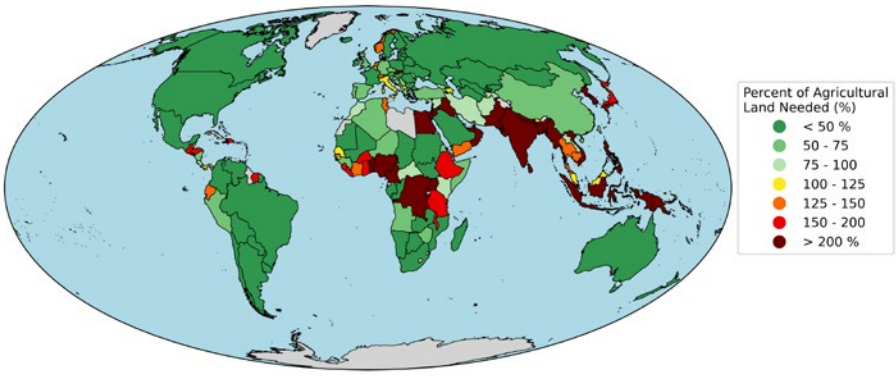

Figure 2.2 Fraction of total agricultural land-use needed to satisfy a domestically sourced EAT-Lancet diet food production demand. The results are normalized to 100%, with values less than 100% indicating nations require less than the totality of their agricultural land. Values above 100% indicate nations that require more than their available agricultural land. Countries without sufficiently diversified food production are presented in grey.

2.3.4 Interventions to reduce agricultural land requirements

Following the patterns observed in our initial results, we explore four major interventions (see Methods) 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.

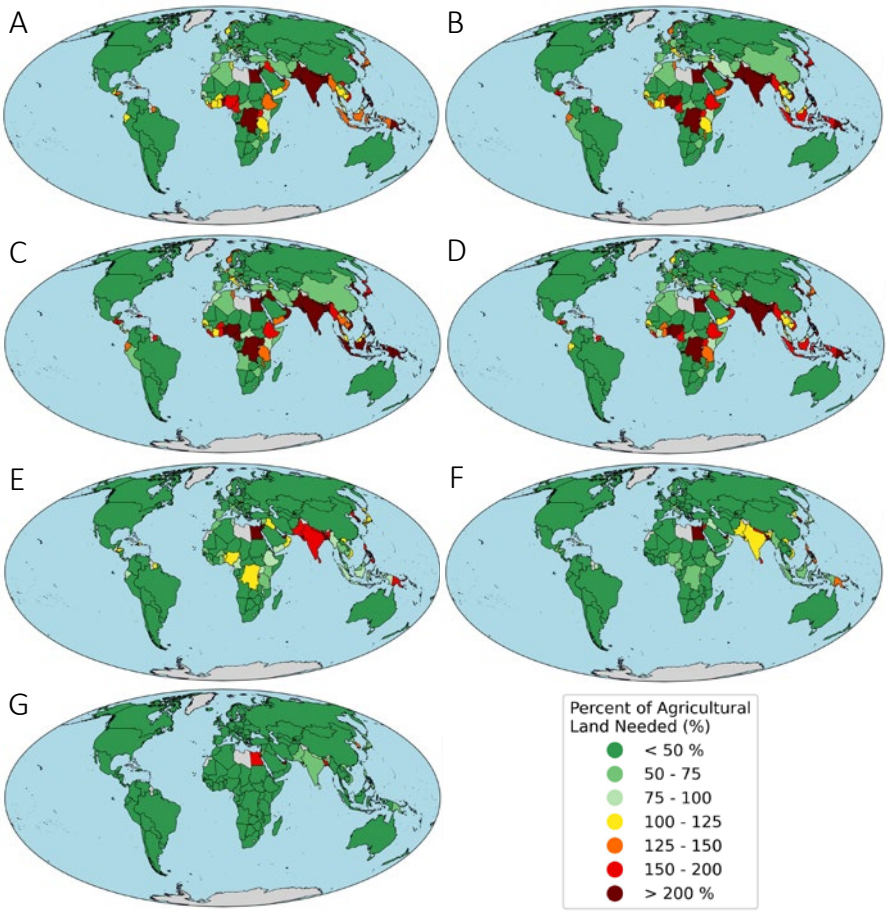

Figure 2.3 EAT-Lancet Diet national agricultural land use of **A.** Reducing animal meat and eggs consumption by 50%, **B.** Improving livestock yields and feed yields to regional averages in sub-Saharan Africa and South & Southeast Asia, **C.** Improving crop yields to regional averages in sub-Saharan Africa and South & 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 & Southeast Asia, **G.** Intervention F with the adoption of a pescatarian diet.

Under no trade conditions, the EAT-*Lancet* diet's reduced consumption of animal products does not result in a significant reduction of global feed production (Figure 2.1). As a result, we explore two interventions

addressing this issue: further increasing plant-based protein consumption and improving livestock and feed yields. In addition to interventions addressing the need for feed production, we also explore two further interventions: improving non-feed crop yields and reducing food waste across the entire supply chain.

Increasing plant-based proteins: As protein production from animals requires significantly more land compared to the production of plant-based proteins (Godfray et al., 2018), further dietary adjustments within the EAT-*Lancet* constraints are possible to reduce the land demand for 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) while proportionally allocating these calories to plant-based proteins (nuts, legumes).

The resulting diet provides 2860 calories, 97 grams of protein, and 103 grams of fat; macronutrient metrics 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 2.3A) and would be particularly effective in Europe, where 6 nations could potentially become capable of domestically sourcing low-animal protein EAT-*Lancet* diets while 2 nations in South and Southeast Asia and sub-Saharan Africa, and Panama in South and Central America would also become feasible candidates. 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 (Willett et al., 2019b). Under the explored low-meat EAT-*Lancet* diet, daily animal product consumption (excluding fish) would decrease from 365 to 121 grams of animal products/capita/day. Although such low levels of animal consumption may be considered unfeasible in many countries, these consumption rates are still expected to be sufficient to satisfy a healthy daily intake (Willett et al., 2019b).

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, except for 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 (Mottet et al., 2017). 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 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 2.3B). If the feed and livestock yields of the nations in these regions were increased to globally average yields however, 7 nations in sub-Saharan Africa and 2 nations in South and Southeast Asia could save enough agricultural land to implement domestically sourced EAT-*Lancet* diets to an additional 324 million people (Appendix A; Figure A1). 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 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 (Enahoro et al., 2019). However, the implementation of shorter national food supply chains may improve accessibility to nutritious feed (Valbuena et al., 2012), and in combination with educational programs addressing the importance of providing balanced feeds (FAO, 2012), regional livestock yields could begin to increase in these regions under a nationally sourced food system (Herrero et al., 2013). Increasing yields by such factors is a daunting task nonetheless, and requires careful attention to potential impacts caused by increased nutrient loading and water usage in these regions (Tuninetti et al., 2022).

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 & Southeast Asia increased 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 2.3C). 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 become candidate nations to potentially domestically source EAT-*Lancet* diets (Appendix A; Figure A1).

Improving both the yields of crops for feed and for human consumption can be addressed through many facets. Many nations in sub-Saharan Africa suffer from poor pest and weed management, severely limiting their potential yields (Oerke, 2006; Parsa et al., 2014). Therefore promoting and incentivizing the education of farmers to incorporate technological innovations and crop management strategies are paramount for the realization of such interventions (Rosa et al., 2018). 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 (Pradhan et al., 2015). Alternatively, introducing high-yielding hybrid crop variants can be effective in helping nations achieve regional, and even global, crop yields (Gianessi, 2010).

Reducing food loss and waste: In addition to the high quantities of feed still observed under the baseline EAT-*Lancet* diets scenario, we find that food waste does not decrease in accordance with the reduction in food production (Figure 2.1), indicating that the global food system waste rate would increase in nationally sourced diets. Therefore, we explore the effects of a low-waste intervention, in which each regional food category's loss rate is reduced to the lowest globally observed value (Appendix A; Table A3).

This intervention would be very effective in Europe, where 7 nations would save sufficient agricultural land to domestically source EAT-*Lancet* diets (Figure 2.3D). In each of Europe, South and Southeast Asia,

and sub-Saharan Africa, 2 nations would become feasible candidates, while North Africa would have 1 additional candidate nation.

2.4 Discussion

Under nationally sourced EAT-*Lancet* diets, two factors play a critical role in increasing the rate at which food is lost or wasted. First, the decentralization of food production away from nations with low food waste supply chains to nations with higher waste supply chains. Secondly, an EAT-*Lancet* diet stipulates an increased share of plant-based proteins, fruits, and vegetables (Table 2.1). These are food groups with high production losses and consumption waste fractions, while meats, which are less consumed under EAT-*Lancet* conditions, generally have a lower loss and waste fraction (Appendix A; Table A3) (Gustavsson et al., 2011).

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 as these have been observed to reduce inefficiencies and lead to improved food surplus management (Garrone et al., 2014). In low-income countries, addressing issues related to infrastructure such as storage facilities, transportation, refrigeration, and packaging is paramount to reducing food losses early in the supply chain (IPCC, 2019). 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 observed late in the supply chains of high-income countries may decrease as a result of improved consumption planning (IPCC, 2019). Currently, overproduction to satisfy trade quality requirements or product takeback obligations represents a significant portion of production losses (Raak et al., 2017). Removing trade from the food system could also remove these burdens, reducing the need for overproduction and the food waste it generates.

2.4.1 Towards a robust EAT-Lancet diet for every nation

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 (7 countries) would be the most effective interventions in helping nations overcome their land-use limitations. On the other hand, improving livestock and feed yields (1 country) and crop yields (1 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 (Enahoro et al., 2019). Nevertheless, if all the issues are addressed concurrently, the four interventions presented in the current work provide 32 additional nations with sufficient agricultural land, leaving 37 countries with no clear path to efficient enough land-use (Figure 2.3E).

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 2.3F). Another 19 nations of the remaining 24 would achieve the same result if they also adopted a pescatarian diet (caloric breakdown available in Appendix A; Table A4; Figure 2.3G). The final 5 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), prevent these already vast interventions from sufficiently reducing their agricultural land demand to levels within their available agricultural land resources.

2.4.2 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 include in this study (Rosa et al., 2018). 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 which would have alternatively been suitable for croplands (Ellis et al., 2020). 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 (Kummu et al., 2020b). Further studies must address how to enact adequate governance that ensures appropriate implementation of these interventions to achieve zero hunger at a global scale and avoid social justice issues, such as affordability and worker rights (Béné et al., 2020; Coleman et al., 2021; Gupta et al., 2021; Hirvonen et al., 2020). 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 minimize local biodiversity and water impacts. Further analysis is also required to determine the infrastructural needs and economic consequences of such a shift in production (Beyer et al., 2022). Despite increases in land-use in certain nations, solving the puzzle of a fair and balanced global food system by implementing these tailored challenges in every nation, would not only ensure food security, but

would also reduce global demand for agricultural land to 683 Mha, or a mere 30% of contemporary values.

2.5 Conclusion

Our study assesses the feasibility of domestically sourcing an EAT-*Lancet* diet within the agricultural constraints of each nation, showing 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 lives 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. Although the food systems 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 compared to increases in food and feed crop yields. Tackling these issues will require major investment in locally tailored agricultural systems, but 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 (Vermeulen et al., 2012).

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 (Summit, 1996). Nevertheless, agricultural land availability is a relatively static resource for most nations, therefore exploring the limitations of this resource for each nation provides a strong foundation and tangible handles for countries that seek domestic food security.

2.6 CRediT authorship contribution statement

Nicolas Navarre: Conceptualization, Methodology, Data curation; Writing – original draft. **Coen de Vos**: Conceptualization, Methodology, Data curation. **Maarten Schrama**: Conceptualization, Writing – review & editing. **José Mogollón**: Conceptualization, Writing – review & editing, Validation.