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Food Self-Sufficiency across Scales: How Local Can We Go?

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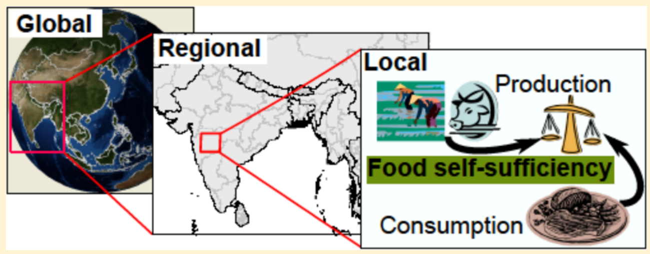
S *Supporting Information*

ABSTRACT: This study explores the potential for regions to shift to a local food supply using food self-sufficiency (FSS) as an indicator. We considered a region food self-sufficient when its total calorie production is enough to meet its demand. For future scenarios, we considered population growth, dietary changes, improved feed conversion efficiency, climate change, and crop yield increments. Starting at the 5′ resolution, we investigated FSS from the lowest administrative levels to continents. Globally, about 1.9 billion people are self-sufficient within their 5′ grid, while about 1 billion people from Asia and Africa require cross-continental agricultural trade in 2000. By closing yield gaps, these regions can achieve FSS, which also reduces international trade and increases a self-sufficient population in a 5′ grid to 2.9 billion. The number of people depending on international trade will vary between 1.5 and 6 billion by 2050. Climate change may increase the need for international agricultural trade by 4% to 16%.



INTRODUCTION

Globally, food and feed demand is increasing and will continue to increase due to population growth and dietary pattern changes.[1] Most of the changes are toward more affluent diets consisting of a large share of animal products with high embodied greenhouse gas (GHG) emissions[2] and crop-based feed.[3] Additionally, food production and consumption are becoming more spatially disconnected with growing dependency on international trade.[4] Trade requires fossil energy and contributes to transport related GHG emissions in order to supply food from field to fork.[5] In 2004, the transport sector was responsible for 13% of the global emissions.[6]

Recently, consumers have become increasingly attracted to local and regional agricultural products.[7] Studies have reported on the social benefits of local food such as building community relationships between consumers and producers, and often creating economic benefits for producers via rural development.[7] The environmental and health benefits of local food compared to nonlocal food is of scientific debate[7−9] because local food can occasionally be inferior.[8] Depending on the production efficiency, agricultural trade may even save water and land area.[10] Moreover, few studies explore the potential of local food to meet local demand.[11] Nevertheless, a global study on this potential over spatial scales for the present and in the future is still missing. To date, studies have focused on food availability, trade, and self-sufficiency mainly on country scales, showing improved food availability over the past decades mostly due to increased food trade.[12]

In the future, global crop calorie demand is expected to increase by 60% to 110% between 2005 and 2050.[13,14] This increased crop demand will be slightly reduced by progress in feed conversion efficiency, the amount of feed needed to produce a unit of animal product.[3] However, the current crop yield trends will not meet the future crop demand.[15] Presently, crop yields vary even across regions with similar growing conditions[16] and in most regions are lower than their biophysical potentials[17] suggesting potential crop yield gaps. Closing these gaps could potentially meet the expected crop demand, but requires nutrient and water management.[18] Moreover, a reduction in mean biophysical crop yields is more likely according to climate change scenarios.[19] Climate change will significantly impact low-input subsistence agricultural systems[20,21] that exhibit large yield gaps.

The goal of this study was to investigate the potential of regions to shift to a local food supply, minimizing food-miles using food self-sufficiency (FSS) as an indicator. We consider a region as food self-sufficient when the total calorie produced in the region is enough to meet its total calorie consumption, and define the FSS status as the lowest possible spatial scale on which the region could obtain FSS. FSS here reflects local and regional food availability aspects of food security that also considers food accessibility and acceptability.[22] More precisely, this study has three main objectives. The first is to identify how local a region can be in meeting its food and feed demand based on the present and potential crop yields. The second is to estimate number of food self-sufficient people at different spatial scales, and required amount of food and feed transfer/trade across these scales. The third is to assess the future FSS status considering the five dimensions that drive food and feed

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production (climate change and crop yields) and consumption (population, dietary patterns, and feed conversion efficiency).

■ MATERIALS AND METHODS

Data Harmonization. We conducted the FSS analysis based on the demand and supply of agricultural products in calorific values on a five arc-minutes (5′) grid, the lowest spatial scale that data on global crop yields are available. The demand side consists of human food consumption and crop calories fed to livestock. Human food consumption comprised of crop and animal calories. The supply side includes crop and animal calorie production. Table 1 presents the overview of data used for this study. We calculated food calorie consumption on a raster grid of 5′ resolution using gridded population data[23] and the average countrywide food calorie intake per cap/day[24] for the year 2000. Since the gridded population data is in 2.5′ resolution, we aggregated it to 5′ by summing up the population counts. We used gridded data on feed calorie consumption, and crop and animal calorie production for 2000.[3] Pradhan et al.[3] downscaled data on countrywide feed calorie consumption and animal calorie production from FAO[24] to 5′ grid using data on gridded livestock density and livestock production system from Wint and Robinson[25] and Robinson et al.[26] respectively. To investigate FSS under different crop yields, we estimated potential crop calorie production on current cultivated land with current cropping patterns for low-input and high-input agriculture (Supporting Information, SI, Text S1). For this, we used data on potential crop yields and area harvested in 2000 for 19 crop types provided by the GAEZv3.0[17] and nutritive factors from FAO[27] (SI Table S1). These 19 crops account for more than 90% of the global crop calories produced in 2000.[24]

Table 1. List of Data Used for the Study

data	resolution	unit	source
food supply	country	kcal/cap/day	FAO[24]
food trade	country	ton/yr	FAO[24]
population projection	country	count	United Nations[32]
dietary patterns projection	country	kcal/cap/day	Pradhan et al.[2]
crop yield	5′	ton/ha	IIASA/FAO[17]
crop harvest area	5′	ha	IIASA/FAO[17]
land cover types	5′	percentage	IIASA/FAO[17]
gridded feed calories	5′	kcal	Pradhan et al.[3]
gridded animal calories	5′	kcal	Pradhan et al.[3]
gridded crop calories	5′	kcal	Pradhan et al.[3]
gridded population	2.5′	count	CIESIN/IFPRI/CIAT[23]
urban rural extents	0.5′		CIESIN/IFPRI/CIAT[23]
nutritive factors	items	kcal/100g	FAO[27]

Cross-scale Food Self-Sufficiency (FSS). We used a novel approach to evaluate FSS across scales. Starting from the 5′ grid, we compared total calories produced and consumed on a grid cell considering the grid as food self-sufficient when its total calorie production was equal to or larger than its total calorie consumption. Then we analyzed FSS at different administrative levels (Admin-4 to Admin-1) from the lowest administrative unit to the country level. The first administrative level (Admin-1) corresponds to state or province and the fourth one (Admin-4) to municipality or county in some countries. We added and then analyzed the total calorie produced and consumed in an administrative unit to identify whether the administrative unit is food self-sufficient or not. We used the GADM database[28] to delimit the administrative units. The GADM provides data on the administrative boundaries for all countries, at all levels, which we converted into 5′ raster using the *Polygon to Raster* tool in ArcMap 10. Further, we assessed FSS on subcontinental and continental scales based on the United Nations classification of geographical region and composition.

Initially, we investigated the current FSS status (CS) using gridded data on food and feed calorie consumption, and crop and animal calorie production for 2000. Since a quarter of the produced food is currently lost/wasted,[29] our second analysis examined how reducing food waste (FW) may enhance FSS. For this, we assumed food waste was food consumption greater than 2550 kcal/cap/day, the global average human energy requirement,[30] and limited the maximum food consumption in the above CS analysis to 2550 kcal/cap/day. Third, we replaced crop production in the CS analysis by crop production under low-input agriculture (LI). As present day agriculture usually demands huge inputs,[31] this analysis focused on understanding how far the current consumption levels could be sustained by low-input agriculture. Moreover, some regions and some crops are under-performing with lower yields than their estimated potentials.[17] Closing such yield gaps will increase the global food availability.[18] To explore how closing yield gaps may enhance FSS, we replaced crop production in the CS analysis by crop production under high-input agriculture (HI) as our fourth analysis. We defined crop yield gaps as differences between the simulated high-input potential crop yields and the downscaled current crop yields for 2000.[17]

The above four analyses considered production and consumption of total calories but not dietary composition. Our fifth and sixth analyses accounted for this using the production and consumption of six food groups including livestock feed, which reflects the food acceptability aspect of the food security. The five (cereals, starchy roots, vegetable oils and oil-crops, sugar-sweeteners and sugar-crops, and total animal products) of the six food groups provided around 90% of the global average calorie intake per cap/day in 2007.[24] Moreover, the other food group (total vegetal products) consisted of fruits and vegetables besides other crops. For these analyses, we defined a region being as food self-sufficient if it is able to produce as many calories in each of the food groups as it consumes. The fifth analysis (FG) considers crop production in 2000, while the sixth (FG_{HI}), the high-input potential crop production.

Considering current crop yield trends,[15] closing yield gaps by 100% sounds ambitious. Hence, we divided our fourth analysis (HI) into four subanalyses to understand how closing yield gaps at different levels (HI_{50}, HI_{75}, HI_{90}, and HI_{100}) would enhance FSS. HI_{50} represents closing yield gaps to attain 50% of the high-input potential crop calorie production and HI_{100} to attain 100%.

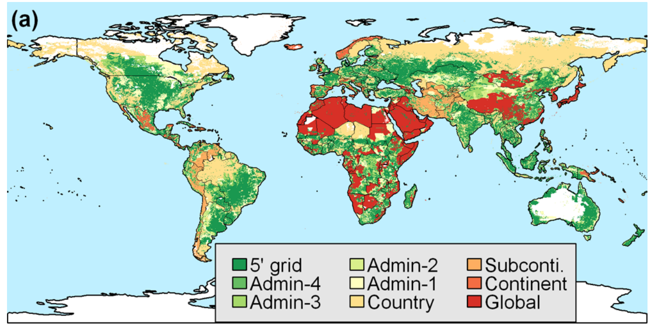
Scenarios 2050. The future food and feed demand will mainly be driven by changes in population, dietary patterns and feed conversion efficiency,[3,13,14] whereas progress on closing yield gaps and climate change will influence the future food and feed supply.[18,19] We defined 36 scenarios considering these five dimensions (population, dietary patterns, feed conversion efficiency, yield gaps, and climate change) to assess FSS for

2050 (SI Figure S1). We classified the scenarios into three groups (I–III) based on changes in population (pop), dietary patterns (dp), and feed conversion efficiency (fce) (SI Text S2). In these three groups, the scenarios differ based on three climate variations (constant climate (no cc), IPCC's A2 scenario and B2 scenario) as well as closing yield gaps to attain the four levels of the high-input potential crop calorie production (HI_{50}, HI_{75}, HI_{90}, and HI_{100}) resulting in 36 ($3 \times 3 \times 4$) scenarios. Scenario group I provides baseline scenarios that consider changes in population size using the year 2000 dietary pattern, whereas, group II takes into account changes in dietary patterns and population size. Scenario group III considers changes in feed conversion efficiency, dietary patterns, and population size. An example of these scenarios is a scenario assuming population growth (pop), constant climate (no cc), and closing yield gaps to attain 90% of the high-input potential (HI_{90}), which is also represented by "pop, no cc, and HI_{90}".

For scenario analyses, we used data on projected feed calorie demand and animal calorie production on 5′ grid;[3] countrywide dietary pattern changes;[2] the midrange population scenario from the United Nations;[32] and crop yields under climate change from the GAEZv3.0.[17] The feed calorie demand and the animal calorie production data provided by Pradhan et al.[3] for 2050 considered changes in population size, dietary patterns, and feed conversion efficiency. On the basis of the high-input crop yields for IPCC's A2 and B2 scenarios with and without CO_2 fertilization effect,[17] we calculated the high-input crop calorie production under climate change using the methodology described in SI Text S1. The United Nations[32] midrange population scenario forecasts the global population to be approximately 9 billion by 2050 and distinguishes between countrywide urban and rural populations. We proportionally distributed the countrywide urban and rural population across the country grids based on the gridded population data[23] and the urban-rural extents[33] for 2000 (SI Text S3). Additionally, we estimated the potential increase in build-up areas (i.e., land for infrastructure and settlement) based on linear relationships between countrywide urban-rural build-up areas and population in a log–log plot (SI Text S3 and Figure S2). Using this estimation of build-up area changes, we derived associated loss of cultivated land and reduction in crop calorie production showing around a 5% decrease in the cultivated area with a 6% to 7% reduction in crop calorie production (SI Figure S3). We considered this loss of crop calorie production in a grid cell during FSS analysis for 2050.

■ RESULTS

Current FSS. Figure 1 presents the lowest spatial scale at which a region would be food self-sufficient in 2000. Here, we found that around 1.9 billion people live within a 5′ grid area where enough crop and animal calories were produced to sustain their food and feed consumption (Figure 2CS). Such regions are widely distributed across the globe (Figure 1a). Moving to larger scales, we found regions with FSS on subnation scales (Admin-4 to Admin-1) in both food self-sufficient and insufficient countries. We observed that additional regions with 1.5 billion people could achieve FSS at their first level administrative units (Admin-1). India, Brazil, Argentina, Nigeria, United States, Germany, and Australia are a few of the countries that are capable of producing enough food and feed to meet their demands. At the country level, about 4.4 billion people subsist in regions that could sustain their food and feed demand without international trade. This includes regions with a population of around 1 billion requiring with-in country food and feed transfer to meet their shortfalls beyond their first level administrative units. Regions like South Asia, South America and West Europe could be self-sufficient at the subcontinental level. On the continental scale, FSS is



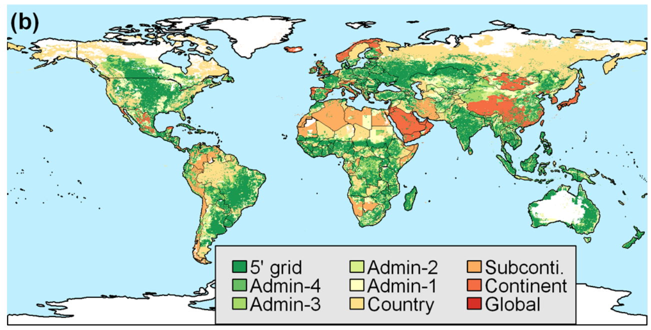


Figure 1. Maps depicting the lowest possible spatial scale on which a region could obtain FSS for 2000: (a) based on current total calorie production and consumption (CS), and (b) considering closing yield gaps to attain 50% of the high-input potential (HI_{50}). The color coding represents the spatial scales that include 5′ grid, the fourth to the first level administrative unit (Admin-4 to Admin-1), country, subcontinent (subconti.), and continent.

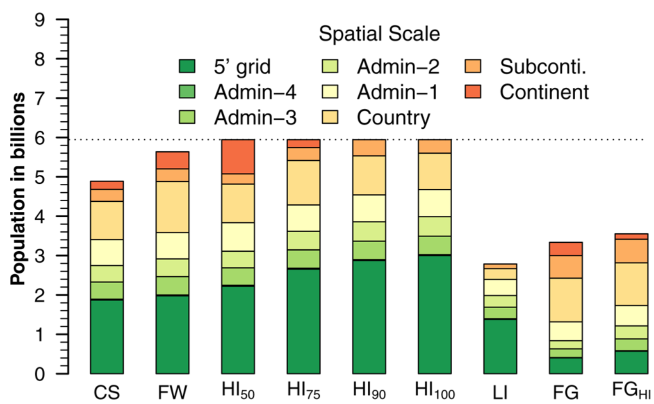


Figure 2. Food self-sufficient population estimated for 2000 based on: current total calorie production and consumption (CS), reducing food waste (FW), closing yield gaps to attain 50%–100% of the high-input potential (HI_{50}–HI_{100}), the low-input crop production (LI), and consumption of the six food groups (FG) under current crop production, and under high-input potential (FG_{HI}). The color coding represents the spatial scales that include 5′ grid, the fourth to the first level administrative unit (Admin-4 to Admin-1), country, subcontinent (subconti.), and continent. The dotted line represents the global population in 2000. The number of people requiring intercontinental food trade was estimated by the differences between the dotted line and the heights of the bars.

achievable on all continents besides Africa and Asia (Figure 1a). This shows that there is a need for cross-continental trade for about 1 billion people living in Asia and Africa (Figure 2). However, these continents consist of countries with low purchasing power and hence, a high number of people suffering from malnourishment and hunger, facing challenges to ensure their food security.[34] Furthermore, we found that reducing food waste would increase the numbers of food self-sufficient people across the scales (Figure 2FW).

Crop Yields. Considering crop yields, we found that it would be possible to achieve FSS for all the continents by closing yield gaps to attain 50% of the high-input potential (HI_{50}) (Figure 1b and 2). In this analysis, the FSS status mainly of Asia and Africa improves (SI Figure S4b,b′), which would also enable their food security. This is because of the high potential in these regions to increase food availability by closing yield gaps.[18] While considering closing yield gaps to attain HI_{90}, we found that FSS can be obtained at the subcontinental level globally. In this case, regions with a population of around 410 million will be dependent on international food and feed trade within their subcontinent. Moreover, this results in 2.9 billion people living in 5′ grid areas that produce enough crop and animal calories to meet their food and feed demand (Figure 2HI_{90}). Globally, closing yield gaps to attain HI_{100} could almost double crop calorie production of which may opportunities lie in developing and transitional regions such as Asia, Africa, East Europe, and South America (SI Table S2).

Concerning trade in terms of countrywide required imports (SI Text S4), our estimations suggest that global food and feed trade of around 1000 trillion kcal/yr in 2000 could be reduced to 400 trillion kcal/yr by closing yield gaps to attain HI_{100}. This means that closing yield gaps does not only increase food availability and enable food security but can also help reduce international trade and minimize food-miles,[5] lowering associated GHG emissions from transportation. However, achieving the high-input potential based on traditional intensified agriculture could exacerbate environmental stress and increase demand for external inputs.[31] Furthermore, agricultural trade may even be environmentally beneficial saving water and land if the trade is from resource abundant regions with efficient agricultural systems to resource scarce regions.[10]

For low-input crop production (LI), we found that even the net food exporting regions, such as North and South America, cannot be food self-sufficient (SI Figure S4c). This mode of labor intensive subsistence agriculture using traditional management techniques[17] may be unable to meet the present global food and feed demand, and to enable regional and global food security (SI Table S2). However, the FSS status of some regions in Africa and Asia can be improved because of their lower current crop production compared to their low-input potential (SI Figure S4c′).

Food Groups. Considering food composition based on production and consumption of the six food groups (FG), the FSS status differs for all the regions requiring food produced in higher spatial scales (SI Figure S4d). This is because current agricultural practices specialize some regions in the intensive production of few crops. Only about 400 million people live in a 5′ grid area where enough varieties of the food groups are produced to sustain their existing dietary compositions (Figure 2FG). For approximately 2.4 billion people, all of the food groups are currently produced within their countries, such as Australia, Brazil, France, Germany, India, and United States. At a continental scale, the number of food self-sufficient people increases only to around 3.3 billion. This shows the present day importance of the international trade in meeting our food and feed demands, and in enabling the global food security. Globally, around 2000 trillion kcal of food were imported in 2000,[24] which is double the required imports estimated based on the difference between total calories produced and consumed at the country scales. Moreover, the above numbers of food self-sufficient people at all the scales do not change much when considering the food groups and closing yield gaps to attain HI_{100} (Figure 2FG_{HI}). From this, we can infer that there is a need to change current cropping patterns by diversifying crop production to meet the dietary composition in addition to closing yield gaps, which would enhance local and regional FSS.

FSS by 2050. Our FSS analysis for 2050 was based on three scenario groups that consider changes in population, dietary patterns, and feed conversion efficiency. Each scenario group consists of three climate variations and closing yield gaps to attain the four different levels of the high-input potential, resulting in 36 scenarios. Among these scenarios, Figure 3 presents a representative FSS status by 2050 for the two extreme scenario groups considering population growth only (scenario group I) as a lower bound, and changes in population and dietary patterns (scenario group II) as an upper bound.

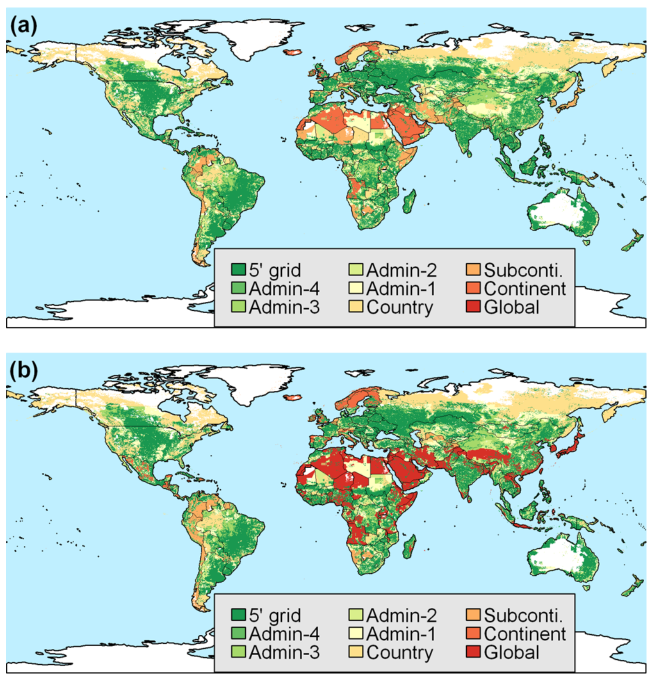


Figure 3. Maps depicting the lowest possible spatial scale on which a region could obtain FSS for 2050 for two different scenarios: (a) population growth with no climate change and closing yield gaps to attain 90% of the high-input potential (pop, no cc, and HI_{90}), and (b) changes in population and dietary patterns with no climate change and closing yield gaps to attain 90% of the high-input potential (pop+dp, no cc, and HI_{90}). The color coding represents the spatial scales that include 5′ grid, the fourth to the first level administrative unit (Admin-4 to Admin-1), country, subcontinent (subconti.), and continent.

Scenario Group I. Looking at scenario group I with a constant climate, we found that closing yield gaps to attain 50% of the high-input potential (HI_{50}) will be insufficient for Asia and Africa to be food self-sufficient by 2050 (SI Figure S5a) due to population growth. However, there is the potential to achieve FSS on a continental scale for all the continents with closing yield gaps to attain HI_{90} (Figure 3a). Comparing this with similar closing yield gap for 2000, we see a decrease in global food self-sufficient people in the 5′ grid from 2.9 billion to 2.4 billion between 2000 and 2050 (Figures 2 and 4). Hence,

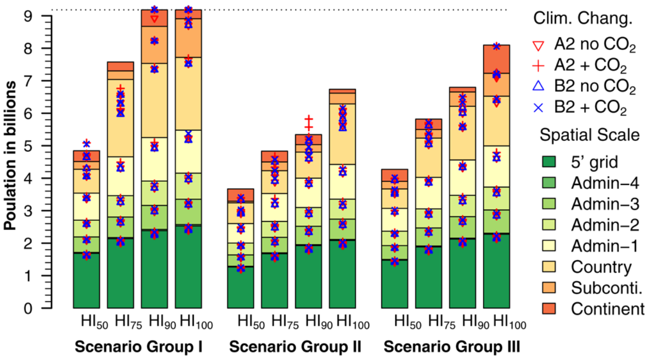


Figure 4. Food self-sufficient population estimated for 2050. Within scenario groups, the scenarios differ in climate and closing yield gaps to attain 50%−100% of the high-input potential (HI_{50}−HI_{100}). Bars represent the food self-sufficient population considering no climate change, whereas, symbols present the population under IPCC's A2 climate scenario without and with CO_2 fertilization (A2 no CO_2, and A2 + CO_2), and respective B2 climate scenario (B2 no CO_2, and B2 + CO_2). The color coding represents the spatial scales that include 5′ grid, the fourth to the first level administrative unit (Admin-4 to Admin-1), country, subcontinent (subconti.), and continent. The dotted line represents the midranged global population by 2050.[32]

in the future a growing number of people will depend on food produced in larger regions. This may increase required global food and feed trade to around 1000 trillion kcal/yr by 2050 from 400 trillion kcal/yr in 2000 with closing yield gaps to attain HI_{100}. Moreover, due to urbanization causing an increase in urban population and a decrease in rural population for some regions,[32] many rural areas could achieve FSS at a lower spatial scale (Mongolia and China in SI Figure S5). Nevertheless, this would also result in urban regions requiring a larger area to sustain their food and feed demand.

Scenario Group II. Outcomes for scenario group II with constant climate show that the number of people living in food self-sufficient regions decreases across all the scales (5′ grid to continent) when the changes in population and dietary patterns are considered compared to those for scenario group I (Figure 4). This is due to changing dietary patterns resulting in an overall increase in food and feed demand (SI Table S2). For example, in this scenario group the food self-sufficient populations in the 5′ grid would decrease to 1.9 billion taking into account closing yield gaps to attain HI_{90}. Figure 3b shows that Asia and Africa might not be self-sufficient in this case resulting in previously self-sufficient countries for scenario group I like Bangladesh, China, India, and Pakistan requiring food produced beyond their continent to meet their calorie demands (also SI Figure S6a′). This might increase global food and feed trade by about 2.5 times (up to 3500 trillion kcal/yr) compared to that under scenario I with closing yield gaps to attain HI_{100}. Therefore, looking at future scenarios of changing dietary patterns toward a high calorie diet with a large share of animal products, we found that closing yield gaps only may be insufficient to ensure FSS for all continents by 2050. This implies a need for agricultural expansion in some regions to achieve FSS and (or) a need for substantially increased international trade to meet the food and feed demands to enable food security. However, expansion of cultivated land is not feasible everywhere because of limited availability of suitable land resources for conversion into agricultural land, which is unevenly distributed across the globe.[35,36]

Scenario Group III. Looking at scenario group III with a constant climate, we find that the number of people living in food self-sufficient regions increases across all the scales compared to that of scenario group II (Figure 4). Changes in feed conversion efficiency considered in this scenario group enables countries, such as China and India that would require food and feed produced beyond their continent in scenario group II−HI_{90}, to achieve FFS at the national scale (SI Figure S6b,b′). However, Africa, a region for which a large increase in feed demand is projected,[3] will still require food and feed produced beyond the continent. Moreover, changes in feed conversion efficiency lower the overall food and feed demand (SI Table S2) that may limit an increase in global food and feed trade to 2800 trillion kcal/yr by 2050.

Climate Change. Considering the impacts of climate change on crop production, we find that in almost all cases a higher number of people would be food self-sufficient under the IPCC's optimistic B2 scenario compared to that under pessimistic A2 scenario (Figure 4). This is mainly due to a lower projected temperature rise for B2 scenario than for A2 scenario. Moreover, a slight increase in the number of food self-sufficient people is observed while taking into account positive fertilization effects of increased atmospheric CO_2 concentration on some crop yields. Some developed countries in the north may gain from increased crop production due to warmer temperatures under both climate scenarios (SI Figure S6c′,d′). In contrast, changing climate in Asian and African developing countries may jeopardize FSS. Overall, climate change may increase global food and feed trade by 4% to 8% under A2 scenario with CO_2 fertilization, and by 10% to 16% without CO_2 fertilization considering our scenario groups (I−III) with closing yield gaps to attain HI_{100}. Under the B2 scenario, this increment will range between 5% and 9% with CO_2 fertilization, and between 9% and 15% without CO_2 fertilization. Moreover, the effects of shifts in dietary patterns and closing yield gaps appear more sensitive than that of climate change in our analysis. In summary, changes in dietary patterns will make local, regional, and global food security and self-sufficiency more dependent on international trade in the future which would further be exacerbated due to climate change.

DISCUSSION

Presently, all continents excluding Africa and Asia can achieve FSS. However, closing yield gaps would also enable Africa and Asia to be food self-sufficient. This would enhance local FSS by increasing the number of self-sufficient people in the 5′ grid from 1.9 billion to between 2.2 and 2.9 billion depending on closing yield gaps between 50% and 100% of high-input potential. However, closing yield gaps requires nutrient and water management (e.g., a 25% increase in current irrigated area is required to close yield gaps to 75%),[18] and traditional intensified agriculture may exacerbate environmental stress.[31] Therefore, modern strategies to close yield gaps should be directed toward sustainable agricultural intensification,[13] increasing food production while simultaneously reducing its contribution to environmental stress.[37] However, looking at the future scenarios with dietary pattern changes and population growth, only bridging yield gaps may not be enough to achieve FSS for Africa and Asia by 2050.

With our approach, we developed several innovations for assessing FSS at the global, regional, and local scales. The first novelty lies in the cross-scale analysis we conducted that enabled us to show FSS at different spatial scales on one global map. To our knowledge, these maps are the first of their kind showing that actions at local levels are plausible to attain FSS in many regions. However, this requires producers to grow diverse crops and consumers to rely more on local products. We can infer this from the reduction in the self-sufficient population from 1.9 billion to 400 million when considering production and consumption of the six food groups instead of the total calories. Nevertheless, some regions may not be able to rely on the local supply because of their low potential yields due their agro-climatic features[17] limiting required resources e.g. water availability.[38] Moreover, our estimation of about 1.6 billion people relying on international agricultural trade in 2000 is higher than estimated by Fader et al.,[4] who calculated about 1 billion people. This discrepancy on the number of trade dependent people may be due to explicit consideration of feed in our analysis, which Fader et al.[4] do not take into account. Similarly, our scenario analysis estimating the need for international trade for 1.5 to 6 billion by 2050 differs from scenarios provided by Fader et al.[4] projecting the need for 0.8 to 5.2 billion without cropland expansion. These differences are due to variations in the scenarios of both studies. Scenarios from Fader et al.[4] mainly account for climate change, crop yield, and population growth while our scenarios additionally consider changes in dietary patterns and feed demand. Although these two studies provide different estimates, both emphasize the present and the future role of international trade in meeting food and feed demand, and in enabling global food security.

The second innovation of our study is to highlight different aspects of food and feed transfer/trade across scales. For example, globally, regions with about 2.5 billion people could be sustained by with-in country food and feed transfer, whereas regions with about only 1 billion people would require intercontinental trade mainly due to existing crop yield gaps. Moreover, our estimation of required global agricultural trade of around 1000 trillion kcal/yr in 2000 is half of the global gross calorie trade calculated based on FAO data.[24] However, the global net calorie trade of about 900 trillion kcal/yr, obtained from the difference between countrywide calorie import and export, is near to our estimation (SI Text S4). This reflects present trade dynamics where a country may import and export agricultural goods at the same time. Additionally, the results we obtained agree with the derived net calorie trade across country, subcontinental and continental scales based on FAO data[24] (SI Figure S7). Further, we showed that the global agricultural trade could be reduced by closing yield gaps which would minimize food-miles, lowering associated GHG emissions from transportation. However, food production efficiencies are important when estimating the overall agricultural emissions besides food-miles.[39] Moreover, agricultural trade is also linked with virtual land, water, and nutrient flows[40−42] that would be environmentally beneficial if the flows are from resource abundant regions to resource scarce regions and may be problematic if the flows are in the opposite direction.

Third, this study considers spatially explicit production and consumption of crop and animal calories including livestock feed. A limited number of studies take into account food and feed explicitly during such analysis.[13,43] In the future, feed will play an increasing role in FSS which is shown by a growing use of crop-based feed.[3] Changing dietary patterns toward affluent diets with a large share of animal products increases feed demand. This in return would lower FSS of regions requiring food and feed produced in larger areas. Thus, shifting diets to lower total calorie intake with a lower share of animal products, reversing current trends, could enhance FSS at a local scale and would increase food availability globally in addition to the reduction of agricultural emissions.[2,44]

Although this study provides clear findings, interpretation of our results also requires an understanding of its limitations. Since our FSS analysis based on the total calorie production and consumption, a food self-sufficient region according to our analysis may depend on agricultural trade to meet its diet and feed compositions. Nevertheless, our study presents the potential of a region to be self-sufficient, which could be achieved by focusing agricultural practices to meet local and regional demands, and shifting dietary choices toward local and regional products. Moreover, two of our analyses considered dietary compositions based on production and consumption of the six food groups. Additionally, total calorie consumption in some regions may be insufficient to meet regions' dietary energy requirements and hence, must be food insecure though appeared self-sufficient in our analysis. However, most countries total calorie intake in 2000 was greater than the minimum dietary energy recommended by the FAO. Currently, 13% of all the food produced is lost during harvesting, postharvesting, and processing,[29] which our analysis did not consider. This may overestimate our FSS results for some regions. Nevertheless, we analyzed how FSS would be enhanced by reducing food waste.

The other limitation is the simplistic approach we used to estimate crop calorie loss due to urbanization that ignores the possibility of build-up land expansion without population growth. Therefore, our result can be considered as a lower bound. However, this is our first attempt to capture the possible reduction in a cultivated area, which most agriculture modeling exercises ignore.[45,46] One reason for this is the relatively small reduction in the total cultivated area due to urbanization; nevertheless, the resulting crop calorie loss is enough to feed around 1 billion people. Moreover, we did not consider variation in subnational population growth during our scenarios analysis, which is another limitation of this study. However, we took into account differentiated urban and rural population growth per country.[32] Additionally, our analysis was based on the average countrywide calorie intake that ignored subnational dietary variation (e.g., differences in calorie intake between urban and rural regions) mainly due to data limitations.

Our study demonstrates a possible implementation of "think global, act local" in the context of sustainable food production and consumption. The study explicitly shows that closing yield gaps will improve local, regional, and global food availability and self-sufficiency. However, the current crop yield trends are insufficient to close these gaps by 2050.[15] This suggests a need to explore ways for sustainable agricultural intensification.[13,18] Furthermore, closing yield gaps will not be enough for some regions to achieve FSS in the future, which implies a need for cropland expansion and/or international agricultural trade. Cropland expansion increases GHG emissions and has negative impacts on biodiversity and ecosystem services,[47] whereas agricultural intensification increases crop yields sometimes with a net emission reduction effect[48] mainly due to avoiding land conversion. Additionally, biofuel, a climate change mitigation option, also competes for the limited cultivated land.[49,50] Moreover, not all locations need to close yield gaps to ensure FSS. This suggests a need to roll back some cultivated land for extensive agriculture that lowers agricultural related environmental stress. Nevertheless, changing dietary patterns will play a crucial role in the future food and feed demand.[3] Additionally, food demand could be reduced and food availability could be increased by lowering food waste and losses[29,51] that would further enhance FSS. Therefore, an underlying question to ensure local, regional, and global food security and self-sufficiency is how to change consumer behavior toward sustainable consumption based on local and regional food with a lower share of animal products and producer practices to grow diverse crop and animal calories that meet local and regional demands.

■ ASSOCIATED CONTENT

Supporting Information

Text S1 Potential crop calories production; Text S2 scenarios analysis; Text S3 change in population and land use; Text S4 trade analysis; Figure S1, scenarios developed for 2050 based on the five dimensions that drive food and feed supply and demand; Figure S2 Relations between country scale built-up area and populations in a log−log plot for the year 2000; Figure S3, crop calorie loss associated with reduction in cultivated area due to increase in built-up area driven by population growth; Figure S4, maps depicting the lowest possible spatial scale on which a region could obtain FSS in 2000; Figure S5, maps depicting the lowest possible spatial scale on which a region could obtain FSS by 2050 based on closing yield gaps to attain the dierent levels of high-input potential; Figure S6, maps depicting the lowest possible spatial scale on which a region could obtain FSS by 2050 based on dierent scenarios; Figure S7, net food exporter and importer for the year 2000; Table S1, list of crop types for which data on harvest area provided; Table S2, regional overview on production of crop and animal calories, and consumption/demand 29 of food and feed. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Notes

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■ REFERENCES

(1) Godfray, H. C. J.; et al. Food security: The challenge of feeding 9 billion people. *Science* **2010**, *327*, 812−818.
(2) Pradhan, P.; Reusser, D. E.; Kropp, J. P. Embodied greenhouse gas emissions in diets. *PLoS One* **2013**, *8*, e62228.
(3) Pradhan, P.; et al. Embodied crop calories in animal products. *Environ. Res. Lett.* **2013**, *8*, 044044.
(4) Fader, M.; et al. Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. *Environ. Res. Lett.* **2013**, *8*, 014046.
(5) Weber, C. L.; Matthews, H. S. Food-miles and the relative climate impacts of food choices in the United States. *Environ. Sci. Technol.* **2008**, *42*, 3508−3513.
(6) IPCC. *Climate Change 2007: Mitigation of Climate Change*, 2007.
(7) Kneafsey, M.; et al. *Short Food Supply Chains and Local Food Systems in the EU. A State of Play of their Socio-Economic Characteristics*; European Commission—JRC: Luxembourg, 2013.
(8) Edwards-Jones, G. Does eating local food reduce the environmental impact of food production and enhance consumer health? *P. Nutr. Soc.* **2010**, *69*, 582.
(9) DeLind, L. B. Are local food and the local food movement taking us where we want to go? Or are we hitching our wagons to the wrong stars? *Agric. Human Values* **2011**, *28*, 273−283.
(10) Fader, M.; et al. Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. *Hydrol. Earth Syst. Sci. Dis.* **2011**, *8*.
(11) Morrison, K. T.; Nelson, T. A.; Ostry, A. S. Methods for mapping local food production capacity from agricultural statistics. *Agric. Syst.* **2011**, *104*, 491−499.
(12) Porkka, M.; et al. From food insufficiency towards trade dependency: A historical analysis of global food availability. *PloS One* **2013**, *8*, e82714.
(13) Tilman, D.; et al. Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. U. S. A.* **2011**, *108*, 20260−20264.
(14) Alexandratos, N.; Bruinsma, J. *World Agriculture Towards 2030/2050: The 2012 Revision*; FAO: Rome, 2012.
(15) Ray, D. K.; et al. Yield trends are insufficient to double global crop production by 2050. *PloS One* **2013**, *8*, e66428.
(16) Licker, R.; et al. Mind the gap: How do climate and agricultural management explain the 'yield gap' of croplands around the world. *Global Ecol. Biogeogr.* **2010**, *19*, 769−782.
(17) IIASA/FAO. *Global Agro-ecological Zones (GAEZ. v3.0)*, 2012; p 196.
(18) Mueller, N. D.; et al. Closing yield gaps through nutrient and water management. *Nature* **2012**, *490*, 254−257.
(19) Nelson, G. C.; et al. Climate change effects on agriculture: Economic responses to biophysical shocks. *Proc. Natl. Acad. Sci. U. S. A.* **2013**, 201222465.
(20) Morton, J. F. The impact of climate change on smallholder and subsistence agriculture. *Proc. Natl. Acad. Sci. U. S. A.* **2007**, *104*, 19680−19685.
(21) Lal, R.; et al. Management to mitigate and adapt to climate change. *J. Soil Water Conserv.* **2011**, *66*, 276−285.
(22) Pinstrup-Andersen, P. Food security: definition and measurement. *Food Security* **2009**, *1*, 5−7.
(23) CIESIN/IFPRI/CIAT. *Global Rural-Urban Mapping Project, Version 1 (GRUMPv1): Population Count Grid*; 2011.
(24) FAO, *FAOSTAT- FAO Statistical Databases: Agriculture, Fisheries, Forestry, Nutrition*; Food and Agriculture Organization of the United Nations: Rome, 2012.
(25) Wint, W.; Robinson, T. *Gridded livestock of the world 2007*; FAO: Rome, 2007; p 131.
(26) Robinson, T.; et al. *Global livestock production systems*; FAO and ILRI: Rome, 2011; p 152.
(27) FAO. *Food balance sheets: A handbook*; Food and Agriculture Organization: Rome, 2001; p 99.

(28) GADM, GADM database of global administrative areas, version 2.0. 2012; www.gadm.org.
(29) Kummu, M.; et al. Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Sci. Total Environ.* **2012**, *438*, 477−489.
(30) Walpole, S. C.; et al. The weight of nations: An estimation of adult human biomass. *BMC Public Health* **2012**, *12*, 439.
(31) Tilman, D.; et al. Forecasting agriculturally driven global environmental change. *Science* **2001**, *292*, 281−284.
(32) United Nations. *World Population Prospect: The 2010 Revision—Highlights and Advance Tables*; UN: New York, 2011.
(33) CIESIN/IFPRI/CIAT. *Global Rural-Urban Mapping Project, Version 1 (GRUMPv1): Urban Extents Grid*; 2011.
(34) FAO. *State of Food Insecurity in the World: Addressing food insecurity in protracted crises*. 2010, p 57.
(35) Fischer, G.; et al. *Global Agro-Ecological Assessment for Agriculture in the 21st Century*; IIASA: Laxenburg, 2001.
(36) Bruinsma, J. *Looking ahead in world food and agriculture: Perspectives to 2050*; FAO: Rome, 2011; pp 233−278.
(37) Pretty, J.; et al. The top 100 questions of importance to the future of global agriculture. *Int. J. Agric. Sust.* **2010**, *8*, 219−236.
(38) Kummu, M.; et al. Climate-driven interannual variability of water scarcity in food production potential: a global analysis. *Hydrol. Earth Syst. Sci.* **2014**, *18*.
(39) Edwards-Jones, G.; et al. Testing the assertion that local food is best: The challenges of an evidence-based approach. *Trends Food Sci. Technol.* **2008**, *19*, 265−274.
(40) Konar, M.; et al. Virtual water trade flows and savings under climate change. *Hydrol Earth Syst. Sci.* **2013**, *17*, 3219−3234.
(41) Qiang, W.; et al. Agricultural trade and virtual land use: The case of China's crop trade. *Land Use Policy* **2013**, *33*, 141−150.
(42) Lassaletta, L.; et al. Food and feed trade as a driver in the global nitrogen cycle: 50-year trends. *Biogeochemistry* 1−17.
(43) Haberl, H.; et al. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proc. Natl. Acad. Sci. U. S. A.* **2007**, *104*, 12942−12947.
(44) Reusser, D.; et al. Relating climate compatible development and human livelihood. *Energy Procedia* **2013**, *40*, 192−201.
(45) Lotze-Campen, H.; et al. Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. *Agric. Econ.* **2008**, *39*, 325−338.
(46) Bodirsky, B. L.; et al. N_2O emissions from the global agricultural nitrogen cycle â€" current state and future scenarios. *Biogeosciences* **2012**, *9*, 1−29.
(47) Nelson, E.; et al. Projecting global land-use change and its effect on ecosystem service provision and biodiversity with simple models. *PloS One* **2010**, *5*, e14327.
(48) Burney, J. A.; Davis, S. J.; Lobell, D. B. Greenhouse gas mitigation by agricultural intensification. *Proc. Natl. Acad. Sci. U. S. A.* 12052−12057.
(49) Fargione, J.; et al. Land clearing and the biofuel carbon debt. *Science* **2008**, *319*, 1235−1238.
(50) Fischer, G. *Looking ahead in world food and agriculture: perspectives to 2050*; FAO: Rome, 2011; pp 95−155.
(51) Liu, J.; et al. Food losses and waste in China and their implication for water and land. *Environ. Sci. Technol.* **2013**, *47*, 10137−10144.