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The use of food imports to overcome local limits to growth

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Key Points:
- Introducing a "carrying capacity plot" to show contributions of food trade and local food supply potential for sustaining population
- Empirical demonstration shows food imports have been used universally to overcome local limits to growth, affecting over 3 billion people
- Where this import strategy has been successful, food security of 1.4 billion people has become dependent on imports

Supporting Information:
- Supporting Information S1
- Dataset S1
- Dataset S2
- Dataset S3
- Dataset S4

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Abstract There is a fundamental tension between population growth and carrying capacity, i.e., the population that could potentially be supported using the resources and technologies available at a given time. When population growth outpaces improvements in food production locally, food imports can avoid local limits and allow growth to continue. This *import strategy* is central to the debate on food security with continuing rapid growth of the world population. This highlights the importance of a quantitative global understanding of where the strategy is implemented, whether it has been successful, and what drivers are involved. We present an integrated quantitative analysis to answer these questions at sub-national and national scale for 1961–2009, focusing on water as the key limiting resource and accounting for resource and technology impacts on local carrying capacity. According to the sub-national estimates, food imports have nearly universally been used to overcome local limits to growth, affecting 3.0 billion people—81% of the population that is approaching or already exceeded local carrying capacity. This strategy is successful in 88% of the cases, being highly dependent on economic purchasing power. In the unsuccessful cases, increases in imports and local productivity have not kept pace with population growth, leaving 460 million people with insufficient food. Where the strategy has been successful, food security of 1.4 billion people has become dependent on imports. Whether or not this dependence on imports is considered desirable, it has policy implications that need to be taken into account.

1. Introduction

Earth's ability to sustain the growing human population has been under debate for centuries. Several scholars, most notably perhaps *Malthus* [1798] and the Club of Rome with its report The Limits to Growth [*Meadows et al.*, 1972], have argued that sooner or later, population expansion will result in an overshoot of human-carrying capacity. Both the Malthusian theory and Limits to Growth report have been criticized for failing to sufficiently acknowledge technological innovation. Indeed, due to the advance of agricultural techniques, notably through the green revolution, global Malthusian catastrophes have been avoided. Consequently, while the existence of resource limits is still recognized [e.g., *Wackernagel et al.*, 2002; *Rockström et al.*, 2009a; *Steffen et al.*, 2015], current demographic theories rarely consider scarcity of resources such as water and land as limiting factors for population growth [*Lee*, 2011]. However, at local scale there are many areas where local limits to growth may already have been exceeded, as scarcity of water and land resources limit sufficient food production, despite the rapid technological and agronomic advancements increasing the efficiency of agriculture [*Fader et al.*, 2013; *Suweis et al.*, 2013; *Kummu et al.*, 2014; *Porkka et al.*, 2016]. While carrying capacity varies over time, it can still be useful to provide a snapshot of the current scale of human need of resources in relation to the biosphere [*Arrow et al.*, 1995].

Human-carrying capacity is notably influenced by resources and technologies available at a given time [*Arrow et al.*, 1995]. Local carrying capacity can be increased by, e.g., expansion of cropland and irrigation, fertilizer application, and technologies and practices that increase the efficiency of food production. Food imports are another way of overcoming current local limits and continuing growth beyond the local human-carrying capacity [*Kaack and Katul*, 2013; *Suweis et al.*, 2013]. In economics terms, trade in goods is viewed as a means of indirectly obtaining locally scarce factors of production, in line with the Heckscher–Ohlin (H–O) theorem [*Earle*, 2001; *Hakimian*, 2003; *Ansink*, 2010; *Reimer*, 2012], with factor endowments being one source of comparative advantage. In the field of water resources, this idea has notably been discussed as virtual water trade (VWT) [*Allan*, 1996, 2001, 2003; *Hoekstra and Hung*, 2005;

Chapagain et al., 2006; *Yang and Zehnder*, 2007; *de Fraiture and Wichelns*, 2010; *Antonelli and Sartori*, 2015], referring to the water used in production of imported products.

The H–O and VWT hypothesis has been expressed and tested in a variety of strong terms: as precise relationships between trade, factor input requirements, and factor endowments [*Bowen et al.*, 1987]; that countries import goods that are more intensive in their scarce factors, and export goods intensive in their abundant factors [*Leontief*, 1953; *Leamer*, 1980; *Hakimian*, 2003; *Sayan*, 2003]; and (equivalently) that water-intensive products (including food) are exported by countries with abundant water, and imported by countries with scarce water [*de Fraiture et al.*, 2004; *Ramirez-Vallejo and Rogers*, 2004; *Hoekstra and Hung*, 2005; *Kumar and Singh*, 2005; *Novo et al.*, 2009; *Debaere*, 2014; *Delbourg and Dinar*, 2014; *Fracasso*, 2014; *Fracasso et al.*, 2016]. The findings from these studies suggest that these hypotheses are too strongly stated, and that they do not hold true generally, even though they appear to apply in some cases, such as the Middle East and North Africa [*Allan*, 1996, 2001; *Yang and Zehnder*, 2002; *Hakimian*, 2003], where water is sufficiently scarce and income sufficiently high [*Yang et al.*, 2003].

Using such techniques as gravity and econometric models, this literature has shown that while resource endowments do play a role, trade is also influenced by other drivers of demand, productivity, and comparative advantage, as well as political barriers [*Wichelns*, 2001; *Tamea et al.*, 2014]. These notably vary over time, highlighting the need for temporal analyses [*Bowen*, 1983; *Yang et al.*, 2003] incorporating the effect of changes in agricultural practices and technology as well as land and irrigation expansion. Additionally, previous studies have noted that it is essential to pay attention to the measure of water endowment used [*Hakimian*, 2003], including "green," soil water that is particularly important for rain-fed agriculture [*Allan*, 2003], which contributes to 60% of global food supply [*Rockström et al.*, 2009b], and is closely related to availability of arable land [*Kumar and Singh*, 2005]. *Yang et al.* [2003] also note that water availability per capita has a threshold effect on trade, and that the threshold changes over time, which may be explained by a resource or carrying capacity limit.

Previous literature is thus inconclusive with respect to food imports being specifically used to overcome local limits to growth. In principle, the increase in carrying capacity through imports can help to avoid conflict, as well as increasing overall resource use efficiency through specialization of production. At the same time, it creates (inter-)dependencies on other regions [*Allan*, 1996, 2001]. There is therefore a crucial trade-off in the use of imports as a strategy to obtain scarce factors of production, such that it merits discussion [*Warner*, 2003, p. 200], even if highlighting dependency may be politically sensitive [*Allan*, 1996, 2001]. Even though a region's "choice" to import emerges from complex interactions amongst a range of actors, rather than being a single conscious decision, there is in principle potential for that "choice" to be altered. Given that food may be imported for many reasons, not just due to limited ability to produce food locally, there is a need to explicitly identify where scarcity is and is not the limiting factor. Conversely, given that importing food is only one means of increasing carrying capacity, there is a need to identify where alternative strategies are being employed. Consistent with previous literature, this requires taking into account factors affecting local food supply potential (LFSP). From our water-focused perspective, a reasonable initial proxy can be obtained by including factors such as availability of both green and blue water, as well as changes over time in cropland, crop yield, technology, and management practices. In principle, LFSP would be further limited by other production factors such as available labor (as well as consumption side factors such as different food utilization and waste practices), though a high estimate or upper bound can still be identified when omitting these. In sum, even when focusing on water as a constraint, LFSP (and carrying capacity) needs to be considered in an integrated manner, rather than focusing on water availability or scarcity specifically.

In this paper, we present a novel method for analyzing and visualizing the different strategies used to overcome local limits to growth. Here, we only consider the specific cases where population pressure intensifies (such that these regions are either approaching their local carrying capacity or have already exceeded it), not when population pressure decreases (due to increasing local carrying capacity or decreasing population) or when population pressure is low. Therefore, we expect to see that *when a region approaches its carrying capacity, net imports of food tend to increase to avoid overshooting it.* The truth of this hypothesis is fairly easy to accept, but the need for discussion of its implications is sufficiently important that it still merits an empirical demonstration. We investigate the hypothesis using the "carrying capacity plot," which

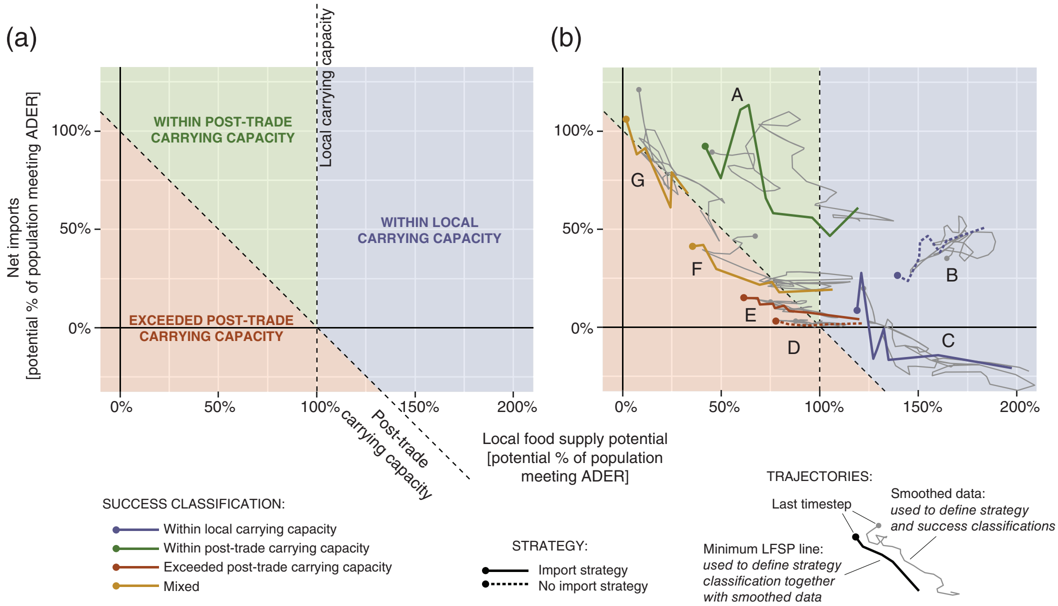

Figure 1. Carrying capacity plot explained (a), and examples of classification (b). Thick lines show the minimum local food supply potential (LFSP) line, i.e., include only those time steps when increasing population pressure decreased LFSP (i.e., local food supply potential). Thin gray lines ("Smoothed data") show the full annual time series (1961–2009) of LFSP and net imports, smoothed with a 7-term Henderson filter [*Gray and Thompson*, 1996] (see Text S3). The success of strategies is evaluated using the smoothed data while both the minimum LFSP line and smoothed data are used to determine whether an food production unit is using the import strategy (see Text S3). Solid colored lines in (b) are examples of regions using the import strategy. Dashed colored lines in (b) are examples of regions with no import strategy. Colors of lines represent the different classes based on the success of a strategy. Dots at the end of lines signify the latest timestep. ADER refers to local average dietary energy requirement.

distinguishes different strategies and their success by showing the historical evolution of a region or population's LFSP and (observed) net food imports relative to their local and post-trade carrying capacity. We also hypothesize that *the implementation and success of that strategy will vary spatially depending on key factors that influence imports and carrying capacity, notably economic power and inability to further increase local production.* FPUs would implement the import strategy when local LFSP cannot be further increased to meet growing population pressure. This would include areas with high aridity, where agricultural land cannot be expanded and/or where water use efficiency cannot be increased. Economic purchasing power, measured by gross national income (GNI) per capita and value of exports (% of gross domestic product (GDP)), is also expected to be associated with the implementation of the import strategy. Using historical data spanning 1961–2009, this paper hence investigates the use of food imports to overcome local limits to growth, and the factors potentially affecting the use of that strategy.

2. Materials and Methods

We developed a novel analysis approach to evaluate the use of imports as a strategy to overcome local limits to growth. The key method of the approach is the carrying capacity plot (Figure 1). It is constructed for a given spatial unit of analysis, such as the food production unit (FPU, see Section 2.1) or country, using estimates of LFSP and observed net imports. Carrying capacity is estimated on the basis of availability and demand of resources needed to sustain a population, in this case focusing on water as a key limiting resource, as also done by *Suweis et al.* [2013]. The carrying capacity plot allows classification of each region in terms of the use of food imports and its success. In this study "food imports" always refer to net imports of dietary energy calculated as the difference between imports of food products (kcal yr^{-1}) and exports of food products (kcal yr^{-1}) to/from the region considered (see Section 2.3 and Text S2, Supporting Information). A brief summary of the method is given in this section, and details are provided in Texts S1–S4. Definitions of all terminology used are also provided in Table S1.

The carrying capacity plot (Figure 1) shows net food imports of a region (*y*-axis) plotted against LFSP (*x*-axis). Both are expressed as the percentage of local population for which country-specific average dietary energy requirement (ADER) [*Food and Agriculture Organisation of the United Nations (FAO)*, 2015b] could be met using that source. Local carrying capacity, before imports, therefore corresponds to an LFSP of 100%. Similarly, post-trade carrying capacity is defined as LFSP + net imports = 100%. By showing LFSP and net imports in relation to local and post-trade carrying capacity, the carrying capacity plot distinguishes different strategies and their success. For regions approaching their carrying capacity, a region is classified as implementing the *import-production substitution strategy* (referred to simply as the *import strategy*) if net imports increase when LFSP decreases (examples A, C and E–G in Figure 1b) (see Text S3 and Figure S1 for details). Regions where this does not occur are classified as not implementing the import strategy. These include regions where net imports (relative to food requirements of the population) show a decreasing trend (B in Figure 1b) or no trend at all (D in Figure 1b) as LFSP decreases.

Strategies to overcome limits to growth (whether import or not) can be considered either successful or unsuccessful, based on the position of a region on the carrying capacity plot (Figure 1b). Regions that have stayed *within their post-trade carrying capacity* (example A in Figure 1b) can be considered to be implementing the chosen strategy successfully. If a region also stays *within its local carrying capacity* (B and C in Figure 1b) imports are not yet required for successful implementation. A strategy can be considered unsuccessful when a region has *exceeded its post-trade carrying capacity* (D and E in Figure 1b) at some point in time and has never recovered. A strategy can also be implemented with *mixed* success. These regions have either exceeded their post-trade carrying capacity and later recovered (F in Figure 1b), or are borderline cases shifting back and forth (G in Figure 1b).

To test for factors impacting the use and success of the import strategy, data were collected on aridity [*Trabucco and Zomer*, 2009], land stress [*Food and Agriculture Organization of the United Nations/International Institute for Applied Systems Analysis (FAO/IIASA)*, 2011; *Klein Goldewijk et al.*, 2011; *Kummu et al.*, 2011; *International Union for Conservation of Nature/United Nations Environment Programme-World Conservation Monitoring Centre (IUCN/UNEP-WCMC)*, 2015], water requirements of food production [*Porkka et al.*, 2016], GNI, and value of exports [*The World Bank*, 2016], and their distribution split according to implementation and success of the import strategy was visualized. A detailed description of these data can be found in Text S4.

2.1. Selection of Unit of Analysis

The analysis was performed for both FPUs and countries. The selection of unit of analysis is a fundamental part of the process, because of the sensitivity of results to its selection, known as the modifiable areal unit problem [see, e.g., *Dark and Bram*, 2007; *Salmivaara et al.*, 2015]. FPUs are a combination of river basin and administrative boundaries [*Cai and Rosegrant*, 2002; *de Fraiture*, 2006], and are therefore arguably the appropriate scale at which food production and the water resources required can be assumed to be managed. The FPU scale allows consideration of local variation, which can be very significant, especially considering local food production potential. However, it naturally has certain shortcomings, the obvious one being lack of domestic trade data and the need for downscaling national data (see Section 2.3 and detailed description in Text S2). Therefore, as one scale cannot be considered objectively better than the other, we chose to offer multiple perspectives by also presenting the country-level results in the Supporting Information.

The original 281 FPUs from *Cai and Rosegrant* [2002] were slightly adjusted by splitting larger regions that were crossing country borders into smaller units, resulting in 309 FPUs [*Kummu et al.*, 2010] (available as a shapefile in Dataset S4). In a few cases (e.g., the Balkan region) FPUs can still cover more than one relatively small country. The analysis focuses on 102 FPUs (3.8 billion people in 2009, about 55% of the world population) that have either exceeded local carrying capacity (LFSP < 100%) or are (have been) approaching local carrying capacity (see Text S3 for details). The locations of the FPUs are presented in Figure 2.

The selection of unit of analysis also determines the meaning of the terms “imports,” “dependency on trade,” and “import strategy.” At country scale, these refer to international trade, while at any sub-national scale they include assumptions (as sufficient data rarely exist) about domestic food transfers. In principle, at country scale the “import strategy” could be thought of as a conscious choice or a policy, while there may not be explicit policy at finer scales. In reality, however, food production and consumption decisions at both scales take place in complex systems in which individuals make choices in mutual interaction with physical and institutional constraints. Import policies do not completely determine trade flows. Therefore, at any scale,

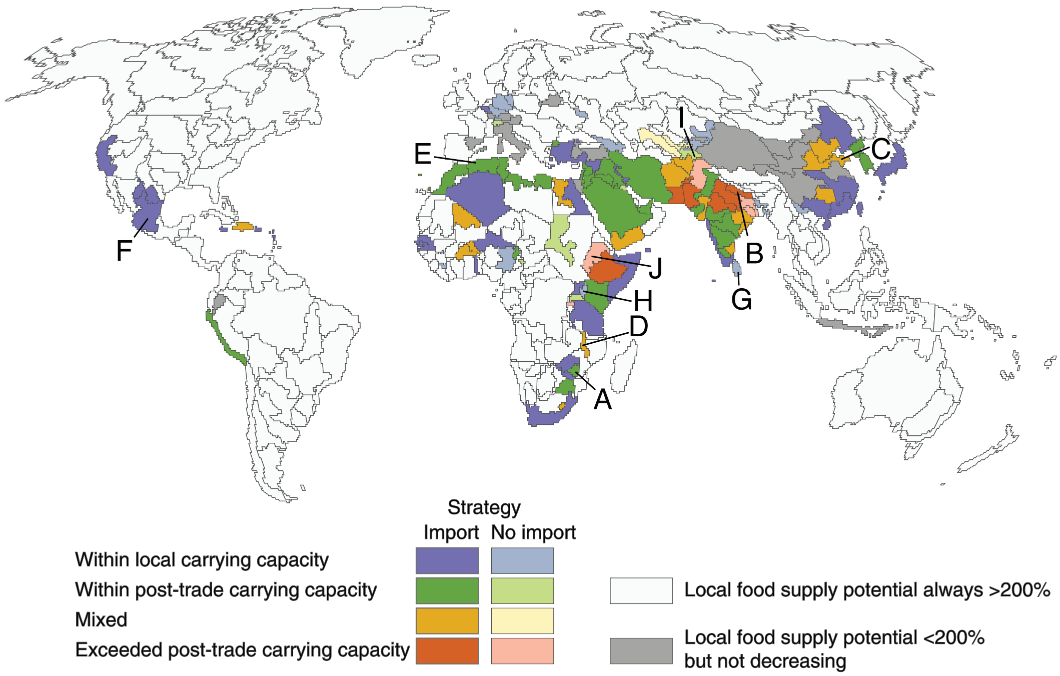

Figure 2. Map of study food production units (FPUs) in different classes based on the implementation and success of import or other strategies. Success categories describe whether carrying capacity is sufficient for the population, based on country-specific dietary energy requirement estimates and analysis of data from FAOSTAT and LPJmL spanning 1961–2009 (see Section 2). Labels A–J refer to panels in Figure 4, showing trajectories of the respective FPUs. Country scale results are found in Figure S3.

one should not interpret "the import strategy" as a conscious decision to use imports but rather as emergent from a complex system. The term "strategy" is still useful because it emphasizes the idea that in this analysis substituting local production with food imports is a response to declining LFSP.

2.2. Estimation of Food Supply Potential

At a given time, LFSP is limited by biophysical factors such as availability of cropland and water resources, factors affecting efficiency of production, including available technologies and infrastructure and prevailing management practices, as well as other production factors such as available labor, agricultural policies, etc. In this analysis, LFSP is measured using the green-blue water (GBW) scarcity indicator (introduced by *Gerten et al.* [2011]) as a proxy variable. The GBW scarcity indicator, simulated using the global hydrology and agriculture model LPJmL [*Bondeau et al.*, 2007; *Rost et al.*, 2008; *Schaphoff et al.*, 2013], gives the ratio of available green and blue water resources and the water requirements of producing a sufficient diet for the population locally. It thus measures a region's capacity of reaching food self-sufficiency if all the accessible water were used. The indicator omits some production factors such as availability of labor and crop nutrients, which means that it may overestimate actual LFSP in regions where production is limited by these omitted factors rather than water availability.

In LPJmL, blue and green water availability is affected by agricultural land extent and hydroclimatic conditions at a given time. Water demand of food production is affected by climate and available technologies and management practices. In this analysis, crop management intensity was calibrated to adjust simulated yields to best match the values reported in FAOSTAT [*Food and Agriculture Organisation of the United Nations (FAO)*, 2015a] for years 1961–2009. The sufficient target diet was based on the average country-specific dietary energy requirement (currently globally about 2,350 kcal cap^{-1} d^{-1}) defined by the *FAO* [2015b], consisting of 80% vegetal- and 20% animal-based food. Following *Rockström et al.* [2007] it was assumed that compared to vegetal foods, an eightfold amount of water is required to produce the same amount of animal calories. Water requirement was adjusted to take food losses and waste along the food supply chain into account [*Kummu et al.*, 2012; *Jalava et al.*, 2016]. Both ADER and food loss rates notably vary from one country to another for reasons such as age structure, body size, and

Table 1. Implementation and Success of the Import Strategy Based on the Sub-National Analysis

	Strategy		
Success Classification	Import	No Import	Total
Within local carrying capacity	27 (1,206)	13 (275)	40 (1,481)
Within post-trade carrying capacity	26 (768)	6 (41)	32 (809)
Mixed	17 (609)	2 (27)	19 (637)
Exceeded post-trade carrying capacity	6 (460)	5 (379)	11 (839)
Total	76 (3,044)	26 (722)	102 (3,766)

Number of food production units (FPUs) and their population (in brackets) in millions in 2009 in different classes based on the implementation and success of import or other strategies. Country-level values are found in Table S2.

level of physical activity, and thus, country-level data on ADER and food waste were used to calculate water demand.

A more detailed description of the estimation of LFSP is provided in Text S1. Figure S2 shows LFSP in all FPUs at three timesteps, and the annual data are available in Dataset S1 (Dataset S2 for country scale data).

2.3. Estimation of Net Imports

Country-level data on dietary energy supply (kcal yr^{-1}) and production (kcal yr^{-1}) for 1961–2009 were calculated following the procedure described in *Porkka et al.* [2013], which is shortly summarized in Text S2.

For the FPU scale analysis, sub-national food supply and production were downscaled from the country-level values, assuming that:

a. Per capita food supply in each FPU would fulfill at least the minimum acceptable supply defined by the *FAO* [2015b] for each country, and any surplus would be distributed within a country based on GDP [*Gennaioli et al.*, 2013].
b. Each FPUs share of country-level food production would follow simulated FPU productivity.

Total net imports (kcal yr^{-1}) (both at FPU and country scale) were calculated as the difference between dietary energy supply and production. Finally, net imports were expressed as the potential percentage of population sustained through that food source by dividing per capita net imports by country-specific ADER. To account for food waste, ADER was adjusted with country-specific food loss rates during distribution and consumer stages of the food supply chain.

FPU level net imports at three timesteps are mapped in Figure S2, and the annual data are available in Dataset S1 (Dataset S2 for country scale data).

3. Results

3.1. Implementation and Success of Import Strategy

The majority of the 102 FPUs and study population was found to implement the import strategy (Table 1), i.e., net food imports (relative to food demand of the population) increased when LFSP decreased (76 FPUs, 3,044 million people with import strategy *vs.* 26 FPUs, 722 million people with no import strategy). A substantial portion of the FPUs with import strategy had not yet exceeded their local carrying capacity during the study period (27 FPUs, 1,206 million people) such that imports are preparing them to cross their local limit to growth in future, with the consequences that implies. This has already occurred in a total of 49 FPUs with import strategy, populated by 1.8 billion people, such that they are now dependent on imports. A quarter of this population lived in FPUs where the import strategy was not successful (class "Exceeded post-trade carrying capacity" in Table 1), while the majority lived in FPUs that stayed within their post-trade carrying capacity with imports, during at least part of the study period.

3.2. Factors Influencing the Implementation of Import Strategy

As expected, aridity was generally quite high in FPUs that have implemented the import strategy (Figure 3). The majority of these FPUs (42 of 76) were classified as either hyper-arid (aridity index [AI] score <0.03), arid

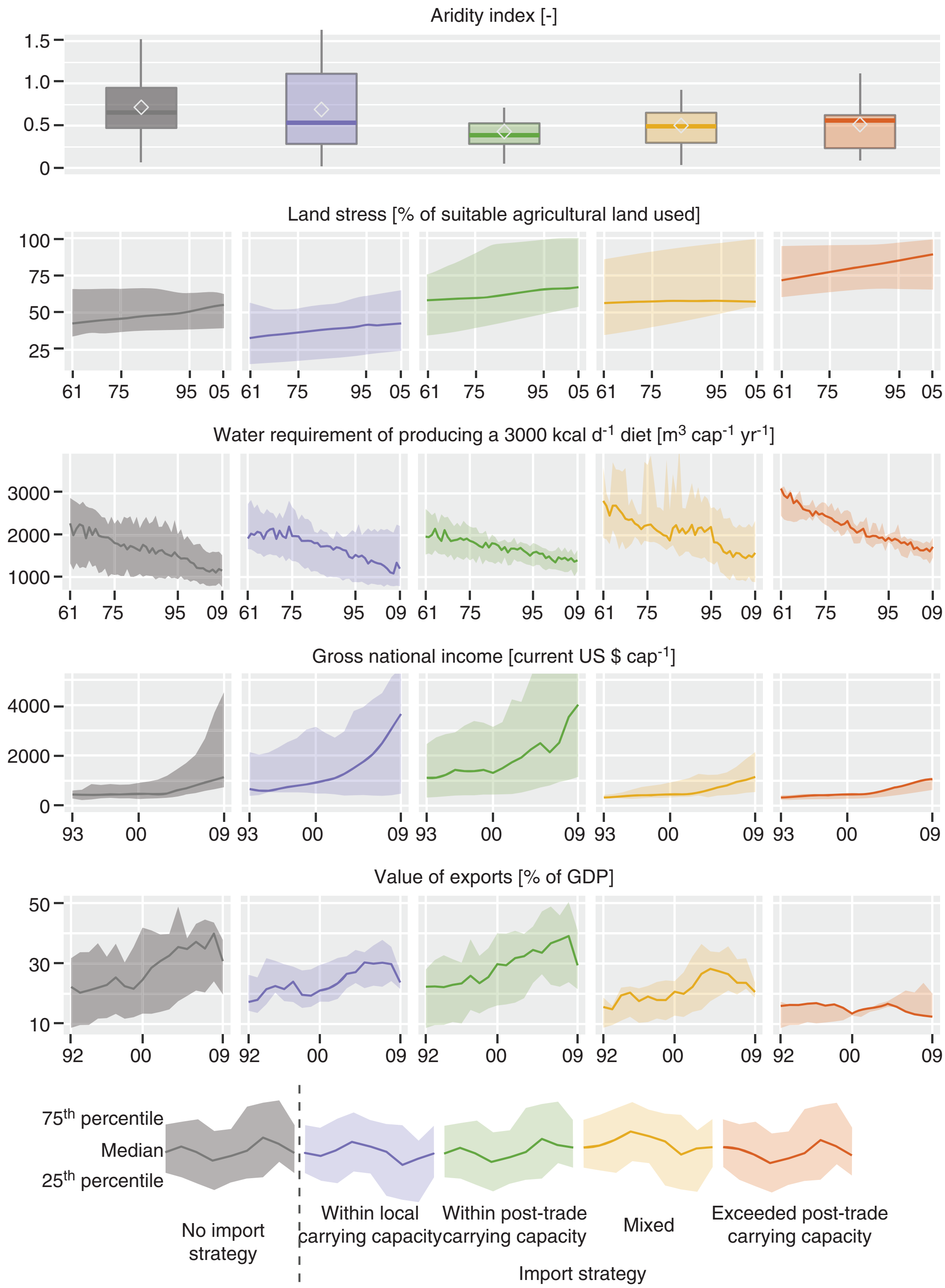

Figure 3. Distribution of characteristics of food production units (FPUs) implementing (colored boxes and lines) and not implementing (gray box and lines) the import strategy: aridity index (AI) (1950–2000 average), land stress (from 1961 to 2005), water requirements of producing a 3000 kcal d^{-1} diet (1961–2009), GNI (1993–2009) and value of exports relative to gross domestic product (1992–2009). Note that high values of AI signify higher humidity and low values aridity. FPUs with import strategy are further divided into those within local carrying capacity, those within post-trade carrying capacity, those that have exceeded post-trade carrying capacity and those with mixed success with the import strategy. Lines represent the median value and ribbons (boxes in the case of AI) the interquartile range (IQR, 25th–75th percentile) of each class. Ends of the whiskers in the box plots represent the lowest datum still within 1.5 interquartile range (IQR) of the first quartile, and the highest datum still within 1.5 IQR of the third quartile.

(AI 0.03 – 0.2) or semi-arid (AI 0.2 – 0.5) (Figure 3). Land stress, defined as the ratio of current cropland and area suitable as cropland, has been relatively high and/or increasing rapidly in FPUs with import strategy (Figure 3), including areas with lower aridity. Thus, FPUs with import strategy tend to experience either aridity or land stress or both. However, similar features were found in some of the FPUs with no import strategy. Water use efficiency and economic activity did not appear to be defining factors as to whether the import strategy was implemented; however, they seemed to be strongly linked to its success (see following sub-section).

A notable exception to this pattern was provided by FPUs that implemented the import strategy despite not having exceeded their local carrying capacity yet. Most of these FPUs are located in, East Asia, the MENA region, North America and Sub-Saharan Africa (Figure 2). Although about a half of these areas were classified as hyper-arid, arid, or semi-arid, this class experienced much less land stress than all the other classes (Figure 3). This suggests that in these FPUs the import strategy was driven by other factors than inability to increase LFSP. One explanation to this may be that many of these FPUs had relatively high GNI and exports (Figure 3), which could have enabled responding to the increasing population pressure with imports rather than fully tapping LFSP.

3.3. Factors Influencing the Success of Import Strategy

While differences between FPUs with import and no import strategies were fairly subtle, the varying success of the import strategy was clearly linked to our hypothesized key factors. Successful implementation of the import strategy was found to be strongly linked to economic power. FPUs that had always succeeded to stay within post-trade carrying capacity with imports had the highest GNI of all the classes throughout 1993 – 2009 (Figure 3). The majority of these FPUs are found in the MENA region, as well as the Korean peninsula and parts of India and Sub-Saharan Africa (Figure 2). Although GNI was generally higher in this class compared to the others, there are some exceptions, such as FPU 218 in Zimbabwe (Figure 4a), which successfully implemented the import strategy despite their relatively low GNI. Indeed, in many FPUs with low GNI, other factors, particularly the value of exports (Figure 3), seemed to explain the successful/unsuccessful implementation of the import strategy.

The few cases (6 FPUs with 12% of study population, Table 1) with unsuccessful import strategy, located in South Asia and Sub-Saharan Africa (Figure 2), were characterized by strong efforts to increase agricultural productivity through both expansion (illustrated with increasing land stress in Figure 3) and intensification of agriculture (illustrated with water requirements of producing food in Figure 3). However, as these FPUs have had population growth rates among the highest in the world [*FAO*, 2015a], these measures have not been sufficient for surpassing the intensifying population pressure, hence the need for imports. This class has the lowest GNI of all classes (Figure 3); however, GNI increase accelerated after the turn of the millennium, suggesting that some of these FPUs might only recently have reached a turning point where they have sufficient economic power for imports to outstrip population growth. One such example may be FPU 87 in Nepal, whose net imports showed a sudden increase around the year 2000 (Figure 4b) — the same time the economic growth rate in Nepal increased suddenly [*The World Bank*, 2016].

FPUs implementing the import strategy with mixed success were in many ways similar to those classified as unsuccessful. About half of them are located in China and South Asia, with the rest scattered in other regions (Figure 2). These FPUs, too, combined a fairly low GNI with high economic growth after year 2000, and high efficiency improvements (Figure 3). However, in these areas, exports formed a much larger share of the GDP than in FPUs that were unsuccessful with the import strategy. These factors may explain their better success, particularly in recent years, as higher water use efficiency decreased population pressure and thus the need for imports, while at the same time larger exports enabled increasing imports. One example of the successful combination of increasing both net imports and LFSP is FPU 288 in China (Figure 4c). Population pressure had pushed the area over its carrying capacity already before the study period, but during 1970 – 1980, through both LFSP improvements and increases in net imports the FPU recovered from the overshoot and has stayed within its post-trade carrying capacity since.

Rather than increasing imports such as to exactly match the post-trade carrying capacity, the majority of FPUs follow the pattern of beginning to implement the import strategy either while still within local carrying capacity or after having already exceeded it. This yields a trajectory more or less parallel to the post-trade

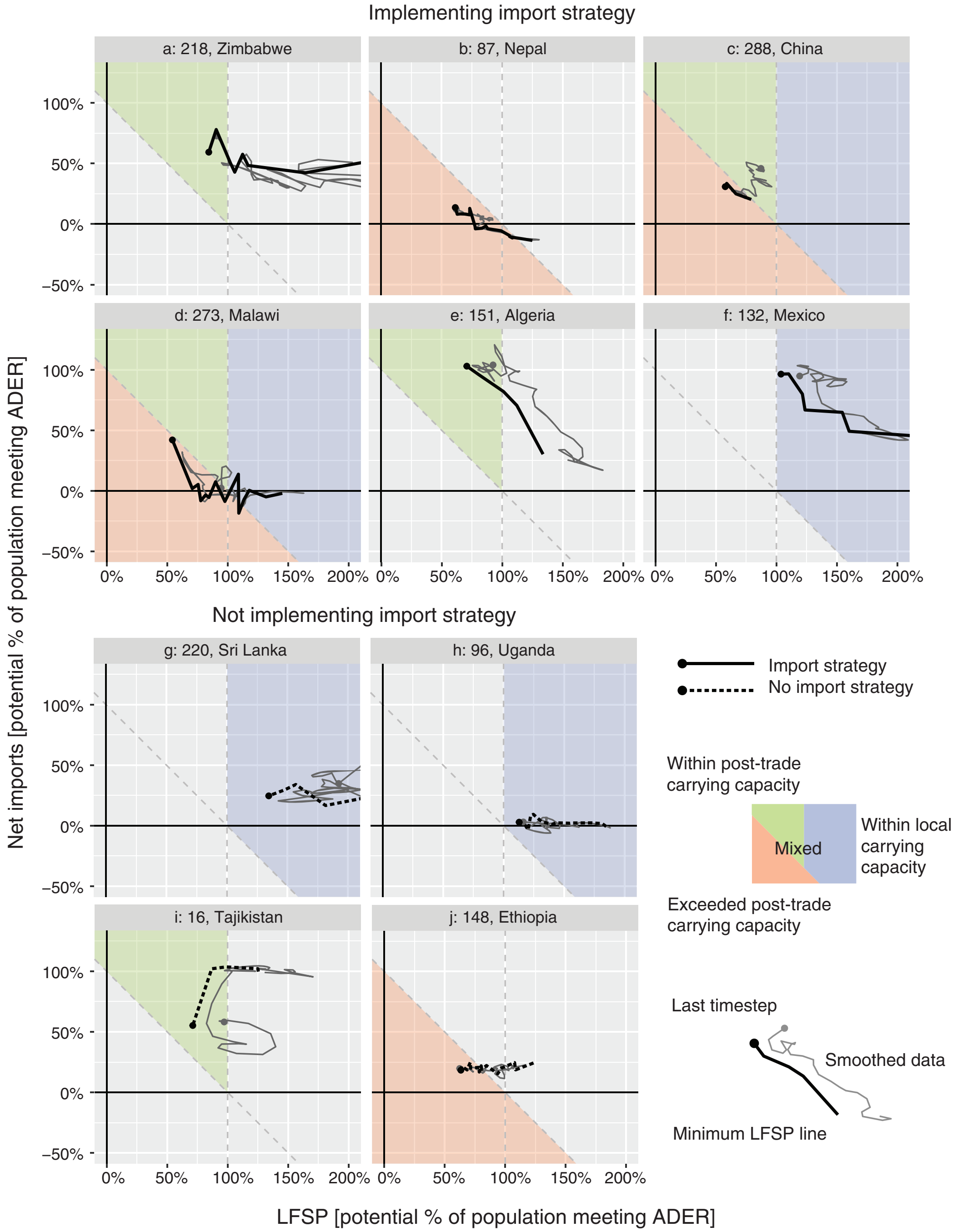

Figure 4. Selected food production units (FPUs) on the carrying capacity plot. See all FPUs in Figures S4–S8 and countries in Figures S9–S12. (a) Successful implementation of import strategy despite low gross national income (GNI); (b) small, sudden increase in net imports, perhaps due to economic conditions; (c) increasing both net imports and local food supply potential (LFSP), with mixed results; (d–f) trajectories that may reflect perception of scarcity; (g) LFSP stagnated; (h) rapidly approaching local carrying capacity; (i) imports driven by other factors than low LFSP; and (j) insufficient imports led to exceedance of post-trade carrying capacity. Location of these FPUs is presented in Figure 2. Black lines show the minimum LFSP line, i.e., include only those time steps when increasing population pressure decreased LFSP. Gray lines show the full, smoothed time series (1961–2009) of LFSP and net imports. Dots at the end of lines signify the latest timestep. Colors in the background of the plots show whether carrying capacity for the FPU shown has been sufficient for the population.

carrying capacity line, below the line in the case of FPU 273 in Malawi (Figure 4d), and above in the case of the relatively wealthy FPU 151 in Algeria (Figure 4e). Another example is given by FPU 132 in Mexico (Figure 4f), where net imports have gone up steadily as LFSP has decreased, despite not having exceeded their local carrying capacity yet. This is likely to be attributable to differences in what individuals or populations *perceive* to be a sufficient food supply or an appropriate diet, as demonstrated by the increased problem of obesity and overweight, particularly in the wealthy industrial countries [*Finucane et al.*, 2011]. A reference food supply higher (lower) in dietary energy or animal products [*Jalava et al.*, 2016], for instance, would shift the local carrying capacity threshold to the right (left). It is not just biophysical scarcity and carrying capacity that determines implementation of the import strategy, but also perceived scarcity and the corresponding culturally influenced carrying capacity. The difference could admittedly also be partly explained by limitations of the analysis, including the water productivity-based proxy used for LFSP (see Section 4).

3.4. Limits to Growth Without the Import Strategy

In 26% of study FPUs (19% of study population), net food imports relative to food demand did not increase when LFSP decreased (i.e., the import-production substitution strategy was not implemented, though gross trade still typically increased). This appears to have occurred for three reasons. First, half of these areas, located in Europe, Central Asia, Sub-Saharan Africa, South Asia, and China (Figure 2), never exceeded their local carrying capacity, and therefore did not have the need to secure food supplies with imports yet. In fact, after an initial decline of LFSP, in most of these cases productivity increases seem to have kept pace with population growth, as LFSP has either stagnated or even started increasing (as in FPU 220 in Sri Lanka, Figure 4g) before the exceedance of local carrying capacity. Indeed, improvements in productivity in regions where the import strategy was not implemented have led to the lowest water use requirements of all classes (Figure 3). However, in a few cases in Sub-Saharan Africa and South Asia (e.g., FPU 96 in Uganda, Figure 4h), population growth has been very high and FPUs are rapidly approaching their local carrying capacity, implying the need to either further intensify agriculture or turn to food imports in the future. These regions are still experiencing considerable yield gaps, thus, agriculture could be intensified with better nutrient and irrigation management [*Mueller et al.*, 2012].

Second, in a handful of cases increases in imports were not needed because net imports were already sufficiently high to absorb the effects of intensifying population pressure. Therefore, in these FPUs post-trade carrying capacity was not exceeded despite decreasing LFSP. Imports in these cases have likely been driven primarily by other factors than limited LFSP (e.g., FPU 16 in Tajikistan, Figure 4i), or the import strategy may have been implemented already before the study period.

Thirdly, in five FPUs (10% of the study population), located in South Asia and Sub-Saharan Africa, the import strategy was not implemented, which led to these regions exceeding their post-trade carrying capacity (e.g., FPU 148 in Ethiopia, Figure 4j). Despite their efforts to increase the efficiency of agriculture, these FPUs have not recovered from the overshoot. Thus, although the import strategy is often implemented in conjunction with increasing LFSP, the results suggest that in a vast majority of cases, once an FPU has exceeded their post-trade carrying capacity, increasing net imports has been necessary for recovering from the overshoot.

4. Discussion and Conclusions

We found that food imports are nearly universally used to overcome local limits to growth, but are implemented to varying extent and with varying success. In the large majority of FPUs, as a region approaches its carrying capacity, net import of food relative to food demand of the population tends to increase. Nearly all cases where this has not occurred are only approaching their carrying capacity threshold—in some of these cases, net imports are likely to increase in future, as their population continues to increase while in others, population pressure has either stagnated or even decreased in recent years, as population growth has not outpaced improvements in food production anymore. Our main analysis was conducted at sub-national FPU scale, including also assumptions of countries' internal food transfers. Results were very similar at country scale, where only international food trade was included. As with FPUs, a majority of the study countries (37 of 49, 76%, see Table S2) were found to use imports as a strategy to overcome local limits to growth, and nearly all implemented the strategy successfully. Where the strategy has not been implemented, either there was no need for increasing imports or the countries exceeded their carrying capacity due to population growth outpacing alternative strategies (see Figures S3 and S9–S12). Both the FPU and country scale results obtained in this study, therefore, support our hypothesis.

Although many issues regarding trade are complex, the message here is simple: as population pressure increases, food availability is becoming increasingly reliant on imports. Explaining and modeling trade in more general circumstances requires complex models that acknowledge a wider range of possible drivers of trade. In contrast, this analysis, through a simple empirical demonstration, clearly shows that if population pressure is sufficiently high, and local LFSP has been exhausted within current limits, food tends to be imported such that sufficient food supply is increasingly dependent on food imports. We can only speculate on the precise mechanism, whether population increases cause imports to increase, or vice-versa, and the functional form of the relationship varies significantly, but the two are clearly linked.

While the increase in imports might seem obvious, it is not necessarily inevitable. From the point of view of a technological optimist or a Malthusian pessimist, in these locations, imports are currently preferred over increases in LFSP or population control, respectively. From a Malthusian perspective, improvements in efficiency of local production are not keeping pace with population growth. Contrary to Malthus' expectation, population continues to grow, rather than stabilize or migrate, as local carrying capacity is increased by the technologies associated with trade (e.g., infrastructure and logistics). In many cases, further improvements in efficiency of food production could, however, also occur. Even in areas that achieve the best current productivity, efficiency improvements are theoretically possible. Ultimately, there is no clear limit to reducing the water consumed by agriculture, given that technological advances could in principle achieve a high degree of recirculation of water and nutrients. These advances may, for example, occur as a result of investment in self-sustaining space colonization [*Monje et al.*, 2003].

The observed use of imports can therefore be considered an economic choice. Faced with scarcity, the use of imports is currently considered the lowest cost option, and dependency on imports is treated as a tolerable risk. Our results again raise the question: have the implications of this economic choice been sufficiently studied? The existence of regions that have been unsuccessful with the import strategy suggests that in these cases the choice may not have been evaluated adequately. This suggests the need for synthesis of research evaluating the alternative options for dealing with limits to (population) growth, specifically for the regions approaching their carrying capacity. Dependency on imports, new advances in agricultural technology, and control of population density and mobility each have significant local implications for these regions, as well as flow-on (and cumulative) consequences for the rest of the world. What are the relative risks, costs, and benefits of these alternative options?

Whether dependency on imports is considered desirable or not, a clear policy priority—locally as well as globally—should be to keep the demand of food under control. Strategies to limit population growth, particularly in regions identified in this analysis, are obviously at the root of this, but in many cases we know that further improvements in food supply efficiency could also occur through changes in diet [*Vanham et al.*, 2013; *Jalava et al.*, 2014, 2016] and reduction in food loss and waste [*Kummu et al.*, 2012; *Jalava et al.*, 2016]. Effective demand side measures will require changes in consumer behavior, particularly in the affluent developed world, but investments in technology and infrastructure could also play a role in this, by, e.g., minimizing food losses through ensuring that appropriate storage facilities are in place. Regardless of the strategies to provide sufficient quantities of food, efforts should also focus on better distribution of food supplies within country and improved access to food on an individual level. Actions to promote social justice and equity, e.g., increasing women's education and improved access to freshwater and sanitation, have been shown to be even more effective in reducing child undernutrition than increased per capita food supply [*Smith and Haddad*, 2015].

In cases where import dependency is considered reasonable, focus should be on ensuring that sufficient quantities of imported food can be reliably obtained, and resources and logistics to access it are available, even at times of global price spikes or economic recession. Production shocks in exporting countries have been shown to pose a risk of food shortages in countries dependent on trade [*Puma et al.*, 2015; *Suweis et al.*, 2015; *Marchand et al.*, 2016; *Tamea et al.*, 2016]. These disturbances are often caused by weather anomalies, which have been projected to become more frequent in some regions in the future due to climate change [*Coumou and Rahmstorf*, 2012], possibly accentuating this risk. A recent example exposing the fragility of the global food system was the food price crisis of 2008, during which many of the world's largest exporters of wheat and rice imposed export restrictions, causing panic and unrest in some trade-dependent countries and increasing food insecurity worldwide [*Puma et al.*, 2015; *Suweis et al.*, 2015].

Vulnerability to disturbances could be reduced by diversifying the sources of staple foods, and by ensuring that trading partners have sufficient reserves to withstand a production shock [*Marchand et al.*, 2016]. Global institutional arrangements, such as physical (for humanitarian assistance) and virtual (as market intervention mechanisms) reserves of staple foods have also been proposed as a solution to reduce the vulnerability of the trade network, accompanied with trade policies that acknowledge food security consequences, by, e.g., reducing biofuel subsidies at times when food prices are high [*von Braun*, 2009]. In the aftermath of global price spikes, many actors from governments of trade-dependent countries to transnational corporations have increasingly turned to large-scale acquisitions of foreign land to secure sufficient food supply in the event of future price spikes [*Saturino et al.*, 2011]. While possibly contributing to efficiency improvements on underperforming areas and improving food security for some importing countries, these investments in land have also been associated with negative consequences to local rural communities [*Rulli and D'Odorico*, 2014; *Dell'Angelo et al.*, 2017]. Similar displacement of social and environmental impacts of food consumption is inherent in all international trade, in many cases resulting in food sovereignty-related [*Chaifetz and Jagger*, 2014] tradeoffs between national food security goals and the protection of human rights and the environment [*Schipanski et al.*, 2016]. As the importance of trade for food security is likely to increase still, international legislation and trade policies to advance both goals will be needed.

In areas where securing food supplies through imports is not desirable or feasible, a priority should be to stay within local limits by decoupling growth in production from resource use and its impacts [*Kummu et al.*, 2016]. Many of the regions identified in this analysis as either approaching or having already exceeded local carrying capacity—particularly those located in Sub-Saharan Africa and South Asia—have not reached their full potential in terms of efficiency of resource use [*Fader et al.*, 2013]. By better irrigation and nutrient management, these yield gaps could be closed, such that the production of maize, wheat and rice could increase by over 50% in South Asia and even double in Sub-Saharan Africa [*Mueller et al.*, 2012]. The intensification of production, however, has to be made practically feasible through investment in knowledge and capital, and supporting infrastructure and regulation. Alternative water sources such as recycling of urban water and desalination are capital-intensive. Further innovations to improve recirculation and water efficiency require a long-term view, supporting research in technologies before they are needed, and sharing the inherent risk. Allocation of highly scarce water requires strong institutions to avoid undesirable externalities. In order to be sustainable, consumers need to consider it cost-effective to buy local. This might be influenced by justifying premium prices, creating a shared vision of why imports are to be avoided, by achieving economies of scale, or by sharing the cost, as in the existing use of subsidies.

This article naturally leaves open opportunities for further investigation of the use of imports to overcome local limits to growth. In this analysis, we focused specifically on the overall trends in regions approaching their carrying capacity, omitting what happens at short time scales. It is possible that while the import strategy is being used in a region in general, it may not be in use at the present time. Consistent with the observation that imports are increasing [Porkka et al., 2013], the majority of the FPUs included in this study have recently experienced increased population pressure (i.e. the last year in which a new minimum LFSP was reached was after 2000 in 60% of FPUs, see Figure S13), such that use of the import strategy is likely to be occurring at the present time. Where population pressure has not been increasing recently, either population may have stabilized or decreased, or other strategies that increase LFSP may be in use. Such FPUs classified as implementing an import strategy are doing so in the long term, but may not have needed to do so in recent times. More detailed analysis of use of trade on shorter time scales would be needed to confirm this.

The proxy for LFSP used here focuses on water as the key limiting resource. Future attempts to estimate LFSP could additionally also take into account other production factors, such as availability of labor, land, and crop nutrients, as well as supply and demand conditions that mean that theoretical potential cannot be attained in practice. As our analysis focused on regions where water is a constraint, the GBW scarcity indicator (see Section 2.2) is likely to provide a good estimate of LFSP in these specific regions and therefore serves as a reasonable initial proxy.

Another interesting question for future research is whether successful implementation of the import (or other) strategy actually translates into food security. The long time scales and proxy methods used do not allow us to determine whether food supply is actually sufficient at any particular point in time. Furthermore, as mentioned above, access to food can be an equally important dimension of food security than having sufficient quantities of food available [*Porkka et al.*, 2013]. The utilization aspect of food security was also omitted from the analysis, as food imports were only measured in terms of sufficient dietary energy, ignoring other nutritional aspects of diets (although data on LFSP did include some assumptions about a balanced diet). The food security implications of the import strategy could thus be investigated more carefully in future studies.

This analysis can be seen as a novel approach to empirically evaluate the use of imports as a strategy to overcome local limits to growth. It builds the foundation for more detailed studies evaluating this issue with more reliable data and models in specific regions. The key message of this article is clear: globally, food imports are being used to overcome local limits to growth, such that food security in those regions has become increasingly dependent on imports. Whether or not this dependence is considered desirable, it has policy implications that need to be taken into account.

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