AGU PUBLICATIONS

Earth's Future

RESEARCH ARTICLE
10.1002/2014EF000250

Key Points:
- We reconstruct the global network of food trade
- We determine the dependency of global access to food on international trade
- We evaluate the water use efficiency of food production and trade

Supporting Information:
- EFT2_42_Auxillary Materials.docx
- EFT2_42_fs01.tif.
- EFT2_42_fs02.tif.
- EFT2_42_ts01.tif.
- EFT2_42_ts02.tif.
- EFT2_42_ts03.tif.
- EFT2_42_ts04.tif.

Corresponding author:
P. D'Odorico, paolo@virginia.edu

Citation:
D'Odorico, P., J. A. Carr, F. Laio, L. Ridolfi, and S. Vandoni (2014), Feeding humanity through global food trade, *Earth's Future*, *2*, doi:10.1002/2014EF000250.

Received 16 APR 2014
Accepted 5 AUG 2014
Accepted article online 12 AUG 2014

Feeding humanity through global food trade

Paolo D'Odorico[1], Joel A. Carr[1], Francesco Laio[2], Luca Ridolfi[2], and Sfefano Vandoni[2]

[1]Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia, USA, [2]Dipartimento di Ingegneria Ambientale, DIATI, Politecnico di Torino, Turin, Italy

Abstract The recent intensification of international trade has led to a globalization of food commodities and to an increased disconnection between human populations and the land and water resources that support them through crop and livestock production. Several countries are not self-sufficient and depend on imports from other regions. Despite the recognized importance of the role of trade in global and regional food security, the societal reliance on domestic production and international trade remains poorly quantified. Here we investigate the global patterns of food trade and evaluate the dependency of food security on imports. We investigate the relationship existing between the trade of food calories and the virtual transfer of water used for their production. We show how the amount of food calories traded in the international market has more than doubled between 1986 and 2009, while the number of links in the trade network has increased by more than 50%. Likewise, global food production has increased by more than 50% in the same period, providing an amount of food that is overall sufficient to support the global population at a rate of 2700–3000 kcal per person per day. About 23% of the food produced for human consumption is traded internationally. The water use efficiency of food trade (i.e., food calories produced per unit volume of water used) has declined in the last few decades. The water use efficiency of food production overall increases with the countries' affluence; this trend is likely due to the use of more advanced technology.

1. Introduction

Global food security depends on a number of rapidly changing factors that control the availability of and access to food commodities. In the last three decades research on food security has emphasized the importance of factors controlling the access to food [e.g., *Sen*, 1981]. More recently, however, scientists have started to focus again on food sufficiency and availability [e.g., *Foley et al.*, 2011; *Tilman et al.*, 2011; *Cassidy et al.*, 2013]. There is a growing concern that the limited resources of the planet will soon limit our ability to keep up with the increasing food demand by human societies [e.g., *Godfray et al.*, 2010]. While the demand for food is steadily increasing and is competing with the rapidly growing need for agricultural products by other sectors such as biofuel production [e.g., *Godfray et al.*, 2010], the supply of food crops is reaching a plateau [*Ray et al.*, 2012]. On the demand side, demographic growth and changes in diet are placing unprecedented pressure on the food production system [e.g., *Tilman et al.*, 2011; *Cassidy et al.*, 2013; *Hermele*, 2014]. The global population has increased by 1 billion every 12–14 years since the 1960s [*U.N. Population Division*, 2012] and has been paralleled by an increase in food availability resulting from the use of industrial fertilizers, irrigation technology, and new cultivars [*Boserup*, 1981; *Erisman et al.*, 2008]. Interestingly, food consumption has not grown linearly with the population size as the per capita demand for food has increased. The portion of the diet consisting of fats and proteins tends to increase with the economic development of emerging countries [*Delgado*, 2003], a phenomenon known as "Bennett's law" [e.g., *U.K. Office for Science*, 2011]. In particular, the consumption of meat and other animal products has been reported to increase with the per capita gross domestic product (GDP) and the gross national income (GNI) [*Tilman et al.*, 2011; *U.K. Office for Science*, 2011]. Because several kilocalories of forage or feed are needed to produce 1 kcal of meat [*Pimentel et al.*, 1973], this increase in the consumption of animal products is further enhancing the human pressure on croplands and rangelands [*Cassidy et al.*, 2013].

On the supply side, after the extraordinary increase in crop yields in the second half of last century (i.e., during the "green revolution"), the rates of agricultural production are expected to reach a plateau [*Ray et al.*, 2012; *Brown*, 2013]. Likewise, it has been argued that capture marine fisheries might be at the verge of a sudden decline [*Coll et al.,* 2008], while the ongoing increase in fish production from aquaculture, is partly sustained by feed inputs from terrestrial sources [*Duarte et al.,* 2009; *Gephart et al.,* 2014]. Moreover, recent U.S. and E.U. policies have mandated the use of a prescribed fraction of energy from renewable sources [*EISA*, 2007; *E.U.*, 2009]. The consequent escalating use of crops for biofuels has started to compete with food production [*Hermele*, 2014]. Further, the intensification of climate extremes is predicted to increase the variability and uncertainty of crop yields [*IPCC*, 2013], thereby contributing to food price volatility [*FAO-OECD*, 2011]. The picture emerging from these analyses is that, in the near future, the rates of global food supply might not meet the escalating demand.

At smaller scales, however, many regions are already in conditions of food shortage due to a local imbalance between production and demand (see Supporting Information, Figure S1) [*Fader et al.,* 2013; *Suweis et al.,* 2013]. The food security of these societies relies on the importation of food products from other regions. It has been argued that the intensification of international trade has been one of the major factors contributing to changes in food supply in the past few decades [*D'Odorico and Rulli*, 2013]. Global trade has been found to account for 12% of the human appropriation of the net primary productivity and 24% of the global ecological (i.e., land) footprint [*Erb et al.,* 2009; *Weinzettel et al.,* 2013; *Meyfroidt et al.,* 2013]. The extent to which global food security depends on international trade, however, remains poorly understood [*Porkka et al.,* 2013]. It is unclear which region of the world is most benefiting from the ongoing intensification of food trade and how trade differentially affects food security in developed, emerging, or developing countries [*MacDonald*, 2013].

There is also some concern that food production might not grow indefinitely due to limitations imposed by land and water resources. Because of the limited potential for sustainable expansion of agricultural land, for most regions of the world, an increase in food production requires the closure of the yield gap in underperforming agricultural lands with strong potential for increased yields [*Foley et al.,* 2011; *Mueller et al.,* 2012]. With nitrogen fertilizers becoming available in almost "unlimited" amounts through industrial synthesis [*Erisman et al.,* 2008], water and suitable land remain the major limiting factors for food production. It is therefore important to evaluate the water use efficiency (WUE) of food commodities (kcal/L) and investigate whether trade contributes to a more effective use of freshwater resources.

Here we investigate the global patterns of food trade, identify regions of self-sufficiency and trade dependency, and evaluate how the reliance on trade has changed in the last few decades. To that end, we reconstruct the global network of international food trade (in kilocalories of food traded/year) and investigate its temporal dynamics. We also relate the food calorie network to the virtual water network [*Carr et al.,* 2012, 2013] and evaluate the WUE of the traded commodities.

2. Methods

Trade data were taken from the FAOSTAT data base [*FAOSTAT*, 2012], which reports the trade flow among countries for a number of commodities between 1986 and 2010. In this study, a set of 153 countries (only countries with population >1 million and for which production data were available) and 251 major food commodities were analyzed (see Supporting Information, Table S1). Each commodity was associated with a country-specific water footprint (m^3/t) taken from the study by *Mekonnen and Hoekstra*, [2012] and a caloric content (kcal/t) taken from the FAO "Nutritive Factors" database [*FAOSTAT*, 2012]. The trade of each commodity was then converted into fluxes of both virtual water (VW) and food calories by multiplying the mass of the exchanged commodity by its water footprint and caloric content, respectively. The virtual water network was then constructed considering each country or territory reported in the FAOSTAT database as a network node connected to other nodes by links representing trade relationships. In the VW network the strength of each (directed) link was calculated as the sum of the VW fluxes associated with all commodities traded along that link [e.g., *Carr et al.,* 2012, 2013]. Likewise, the food calorie network was determined by calculating for each link the total calories traded as the sum for all the commodities exchanged through that link.

Production rates were available for each crop type from the FAOSTAT database [*FAOSTAT*, 2012]. For each country, the total amount of water used for food production was calculated by multiplying the water footprint of each commodity by the corresponding yield, and then by adding up these values for all the food commodities included in this study [*Carr et al.,* 2012]. The same approach was used to calculate the calories of the food commodities produced by each country. The analysis of food calorie production and of the associated consumption of virtual water is affected by problems of double accounting that were addressed as follows.

In the case of secondary products — which are products derived from primary crops (e.g., bread is a derived product of wheat; meat and milk can be derived products of feed) — caution was used to avoid double accounting of the water resources required for their production. If a country produces both wheat and bread, and part of the wheat is used to make the bread, by adding the water footprint of both we would count part of the water consumption twice. Likewise, a similar problem of double accounting can emerge from the calculation of the calories of food produced by each country.

Because the water footprint of primary crops is much higher than the water consumption of processing, all secondary products were not included in the calculation of the water footprint and caloric content of food, except for animal-based food products such as meat, milk, or eggs, which were treated as primary products, while all the products derived from them were treated as secondary (Supporting Information, Table S1). The animal-based products can be either from feed-fed animals or from livestock raised in rangelands. While feed is included in the crop data reported by FAOSTAT, forage from rangeland and pasture is not. Therefore, in this study we considered both a production, P, that included crops used as feed and other uses, and a production, P', obtained subtracting from P the amounts used as feed and other nonfood uses; we included (both in P and in P') all the animal-based food products that are here treated as primary (Supporting Information, Table S1) but we excluded all the secondary products. Thus, while P is the total food production (with no double accounting of primary and derived products), P' is the food production for human consumption. The fraction of food production that is available for human consumption can be calculated as $\beta = P'/P$ (Supporting Information, Table S2). The feed (seed and "other uses") data were obtained from the *Food Balance Sheets* which were available only until the year 2009 [*FAOSTAT*, 2012].

Because a similar issue of double accounting does not emerge in the case of trade, in the analysis of the global patterns of trade we did not remove the secondary products. If a country produces and exports bread made with wheat imported from another country (or produced domestically), the net calorie and virtual water export would be calculated as the difference between bread exports and wheat imports (or the whole bread exports if domestic wheat was used) without incurring into any double accounting. Therefore, while secondary products were not removed from the trade data, we considered two types of trade, namely, the total trade T and the portion of trade for direct human consumption, T', which was calculated as $T' = \beta T$. It has been noted that food production and trade can be analyzed and interpreted in more than one way [*Giampietro and Mayumi*, 2000]. While T' is the total food trade for human consumption, from a different perspective global food security depends also on the trade of feed, which is included in T. The water use efficiencies of production (P') and trade (T') were then calculated for each country as the ratio between that country's total calories of production (P') or trade (T') divided by the corresponding water footprint. The calculation of country-specific water use efficiencies should have used crop water requirements for the country of provenance of each commodity. However, it is not possible to bring the calculations to this level of accuracy because the available data do not provide information on the amounts of imported goods used for food, feed or other uses. To develop a consistent trade network throughout the study period (1986–2010), countries that have changed in recent years (e.g., the unification of Germany or Yemen, the splitting of Czechoslovakia or the disintegration of Yugoslavia and the Soviet Union) were dealt with by considering their more aggregated (i.e., unified) configuration, as described by *Carr et al.* [2013].

3. Results

Globally, 80% of the human diet (measured in terms of caloric content) is accounted for by the 13 products reported in Table 1. More than 50% of the global diet is contributed by wheat (20%), rice (16%), maize (13%), and soybean (8%), which account for 61% of the global production of protein for human intake. These values refer to 2009 and include only food for direct human consumption (i.e., excluding feed or crops for nonfood uses). The analysis of global trade data shows that 80% of the food calories that are traded are contributed by 15 products, which account for 52% of the protein trade for human

Table 1. The Major Food Commodities That Explain 80% of the Total Food Calories Produced[a]

Production													
1986							2009						
Commodity	% Cal	% Cal Cum.	% Prot.	% Prot. Cum	β	WUE	Commodity	% Cal	% Cal Cum.	% Prot	% Prot. Cum.	β	WUE
Wheat	23.7	23.7	19.7	19.7	0.78	1.321	Wheat	20.4	20.4	17.2	17.2	0.81	1.321
Rice (milled equivalent)	18.4	42.1	11.6	31.3	0.95	0.970	Rice (milled equivalent)	16.1	36.5	10.4	27.6	0.88	0.970
Maize	9.7	51.9	10.7	42.0	0.33	1.298	Maize	12.8	49.3	12.7	40.2	0.40	1.298
Soy beans	5.3	57.2	14.2	56.3	0.97	0.356	Soybean	8.0	57.2	20.5	60.8	0.96	0.356
Sugarcane	4.7	61.9	0.7	57.0	0.97	0.752	Sugarcane	5.4	62.7	0.8	61.6	0.98	0.752
Pig meat	3.4	65.3	3.0	60.0	1.00	0.834	Pig meat	3.8	66.5	3.2	64.8	1.00	0.834
Sugar beet	3.3	68.6	1.48	61.5	0.96	2.465	Rape and mustard seed	3.1	69.6	2.9	67.8	0.91	1.515
Barley	2.6	71.3	5.52	67.0	0.26	1.342	Potatoes	2.1	71.8	1.1	68.8	0.86	1.782
Potatoes	2.5	73.7	1.24	68.3	0.74	1.782	Barley	2.1	73.8	2.5	71.3	0.38	1.342
Sorghum	1.9	75.6	2.1	70.4	0.46	0.674	Poultry meat	1.9	75.7	2.5	73.8	0.99	0.616
Rape and mustard seed	1.6	77.2	1.5	71.9	0.93	1.515	Vegetables, other	1.8	77.5	0.8	74.7	0.94	0.465
Groundnuts (shelled eq)	1.4	78.7	1.5	73.5	0.99	0.918	Sugar beet	1.7	79.2	0.7	75.4	0.94	2.465
Bovine meat	1.4	80.0	3.7	77.3	1.00	0.141	Groundnuts (shelled eq)	1.5	80.7	1.6	77.0	0.96	0.918

[a]For each of these commodities we also report their contribution to the total production of protein for human consumption (expressed as a % of the total) and the cumulated contribution. These values are based on production data (P') for direct human consumption (i.e., excluding secondary products, feed and other nonfood uses); β is the fraction of food production that is available for human consumption. Water use efficiency (WUE) is expressed in kcal/L.

consumption (Table 2). In 2009 more than 50% of the global food trade (in caloric content) was accounted for by wheat (22%), soybean (13%), palm oil (8%), and maize (7%). Interestingly, there have been no major changes in the main food products traded for direct human consumption between 1986 and 2009, except for an increase in the trade of palm oil. The amount of food calories shown in Figure 1 is not trivial when compared with other major rates of energy consumption and trade sustaining the "metabolism" of our societies: globally, the caloric content of food trade is about 13% of the global crude oil trade, while the caloric content of all food products for direct human consumption is about 75% of the global consumption of electric energy, and 10% of the total energy consumption—including energy used for power generation, heating, transportation, and industrial uses, both from fossil fuels and renewable sources (Supporting Information, Table S3).

There are some regional differences in the major food commodities (Supporting Information, Table S4): more than 50% of the food calories produced in 2009 were from rice (32%) and wheat (22%) in Asia; soybean (33%) and sugarcane (24%) in South America; maize (33%) and sugarcane (22%) in Central America; maize (41%) and soybean (19%) in North America; wheat (36%) and barley (10%) in Europe; and wheat (50%) and barley (14%) in Oceania. While the major food commodities produced in Asia, Africa, Europe, Central America, and Oceania remained overall the same between 1986 and 2009, important changes occurred in South America, where the production of soybean has increased, concurrently with an increase in soybean exports from Brazil and Argentina to China.

The total amount of food produced (kcal/y) has steadily increased over the past three decades (Figure 1a). Likewise, the total amount of food traded has also increased (Figure 1b). The increase in production is not only due to the rise in food demand associated with demographic growth. Globally, the amount of food produced per capita (Figure 1c) has also increased, which suggests the occurrence of some important dietary changes with an average increase in calorie uptake per capita and, possibly, an increasing trend in food waste. Interestingly, over the past three decades the fraction of food for direct human consumption that is traded in the international market has increased from 15% in 1986 to 23% in 2009 (Figure 1d). Such an increase is contributed by food from both plant and animal sources. Thus, presently, about one fourth of food production is traded, implying that roughly one fourth of our current reliance on food is through international trade.

Table 2. The Major Food Commodities That Explain 80% of the Total Food Calories Traded[a]

Trade													
1986							2009						
Commodity	% Cal	% Cal Cum.	% Prot.	% Prot. Cum.	β	WUE	Commodity	% Cal	% Cal Cum.	% Prot.	% Prot. Cum.	β	WUE
Wheat	28.5	28.5	24.4	24.4	0.78	1.321	Wheat	22.4	22.4	16.1	16.1	0.78	1.321
Soybean	10.2	38.6	21.8	46.2	0.97	0.356	Soybean	13.3	35.6	27.6	43.7	0.97	0.356
Sugar (raw equivalent)	9.1	47.7	0	46.2	0.99	1.970	Palm oil	7.9	43.5	0	43.7	0.61	1.878
Maize	8.0	55.8	9.9	56.3	0.33	1.298	Maize	7.5	51.0	0	43.7	0.33	1.298
Rice (milled equivalent)	4.4	60.2	0	56.3	0.95	0.970	Sugar (raw equivalent)	7.2	58.2	0	43.7	0.99	1.970
Palm oil	3.8	63.9	0	56.3	0.61	1.878	Rape and mustard seed	4.3	62.6	3	46.9	0.93	1.515
Soybean oil	2.8	66.8	0	56.3	0.92	0.480	Rice (milled equivalent)	4.1	66.6	0.1	47.0	0.95	0.970
Barley	2.3	69.1	6.9	63.4	0.26	1.342	Soybean oil	3.0	69.6	0	47.0	0.92	0.480
Rape and mustard seed	2.0	71.1	1.6	65.0	0.93	1.515	Pig meat	2.2	71.8	0.6	47.6	1.00	0.834
Sunflower seed oil	2.0	73.1	0	65.0	0.94	0.933	Sunflower seed oil	2.2	74.0	0.0	47.6	0.94	0.933
Cassava	1.9	75.0	0	65.0	0.59	1.081	Barley	2.1	76.1	2.8	50.4	0.26	1.342
Fats, animals, raw	1.8	76.7	0	65.0	0.45	2.195	Cocoa beans	1.4	77.6	0.1	50.5	0.99	0.081
Sorghum	1.5	78.3	1.8	66.8	0.46	0.674	Oilcrops, other	1.2	78.8	0	50.5	0.94	0.387
Oilcrops, other	1.4	79.7	0	66.8	0.94	0.387	Rape and mustard oil	1.2	79.9	0	50.5	0.87	1.461
Rape and mustard oil	1.4	81.0	0	66.8	0.87	1.461	Poultry meat	1.1	81.0	1.2	51.7	0.99	0.617

[a]For each of these commodities we also report their contribution to the total trade of protein for human consumption (expressed as a % of the total) and the cumulated contribution. These values are b based on trade data (T') for direct human consumption (i.e., excluding secondary products, feed and other nonfood uses); β is the fraction of food production that is available for human consumption. Water use efficiency (WUE) is expressed in kcal/L.

This global scale analysis hides some important regional differences. From 1986 to 2009, food production has increased mostly in South America (≈121%), Africa (≈81%), Asia (≈58% increase), and North America (≈57%), while yields in Europe have been stagnating (Figure 2). This pattern is in agreement with a global assessment of the yield gap (i.e., the difference between actual and maximum potential crop yields) based on agricultural production data for the year 2000 [*Mueller et al.,* 2012]: while Western Europe had a small potential for crop yield increase, Africa, South and Southeast Asia, South America, and—to a lesser extent—North America still had relatively large yield gaps.

To place these numbers in the perspective of global food security we calculated the number of people who could be fed by the food that is produced and traded. To this end, a balanced diet of 2700 kcal/d (including waste [*Porkka et al.,* 2013]) was used as a reference value [e.g., *Falkenmark and Rockstrom*, 2006; *Cassidy et al.,* 2013]. By considering this average caloric content, this analysis does not account for the composition of the diet (e.g., the proportion of carbohydrates, proteins, and fats), nor for the geographic differences in the current rates of food consumption. Nevertheless, these baseline calculations show how, on average, the food production globally would be sufficient to feed more than 9.4 billion people (Figures 1c and 3). This estimate is overall consistent with a recent study by the FAO that showed how the current rates of food production would be sufficient to feed about 12 billion people with a lower baseline diet of 2400 kcal/d per capita [*FAOSTAT*, 2012]. Likewise, the number of people who could be fed by the traded food accounts for about 2 billion people (Figure 3). Thus, with the current rates of food production (and without accounting for food waste), the global food production should be sufficient to meet the demand of the world's population (Figure 3). However, even though access to food is recognized as a human right [*U.N.*, 1948], today more than 10% of the global population is still undernourished [*FAO*, 2012].

When performed at the country scale, this analysis allows us to relate food production to the number of people it could sustain, and to compare this number to the actual population of that country. Figure 4 shows a global map of caloric self-sufficiency, based on a diet of 2700 kcal/d per capita. As noted, this

10.1002/2014EF000250

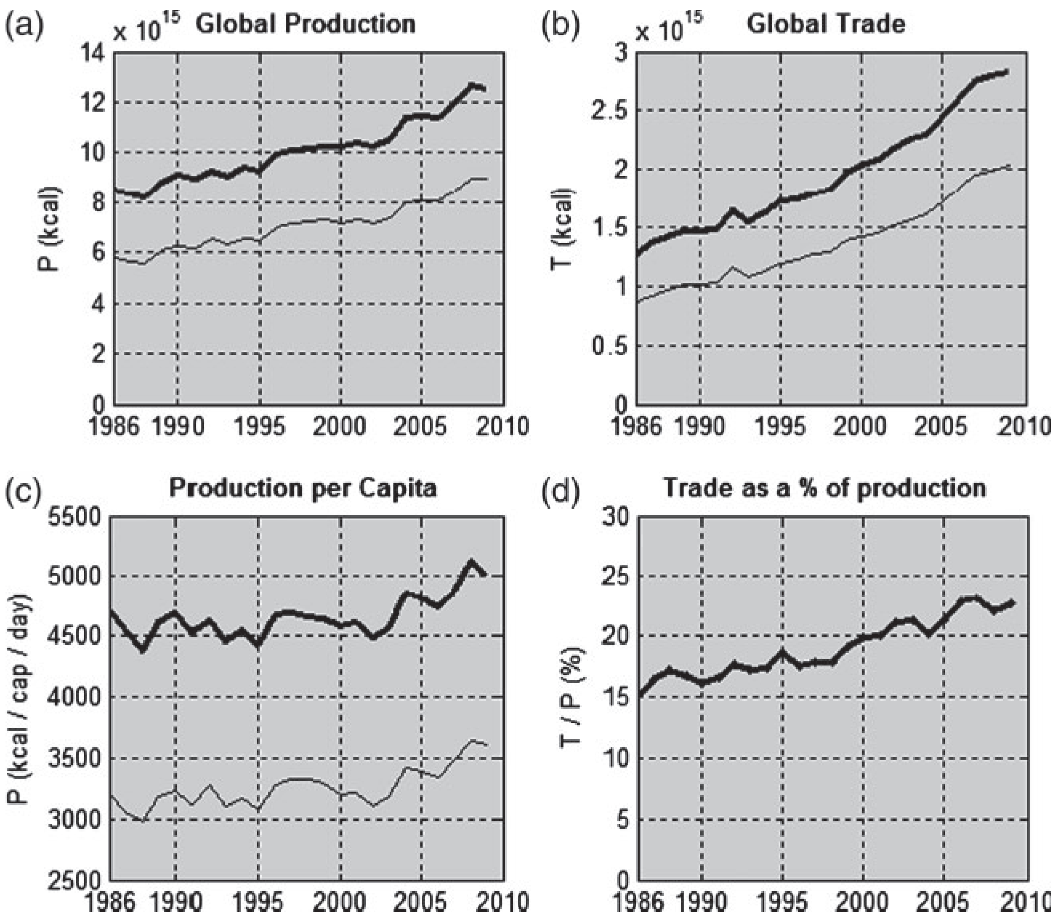

Figure 1. (a) Total amount of food traded (kcal/y); (b) global food production (kcal/y); (c) global food production per capita (kcal/y/cap); (d) percentage of global food production that is traded (%). Thin lines refer to food production and trade for direct human consumption (P' and T'). Thick lines refer to food production, P, including feed and other uses (but excluding secondary products) and food trade, T, including secondary products, feed and other uses. In panel (d) the thin and thick lines coincide.

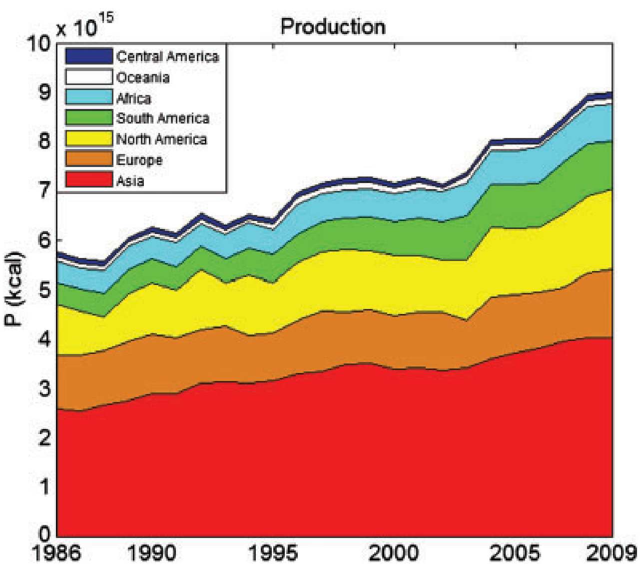

Figure 2. Global food production by regions. Based only on P', i.e., primary plant and animal products available as food for direct human consumption (i.e., excluding feed and other uses).

analysis, however, does not account for the impact of diet composition on food self-sufficiency. Protein deficiency may lead to physiological unbalance, particularly in young children, and is a major cause of malnutrition in subsistence societies, whose diets are often poor in proteins and relatively rich in carbohydrates [e.g., *Cuny*, 1999]. Examining the diet in terms of total caloric intake, however, is an important first step in the assessment of food security. The effect of trade on food security is shown in Figure 4: different shadings are used to indicate whether the per capita calorie requirement of the reference diet (2700 kcal/d) can be met considering food commodities available through domestic production and trade. We denote this condition as "sufficiency."

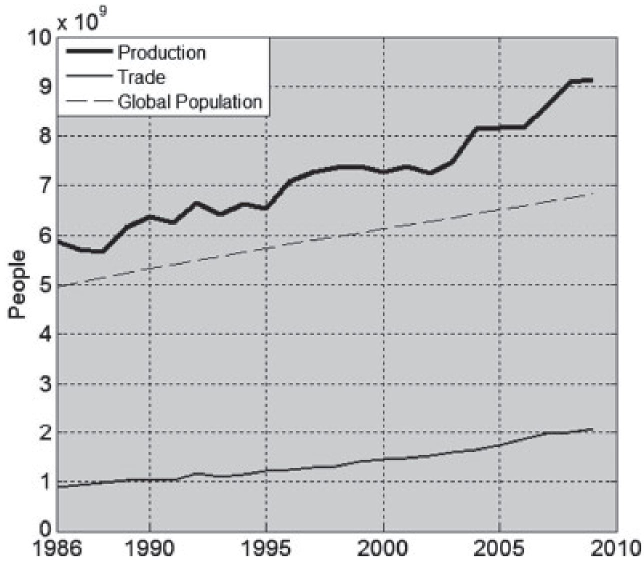

Figure 3. Number of people who could be fed by the global food production with an average balanced diet of 2700 kcal/d (thick line); global population (dashed line) and number of people who could be fed by the food traded in the international market (thin solid line). Based on production and trade data (P' and T') for direct human consumption (i.e., excluding secondary products, feed and other nonfood uses).

North Africa and the Middle East are overall not self-sufficient but rely on trade to meet their food requirements (Figure 4). Conversely, most of the Sahel and East Africa are not sufficient (Figure 4) despite their net food imports (Figure 5). The United States, Canada, Argentina, Brazil, Indonesia, Malaysia, France, and Australia are both major food producers [*Porkka et al.,* 2013] (Supporting Information, Figure S1) and major exporters (Table 3); despite their substantial exports, these countries maintain their sufficiency state. India, Pakistan, and China are also major food producers (in absolute terms, Supporting Information, Figure S2). Despite its net imports (Figure 5), India has remained "barely sufficient" throughout the study period (Figure 4). Conversely, Pakistan is not self-sufficient and relies on trade to maintain access to a barely sufficient amount of food (Figure 4). The case of China is different because it is a net importer despite its self-sufficiency (Figure 4) and its excess in food availability (Supporting Information, Figure S1). Similarly, most of Western Europe is self-sufficient and a net importer. On the other hand, in a number of African countries as well as in Afghanistan and Mongolia food imports are not strong enough to provide food sufficiency (Figures 4 and 5). Trade does not seem to induce a loss in self-sufficiency (except for Kazakhstan in 2000), nor an increase in water stress in countries that are not self-sufficient. At most, we have found that a limited number of self-sufficient countries [Zambia (2000), Bolivia (2000), and Indonesia (2010)] became barely self-sufficient as an effect of trade (Figure 4). This suggests that trade does not seem to erode the global food security.

The increasing globalization of food in the course of the past three decades is reflected not only in the rising volume of traded food calories, but also in the increase in the interconnection of the global food calorie network (Figure 5). The total number of trade links in the network has increased from 8004 in 1986 to 13,945 in 2009 while the average number of links per country has more than doubled (Figure 5c). There have also been some changes in the major contributors to net food exports (Table 3): while in 1986 the United States contributed to 26% of the food placed on the global trade market (evaluated in terms of net trade flows), by 2009 it had decreased to 17%. This decline in the predominance of the United States as a net food exporter was paralleled by a similar decline of France and the emergence of Indonesia and Brazil as major exporters. Interestingly, 50% of the net exports are controlled by about five countries (Table 3).

It is also interesting to relate the availability and trade of food calories to the resources used in the production process. We focus in particular on water, which remains a major limiting factor for agriculture. Food production requires more water than any other human activity; it has been estimated that most of the human appropriation of freshwater resources (80%–90%; e.g., *Falkenmark et al.*, 2004) is used in agriculture. Some countries do not have enough renewable water resources to produce all the food they need and therefore depend on imports from other regions. Thus, trade is associated with a virtual transfer of the water used in the production of the traded commodities (*Allan*, 1998). Recent research has investigated the global patterns of virtual water trade (*Hoekstra and Chapagain*, 2008; *Carr et al.,* 2012), while their relationship with food production and trade remains poorly understood. We found that the WUE of the traded commodities was about the same as that of production in 1986 and it declined in the course of the study period (Table 4). This suggests that in the last few decades the increase in food trade has

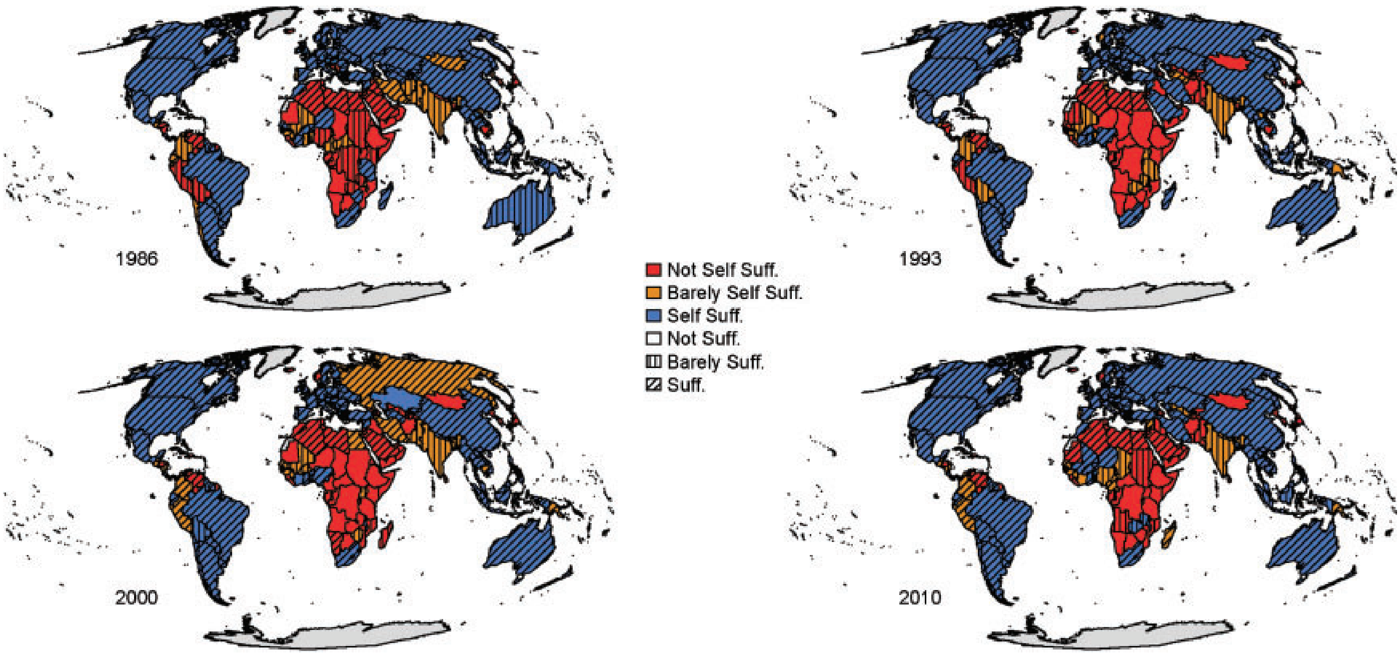

Figure 4. Global maps of country sufficiency and self-sufficiency defined by comparing the per capita food production to a diet of 2700 ± 10% kcal/person/d (including waste). Countries were classified as not self-sufficient if production <2430 kcal/d; barely self-sufficient if the production was between 2430 and 2970 kcal/d; self-sufficient if the production >2970 kcal/d. Likewise, countries were classified as not sufficient, barely sufficient, and sufficient if their average food supply per capita (accounting both for production and net trade) was below, in between, or above those two values, respectively.

focused on food commodities with relatively low WUE. To better understand these patterns we have considered plant, animal, and luxury products separately. The WUE of animal-based food products is overall much lower than that of plant products (about 30%). The WUE of the traded plant products has decreased over time. A (smaller) decline is observed also for the traded animal products, while the luxury products have maintained an almost constant WUE. The traded animal products have a higher WUE than the total production of animal-based food commodities, while the opposite is true about luxury products (Table 4). In the case of plant products, at the beginning of the study period the WUE of trade was higher than that of production, but it then decreased below the WUE of production. The global distribution of the WUE of food production does not reflect any obvious climatic pattern, while it appears to overall increase with countries' affluence (Figure 6).

4. Discussion

Decades of research on social development and famine indicate that food security depends not only on food availability and the ability of the planet to produce enough to nourish the entire global population [*Malthus*, 1798; *Cohen*, 1995; *Lee*, 2011], but also on other factors that affect the access to food, including trade [*Sen*, 1981], political stability and lack of conflict [*Deveroux*, 2001], and the existence of institutions and norms of resource governance [e.g., *Ostrom*, 1990]. By evaluating countries' reliance on national production and international trade, this study developed a country-scale analysis of food security with a focus on food sufficiency and availability. Several countries around the world are not in conditions of food self-sufficiency but depend on imports from other regions [*Fader et al.*, 2013; *Suweis et al.*, 2013]. In the past two to three decades, most of Africa and the Middle East have not been self-sufficient. Trade, however, appears to have improved the situation in the Sahel region, which is now closer to conditions of sufficiency than in the previous decades (Figure 4). In other countries of sub-Saharan Africa and central Asia, however, trade was unable to eradicate food insufficiency. At the same time, only few countries lost their self-sufficiency because of trade. Thus, trade seems to be enhancing rather than eroding food security. Overall, in the last two decades there has been an increase in the number of (trade-dependent) countries that reach sufficiency through their reliance on trade. The ongoing intensification of trade and the fact that, globally, about 23% of the food is traded suggest that global food security can be

10.1002/2014EF000250

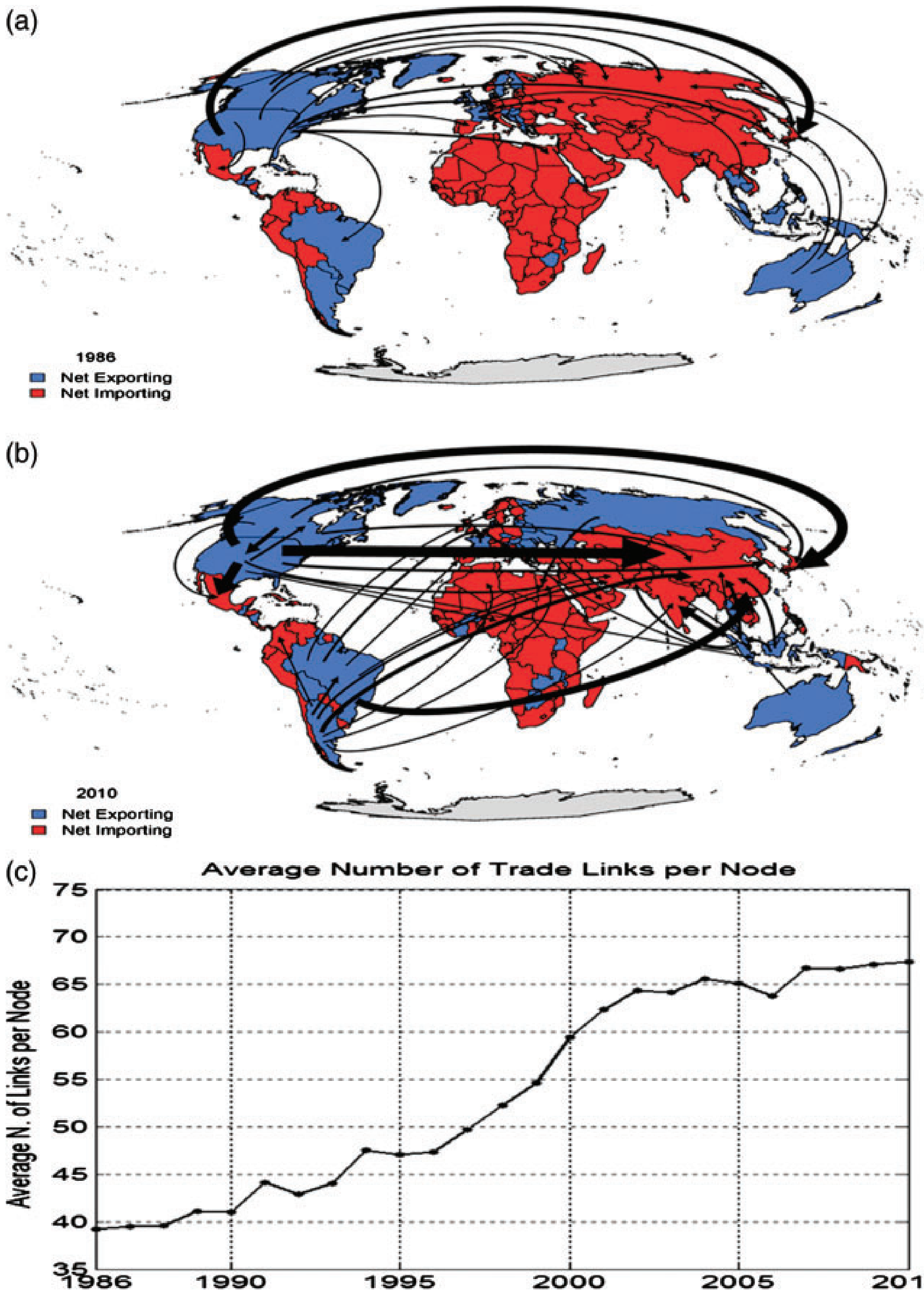

Figure 5. The global network of food trade in 1986 (a) and 2010 (b). (c) Changes in the average number of export links per country (or "degree") during 1986–2010.

threatened not only by regional climate extremes (drought, flood, frost) but also by price volatility and changes in the food market [*Headley*, 2010]. Countries that strongly rely on trade are expected to be particularly vulnerable, especially if their economies are not strong enough to absorb the shocks of food price volatility in the global market [*FAO-OECD*, 2011; *Fader et al.*, 2013; *D'Odorico et al.,* 2010]. At the same time trade plays a crucial role in allowing societies in conditions of food deficit to meet their demand through imports from other regions of the world.

Table 3. Major Contributors to Net Food Exports

1986			2010		
Country	%	% cum	Country	%	% cum
United States	25.8	25.8	United States	17.0	17.0
France	8.9	34.7	Brazil	9.9	26.9
Canada	7.9	42.6	Argentina	8.5	35.4
Australia	6.7	49.3	Indonesia	5.9	41.3
Argentina	6.4	55.7	France	5.9	47.1
Thailand	3.8	59.4	Canada	5.6	52.8
Malaysia	3.7	63.1	Malaysia	5.4	58.1
Brazil	3.5	66.6	Germany	3.4	61.5
United Kingdom	3.0	69.6	Australia	3.1	64.6
China. mainland	2.9	72.4	Netherlands	3.1	67.7

Table 4. Global Water Use Efficiency of Food Commodities Produced and Traded (kcal/L)

WUE	Production		Trade	
(kcal/L)	1986	2010	1986	2010
All products	1.372	1.346	1.392	1.206
Plant	1.736	1.640	1.931	1.601
Animal	0.532	0.528	0.695	0.622
Luxury	1.443	1.528	0.486	0.480

Because of the globalization of food and the strong interconnection existing within the food trade network, the effect of episodic regional declines in crop production can be felt globally [*Suweis et al.,* 2013]. For instance, the recent food crisis of 2007 was likely induced by droughts in Russia, Ukraine, and the United States, and an increase in global crop demand for agrofuels. The consequently escalating food prices caused riots and social unrest in some developing countries [*Hermele*, 2014]. To curb the food price increase, some governments banned exports, while trade-dependent countries started to panic [*Maetz et al.,* 2011]. This food crisis and the episodes that followed in 2011 demonstrate that uncertain and unreliable food markets can lead to food insecurity [*FAO-OECD*, 2011; *Headley*, 2010; *Welton*, 2011]. This effect is expected to become even stronger as the reliance on trade and the globalization of food increase [*Fader et al.,* 2013; *Suweis et al.,* 2013]. However, the ongoing development of tissue engineering technologies for in vitro meat production might provide in a near future new means to enhance food security without requiring soils and water, though the environmental and ethical implications of such transition in the meat industry is still difficult to foresee [*Tuomisto and Teixeira de Mattos*, 2011; *Post*, 2012].

To date, however, water remains one of the major factors constraining food production. The WUE of food production tends to increase with affluence (Figure 6b), which presumably reflects access to modern water efficient technologies in the economically more developed countries.

5. Conclusions

It has been observed that the international trade of food commodities induces a virtual transfer of embodied land [*Kitzes et al.,* 2009], water [*Allan*, 1998], carbon [*Kastner et al.,* 2011], nitrogen [*Galloway et al.,* 2007], and other land based resources [e.g., *Hermele*, 2014], while most of the environmental impacts of agricultural production remain in the producing countries [*Meyfroidt et al.,* 2013]. Thus, trade is associated with the globalization of resources [e.g., *Hoekstra and Chapagain*, 2008], the externalization of environmental impacts [e.g., *O'Bannon et al.,* 2014], and the establishment of teleconnections between those impacts and their drivers (e.g., consumer behavior, price volatility, or climate fluctuations) [*DeFries et al.,* 2010; *Schmitz et al.,* 2012; *Meyfroidt et al.,* 2013]. An often overlooked aspect of international trade is

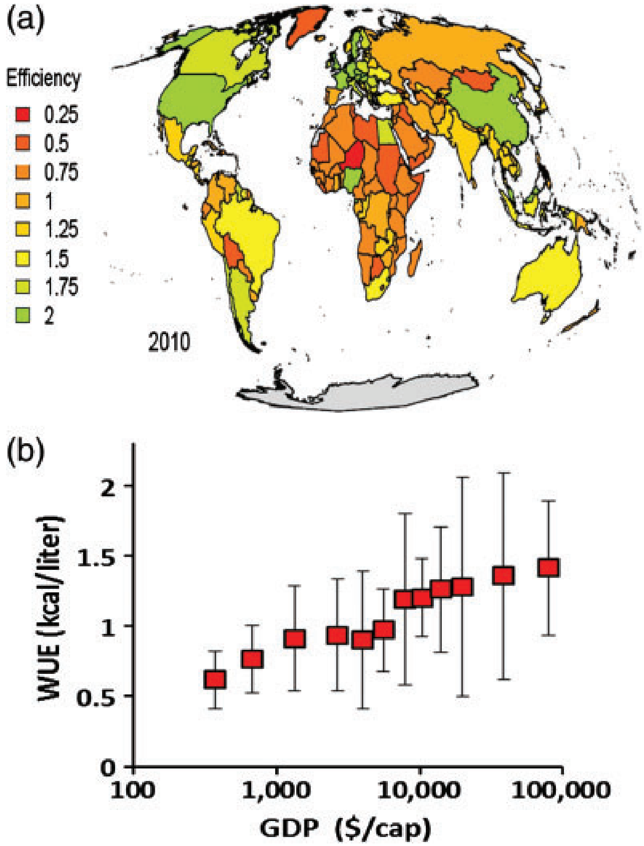

Figure 6. Global map of WUE (kcal/L) of food production for 2010 (based on all food commodities). (a) Global map; (b) dependency on per capita gross domestic product (GDP). Averages (squares) and standard deviations (error bars) were calculated after binning the raw data.

its impact on food security [*Fader et al.,* 2013]. This study reconstructed the global network of food calorie trade and evaluated its changes in the course of the past three decades. We found that, globally, about one fourth of the food produced for human consumption is traded internationally. While the caloric content of the food produced worldwide would be sufficient to feed the whole global population, there are countries in conditions of chronic food scarcity. In these countries the food demand by the local population by far exceeds the supply allowed by the land, water, climate, and soils locally available for food production (Figure 4 and Supporting Information, Figure S2). This unbalanced condition can be sustained either by accepting that actual food consumption does not meet the demand (hence the persistence of malnourishment) or by relying on international trade for the redistribution of food commodities among different regions of the world.

Acknowledgment
Data used in this manuscript are publicly available online through the FAOSTAT data base (http://faostat.fao.org).

References

Allan, J. A. (1998), Virtual water: A strategic resource global solutions to regional deficits, *Ground Water*, *36*(4), 545–546.
Boserup, E. (1981), *Population and Technological Change*, University of Chicago Press, Chicago, Ill.
Brown, L. R. (2013), *Full Planet, Empty Plates: The New Geopolitics of Food Scarcity*, pp. 161, W.W. Norton & Company Publishing, New York.
Carr, J. A., P. D'Odorico, F. Laio, and L. Ridolfi (2012), On the temporal variability of the virtual water network, *Geophys. Res. Lett.*, *39*, L06404, doi:10.1029/2012GL051247.
Carr, J. A., P. D'Odorico, F. Laio, and L. Ridolfi (2013), Recent history and geography of virtual water trade, *PLOS One*, *8*(2), e55825, doi:10.1371/journal.pone.0055825.
Cassidy, E. S., P. C. West, J. S. Gerber, and J. A. Foley (2013), Redefining agricultural yields: From tonnes to people nourished per hectare, *Environ. Res. Lett.*, *8*, 034015.
Cohen, J. E. (1995), *How Many People Can the Earth Support?*, WW Norton & Company, New York.
Coll, M., S. Libralato, S. Tudela, I. Palomera, and F. Pranovi (2008), Ecosystem overfishing in the ocean, *PLoS One*, *3*(12), e3881, doi:10.1371/journal.pone.0003881.
Cuny, F. C. (1999), *Famine, Conflict and Response*, Kumarian Press, West Hartford, Conn.
DeFries, R. S., T. K. Rudel, M. Uriarte, and M. Hansen (2010), Deforestation driven by urban population growth and agricultural trade in the twenty-first century, *Nat. Geosci.*, *3*, 178–181.
Delgado, C. L. (2003), Rising consumption of meat and milk in developing countries has created a new food revolution, *Am. Soc. Nutr. Sci.*, *133*(Suppl. 2), 3907–3910.
Deveroux, S. (2001), Sen's entitlement approach: Critiques and counter-critiques, *Oxford Dev. Stud.*, *29*(3), 245–263.
D'Odorico, P., and M. C. Rulli (2013), The fourth food revolution, *Nat. Geosci.*, *6*(6), 417–418, doi:10.1038/ngeo1842.
D'Odorico, P., F. Laio, and L. Ridolfi (2010), Does globalization of water reduce societal resilience to drought?, *Geophys. Res. Lett.*, *37*, L13403, doi:10.1029/2010GL043167.
Duarte, C. M., *et al.* (2009), Will the oceans help feed humanity?, *BioScience*, *59*, 967–976.
EISA (2007), *Energy Independence and Security Act of 2007*, Public Law 110–140, 110th Congress of the United States of America, Washington, D. C.
Erb, K. H., F. Krausmann, W. Lucht, and H. Haberl (2009), Embodied HANPP mapping the spatial disconnect between global biomass production and consumption, *Ecol. Econ.*, *69*, 328–334.

Erisman, J. W., M. A. Sutton, J. Galloway, Z. Klimont, and W. Winiwarter (2008), How a century of ammonia synthesis changed the world, *Nat. Geosci.*, *1*, 636–639.
E.U. (2009), Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC., *Official Journal of the European Union* L 140, 5 June 2009, pp. 16–47.
Fader, M., D. Gerten, M. Krause, W. Lucht, and W. Cramer (2013), Spatial decoupling of agricultural production and consumption: Quantifying dependences of countries on food imports due to domestic land and water constraints, *Environ Res. Lett.*, *8*, 014046.
Falkenmark, M., and J. Rockstrom (2006), The new blue and green water paradigm: Breaking new ground for water resources planning and management, *J. Water Resour. Plann. Manage.*, *132*(3), 129–132.
Falkenmark, M. J., J. Rockström, and H. Savenjie (2004), *Balancing Water for Humans and Nature*, Earthscan, London, U. K.
FAO (2012), *Statistical Yearbook 2012 – World Food and Agriculture. Part 3: Feeding the World*, FAO, Rome, Italy.
FAO-OECD (2011), *Food and Agriculture Organization/Organization for Economic Co-operation and Development: Price Volatility in Food and Agricultural Markets: Policy Responses*. Food and Agriculture Organization of the United Nations, Rome, Italy.
FAOSTAT (2012), Food and Agriculture Organization (FAO): FAOSTAT. [Available at http://faostat.fao.org].
Foley, J. A., *et al.* (2011), Solutions for a cultivated planet, *Nature*, *478*, 337–342.
Galloway, J. N., *et al.* (2007), International trade in meat: The tip of the pork chop, *Ambio*, *36*(8), 622–629.
Gephart, J., M. L. Pace, and P. D'Odorico (2014), Freshwater savings from marine protein consumption, *Environ. Res. Lett.*, *9*, 014005, doi:10.1088/1748-9326/9/1/014005.
Giampietro, M., and K. Mayumi (2000), Multiple-scale integrated assessment of societal metabolism: Introducing the approach, *Popul. Environ.*, *22*(2), 109–153.
Godfray, H. C. J., et al. (2010), Food security: The challenge of feeding 9 billion people, *Science*, *327*, 812–818.
Headley, D. (2010), Rethinking the global food crisis: The role of trade shocks, *Food Policy*, *36*, 136–146.
Hermele, K. (2014), *The Appropriation of Ecological Space*, Routledge, New York.
Hoekstra, A., and A. Chapagain (2008), *Globalization of Water*, Malden, Mass., Wiley Blackwell, Hoboken, N. J.
IPCC (2013), Summary for policymakers, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, Cambridge Univ. Press, Cambridge, U.K.
Kastner, T., K.-H. Erb, and S. Nonhebel (2011), International wood trade and forest change: A global analysis, *Global Environ. Change*, *21*, 947–956.
Kitzes, J., et al. (2009), A research agenda for improving national Ecological Footprint accounts, *Ecol. Econ.*, *68*, 1991–2007.
Lee, R. (2011), The outlook for population growth, *Science*, *333*, 569–573.
MacDonald, G. K. (2013), Eating on an interconnected planet, *Environ. Res. Lett.*, *8*, 021002, doi:10.1088/1748-9326/8/2/021002.
Maetz M, Aguirre M, Kim S, Matinroshan Y, Pangrazio G, Pernechele V. 2011. Food and agricultural policy trends after the 2008 food security crisis. Renewed attention to agricultural development. Resources for Policy Making. Applied Work EASYPol Module 125, FAO, Rome, Italy.
Malthus, T. (1798), in *An Essay on the Principle of Population*, edited by A. Flew, 1st ed., pp., Penguin English Library, London, U. K. (1970).
Mekonnen, M. M., and A. Y. Hoekstra (2012), A global assessment of the water footprint of farm animal products, *Ecosystems*, *15*, 401–415.
Meyfroidt, P., E. F. Lambin, K.-H. Erb, and T. W. Hertel (2013), Globalization of land use: Distant drivers of land change and geographic displacement of land use, *Curr. Opin. Environ. Sustain*, *5*, 438–444.
Mueller, N. D., et al. (2012), Closing yield gaps through nutrient and water management, *Nature*, *490*, 254–257.
O'Bannon, C., J. A. Carr, D. A. Seekell, and P. D'Odorico (2014), Globalization of agricultural pollution due to international trade, *Hydrol. Earth Syst. Sci.*, *18*, 503–510, doi:10.5194/hess-18-503-2014.
Ostrom, E. (1990), A general framework for analyzing sustainability of social-ecological systems, *Science*, *325*(5939), 419–422.
Pimentel, D., L. E. Hurd, A. C. Bellotti, M. J. Forster, I. N. Oka, O. D. Sholes, and R. J. Whitman (1973), Food production and the energy crisis, *Science*, *182*, 443–449.
Porkka, M., M. Kummu, S. Siebert, and O. Varis (2013), From food insufficiency towards trade dependency: A historical analysis of global food availability, *PLoS One*, *8*(12), e82714, doi:10.1371/journal.pone.0082714.
Post, M. J. (2012), Cultured meat from stem cells: Challenges and prospects, *Meat Sci.*, *92*, 297–301.
Ray, D. K., N. Ramankutty, N. D. Mueller, P. C. West, and J. A. Foley (2012), Recent patterns of crop yield growth and stagnation, *Nat. Comm.*, *3*, 1293, doi:10.1038/ncomms2296.
Schmitz, C., A. Biewald, H. Lotze-Campen, A. Popp, J. P. Dietrich, B. Bodirsky, M. Krause, and I. Weindl (2012), Trading more food: Implications for land use, greenhouse gas emissions, and the food system, *Global Environ. Change*, *22*, 189–209.
Sen, A. (1981), *Poverty and Famines: An Essay on Entitlements and Deprivation*, Oxford Univ. Press, New York.
Suweis, S., A. Rinaldo, A. Maritan, and P. D'Odorico (2013), Water-controlled wealth of nations, *Proc. Natl. Acad. Sci. U.S.A.*, *110*(11), 4230–4233.
Tilman, D., C. Balzer, J. Hill, and B. L. Befort (2011), Global food demand and the sustainable intensification of agriculture, *Proc. Natl. Acad. Sci. U.S.A.*, *108*, 20260–20264.
Tuomisto, H. L., and M. J. Teixeira de Mattos (2011), Environmental impacts of cultured meat production, *Environ. Sci. Technol.*, *2011*(45), 6117–6123.
U.K. Office for Science (2011), Foresight. The future of food and farming, *Final Project Report,* The Government Office for Science, London, U. K.
U.N. (1948), Universal declaration of human rights (UDHR), Article 25, United Nations.
U.N. Population Division (2012), *World Population Prospects: The 2012 Revision,* Department of Economic and Social Affairs of the United Nations Secretariat, New York.
Weinzettel, J., E. G. Hertwich, G. P. Peters, K. Steen-Olsen, and A. Galli (2013), Affluence drives the global displacement of land use, *Global Environ. Change*, *23*, 433–438.
Welton, G. (2011), The impact of Russia's 2010 grain export ban, *Oxfam Research Reports*, Oxford, U. K.

