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Meeting future food demand with current agricultural resources

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ABSTRACT

Meeting the food needs of the growing and increasingly affluent human population with the planet's limited resources is a major challenge of our time. Seen as the preferred approach to global food security issues, 'sustainable intensification' is the enhancement of crop yields while minimizing environmental impacts and preserving the ability of future generations to use the land. It is still unclear to what extent sustainable intensification would allow humanity to meet its demand for food commodities. Here we use the footprints for water, nitrogen, carbon and land to quantitatively evaluate resource demands and greenhouse gas (GHG) emissions of future agriculture and investigate whether an increase in these environmental burdens of food production can be avoided under a variety of dietary scenarios. We calculate average footprints of the current diet and find that animal products account for 43–87% of an individual's environmental burden – compared to 18% of caloric intake and 39% of protein intake. Interestingly, we find that projected improvements in production efficiency would be insufficient to meet future food demand without also increasing the total environmental burden of food production. Transitioning to less impactful diets would in many cases allow production efficiency to keep pace with growth in human demand while minimizing the food system's environmental burden. This study provides a useful approach for evaluating the attainability of sustainable targets and for better integrating food security and environmental impacts.

1. Introduction

Global food production is one of the most significant ways by which humans have modified natural systems (Vitousek et al., 1997). These impacts are well studied, ranging from the depletion of rivers and groundwater for irrigation (Falkenmark and Rockström, 2004; Hoekstra and Mekonnen, 2012) to nutrient pollution from the large-scale anthropogenic fixation and application of reactive nitrogen for fertilizers (Galloway et al., 2008; Schlesinger, 2008) to greenhouse gas emissions from mechanized cultivation, land use change, ruminant production and food trade (Vermeulen et al., 2012). With humanity already exceeding its sustainable use of Earth's systems in a number of ways (Wackernagel et al., 2002; Rockström et al., 2009; Hoekstra and Wiedmann, 2014; Galli et al., 2014; Steffen et al., 2015), there is growing concern that the combination of population growth and increasing per-capita global affluence (Tilman et al., 2011) portend yet more profound and pervasive consequences (Moore et al., 2012; Ercin and Hoekstra, 2014). Thus, there is widespread agreement that food production must increase substantially while at the same time minimizing environmental impacts, an approach known as 'sustainable intensification'. Potential solutions to address this apparent dilemma include closing crop yield gaps, reducing food waste, moderating diets and reducing inefficiencies in resource use (Foley et al., 2011).

A number of recent studies have asked by how much food supply can increase if a single one of the above solutions was implemented. For instance, Mueller et al. (2012) found that by maximizing crop yields (i.e. closing yield gaps), global crop production could increase by 45–70%. Kummu et al. (2012) determined that an additional 1 billion people could be fed if food waste was halved from 24% to 12%. Also by changing from current diets to a globally adequate diet (3000 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$; 20% animal kcal), Davis et al. (2014) found that an additional 0.8 billion people could be fed. Finally in another recent study, Mueller et al. (2014) determined that nitrogen application, when more

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efficiently distributed across the planet, could be reduced by 50% while still achieving current levels of cereal production. While these and other studies (Jalava et al., 2014; Wada et al., 2014) have certainly helped determine to what extent certain improvements are possible, they do not provide an integrated view of future human demand, food production and its multiple environmental impacts. In addition, many lack a temporal component. Thus it is unclear whether such advances can keep pace with projected increases in human demand.

This question of timing can be addressed in two ways. The first approach is based on past trends, where one estimates how much improvement is possible within a given period of time and whether this will achieve a pre-determined target. This is exemplified in a study by Ray et al. (2013), where the authors asked whether historical rates of crop yield improvement would be sufficient to meet the doubling in human demand by the year 2050. While such an approach helps in understanding what may be expected if past trends continue, it is necessarily data-intensive. In addition, relying on past trends may not accurately capture future factors adequately (e.g., climate change, improved technologies). The second approach instead starts with a pre-determined target (e.g., a desired level of GHG emissions by 2050) and then asks to what extent improvements must be made in order to meet that target. This approach is useful when a continuation of past trends is undesirable and is especially valuable in situations where historical data may be lacking, both of which apply to the product- and country-specific footprints of food production.

Here we combine both approaches to examine the extent to which production efficiencies (i.e., footprint intensities) and dietary patterns will need to change by mid-century in order to maintain current levels of resource use and emissions (i.e., environmental burdens), which many argue are already unsustainable (Wackernagel et al., 2002; Rockström et al., 2009; Hoekstra and Wiedmann, 2014; Galli et al., 2014; Steffen et al., 2015). We begin by calculating what the total food-related environmental burdens for water, GHGs, nitrogen and land would be in the year 2050 under constant (circa 2009) footprint intensities and for several future diet scenarios (Tilman and Clark, 2014). By examining these changes relative to the year 2009, we determine the improvement in footprint intensity required to prevent an overall increase in the environmental burden of a resource and compare the required change to projections of historical improvements in production efficiencies. In instances where the required change exceeds the relative potential enhancement in footprint intensity, the overall environmental burden of that resource must necessarily increase to support human demand. In considering these multiple environmental metrics and diet scenarios simultaneously, we also provide a much needed assessment of the tradeoffs that may occur and how dietary choices affect each environmental burden differently. In doing all of this, we present a quantitative, multi-metric assessment of how changes in efficiency and dietary patterns can combine to increase food supply and minimize environmental impacts from agriculture.

2. Methods

2.1. Data

Data on historic diets, harvested area, and agricultural production came from the FAO's FAOSTAT database (2015a). Affluence-based dietary projections (i.e. based on projected growth in per capita GDP or a 'GDP-based scenario'), alternative diet scenarios and protein conversion ratios and feed compositions for livestock and animal products were from Tilman and Clark (2014). Alternative diet scenarios were Mediterranean, pescetarian and vegetarian (see Table 1; Supplementary Table 1a). In using the alternative diet values derived by Tilman and Clark (2014) from various dietary recommendation studies, we also note that the definition of each alternative diet can vary substantially between studies and regions. This is particularly true for the composition of the Mediterranean diet utilized by Tilman and Clark and those recommended in other literature sources (Trichopoulou et al., 2003; Bach-Faig et al., 2011; Dernini et al., 2013). While we utilize the former for consistency, our approach provides a straightforward means by which to incorporate other alternative diets, additional nutrient requirements, or variations of the scenarios presented here (e.g., Jalava et al., 2014). Country-level water footprint data for plant and non-seafood animal products (centered on the year 2000) were taken from two studies by Mekonnen and Hoekstra (2010a, 2010b). Our study only considered consumptive uses of irrigation water and rainwater (i.e. blue and green water footprints, respectively). Product-specific global carbon emission values for the year 2009 came from Tilman and Clark (2014). Crop-specific synthetic nitrogen application for the year 2010 (for 26 countries, the EU-27 and the rest of the world;

Table 1
Global average demand of current diet and selected diet scenarios. Current diet composition was calculated as the population-weighted average of each country's diet (FAO, 2015). As a result, an individual country's diet may differ substantially from this average global diet (e.g., no pork consumption in many Middle Eastern countries). For diet scenarios, per capita demand for each commodity group was calculated as the product of current per capita demand and the ratio, r_{kcal}, of 2050 per capita calorie demand to current (circa 2009) per capita calorie demand, as reported by Tilman and Clark (2014) (Supplementary Table 1). The r_{kcal} values derived from Tilman and Clark (2014) for 'Fruits/Vegetables' were used for fruits, vegetables and oils, 2) for 'Nuts/Pulses' were used for oilcrops and pulses, and 3) 'Dairy/Eggs' were used for milk and eggs. The composition of the future diet scenarios is therefore determined by a combination of the current diet composition and the r_{kcal} values.

Diet (kg cap^{-1} yr^{-1})	Current	GDP-based	Mediterranean	Pescetarian	Vegetarian
Cereals	146	147	86	99	106
Fruits	72	53	350	75	75
Oilcrops	7	3	2	10	11
Pulses	7	3	2	10	10
Roots/Tubers	61	74	32	54	58
Sugar crops	24	37	20	20	20
Oils	12	9	28	12	12
Vegetables	131	100	314	136	136
Beef	10	14	5	0	0
Milk	88	135	162	112	159
Pig meat	15	19	2	0	0
Poultry meat	14	14	5	0	0
Eggs	9	13	16	11	16
Seafood	18	30	21	38	0
Total	*613*	*650*	*1044*	*576*	*602*

Supplementary Table 2) was taken from a recent study by the International Fertilizer Industry Association (IFA) (Heffer, 2013). Historic population data and projections were from the UN Population Division (UN-DESA, 2013).

2.2. Obtaining current global footprint intensities

The true footprint of a good can be defined as all of the inputs – both direct and indirect – needed to produce and deliver a certain good along its full supply chain (see Galli et al., 2012; Wiedmann et al., 2015). To avoid confusion in terminology, we adopt the more general term of ‘footprint intensity’ to describe the product-specific ratio of inputs to product output. In describing the methods used in this study, it is important to highlight the differences between the approach we utilize here to develop certain footprint intensities (i.e., land and nitrogen) and what others have done in previous studies. While the footprint intensities for water and GHGs came from studies which employed life-cycle assessments and comprehensive input-output models, a lack of comprehensive country- and crop-specific values for land and nitrogen required us to develop methodologies that captured their major direct requirements in food production.

For land, we calculated the footprint intensity as simply the harvested area of a crop divided by the production of that crop (i.e., the inverse of the yield). Though cropland represents the most extensive requirement of land in the production of a food item, Weinzettel et al. (2013) have shown that calculating a true land footprint must also account for the other land requirements of an item’s production (e.g., the space occupied by a barn or processing plant) – requirements which our approach does not include. Similarly for nitrogen, we calculated the footprint intensity simply as the ratio of synthetic nitrogen applied to an area and the crop production of that area, and assumed that all anthropogenic nitrogen inputs will eventually reach the environment (Galloway et al., 2003). While this approach does not capture potential recycling or losses at each step along the supply chain, it agrees broadly with the overall inputs and outputs of the nitrogen footprint model described by Leach et al. (2012). It is also worth noting that because our study only considers consumption patterns from a global perspective – country-specific values are only calculated for the footprint intensities of production – we avoid many of the difficulties associated with obtaining accurate footprint intensity values (e.g., accounting for virtual trade of resources). A detailed description of how the footprint intensities for land, water, nitrogen and GHGs were calculated is included in the Supplementary Methods.

2.3. Projections of diet, demand and efficiencies

Changes in annual per capita demand for each commodity group were calculated as linear trends from 2009 values (from FAO (2015)) to the 2050 projected values from Tilman and colleagues (23). The percent changes in per capita demand for ‘empty calories’, ‘fruits/vegetables’ and ‘pulses/nuts’ – as reported by Tilman and Clark (2014) – were used in this study for sugar crops, vegetable oils and oil crops, respectively. For a given year (x) and environmental metric (EM), the total global environmental burden of food production ($g_{EM,x}$) assuming a constant footprint intensity was calculated as:

$$g_{EM,x} = p_x \sum \left(d_{g,x} \eta_{g,2009} \right) \tag{8}$$

where p_x is the projected population in year x, $d_{g,x}$ is the projected per capita demand for commodity group g in year x, and $\eta_{g,2009}$ is the current global footprint intensity of commodity group g corresponding to the environmental metric of interest. We assume that any future growth in seafood demand – for GDP-based, Mediterranean and pescetarian diets – will be met by aquaculture, as production from global capture fisheries has already leveled off (FAO, 2014; Pauly and Zeller, 2016). For global demand for seafood under a vegetarian diet (which decreases to zero by 2050), we assume a constant percentage (39.9%) of seafood production contributed by aquaculture through time.

Historical changes in production efficiency for 1985 through 2011 were estimated using data from FAO (2015): total agricultural land (‘arable land plus permanent crops’ + ‘permanent meadows and pastures’), nitrogen applied to agricultural land, greenhouse gas emissions from agriculture (including from livestock) and area equipped for irrigation. Each of these was used to divide total crop and animal production (in tonnes) to calculate historical resource use efficiency. Linear regressions fit to these historical changes in production efficiency (PE; e.g., tonnes of applied N per tonne of food produced) were then extrapolated to the year 2050 (Supplementary Table 6). Finally, the percent change in overall environmental burden required to support food production (ΔEB) in year x was calculated as:

$$\Delta EB = 100\left[\left(\frac{g_{EM,x} - g_{EM,2009}}{g_{EM,2009}}\right) + \left(\frac{PE_{EM,x} - PE_{EM,2009}}{PE_{EM,2009}}\right)\right] \tag{9}$$

where $PE_{EM,x}$ is the production efficiency in year x estimated from the linear extrapolation of historical PE. If this sum is positive for a particular environmental metric, then its overall environmental burden will likely need to increase – because efficiency changes cannot keep pace – in order to sustain that particular diet.

While the methods described above are sufficient to capture the expected environmental impacts associated with future changes in diet and efficiency, our approach is limited in several ways. First, our study focuses on the global scale utilizing national-level data. As such, we do not capture inter-country heterogeneity in diets as well as intra-country inequality in food access. Second, though adequate to demonstrate the efficacy of less impactful dietary choices, we consider a limited number of future diet scenarios. Third, our extrapolations of production efficiency do not account for potential effects of climate change. Because it remains unclear whether historical trends in production efficiency can continue, conclusions related to efficiency improvements should therefore be viewed with a level of caution. Lastly, the process of ‘sustainable intensification’ aims to increase food production through yield improvements while minimizing humanity’s pressure on the environment. This approach requires an enhancement in production efficiency (i.e., the amount of food produced per unit amount of resource used). However, when commodities are produced more efficiently, their consumption rates also tend to increase, a phenomenon known as Jevons’ Paradox (Jevons, 1866). Because this phenomenon would be inconsistent with the notion of ‘sustainable intensification’, such interactions between production efficiency and consumption rates have not been addressed in this study. Rather, we investigated scenarios of reduced per capita consumption rates associated with changes in diet.

3. Results

We estimate that 776 m^3 H_2O, 15.3 kg N, 299 kg CO_2eq and 0.85 ha are required annually to support an average global diet; where available, these estimates agree well with published values in the literature (Falkenmark and Rockström, 2006; Kastner et al., 2012; Galloway et al., 2014). Not surprisingly, animal products account for much of this required water (43%), nitrogen (58%), GHG (74%) and land (87%) (Fig. 1). By comparison, these products provide 18% of an individual’s caloric intake and 39% of protein intake (FAO, 2015). As expected, we also observe large variation

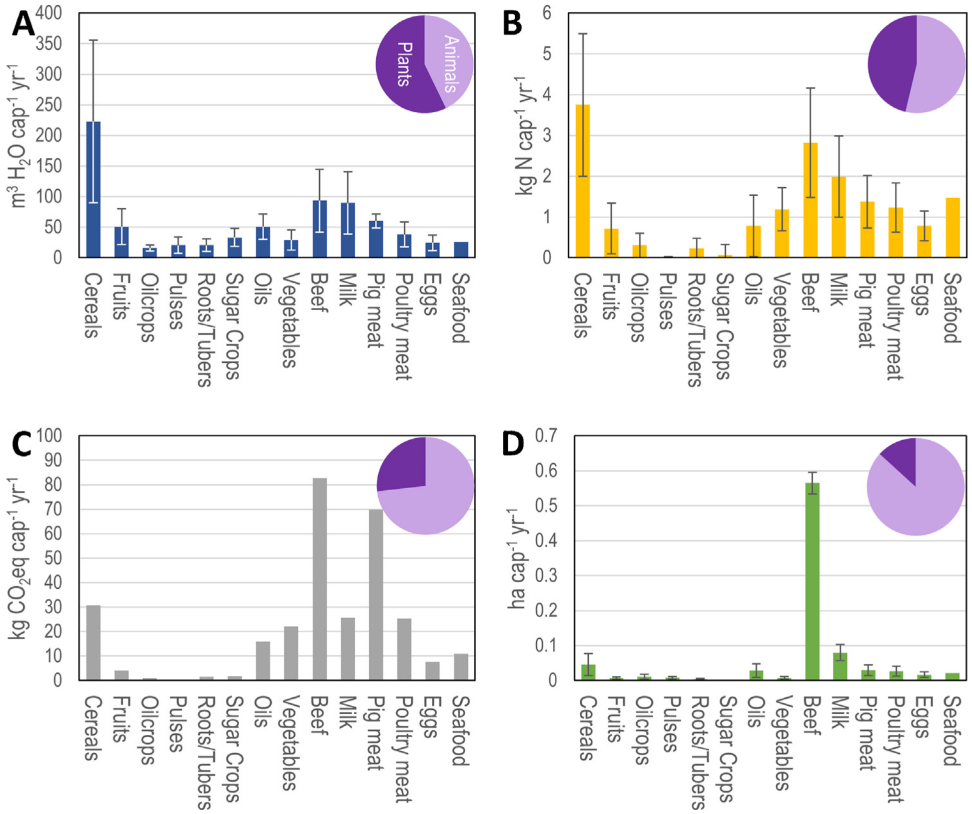

Fig. 1. Per capita environmental burdens (EBs) of current diets.
Water (A), nitrogen (B), carbon (C), and land (D) footprints associated with the food commodities comprising the average global diet in the year 2009. For N use, the standard deviations of sugar crops and starchy roots were larger than their means. The same was true for carbon use values of starchy roots and vegetables. Uncertainty for beef and milk production only accounts for land use for feed production. Values can be found in Supplementary Table 1a. Pie diagrams (inset) show the relative contribution of plant and animal products to the footprint of current diets.

within each footprint intensity of the current diet (Supplementary Table 1a), reflecting the different efficiencies with which food products can be produced in different climates, soil regimes and production systems. While this variation was modest for land use (7% of the mean), it was more substantial for nitrogen (18%) and water (21%).

We also find that substantial changes can occur in the environmental burden of potential future diets. For land use, changes in beef consumption had the most important influence, contributing to a large increase under a GDP-based future and to substantial reductions in land use for other diet scenarios. For other metrics, the changes in environmental burden were distributed more diffusely across commodity groups (Fig. 2). For instance, the absence of pork in pescetarian and vegetarian diets contributed to a substantial reduction in per capita GHG emissions. Conversely, the increased consumption of aquaculture seafood in the GDP-based diet led to a sizeable increase in required nitrogen. Interestingly, fruits contribute the largest increase in water demand for the Mediterranean diet. Relative to the current diet, the GDP-based diet required increases in all four environmental burdens, the Mediterranean diet produced apparent tradeoffs (increases in nitrogen and water demand and decreased land and GHG requirements per capita), and pescetarian and vegetarian choices led to consistent and marked decreases.

Finally, in examining the increase in overall human demand, we estimate that average footprint intensities will need to improve substantially (H_2O: 65%, N: 85%, GHG: 72%, Land: 97%) in order to prevent further increases in environmental burdens (Fig. 3 (upper panels); Supplementary Table 7). GDP-based growth in food demand likely cannot be met without substantially increasing total resource demand and GHG emissions (Fig. 3). With existing technology and production systems, efficiency improvements alone cannot be relied upon – if affluence continues to dictate dietary choices – to minimize the environmental burden of population growth and dietary change. Transitioning to alternative – and generally less impactful – diets would in many cases allow enhancements in footprint intensities to keep pace with growth in human demand and, in turn, prevent growth in overall resource demand and GHG emissions. For instance, the composition of the Mediterranean diet (i.e., increased fruits/vegetables/milk and decreased cereals/beef) minimizes additional land requirements but requires growth in GHG emissions and water and nitrogen demands comparable to the GDP-based diet. Shifting to pescetarian or vegetarian diets reduces environmental burdens relative to other diets and may even decrease all environmental burdens below current levels. Moreover, the similar reductions observed in these two scenarios support our assumptions about seafood footprint intensities and provide further evidence that a transition away from terrestrial animal products – especially ruminants – is an important strategy for reducing the environmental impacts of the food system.

4. Discussion

4.1. Agriculture's growing environmental burden – The roles of consumption, production and trade

Sustainable intensification involves enhancing agricultural yields while simultaneously minimizing environmental impacts. Yet, the focus of most recent studies has been on whether and how

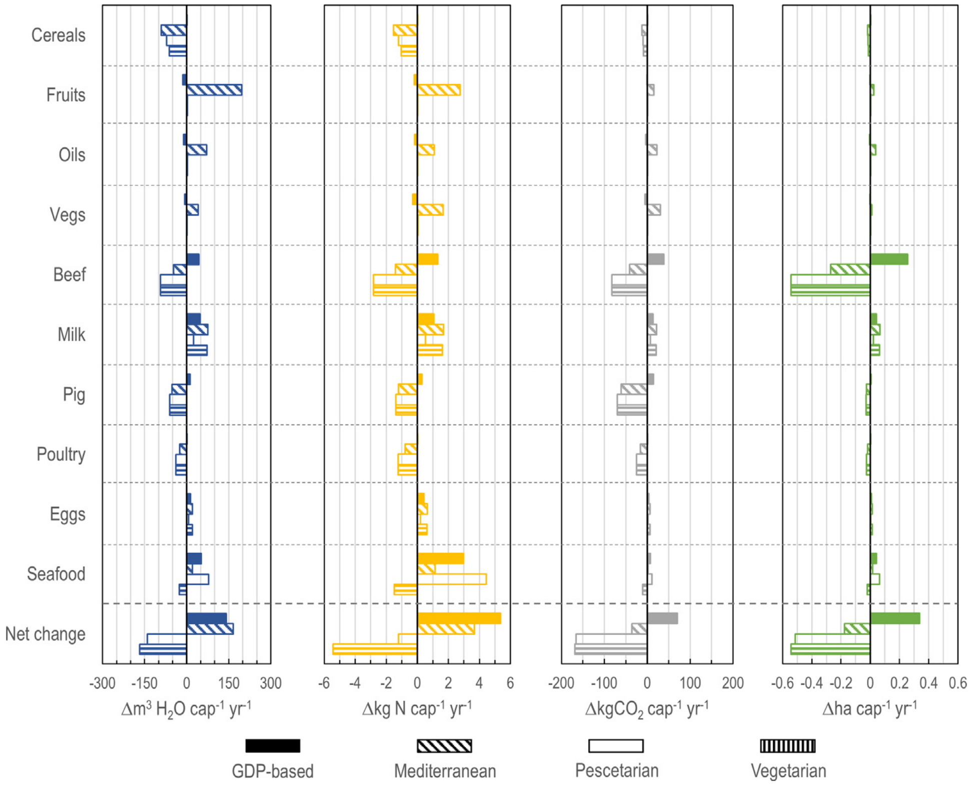

Fig. 2. Change in per capita EBs of future diet scenarios.
Using year 2009 footprints, bars show the difference in per capita environmental burden between the 2050 scenario diets (GDP-based, Mediterranean, pescetarian, vegetarian) and the 2009 dietary composition. Several commodity groups (oil crops, pulses, roots/tubers, and sugar crops) were not included in this figure because their changes in footprint intensity between diets was generally small in comparison to the groups shown. Detailed information on all commodity groups can be found in the Supplementary Table 1a.

increases in food production can keep pace with growth in demand (e.g., Alexandratos and Bruinsma, 2012; Mueller et al., 2012; Ray et al., 2013). In light of this, our study attempts to fill an important knowledge gap by providing a much needed assessment of the potential environmental consequences of future food demand. Our findings make apparent that continued improvements in footprint intensities will be insufficient to prevent further increases in the environmental burden of agriculture should current dietary trends

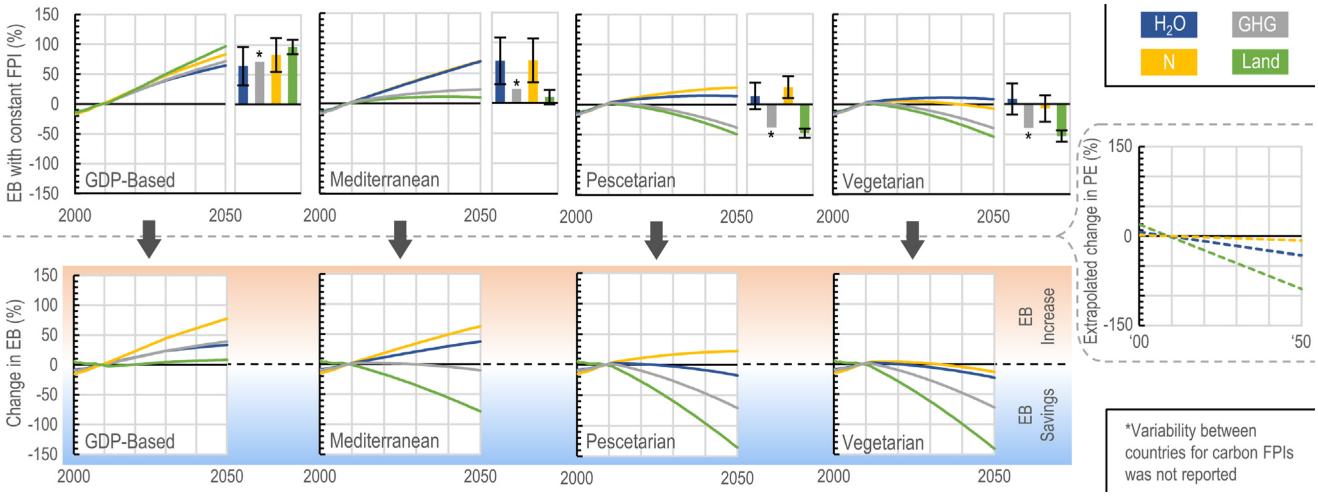

Fig. 3. Relative change in overall EBs for different diet scenarios from 2009 to 2050.
Upper panels show the product of changing population, changing diets and constant (year 2009) footprint intensities (FPIs), relative to year 2009 environmental burdens. Bar plots represent the variability among countries of relative change in the year 2050. This variability is due to differences in available technologies and agricultural practices as well as to climate, soil texture and other geographic constraints. Because the Tilman and Clark (2014) values only reported the standard error between carbon footprint studies that they considered, we do not include an estimate of the variability between countries for carbon footprint. Dashed lines are extrapolations of historical trends (1985–2011) in production efficiency (PE; e.g., tonnes of applied N per tonne of food produced); projected change in H_2O and GHG PEs are nearly identical. Lower panels show the sum of percent change in EB under constant footprints and the percent change in production efficiency. If this sum is positive (i.e., above the x-axis) for a particular environmental metric, then its overall EB will likely need to increase – because efficiency changes cannot keep pace – in order to sustain that diet. Values are presented in Supplementary Tables 6–7.

continue. Altering consumption patterns can yield – in most cases – improvements in resource use and emissions relative to an affluence-based diet and has the potential to contribute to resource savings and emissions reductions when combined with improved production efficiencies (Fig. 3). Indeed, shifts in historical demand demonstrate that such changes are possible. For example, the on-going transition in livestock production away from ruminants (e.g., cattle) and towards monogastrics (e.g., pigs and chickens) has reduced the land and GHG requirements per animal unit and led to an overall plateauing in the sector's land requirements (Steinfeld and Gerber, 2010; FAO, 2015) – though this has also been accompanied by an increase in nitrogen per animal unit (Davis et al., 2015a). Achieving continued demand-side changes is the real issue, as historical shifts in diets have been influenced more by accessibility, cost and technology than by government programs or environmental concerns (e.g., Duffey and Popkin, 2008; Tilman et al., 2011; Popkin et al., 2012; Eshel et al., 2014).

4.1.1. Consumption

Combining economic, nutritional and environmental considerations, several new studies have also shed light on how better to connect dietary changes with improved environmental stewardship. For instance, Jalava et al. (2014) showed that – by modifying diets to: 1) reflect nutrient recommendations from the World Health Organization and 2) reduce animal-source proteins – countries could realize substantial water savings from food production. The present study builds on these findings, showing that certain dietary changes can lead to resource savings across a suite of environmental impacts. Further, Gephart et al. (2016) employed an optimization technique to identify diets that minimize water, carbon, nitrogen, and land footprints while at the same time meeting an individual's nutrient requirements. Tilman and Clark (2014) also linked healthier diets to improved environmental sustainability, showing that environmentally burdensome diets also have higher incidence of heart disease, diabetes and cancer. In addition, it has been speculated that as societies become more affluent their health and environmental concerns should draw down the rates of meat consumption, according to a Kuznet-like inverted U curve (Cole and McCoskey, 2013). However, because these changes are expected to take place at (high) income levels that most countries will not attain for the next several decades, it is likely that per capita consumption of animal products will increase globally in the near future.

Even without altering diets, reducing consumer food waste – as well as minimizing losses throughout the food supply chain – can decrease environmental impacts and contribute substantially to food security (Gustavsson et al., 2011; Kummu et al., 2012). This is particularly true for animal products, with recent studies demonstrating that large crop areas are required to support consumer waste of beef, pork and poultry (West et al., 2014) and that the crops lost via consumer waste of animal foods could feed 235 million people (Davis and D'Odorico, 2015). While this growing body of knowledge shows that healthy diets and responsible food use are also beneficial for the environment, further research is required to identify mechanisms that might effect such changes in consumption patterns.

4.1.2. Production

With regard to production, overall agricultural inputs will likely need to increase, but a continuation of historical gains in major crop yields may be insufficient to meet demand by mid-century (Ray et al., 2013). For this reason, certain production increases required to support aspects of the alternative diets (e.g., fruit/vegetable demand of Mediterranean scenario; pulse/oilcrop demand for vegetarian scenario) may therefore be unrealistic to achieve and, in turn, limit the options for modifying diets (Supplementary Table 8). In addition, historical trends in improving yields and production efficiencies may falter in the coming years. For example, crop yields have plateaued or stagnated in many agricultural areas (Grassini et al., 2013) and increases in fertilizer application have resulted in diminishing returns from cereal production over the past several decades (Tilman et al., 2002; FAO, 2015). Also, large volumes of additional irrigation water (i.e., blue water) will likely be required to further improve crop yields (Mueller et al., 2012; Davis et al., 2015b). Furthermore, high-yielding cereals – in particular, wheat, rice, and maize – have replaced more nutrient-rich varieties, contributing to diminished nutrient content in the world's cereal supply (DeFries et al., 2015). These trends based on various studies therefore likely mean that our estimations of additional resource requirements are conservative, as we assumed a linear continuation of improving production efficiencies.

4.1.3. Trade

While it is clear there are obstacles for 'sustainable intensification' of the global food system, the variation that we calculate within the footprint intensity of each commodity group indicates that there still exists considerable scope for improving the environmental burden of agriculture. Much of this can be explained by three factors: climate, technology and composition. Climate extremes (e.g., heat waves, droughts) can lead to crop failures and animal heat stress. Limited access to advanced techniques, farming equipment, irrigation infrastructure, high-yielding varieties or other agricultural technologies can prevent high yields. And certain products within a commodity group can be more resource-demanding than others. To cope with these stressors, limitations and uncertainties, countries have increasingly turned to international food trade to meet domestic demands. Indeed, food trade has contributed to important resource savings (e.g., Chapagain et al., 2006) and allowed the populations of many countries to exceed what could be supported by locally available resources (Allan, 1998; Davis et al., 2014; Puma et al., 2015). Yet this virtual trade of natural resources appears to have created a disconnect between where food production occurs and where that food is consumed, effectively separating consumers from the environmental impacts of their dietary choices (Lambin and Meyfroidt, 2011; Fader et al., 2013; Weinzettel et al., 2013; Caro et al., 2014). There is also concern that the global food system has lost resilience and become too rigid and homogeneous to respond to unanticipated climatic and economic shocks (D'Odorico et al., 2010; Puma et al., 2015; Suweis et al., 2015). For example, water-rich countries may soon reduce their virtual water exports in order to preserve domestic food supplies and water resources (Suweis et al., 2013). Thus while a globalizing food trade system may have allowed for more efficient use of natural resources for food production, these improvements have likely come at the expense of system resilience and nations' long-term food self-sufficiency.

4.2. A new food revolution? Beyond changes in efficiency and consumption

These various lines of evidence – unsustainable dietary changes, faltering yield trends and greater reliance on food trade – all point toward the need for a new food revolution combining existing technologies and approaches with a new generation of innovations. While the Green Revolution focused on increasing supply, how those changes would affect the environment was not a primary consideration. Over the past several decades however, the environmental impacts of a rapidly increasing food production have contributed substantially in pushing humankind's footprint to the brink of (or beyond) numerous planetary thresholds (Rockström et al., 2009; de

Vries et al., 2013; Hoekstra and Wiedmann, 2014; Steffen et al., 2015). Therefore, as our study shows, a new food revolution should not aim at increased human appropriation of natural resources but at changes in consumer habits and improved efficiencies in the production system. As our projections show, an integrated approach combining efficiency improvements with shifted consumption patterns can simultaneously meet future demand and minimize agriculture's environmental impacts.

Population growth, globalization and urbanization, and climate change make future sustainable agriculture an unprecedented challenge. Yet, there is hope for real improvement in agricultural resource demand, some examples of which we highlight in this final section. For instance, while food trade remains a necessary feature of the global food system, accompanying trade flows with technology transfers can improve the food security outlook for both the importer and exporter. By facilitating such diffusions of technologies from the most efficient countries into under-performing areas, decision-makers can better ensure that projections of resource demand tend towards the lower side of their variabilities, thereby closing the 'technology gap'. Investments in technology, however, are often associated with important shifts between systems of production (e.g., from subsistence farming to large-scale commercial agriculture) that will likely require new policies to protect rural livelihoods and ecosystems. Through technological innovation, import-reliant nations could improve their food self-sufficiency, decrease their dependence on food imports and minimize local environmental impacts. As another example, genetically engineered organisms (GEOs) or transgenic products have received increased attention as a possible avenue for raising yield ceilings, but not without their share of controversy. To be sure, the 'organic movement' is in large part a response to the growing prevalence of GE crops available to consumers. What is less understood is the introduction of GE animals for food. As animal products are generally more environmentally burdensome, intervening to improve their yields and feed conversion efficiencies – while addressing ethical concerns related to animal welfare – could substantially reduce competition for crop use and resource demand. The recent approval of the GE-Atlantic salmon may be that threshold event that presents both great uncertainty and opportunity for more efficient animal products. However, a number of uncertainties remain regarding their related ethics, their potential long-term health and environmental impacts as well as their cultural acceptance and incorporation into diets. Other approaches include land sparing, wildlife-friendly farming (Fischer et al., 2008), vertical farming (Despommier, 2013), incorporating insects into feeds/food (van Huis, 2013), nutrient capture and recycling (e.g., Elser and Bennett, 2011), sustainability food labels (Leach et al., 2016) and better integrated nutrient and energy cycles of crop and animal production (Beede, 2013).

There also exist a host of more speculative – but potentially promising – ways to meet future demand and minimize environmental impacts. One such approach is the large-scale implementation of precision agriculture that utilizes remote sensing and responds in real-time to crop resource requirements and to weather and climatic conditions. Also, with cost being such an important factor in consumer choices, policy-makers can seek a market-based solution for modifying consumption patterns by better incorporating the true environmental costs to produce a food item. While this approach would require the approval of various vested interests, development of valuation criteria, and programs to support access to food and agricultural resources for low-income communities, it could effectively and impartially transition diets towards minimized environmental burdens. This solution could also be combined with internationally defined 'sustainable targets' or caps (Hoekstra and Wiedmann, 2014), for which each country would then be allowed to implement the solutions most suitable to its economic, social and environmental landscapes.

5. Conclusion

The need for both demand- and supply-side solutions to achieve 'sustainable intensification' of the global food system is apparent. Our study quantified the extent to which changes in consumption patterns and efficiency can play a role in improving the environmental burden of the global food system. If dietary trends continue to grow based on GDP, improvements in efficiency likely will not be sufficient to prevent further increases in agriculture's environmental burden, and additional solutions will be urgently needed. Land use and GHG emissions are the most responsive to changes in diet – in large part due to the reduction/elimination of beef demand – while improvements in nitrogen and water uses were more modest. This indicates that changes to efficiency and consumption patterns are not a panacea for comprehensive reductions in the environmental burden of agriculture but are still essential mechanisms towards realizing environmental sustainability of the global food system. This study provides a useful approach for evaluating the attainability of sustainable targets and for better integrating food security and environmental impacts.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2016.05.004.

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