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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 cap^{-1} 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*