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To cite this article: Michael Clark and David Tilman 2017 *Environ. Res. Lett.* **12** 064016

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LETTER

Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice

Michael Clark[1,4] and David Tilman[2,3]

[1] Natural Resources Science and Management, University of Minnesota, St Paul, Minnesota 55108, United States of America
[2] Department of Ecology, Evolution and Behavior, University of Minnesota, St Paul, Minnesota 55108, United States of America
[3] Bren School of Environmental Science and Management, University of California Santa Barbara, California 93106, United States of America
[4] Author to whom any correspondence should be addressed.

E-mail: maclark@umn.edu

Keywords: life cycle assessment, environmental sustainability, food, organic, agricultural efficiency

Supplementary material for this article is available online

OPEN ACCESS

RECEIVED
28 December 2016

REVISED
5 April 2017

ACCEPTED FOR PUBLICATION
12 April 2017

PUBLISHED
16 June 2017

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Abstract

Global agricultural feeds over 7 billion people, but is also a leading cause of environmental degradation. Understanding how alternative agricultural production systems, agricultural input efficiency, and food choice drive environmental degradation is necessary for reducing agriculture's environmental impacts. A meta-analysis of life cycle assessments that includes 742 agricultural systems and over 90 unique foods produced primarily in high-input systems shows that, per unit of food, organic systems require more land, cause more eutrophication, use less energy, but emit similar greenhouse gas emissions (GHGs) as conventional systems; that grass-fed beef requires more land and emits similar GHG emissions as grain-feed beef; and that low-input aquaculture and non-trawling fisheries have much lower GHG emissions than trawling fisheries. In addition, our analyses show that increasing agricultural input efficiency (the amount of food produced per input of fertilizer or feed) would have environmental benefits for both crop and livestock systems. Further, for all environmental indicators and nutritional units examined, plant-based foods have the lowest environmental impacts; eggs, dairy, pork, poultry, non-trawling fisheries, and non-recirculating aquaculture have intermediate impacts; and ruminant meat has impacts ~100 times those of plant-based foods. Our analyses show that dietary shifts towards low-impact foods and increases in agricultural input use efficiency would offer larger environmental benefits than would switches from conventional agricultural systems to alternatives such as organic agriculture or grass-fed beef.

Introduction

Global agriculture feeds over 7 billion people, but is also a major cause of multiple types of environmental degradation. Agricultural activities emit 25%–33% of greenhouse gases (Steinfeld *et al* 2006, Edenhofer *et al* 2014, Tubiello *et al* 2014); occupy 40% of Earth's land surface (FAO 2016a); account for >70% of freshwater withdrawals (Molden 2007), drive deforestation and habitat fragmentation (Ramankutty and Foley 1999) and resultant biodiversity loss (IUCN 2016); and eutrophy and acidify natural aquatic and terrestrial ecosystems with agrochemicals (Vitousek *et al* 1997). These impacts are likely to increase globally over the next several decades because of increases in population growth and income-dependent dietary shifts towards more meat-based diets (Tilman *et al* 2011, Bajzelj *et al* 2014, Tilman and Clark 2014, Springmann *et al* 2016).

We need to understand the linkages between diets, agricultural production practices, and environmental degradation if we are to reduce agriculture's environmental impacts while providing a secure food supply for a growing global population. To quantify these processes and linkages, we review and synthesize published information from 742 food production systems of over 90 foods from 164 published life cycle

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assessments (LCAs). LCAs are an internationally recognized way to account the inputs, outputs, and environmental impacts of a food production system. Using our meta-analysis of LCAs, we examine the comparative environmental impacts of different food production systems, different agricultural input efficiencies, and different foods.

Food production systems such as organic agriculture and grass-fed beef have been proposed as potential ways to reduce agriculture's environmental impacts (e.g. Ponisio *et al* 2014). Organic agriculture, for example, is often promoted as having lower environmental impacts relative to high-input conventional systems because it replaces agrochemical inputs with natural inputs such as manure or with ecosystem services such as pest control (Azadi *et al* 2011). Recent analyses examining the comparative impacts of organic and conventional systems have, of necessity, been limited to a few environmental indicators or in statistical strength of their inferences because of small sample size (Mondelaers *et al* 2009, Seufert *et al* 2012, Tuomisto *et al* 2012, Ponisio *et al* 2014). Recent increases in the number of published LCAs enables more complete analysis of the comparative impacts of organic and conventional systems across a range of environmental indicators and foods. In addition, we combine *de novo* analyses to determine the comparative environmental impacts of three other sets of production systems: grass-fed and grain-fed beef; trawling and non-trawling fisheries; and greenhouse grown and open-field produce.

Increases in agricultural input efficiency, or the amount of food produced per unit of fertilizer or feed input, may also reduce agriculture's environmental impact (e.g. Robertson and Swinton 2005). Agricultural systems depend on fertilizer and feed inputs to obtain and/or maintain high productivity. However, excessive application of these inputs increases agriculture's environmental impact without increasing yields or farmer profits (Vitousek *et al* 2009). Our analyses examine the extent to which increases in agricultural input efficiency could reduce the environmental impact of producing a given type of food.

Previous analyses have shown that foods can differ greatly in their environmental impact (e.g. Clune *et al* 2017). However, these have been limited to animal-based foods (de Vries and de Boer 2010, Nijdam *et al* 2012) or to a single environmental indicator (e.g. Mekonnen and Hoekstra 2010, Clune *et al* 2017). It is thus currently unclear how foods differ in their impacts across a range of environmental indicators, and whether foods with low impacts for one environmental indicator have similarly low impacts for other environmental indicators. Our meta-analysis enables us to make these comparisons for five environmental indicators: greenhouse gas emissions (GHGs), land use, fossil fuel energy use, eutrophication potential, and acidification potential.

The analyses and results presented here expand on current knowledge of how food production system, agricultural input efficiency, and food choice affect agriculture's environmental impacts. The results can be used to create a more sustainable agricultural future.

Methods

Publication selection and issues covered

We searched Web of Knowledge, PubMed, AGRICOLA, and Google Scholar for food LCAs published before July 2015. We excluded several publications because a lack of defined system boundaries made direct comparisons with other LCAs impossible. In addition, some LCAs conducted by for-profit companies were excluded because of potential biases. In total, we used 164 publications that analyzed 742 unique food production systems a (supplementary table 1 available at stacks.iop.org/ERL/12/064016/mmedia). We used five different environmental indicators in our analyses. These indicators are greenhouse gas emissions, land use, energy use, acidification potential (a measure of nutrient loading), and eutrophication potential (a measure of nutrient runoff) to give a broad overview of the environmental impacts of food production. The data for other environmental indicators, such as biodiversity impacts, were not present in adequate amounts to include in our analyses.

Our analyses include all relevant pre-farm and on-farm activities (fertilizer production and application, seed production, farm energy use, feed and fodder production, manure production (when used for fertilizer), manure management, infrastructure construction, etc) and their associated environmental impacts up until a food leaves the farm. Our analyses are thus of 'cradle-to-farm gate' activities; a paucity of data on post-farm gate impacts limited our ability to analyze them in a balanced manner, although a previous analysis showed that the vast majority of a food's greenhouse gas emissions stem from 'cradle-to-farm gate' activities (Weber and Matthews 2008). In-depth examples of the activities included in 'cradle-to-farm gate' system boundary can be found in Pelletier (2008), Hokazono and Hayashi (2012), and Torrellas *et al* (2012).

The majority of LCA publications included in these analyses are from agricultural systems in Europe, North America, and Australia and New Zealand (86% of systems are from these regions). Systems from China (2%), Japan (2%), the rest of Asia (5%), South America (4%), and Africa (.4%) are much less common. The results presented here are therefore indicative of highly industrialized systems and should be interpreted with this in mind. However, because the majority of systems analyzed here are highly industrialized systems, comparisons across publications will be more indicative of environmental differences between foods than if production systems were highly variable.

We found sufficient data to compare the environmental impacts of four sets of alternative production systems: organic versus conventional systems; grass-fed versus grain-fed beef; trawling versus non-trawling fisheries; and greenhouse-grown versus open-field produce. We were also able to examine how agricultural input efficiency, or the amount of food produced per unit of agricultural input, affects a food's environmental impact, as well as how foods differ in their environmental impacts across the five environmental indicators examined.

Description of environmental indicators

Five environmental indicators were used in this analysis: greenhouse gas emissions, land use, energy use, acidification potential, and eutrophication potential. The analyses were limited to these indicators because a very limited number of publications reported data for other indicators such as human health, ecotoxicity, or biodiversity. An explanation of the indicators included in the analyses is below.

Greenhouse gas emissions (GHGs) are reported in carbon dioxide equivalents, and include the greenhouse gas emissions from carbon dioxide, methane, and nitrous oxide. GHGs from activities in the results presented include, but are not limited to, fertilizer production and application, manure management, enteric fermentation.

Energy use is reported in kilojoules and includes the energy used during pre-farm and on-farm activities including, but not limited to, fertilizer production, infrastructure construction and machinery use.

Land use is a measurement of how much land is occupied during food production. It accounts for land used to grow crops and/or livestock feed, to house animals, and to pasture ruminants.

Acidification potential is reported in SO_2 equivalents and includes acidification potential from sulfur dioxide, nitrogen oxides, nitrous oxide, and ammonia, among others. Acidification potential is a measurement of the potential increase in acidity of an ecosystem. Excess acidification makes it more difficult for plants to assimilate nutrients, and thus results in decreased plant growth. Activities such as fertilizer application, fuel combustion, and manure management are included in the results presented here.

Eutrophication potential (a measure of nutrification) is reported in PO_4 equivalents and includes eutrophication potential from phosphate, nitrogen oxides, ammonia, and ammonium, among others. Eutrophication is a measurement of the increase in nutrients entering an ecosystem. Eutrophication has substantial environmental impacts including, but not limited to, algal blooms and aquatic dead zones.

Alternative production systems

To control for environmental and agronomic differences between publications, as well as differences in nutrient contents between foods, we compared alternative production systems by food item within publication. We first calculated the ratio of impacts of different production systems by food item within each publication, and then calculated the response ratio by taking the natural log of the ratio of impacts (Hedges *et al* 1999). We then aggregated foods into groups of similar food types (cereals; fruits; vegetables; pulses, nuts and oil crops; dairy and eggs; and meats) to improve the power of statistical tests. We tested for significant differences between alternative production systems using *t*-tests on the response ratio.

Agricultural input efficiency

In determining how agricultural input efficiency, or the amount of food produced per unit of agricultural input, affects a food's environmental impact, we performed regressions between a food's environmental impact and its nutrient use efficiency in crop systems or its feed use efficiency in livestock systems. We limited analyses to non-rice cereal crops and non-ruminant livestock because flooding in rice paddies and digestive processes in ruminants do not make them directly comparable with other crop and livestock systems. There is not adequate data to perform similar analyses limited to ruminant systems: comparisons would be severely limited for beef ($n = 7$ for GHGs and $n < 5$ for all other indicators), and only three studies provide feed use efficiency in dairy systems. For the analysis on nutrient use efficiency, we excluded crop systems that applied manure because the variable nitrogen content of manure made it impossible to calculate nitrogen inputs in these systems. In total, we examined the agricultural input efficiency of 49 non-rice cereal production systems and 53 non-ruminant livestock production systems.

Different foods

LCAs commonly report a food's environmental impact on a per mass basis (e.g. impacts per kg of food). However, because the nutritional values of foods come from their calories, protein, and/or micronutrients, and not from mass per se, we also calculated a food's environmental impacts per kilocalorie, gram protein, and USDA serving (2016). To compare differences between broad types of foods, we aggregated foods into 13 food groups composed of similar foods (supplementary table 2).

Results and discussions

Environmental impacts of alternative food production systems

Organic versus conventional agriculture

Organic agriculture is a fast-growing sector in many western nations, perhaps because it is perceived as being more sustainable or healthier than conventional agricultural systems (Rigby and Cáceres 2001). Our analyses based on 46-paired organic—conventional

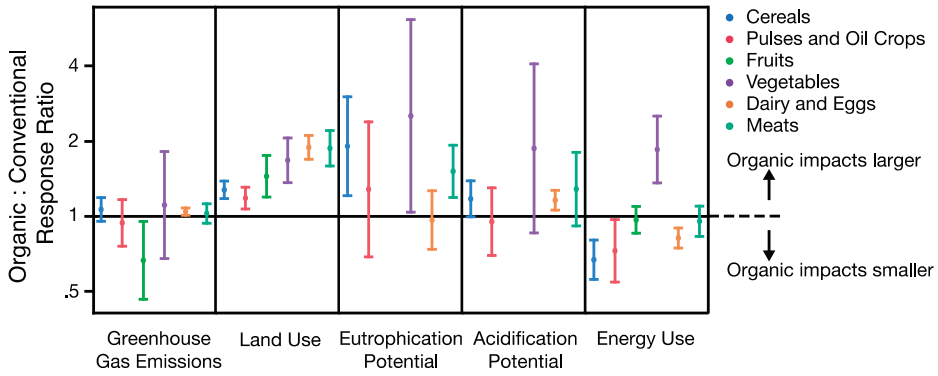

Figure 1. Response ratio of the environmental impacts of organic and conventional food production systems. Comparisons were made within publication to control for agronomic and environmental differences between publications. Plotted on a log base 2 scale, where a ratio greater than one indicates organic systems have higher impacts; a ratio less than one indicates organic systems have lower impacts. Bars are means and standard errors.

systems examine the comparative environmental impacts of these agricultural systems across five environmental indicators and a broad range of foods. We found that organic systems require 25%–110% more land use ($p < 0.001$; $n = 37$), use 15% less energy ($p = .0452$; $n = 33$), and have 37% higher eutrophication potential ($p = .0383$; $n = 20$) than conventional systems per unit of food. In addition, organic and conventional systems did not significantly differ in their greenhouse gas emissions ($p = .5923$; $n = 44$) or acidification potential ($p = .299$; $n = 26$), although these were 4% lower and 13% higher in organic systems, respectively (figure 1).

The differences in environmental impacts between organic and conventional systems are primarily driven by differences in nutrient management techniques. Organic agriculture is largely dependent on manure as a nitrogen input in contrast to conventional agriculture's use of synthetic fertilizers. Application of manure, which releases nutrients in response to environmental conditions and not crop nutrient demand (Seufert *et al* 2012), often results in temporal mismatches between nutrient availability and nutrient demand and thereby increases the proportion of nutrients that are not assimilated by plants (Cassman *et al* 2002). These temporal mismatches in organic systems result in reduced crop growth and yields and thus in increased land use. In addition, nutrient applications not incorporated into plant growth cause eutrophication and acidification, thereby driving the higher eutrophication potential and tendency for higher acidification potential in organic systems. In contrast, energy use is lower in organic systems because of organic's reduced reliance on energy-intensive synthetic fertilizer and pesticide inputs. GHG emissions are similar in organic and conventional systems because of the trade-off between application of synthetic fertilizer in conventional systems and use of manure in organic systems. Indeed, while production of conventional fertilizer is energy- and GHG-intensive, mismatches between nutrient availability and demand in organic systems dependent on manure increase the portion of reactive nitrogen in organic systems that turns into nitrous oxide, a potent greenhouse gas (Myhre *et al* 2013), causing organic and conventional systems to have similar GHG emissions. Because we limited comparisons to within publication, the results presented here are therefore indicative of comparative environmental differences of organic and conventional systems at a local scale. It is, however, possible that the comparative environmental impacts of organic and conventional systems might differ at a regional, national, or global scale (e.g. Bengtsson *et al* 2005 and Phalan *et al* 2011).

Previous analyses have shown that increasing nutrient application and adopting techniques such as rotational farming, cover cropping, multi-cropping, and polyculture in organic systems can halve the land use difference between organic and conventional systems (Seufert *et al* 2012, Ponisio *et al* 2014). Additionally, while the overall pattern is for higher land use in organic systems, organic systems have similar land use for legumes and perennial crops while the land use difference between organic and conventional systems is smaller in rain-fed systems and in systems with weakly-acidic to weakly-alkaline soils (Pimentel *et al* 2005, Seufert *et al* 2012).

Organic systems might offer health and environmental benefits we could not investigate with our data set. Organic foods have higher micronutrient concentrations (Hunter *et al* 2011, Palupi *et al* 2012) and lower pesticide residues (Baker *et al* 2002) than conventional foods, although these differences may not translate into improved human health outcomes (Dangour and Lock 2010, Hunter *et al* 2011). On-farm and near-farm biodiversity (Mäder *et al* 2002, Bengtsson *et al* 2005, Hole *et al* 2005) tends to be higher in organic agricultural systems, probably because of its lower fertilizer, herbicide and pesticide inputs. In addition, soil organic carbon is higher in organic systems (Gattinger *et al* 2012) because manure application promotes carbon storage in agricultural soils. However, organic agriculture would likely have a net negative impact on biodiversity and soil organic

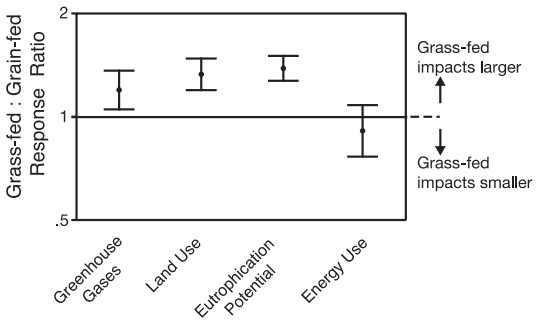

Figure 2. Response ratio of the environmental impact of grass-fed and grain-fed beef. Comparisons were made within publication to control for agronomic and environmental differences between study locations. A ratio greater than one indicates grass-fed beef has higher impacts; a ratio less than one indicates grass-fed beef has lower impacts. Bars are means and standard errors.

carbon at larger spatial scales because of the greater land clearing required under organic agriculture and because biodiversity (Balmford *et al* 2005, Phalan *et al* 2011) and carbon stocks (Gilroy *et al* 2014) decrease dramatically with conversion from natural habitats.

Although organic systems have higher land use and eutrophication potential and tend to have higher acidification potential, this should not be taken as an indication that conventional systems are more sustainable than organic systems. Conventional practices require more energy use and are reliant on high nutrient, herbicide, and pesticide inputs that can have negative impacts on human health (Townsend 2003, Schwarzenbach *et al* 2010, Mostafalou and Abdollahi 2013) and the environment (Vitousek *et al* 2009, Foley *et al* 2011). Developing production systems that integrate the benefits of conventional, organic, and other agricultural systems is necessary for creating a more sustainable agricultural future.

Grass-fed versus grain-fed beef

We quantitatively analyzed the environmental differences between grass-fed and grain-fed beef using 7 paired grass- and grain-fed systems. We define grass-fed systems as those where beef is raised solely on pasture or seasonally on pasture and supplemented diets of grass, silage, and fodder while overwintering. We found that grass-fed beef had higher land use requirements than grain-fed beef ($p = .0381$, $n = 4$). Grass-fed and grain-fed beef had similar impacts per unit food for the other environmental impacts examined ($p > .05$ for all other indicators), although grass-fed beef had, on average, 19% higher GHGs ($p = .2218$; $n = 7$) per unit food than grain-fed beef (figure 2).

The higher land use and tendency for higher GHG emissions in grass-fed beef stem from the lower macronutrient densities and digestibility of feeds used in grass-fed systems (Feedipedia 2016) because they cause grass-fed beef to require higher feed inputs per unit of beef produced than grain-fed systems. Furthermore, the nutritional yields (e.g. kcal ha^{-1}) of grass, silage, and fodder are often lower, possibly because the land on which they are grown is often less fertile than that used to produce feed (e.g. maize, soy, etc) used in grain-fed systems. The combination of higher feed inputs and lower nutritional crop yields for feeds drive the higher land use observed in grass-fed systems. Additionally, because grass-fed cattle grow slower and are slaughtered 6–12 months older than grain-fed cattle, lifetime methane emissions, and thus GHGs per unit of food, tend to be higher for grass-fed beef. The source of GHGs in grass-fed and grain-fed systems further supports this explanation. Indeed, 30% and 52% of GHGs in grain-fed systems result from feed production and enteric fermentation, respectively. In contrast, feed production and enteric are responsible for 20% and 61% of GHGs, respectively, in grass-fed systems.

Grass-fed beef may have environmental and human health benefits we could not analyze with our data. For example, grass-fed systems promote soil carbon sequestration (Derner and Schuman 2007) and within-pasture nutrient cycling while simultaneously decreasing eutrophication (Smith *et al* 2013). Additionally, grass-fed beef has higher micronutrient concentrations and a fatty acid profile that might lead to improved human health outcomes relative to consumption of grain-fed beef (Daley *et al* 2010). Furthermore, grass-fed beef may promote food security in cropland-scarce regions because it can be grown on land not suitable for crop production (Smith *et al* 2013).

Trawling versus non-trawling fisheries versus aquaculture

We classified commercial fisheries into trawling fisheries—where nets are physically dragged across a seabed—and non-trawling fisheries (midwater trawl, short and long-line fishing, and seine nets). Our analyses of 10 paired systems of trawling and non-trawling fisheries show that trawling fisheries emit 2.8 times more GHGs than non-trawling fisheries ($p = .004$; $n = 10$) (figure 3) because of the high fuel requirements of dragging a net across a seabed. Response ratios differ greatly between fish, with non-schooling fish (flat fish) having comparatively higher impacts under trawl fisheries than do fish that form schools (mackerel, cod). Previous analyses have also shown that trawl fisheries negatively impact non-targeted species through high bycatch rates relative to other fish capture methods and through ecosystem degradation from dragging a net across a seabed (Dayton *et al* 1995). Shifting from trawling to non-trawling fisheries would thus simultaneously decrease GHGs, bycatch rates, and ecosystem degradation.

Aquaculture, which accounts for ~45% of global fish production, could be a sustainable alternative to wild-caught fisheries (FAO 2016b). Our examination of 142 fishery and aquaculture systems indicates that,

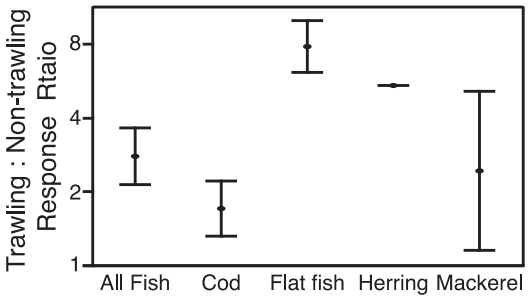

Figure 3. Response ratio of the greenhouse gas emissions of trawling and non-trawling fisheries (e.g. line, purse and seine net). A ratio greater than one indicates trawling fisheries have higher greenhouse gas emissions than non-trawling fisheries. Bars are means and standard errors.

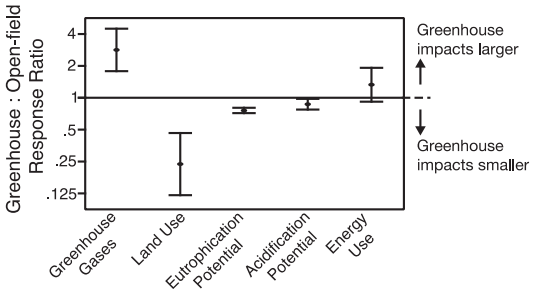

Figure 5. Response ratio of environmental impacts of greenhouse grown and open field produce. Comparisons were made within publication to control for agronomic and environmental differences between study locations. Bars are means and standard errors. A ratio greater than one indicates greenhouse systems have higher impacts; a ratio less than one indicates greenhouse systems have lower impacts.

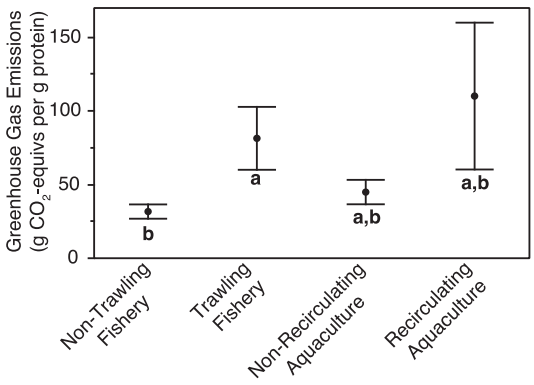

Figure 4. Greenhouse gas emissions from non-trawling (e.g. line, purse and seine net) and trawling fisheries, and from non-recirculating (e.g. pond, bag, flow-through) and recirculating aquaculture systems per gram protein. Significant differences are denoted by letters and were calculated using a Tukey post-hoc test.

on average, non-recirculating aquaculture (e.g. aquaculture in ponds, fjords, rivers, etc) and non-trawling fisheries emitted similar GHGs per unit of food and had emissions similar to pork, poultry, and dairy (figures 4 and S1). In contrast, trawling fisheries and recirculating aquaculture (in tanks and other systems in which pumps and filters are used) emitted several times more GHGs than non-trawling fisheries and non-recirculating aquaculture because of their high energy requirements (figure 4). Aquaculture-raised fish from non-recirculating systems could thus be a lower-emission alternative to trawling fisheries, an equal-emission alternative to non-trawling fisheries, and could alleviate pressure on over-harvested fisheries (Costello *et al* 2012).

There can be marked differences in environmental impacts even among the lower-impact non-recirculating aquaculture systems. For instance, aquaculture at high fish densities can eutrophy closed bodies of water and cause gene exchange between farmed and wild fish varieties (FAO 2016b). In addition, shrimp aquaculture systems that require deforestation of mangroves have high environmental impacts while integrated rice-catfish agriculture-aquaculture systems have comparatively low impacts (Folke and Kautsky 1992, Páez-Osuna 2001).

Greenhouse grown versus open-field produce

Greenhouse systems allow crops to be grown in climates and regions not suitable for crop production. Our analysis of five paired greenhouse–open-field systems shows that greenhouse production systems tend to emit almost three times more GHGs (figure 5; $p = .089$) because of the energy required to maintain greenhouses at ideal growing conditions. While our analyses show that, on average, greenhouse production systems tend to have higher energy use than open-field systems, it is important to note that energy requirements and thus greenhouse gas emissions can differ greatly between greenhouses. For example, greenhouses that are both heated and lighted will require substantially more energy to maintain than will greenhouses that are neither heated nor lighted. Land use in greenhouse systems was, on average, one quarter of that in open fields, but this difference was not significant ($p = .166$; $n = 3$). Crop yields are higher, and thus land use lower, in greenhouse systems because they are maintained at ideal conditions for plant growth. The limited sample size of these analyses prevents concrete conclusions from being drawn. Future analyses examining the environmental differences between greenhouse and open-field production systems are needed to fully elucidate their comparative environmental impacts.

Environmental impacts of agricultural input efficiency

We found large differences among studies in the environmental impacts of producing the same food (supplemental figure 1). To examine why foods may vary in their environmental impacts, we analyzed agricultural input efficiency, or the amount of food

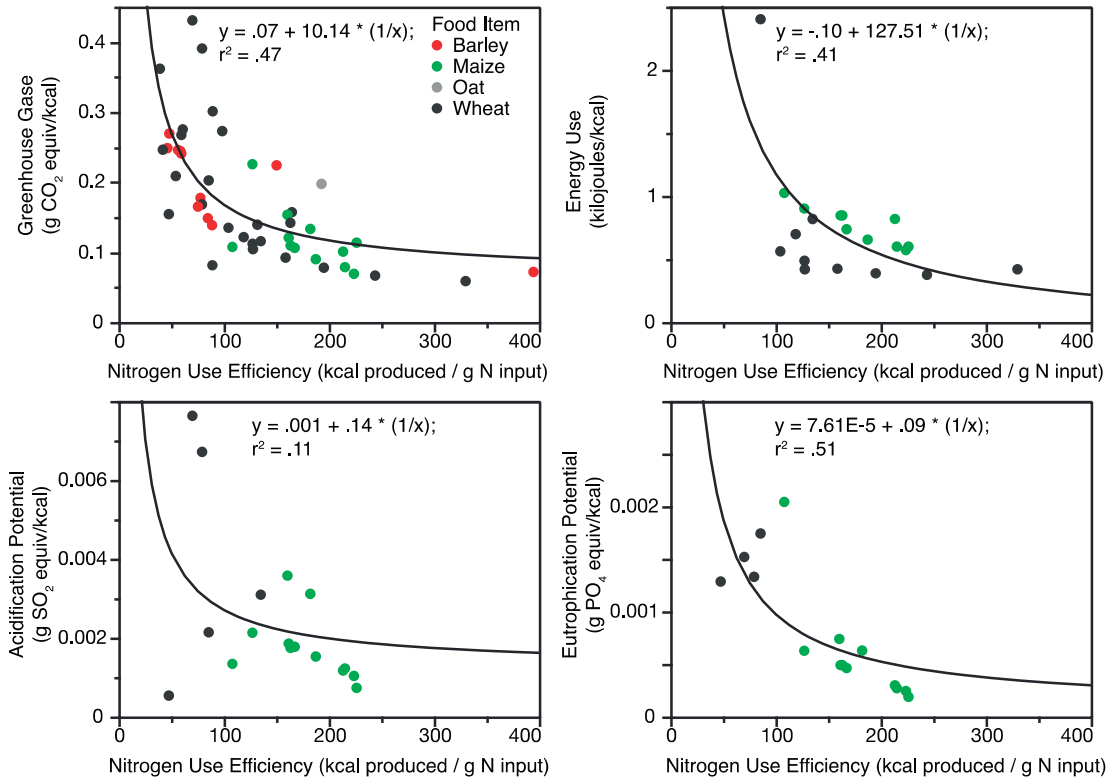

Figure 6. Correlations between nitrogen use efficiency, or calories produced per g of nitrogen input, and the environmental impacts of non-rice cereal crops. Regression lines are reciprocal fits between nitrogen use efficiency and a food's environmental impact. All relationships are significant at $p < .05$ except for acidification potential.

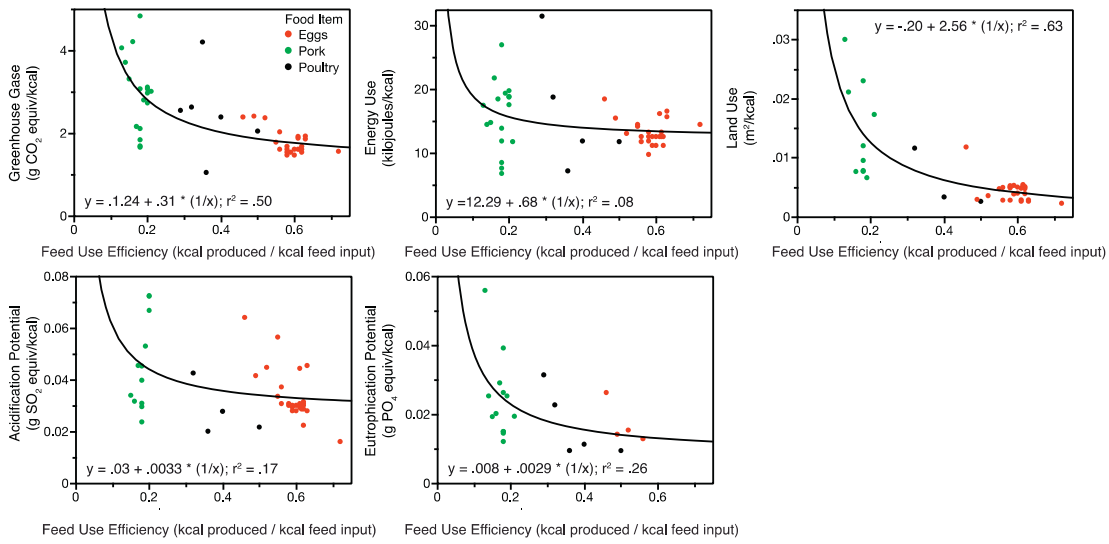

Figure 7. Correlations between feed use efficiency, or kcal of food produced per kcal of feed input, and environmental impacts in non-ruminant livestock systems. Regression lines are reciprocal fits between feed use efficiency and a food's environmental impacts. All relationships are significant at $p < .05$.

produced per unit of fertilizer or feed input, in 49 non-rice cereal production systems and 53 non-ruminant livestock systems. We found that higher agricultural input efficiency is consistently associated with lower environmental impacts for both non-rice cereal systems (figure 6) and non-ruminant livestock systems (figure 7). While the fits shown in figures 6 and 7 are across all food items, fits for individual food by environmental indicator are almost always downward sloping and significant. Increasing agricultural input efficiency reduces a food's environmental impact because of the environmental impacts of producing agricultural inputs such as fertilizer, pesticides, and livestock feeds. However, the environmental benefits of increasing agricultural input efficiency would not be equal across all systems, with improvements in

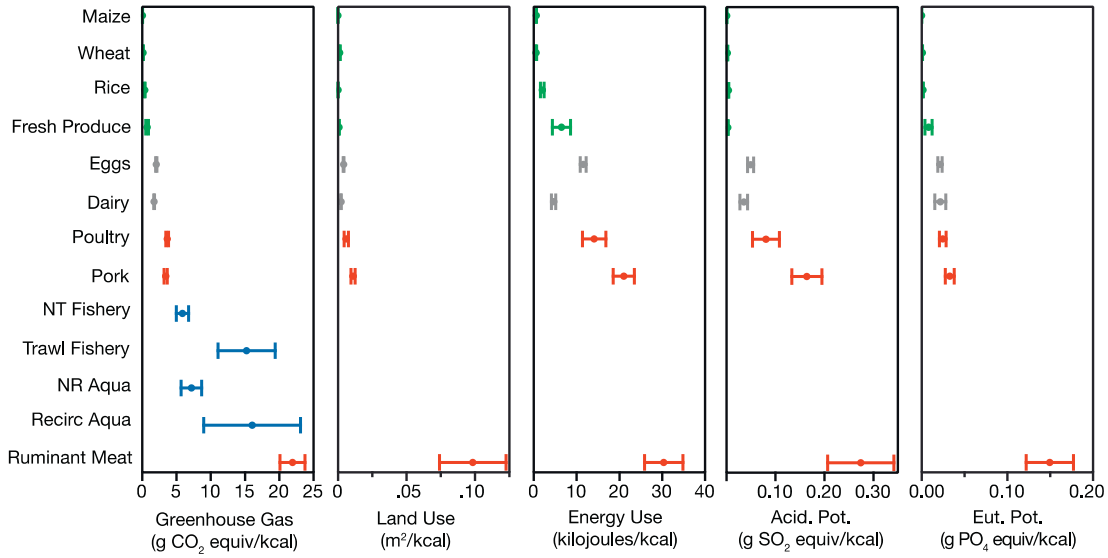

Figure 8. Environmental impacts of broad groups of foods per kilocalorie. The environmental indicators examined are greenhouse gas emissions, land use, energy use, acidification potential (Acid. Pot.) and eutrophication potential (Eut. Pot.). Bars show means and standard errors. Plant-based foods are in green; dairy and eggs are in grey; meats are in red; and seafood is in blue. Data from foods grown in greenhouses are not included when plotting this figure. Trawl Fishery = bottom-trawling fisheries; NT Fishery = all other fisheries (e.g. line, purse net, seine net, etc); Recirc Aqua = recirculating aquaculture; NR Aqua = non-recirculating aquaculture (e.g. pond, net pen, flow-through, etc).

agricultural input efficiency having the largest environmental benefit in the least efficient systems. Further, improving efficiency in more efficient systems may only be possible at an economic cost. Emphasis should therefore be placed on improving efficiency in less efficient systems, although efficiency improvements in more efficient systems would still have environmental benefits.

Several technologies and management techniques can increase agricultural input efficiency. Precision farming, where nutrient and pesticide inputs are temporally and spatially applied to match crop requirements, has increased fertilizer input efficiency and farmer profits without decreasing crop yields for a variety of crops in geographically diverse areas (Robertson and Vitousek 2009). Conservation tillage and cover cropping, particularly with nitrogen fixing crops because they simultaneously reduce required nitrogen inputs, also increase fertilizer input efficiency by reducing nutrient loss from agricultural systems (Robertson and Vitousek 2009, Ponisio *et al* 2014). Feed input efficiency in livestock systems can also be increased. For example, pork from pigs fed diets supplemented with amino acids required less feed and emitted 5% fewer GHGs and had 28% lower eutrophication potential than pork from pigs fed unsupplemented diets (Ogino *et al* 2013). Similar benefits have also been found in poultry, beef, and dairy systems (Robertson and Vitousek 2009). In addition, using agricultural wastes and byproducts as animal feeds could reduce the environmental impacts of livestock production by 20% without reducing food quality or farmer profits (zu Ermgassen *et al* 2016).

The location of food production can also influence its environmental impact because differences in climatic and soil conditions often affect agricultural input efficiency. Indeed, spatially locating food production in areas with the most suitable climatic and soil conditions for a crop can increase agricultural input efficiency and decrease environmental impacts (Polasky *et al* 2008, Johnson *et al* 2014, Chaplin-Kramer *et al* 2015). For example, preferentially locating agricultural land to maximize single ecosystem services would increase carbon stores by ~6 billion metric tonnes (worth ~$1 trillion 2012 USD) (Johnson *et al* 2014) and substantially decrease projected rates of agriculturally-driven biodiversity loss (Chaplin-Kramer *et al* 2015). Globally leveraging environmental and soil conditions to increase agricultural input efficiency could thus provide substantial environmental benefits.

Environmental Impacts of different foods

Many analyses have shown that dietary choice can greatly influence the environmental impacts of the agricultural food system (de Vries and de Boer 2010, Nijdam *et al* 2012, Tilman and Clark 2014, Clune *et al* 2017), although these analyses were limited to animal-based foods or a single environmental indicator. Our analyses expand on these earlier studies and show that foods with low impact for one environmental indicator tend to have low impacts for all environmental indicators examined (figure 8). Indeed, for all indicators examined, ruminant meat (beef, goat and lamb/mutton) had impacts 20–100 times those of plants while milk, eggs, pork, poultry, and seafood had impacts 2–25 times higher than plants per kilocalorie of food produced. This clear trend of ruminant meat

having high impacts and other animal-based foods having intermediate impacts also holds when foods are examined per gram protein, USDA serving, or unit mass (supplemental figure 1). Isocaloric shifts from high-impact to lower-impact but nutritionally similar foods, such as shifts from ruminant meats to fish, pork, poultry, or legumes, would have large diet-related environmental benefits while also improving human health outcomes (e.g. Tilman and Clark 2014). These dietary shifts, however, would likely decrease the total cost of the diet; it is possible that increased consumption of other material goods could offset the environmental benefits of consuming lower-impact foods.

Most of the 742 LCA food analyses used were based on high-input systems in Europe and North America; the results presented here are thus indicative of the impacts of high-input systems in developed nations. In contrast, the impacts of low-input systems common in developing nations are not yet well studied, although a recent analysis indicates that GHGs may be higher in these systems because of lower agricultural input efficiency (Herrero *et al* 2013). LCA analyses on less-studied but nutritionally and culturally important foods such as quinoa, cassava, and millet, as well as analyses from additional regions and management regimes would provide further insight and a clearer understanding of the environmental impacts of different foods and food systems globally.

Conclusions

Our analyses show that the comparative environmental impacts of agricultural production systems differ depending on the systems, food, and environmental indicator examined. Per unit of food produced, organic systems had higher land use and eutrophication potential, tended to have higher acidification potential, did not offer benefits in GHGs, but had lower energy use; trawling fisheries emitted almost 3 times more GHGs than non-trawling fisheries; grass-fed beef required more land and tended to emit more GHGs than grain-fed beef; and high agricultural efficiency was consistently correlated with lower environmental impacts. Combining the benefits of different production systems, for example organic's reduced reliance on chemical inputs with the high yields of conventional systems would result in a more sustainable agricultural system.

Agricultural input efficiency, or the amount of food produced per unit of input, is inversely correlated with a food's environmental impact in non-rice cereal systems and non-ruminant livestock systems. Increasing agricultural input use efficiency would have environmental benefits without necessitating dietary change. However, because the marginal environmental benefits of increasing agricultural input efficiency is larger in less efficient systems, special emphasis should be placed on improving efficiency in the least efficient agricultural systems.

The difference in environmental impacts between foods is large compared to the difference between production systems and systems with different agricultural input efficiencies producing the same food. Ruminant meats, for example, have impacts that are 3–10 times those of other animal-based foods and 20–100 times those of plant-based foods for all indicators examined. Because the majority of production systems included in these analyses are from Europe and North America, the results presented here are indicative of trends in highly industrialized and high-input agricultural systems. Analyses of the environmental impacts of low-input agricultural systems are necessary to elucidate the extent to which the trends observed here also apply to lower-input agricultural systems.

The analyses presented here greatly expand current knowledge of the environmental impacts of food production. However, there are still large knowledge gaps which, if addressed, would further our understanding of agriculture's environmental impacts. For example, analyses on the environmental impacts of agricultural systems in low-income countries, on staple crops not common in Westernized diets (quinoa, yams, sorghum, millet, etc), on fish produced via aquaculture, and on agricultural input efficiency in non-cereal crops and in ruminant systems are limited. In addition, agricultural production has a multitude of environmental impacts beyond the five environmental indicators analyzed here; few LCAs analyses have examined agriculture's other environmental impacts such as water use, pesticide use, or impact on biodiversity. Analyses into these, and other, understudied aspects of agriculture's environmental impacts are needed to more fully elucidate agriculture's entire environmental impact.

Despite current knowledge gaps, it is clear that current agricultural trajectories would substantially increase agriculture's environmental impacts by midcentury (Tilman *et al* 2001,Tilman *et al* 2011, Bajzelj *et al* 2014, Tilman and Clark 2014). Many interventions would, however, greatly reduce agriculture's future environmental impacts. Adoption of low-meat and no-meat diets in nations with excess meat consumption (Springmann *et al* 2016), sustainable increases in crop yields (Foley *et al* 2011, Mueller *et al* 2012), and adoption of low-impact and otherwise more efficient agricultural systems (Robertson and Vitousek 2009), would offer large environmental benefits. In addition, over 30% of food production is wasted; reducing food waste would offer environmental benefits without requiring shifts in production practices or diets (Foley *et al* 2011). Implementing policy and education initiatives designed to increase adoption of lower-impact foods, of lower-impact production systems, and of systems with high agricultural input efficiency is necessary before

agriculture causes substantial, and potentially irreversible, environmental damage.

Acknowledgments

We would like to thank Kaitlin Kimmel, George Furey, Adam Clark, David Williams, and James Gerber for comments on the manuscript. We would also like to thank the Balzan Foundation, the McKnight Presidential Chair (DT), and the University of California, Santa Barbara for support.

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