# Rethinking Agricultural Trade Relationships in an Era of Globalization

GRAHAM K. MACDONALD, KATE A. BRAUMAN, SHIPENG SUN, KIMBERLY M. CARLSON, EMILY S. CASSIDY, JAMES S. GERBER, AND PAUL C. WEST

*Agricultural trade plays an important role in global food security and resource sustainability. Global food commodities trade is worth more than US$520 billion per year, could feed approximately two billion people, uses about 13% of worldwide cropland and pasture, and has geographically concentrated irrigation water demands. However, researchers rarely compare these monetary, nutritional, and resource metrics, which limits our ability to holistically evaluate the drivers and implications of trade. We found that each metric suggests distinct conclusions about the geography of globalized agriculture. For example, traded animal products have a disproportionate influence according to value-based and embodied pasture metrics. Traded wheat, soybean, and maize contain the most calories, use the most cropland, and strongly influence irrigation water consumption. We typify engagement in trade by assessing how countries allocate cropland to domestic versus foreign demand. Simultaneous consideration of multiple metrics could enhance decisionmaking surrounding trade by capturing the complex biophysical and economic context of agricultural globalization.*

*Keywords: agriculture, food security, globalization, trade, virtual water*

**Globalization has transformed the geography of food** systems. As agricultural trade becomes increasingly important to national food supplies (Porkka et al. 2013), it alters the distribution of land and water use across regions. About one-fifth of both global cropland area and agricultural water use is allocated to the production of agricultural commodities consumed abroad (Hoekstra and Mekonnen 2012, Kastner et al. 2014a). The environmental burden of food production may therefore be shifted to export-producing regions, whereas some importing nations become increasingly reliant on foreign resources for their food security (Erb et al. 2009, Fader et al. 2013). Quantifying the drivers and implications of globalization is vital to understanding how to sustainably meet growing local, regional, and global food demands (Foley et al. 2011, Lambin and Meyfroidt 2011). In studies in a variety of disciplines, the nature and implications of global agricultural trade have been examined (Meyfroidt et al. 2013), but the unique insights and limitations of different metrics used to quantify trade relationships remain largely unexplored.

Agricultural trade is ultimately an economic exchange, providing food or other materials to importing nations and export revenues to producing countries (Anderson 2010). Governments, corporations, and researchers commonly analyze these relationships as monetary value (e.g., in dollars) or mass (e.g., in tons) traded. These metrics provide a straightforward way to assess the magnitude of trade flows and also enable comparison with domestic indicators (e.g., gross domestic product [GDP]) or production (e.g., tons of wheat harvested). However, trade volumes do not necessarily reflect other critical characteristics of agricultural products, such as nutritional composition. For example, although agricultural trade is a small fraction of global GDP (Anderson 2010), 80% of people now live in net-food-importing countries, in which calorie imports exceed calorie exports (Porkka et al. 2013). Converting mass to calories—a measure of dietary energy—begins to address the role of trade in the nutritional security of nations (D'Odorico et al. 2014).

Moving beyond physical trade volumes, a growing body of research links trade volumes with data on agricultural production to quantify the embodied or virtual resources used to produce agricultural exports. Such studies apply biophysical accounting approaches (Meyfroidt et al. 2013, Kastner et al. 2014b), which typically multiply the mass traded by the country- and commodity-specific coefficients of resource requirements per unit mass (e.g., liters of water required per kilogram of wheat). Hydrologic models used to examine the

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### Box 1. Tracing the origins of global agricultural trade.

In the present study, we used bilateral trade data from FAOSTAT (2013), a comprehensive, publicly available source of country-reported trade volumes (table S1). This database covers hundreds of agricultural commodities, including whole crops, live animals, and processed food products (e.g., flour, oil, wine, sugar, and cheese).

We analyzed approximately 390 traded food commodities derived from 139 crops and 10 livestock animals (table S2 and S3). For water, we focused on 84 commodities derived from 16 major food crops with detailed crop water productivity data (box 2). To reduce interannual variability and to capture predominant relationships over time, we calculated the mean annual trade flows from 2000 to 2009. Processed commodities were grouped according to the crop or livestock product they were most likely to be derived from, following the breakdowns in FAO (2003). We excluded nonfood commodities (e.g., cotton linters) and those not directly linked to a particular crop (e.g., compound animal feeds), which formed a small fraction of total trade volumes.

#### Country-reported trade volumes: Monetary value and calories

Most countries report annual import and export volumes, as well as the countries with which they traded each commodity. However, the agreement about trade volumes among trade partners can be highly inconsistent; our assessments suggested that using only importer country–reported data underestimated FAO total trade volumes. To account for this inconsistency, we used importer country–reported volumes when a country reported at least 75% of the trade flows attributed to them by all of their trade partners for a given commodity in a given year. If an importer country reported less than 75% of total exporter-attributed trades, we followed Ghelar's (1996) approach and used the reported volume of the importing or exporting partner country that more consistently reported its trade volumes relative to all of its trade partners in each commodity year.

#### Producer–consumer adjusted data for embodied resources

To account for countries exporting crop commodities not grown on their own lands, a process that may occur through value-added processing of imports and subsequent reexport, we compared the whole-crop equivalent mass of exported crop commodities with the annual national crop production for each exporting country (see the supplemental material for details). If a country did not produce enough of a given crop to match the exports and domestic consumption each year, we followed Kastner and colleagues' (2011, 2014a) approach to trace crop products back to the most likely producing nation. Our estimates of embodied resources therefore omit intermediary trading partners and approximate crop trades between the original producing and final consuming nations using a simplified input–output model that considers the supply chain for commodities derived from a single crop. This helps to avoid misattribution of embodied resources. However, unlike full MRIO approaches, our approach cannot determine exactly which processed commodities underlie embodied resource use.

virtual water footprint of crop and livestock exports (e.g., Fader et al. 2011, Dalin et al. 2012) highlight the shared nature of water resources among countries (Hoekstra and Mekonnen 2012). Similar applications have also focused on the cropland area required to produce exports (Qiang et al. 2013, Kastner et al. 2014a) and the impact of trade on nutrient cycles resulting from fertilizer use (Schipanski and Bennett 2012, Lassaletta et al. 2014).

Economic supply chain models are also commonly used to assess the environmental impacts of agricultural imports (Meyfroidt et al. 2013). Such approaches include environmentally extended multiregion input–output (MRIO) models, which trace the consumption of commodities through value chains back to the original producing sectors and countries. Applications include estimates of industrial greenhouse gas emissions associated with merchandise exports (Davis and Caldeira 2010), biodiversity threats from different export sectors (Lenzen et al. 2012a), and total land use or material footprints embodied in imports (Weinzettel et al. 2013, Wiedmann et al. 2013). In contrast to biophysical accounting approaches in which mass is used, economic supply chain models typically quantify trade flows using monetary values.

In an era of agricultural globalization, trade-related policies will benefit from understanding the unique advantages and limitations of commonly used metrics. One reason to expect differences in trade across metrics is that commodity prices are not necessarily linked to the nutritional and agroenvironmental dimensions of food. For example, two foods might have different prices, despite involving the same mix of crop ingredients and embodied land use (Kastner et al. 2014b). Monetary value can change with processing, inflation, price fluctuations, and transport costs, but a resource metric such as cropland area offers a fixed biophysical unit of measurement.

Here, we examine how different metrics affect our understanding of agricultural globalization using comprehensive agricultural trade data from the Food and Agriculture Organization of the United Nations (FAO) from 2000 to 2009. We first compared global trade and bilateral relationships in terms of monetary value and dietary energy (for the methods, see box 1). We then juxtaposed these metrics with estimates of embodied land use and water consumption (for the methods, see box 2), focusing on factors that help to explain how and why countries engage in trade. These results offer a unique fusion of

**Box 2. Calculating embodied resources in export-producing countries.**

**Cropland harvested area use in export-producing nations**

To calculate the harvested area used to produce exports, we divided the mass (metric tons) of crop commodities exported by the yield (tons per hectare) of that crop in the exporting country (Qiang et al. 2013, Kastner et al. 2014a). The harvested area may differ from the total cropland area when multiple crops are harvested from the same land in a single year or when cropland is fallowed (Monfreda et al. 2008).

Estimating the land area required to produce livestock products required several steps for each country and year (which are detailed in the supplemental material): calculating the fraction of animal feed derived from croplands or pasture; the mix of feed crops; and the efficiency of feed conversion by animals to meat, eggs, or milk. We estimated the use of major crops as feed, average feed yields, and the feed inputs required to produce different animals (e.g., pigs, cattle, dairy, mutton, poultry and eggs) following the approach of Cassidy and colleagues (2013) with FAOSTAT (2013) data. We assumed that domestic nonruminant feed demands were met first, with any leftover feed available to ruminants (Pradhan et al. 2013). Next, we iteratively attributed any remaining ruminant feed demand to forage crops (Monfreda et al. 2008) and then to permanent pastures and meadows (FAOSTAT 2013). Approximate pasture yields (metric tons of ruminant product per hectare of pasture) were calculated for each country. Our method also accounts for whether feed used to produce animal product exports was imported or grown domestically. We therefore allocated embodied land area and yields to feed-producing countries (Kastner et al. 2014a).

**Total and irrigation water use in export-producing nations**

Studies on embodied water consumption typically use country-reported trade statistics and one of three global crop water balance models: the Water Footprint Network (Hoekstra and Mekonnen 2012, following the CROPWATCH model approach), the LPJmL model (Fader et al. 2011), and the H08 model (Dalin et al. 2012). We built on this previous work by using producer–consumer-adjusted trade data and recent crop water productivity factors from Brauman and colleagues (2013). These factors were developed using spatially distributed, crop-specific water use and caloric yields for irrigated versus rainfed systems from Siebert and Döll (2010). For each crop and country, we calculated production-weighted crop water demand (liters per calorie) across rainfed and irrigated areas. We assumed that irrigation consumption for export was proportional to the national fraction of irrigation in total water consumption. Calorie exports from irrigated and rainfed systems were then multiplied by country-specific crop water demand. Crop water productivity data represent the water balance and irrigated areas circa 2000.

the economic, nutritional, and embodied resource dimensions of global food trade.

Agricultural products are often processed and reexported by intermediary trading countries, which can obscure resource use in original producing countries. Most biophysical accounting studies have omitted reexport trade flows or have attributed resource use to intermediary trade partners (e.g., virtual water footprints by Hoekstra and Mekonnen 2012 and Dalin et al. 2012). We apply basic elements of MRIO to account for indirect producer–consumer relationships within a high commodity resolution biophysical accounting approach to calculate embodied land and water use (box 2).

## The composition of global agricultural trade

Using importer and exporter country–reported trade statistics for hundreds of agricultural commodities and more than 20,000 bilateral trade relationships (box 1, table S2), the mean value of global agricultural trade totaled US$522 billion per year from 2000 to 2009. This corresponds to 26% of world gross agricultural production, based on farm gate prices (FAOSTAT 2013); however, the traded commodities in our study may have undergone processing, which greatly increases their value over farm prices. Trade also represents a sizeable fraction of global food production, with 2.6 quadrillion calories traded globally, or more than 20% of global calorie production (FAOSTAT 2013). If all these calories were available as food, trade could theoretically feed approximately 2.6 billion people each year on a 2700 kilocalories (kcal) per capita per day diet (for alternative estimates, see supplemental figure S2).

We sorted commodities dervied from 139 crops and 10 livestock animals into 11 commodity groups (figure 1). Comparing the caloric and monetary values of trade indicates large differences in the contribution of commodity groups to global trade. Wheat, soybean, and maize formed 50% of the calorie exports but just 21% of the value. Almost half (44%) of the value traded was attributable to meat and animal products, combined with fruits and nuts, which typically have much higher embodied values (i.e., dollars per million calories traded) than do wheat and maize commodities (figure 1c). Oil crops also contribute much more to calories traded than to value traded, which reflects their often relatively lower embodied values and high calorie densities. The embodied values per calorie ranged widely within and across commodity groups in traded products. Animal products and vegetables had particularly large ranges, reflecting a mix of low-value (e.g., peas and rendered fats, less than $100 per million kcal) and high-value commodities (e.g., asparagus and foie gras, more than $12,000 per million kcal).

## The structure of agricultural trade relationships

We identified 20 major exporting countries and 33 major importing countries that accounted for more than 70% of

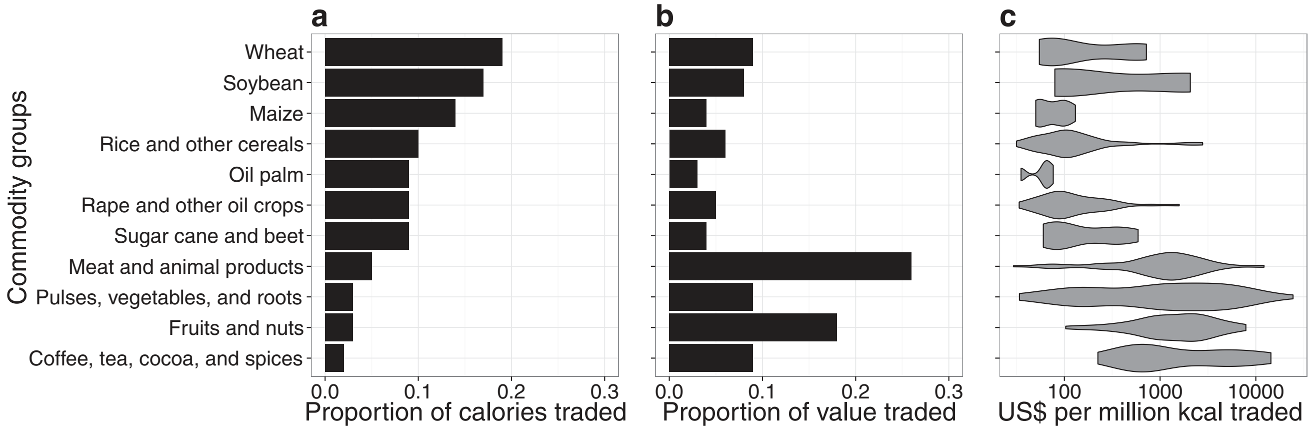

***Figure 1. The composition of global agricultural trade in terms of (a) calories and (b) monetary value. These graphs highlight the differences in the relative share of major staple crops (e.g., wheat, soybean, maize, rice) for calories versus higher-value commodities (e.g., meat and animal products, fruits and nuts) for monetary value. (c) Commodities dervied from 139 crops and 10 livestock animals were sorted into 11 common commodity groupings (shown on the*** y***-axis), for which we calculated the embodied values of traded commodities in dollars (US$) per million calories (kcal) traded. The width of the grey areas in panel (c) indicates the relative distribution of all processed and primary commodities within each commodity group (e.g., most meat and animal product commodities fall in the range $1000 to $5000 per million kcal traded, as indicated by the widest section of the grey area). Note the logarithmic scale of the embodied values.***

global trade across the four main components of our analysis (i.e., monetary value, calories, embodied cropland area, and total embodied water consumption). Focusing on these major trading countries (see supplemental figure S1 for a map), we compared the structure of bilateral trade across metrics.

**Value and calories traded.** The structure of global trade differed considerably between monetary value and calories (figure 2). Globally, 41% percent of agricultural export value was concentrated in exports from EU countries, most of which was imported by other EU countries. The next largest share of monetary value (21%) was concentrated in exports from or trade among NAFTA (North American Free Trade Agreement) nations—the United States, Canada, and Mexico. The caloric pattern suggests far less concentration within the European Union; just 24% of exports and 30% of imports were associated with EU countries. Exports to China from Southeast Asia (Indonesia, Malaysia, and Thailand) and from South America (Brazil and Argentina) had higher shares of calories (9%–10% of global trade flows) than of monetary value (4%–5%) traded.

**Embodied land use and water consumption.** We found that about 20% (245 million hectares [ha]) of global harvested cropland area was devoted to export production. This echoes findings by Kastner and colleagues (2014a), who showed that approximately 20% of the global harvested area in 2008 was used for exports. Our estimates of pasture and forage area embodied in ruminant product exports represent approximately 11% of the permanent pasture area (365 million hectares) and about 9% of forage crop area (13 million hectares). Globally, the combined agricultural land used for exports was more than half the size of the United States, encompassing about 13% of global agricultural land use (harvested food croplands + forage croplands + permanent pasture).

The embodied cropland area network (figure 3a) was dominated by large exports from the Americas to East Asia. For example, the United States used about 6.1 million harvested hectares (approximately 6% of its domestic nonforage cropland) to produce exports to China alone. Brazil and Argentina, the next largest cropland exporters, each contributed 9%–10% to the global harvested area embodied in trade. Although Brazil's largest embodied cropland trading partner was China (4.2 million hectares, largely for soybean), it also exported more than a million embodied hectares to France, Germany, Russia, Iran, and Spain from a mix of soybean, sugar, meat, and coffee. Brazil's harvested area exports evolved considerably after 2005, with a proportionally much larger share going to China by 2010 (Karstensen et al. 2013). Less than 10% of cropland area used to produce agricultural exports worldwide was in the European Union, including intra-EU trade.

Pasture and forage area embodied in ruminant exports originates primarily in Australia (57% of the global total), although this country represented only 11% of the global pasture area (FAOSTAT 2013). The United States and Brazil exported 5%–7% of embodied pasture and forage land, a more similar proportion to their shares of global pasture area (6%–7%). Japan, Russia, South Korea, and the United Kingdom were large embodied pasture importers—as were the United States and China—even though the United States and China collectively contain 19% of global pasture area.

We assessed the amount of water consumption embodied in exports (hereafter, *embodied water*) derived from 16 major

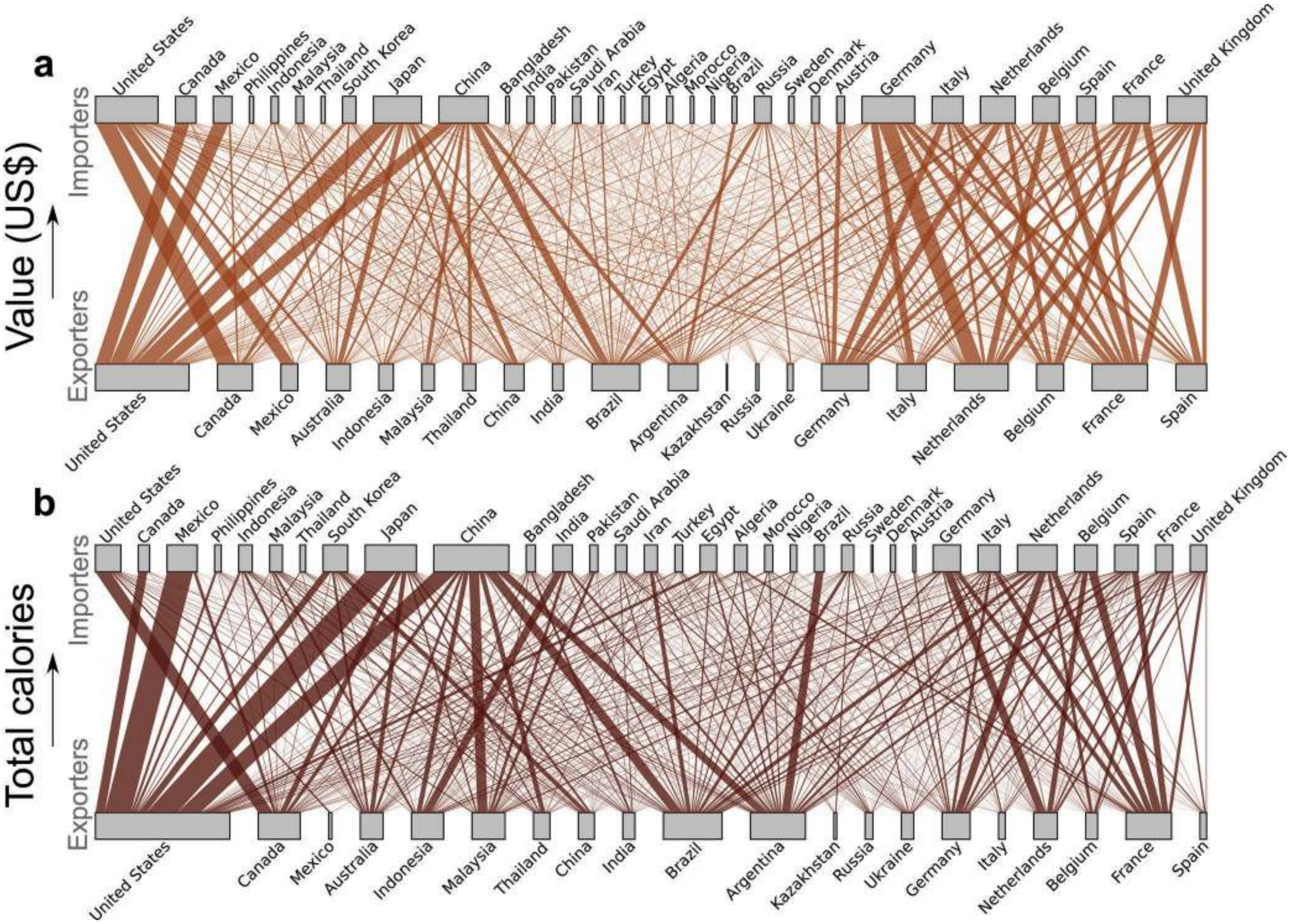

***Figure 2. The structure of global agricultural trade for major importing and exporting countries in terms of (a) monetary value and (b) calories. These network graphs highlight the greater concentration of monetary value traded among European Union countries (grouped on the right) and NAFTA countries (grouped on the left) than for calories. The countries are sorted geographically by region. Brazil, Argentina, Malaysia, and Indonesia each contribute more to global calorie trade than to monetary trade. For this comparison, we used the country-reported trade database for both metrics, which includes both direct and indirect trade relationships. The line thickness indicates the relative magnitude of each trade flow.***

food crops with fine resolution water productivity data from Brauman and colleagues (2013). These 16 crops accounted for more than 85% of the traded calories from 2000 to 2009. We found that approximately 810 cubic kilometers (km$^3$) per year of water was consumed to produce exports of these crop commodities worldwide (approximately 65 km$^3$ per year as irrigation water, plus about 745 km$^3$ per year from rainwater). We therefore estimated that 8% of the total water embodied in international trade was derived from irrigation, which closely reflects the results from Hoekstra and Mekonnen (2012) for 1996–2005 for these 16 major food crops (9% of total embodied water from irrigation, including about 63 km$^3$ per year as irrigation water plus around 707 km$^3$ per year from rainwater). We found that the structure of total embodied water trade was highly correlated with embodied cropland area trade across more than 20,000 trade flows (Spearman's $\rho = .99$, $p < .001$), suggesting that cropland area adequately captured patterns in total water use. We therefore focus here on embodied irrigation water consumption, given its more direct role in freshwater scarcity and distinctive geographic distribution compared with embodied land.

In some cases, embodied irrigation water for exports flows from countries with relatively high per capita water availabilities to more water-limited countries (figure 4), which might reflect a comparative advantage in embodied irrigation based on relative water availabilities (Wichelns 2004). The United States (29% of embodied irrigation consumption), Pakistan (15%), India (14%), Thailand (11%), China (3%), Mexico (2%), Australia (2%), Egypt (2%), and France (2%) contributed disproportionately (about 80%) to the global embodied irrigation water trends. Major exporting countries have distinctive embodied irrigation water trade structures. For example, the United States is relatively

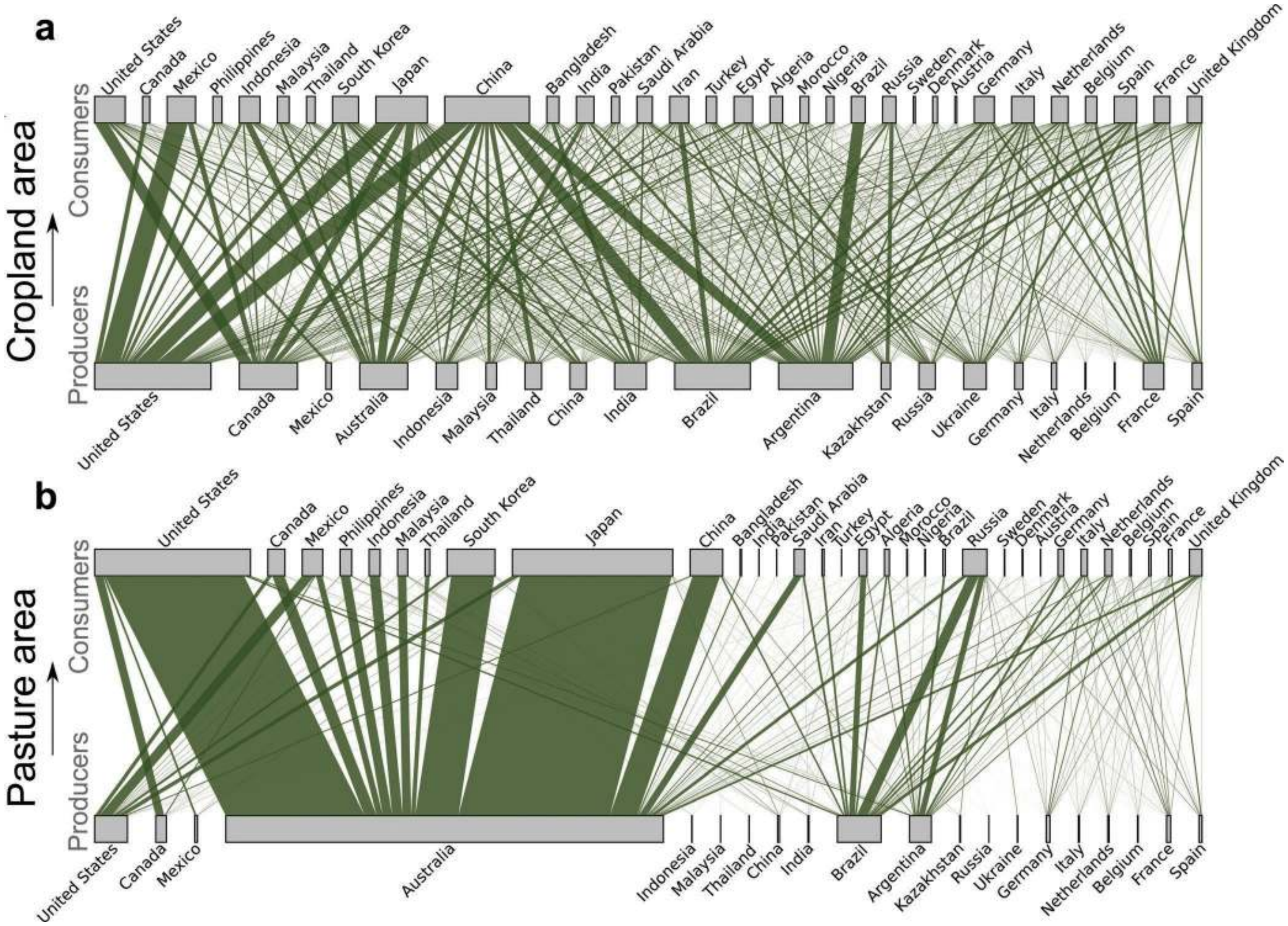

***Figure 3. The structure of trade among major trading countries in terms of (a) embodied cropland harvested area (245 million hectares) and (b) embodied pasture or forage area (377 million hectares) based on biophysical accounting techniques. Embodied land use is concentrated in major export-producing countries, such as the United States, Brazil, Argentina, Canada, and Australia. These network graphs are based on the producer–consumer trade database and therefore omit indirect trade relationships wherever possible. Panel (a) includes all 139 crops and 10 livestock animals, whereas (b) includes only ruminant product exports (including milk). See supplemental tables S2 and S3 for a detailed list.***

water rich and exports large amounts of embodied irrigation water to key importing countries; in contrast, a more water-limited country, such as Pakistan, allocates water consumption across a greater number of small bilateral trades, typically to other water-limited countries.

## Trade composition and resource endowments

Country engagement in food and embodied resource trade may arise from complex interactions among domestic resource endowments, population, affluence, overall agricultural productivity, and evolving trade policies (Dalin et al. 2012, Fader et al. 2013, Weinzettel et al. 2013). Several studies have examined how countries compensate for limited productive land areas, resource scarcity, or domestic policies that favor nonagricultural land uses by importing crops (Erb et al. 2009, Lambin and Meyfroidt 2011, Haberl et al. 2012). We explored some of these factors and how they influence trade structure among metrics.

The trade structure for each metric was closely linked to export composition—the relative mix of commodities exported and the degree of specialization. Export composition, itself, is driven by various factors, including technology, wages, and the relative endowment of productive resources (Anderson 2010). Economists have assessed such instances of comparative advantage using a variety of models with varying levels of complexity (Maneschi 1999); a classic example is the Heckscher–Ohlin model, which predicts that a nation gains comparative advantage by exporting commodities that intensively use its relatively abundant factors. To assess the influence of relative factor endowments on our results for two metrics with divergent trade structures, we calculated embodied export values in terms of cropland

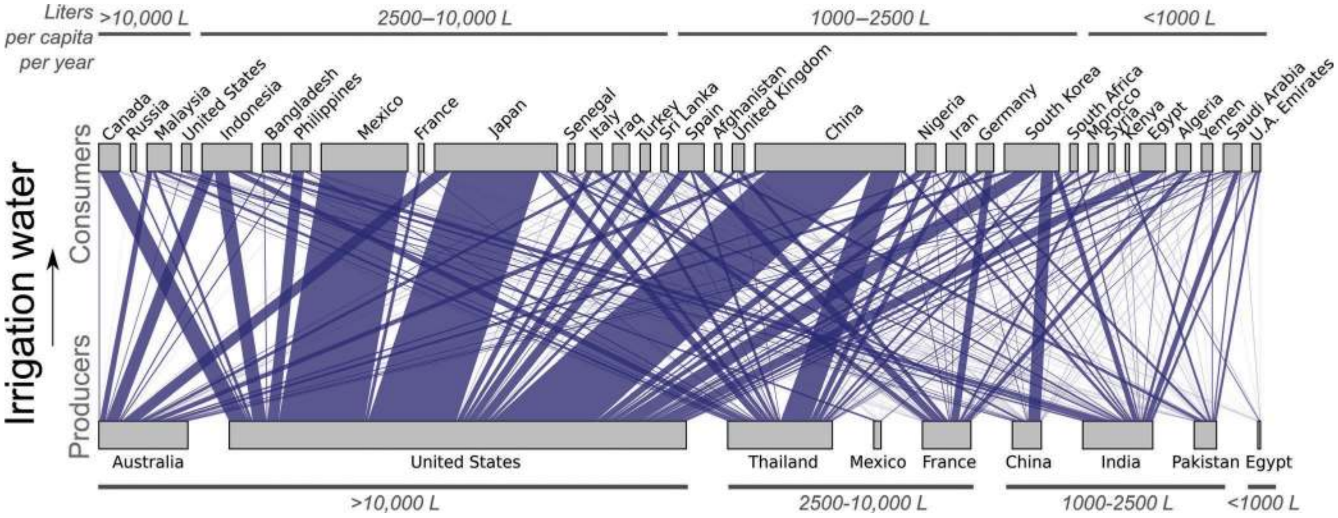

***Figure 4. The structure of global embodied irrigation water consumption for 16 major food crops from Brauman and colleagues (2013), highlighting how embodied irrigation water often flows from more water-rich to more water-limited countries. These countries represent approximately 80% of all irrigation water consumption for the production of 84 exported food commodities. Importing and exporting countries are sorted according to quartile groups of per capita total renewable freshwater (in liters [L] per inhabitant per year), which represents the sum of all internal surface water resources, the net renewable surface waters entering the country, and renewable groundwater (FAO Aquastat 2014). The quartile groups are indicated by the horizontal lines.***

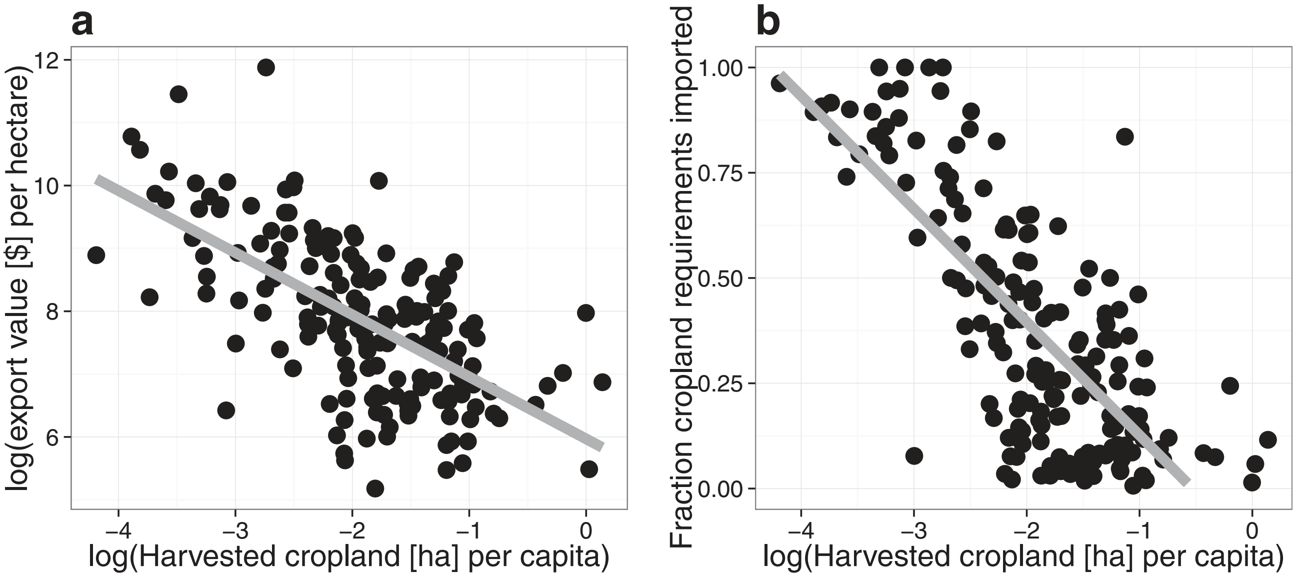

***Figure 5. Cropland harvested area per capita is a simple indicator of how countries engage in trade. (a) Across a subset of 177 countries with more than 0.01 hectares (ha) of cropland per capita summed over 139 food crops, we found that countries with low cropland endowments typically export commodities with higher embodied values per hectare (in dollars per cropland area used for exports), and vice versa. This relationship supports the influence of comparative advantage on trade structure (*****$R^2 = .40$, $p < .001$*****). (b) Harvested area per capita is also a moderately strong predictor of the fraction of cropland requirements met by imports (*****$R^2 = .38$, $p < .001$*****). Linear regression lines are shown in grey.***

(US dollars per cropland hectare used; figure 5a). Across countries, the export value per unit of embodied cropland was negatively and linearly correlated with increasing per capita endowment of cropland ($R^2 = .40$, $p < .001$). For example, Australia had more than one harvested hectare per person and its exports were worth roughly $960 per embodied hectare; in contrast, Belgium had less than 0.1 hectares per person, and its exports were worth more than 15 times those of Australia per unit cropland (more than $15,000 per hectare). Although we considered only one factor of

*Table 1. Summary statistics for cropland area embodied in global trade by commodity or commodity group.*

| Commodity groups | Crop harvested area (in millions of hectares) | Percentage of global harvested area by commodity | Key exporting countries[a] | Key producing countries[a] |
|---|---|---|---|---|
| Wheat | 50 | 23 | 8 | 16 |
| Soybean | 46 | 52 | 4 | 5 |
| Rapeseed and other oil crops | 32 | 37 | 14 | 17 |
| Meat and animal products | 27 | Not calculated | 13 | Not calculated |
| Rice and other cereals | 22 | 7 | 13 | 15 |
| Coffee, tea, cocoa, and spices | 17 | 69 | 13 | 15 |
| Maize | 14 | 10 | 5 | 11 |
| Pulses, vegetables, and roots | 12 | 7 | 14 | 12 |
| Fruits and nuts | 11 | 13 | 28 | 16 |
| Sugar cane and beet | 8 | 29 | 7 | 10 to 11 |
| Oil palm | 6 | 47 | 2 | 4 |

*Note:* These results are based on the producer–consumer database. Key exporting and producing (domestic + trade) countries are shown on a harvested cropland area basis. If the number of key producing countries was less than that of key exporting countries, total production is more concentrated than exports, and vice versa. [a]Based on the relative share of global embodied and total harvested areas in major producing countries for each commodity group, calculated with the inverse Herfindahl index of market concentration.

production (cropland area), these results support the influence of comparative advantage on trade in embodied land across countries.

We also examined export specialization among countries. Exporters contributing greater shares of global trade value often specialize in more high-value commodities (e.g., Belgium and the Netherlands). Countries exporting maize or oil crops had greater shares of calorie trade (e.g., the United States and Malaysia), and countries exporting wheat, soybean, and beef contributed most to embodied land area (e.g., Australia, Argentina, and Brazil). These patterns reflect the interaction of trade volumes, commodity prices, calorie densities, and agricultural land productivities. For example, oil palm uses less land to produce the same amount of calories as soybean (global mean yield of 19.2 million kcal per hectare versus 5.3 million kcal per hectare, respectively) and both are worth less money than cocoa beans per calorie ($65–$96 per million kcal versus $438 per million kcal, respectively). This is a primarily physical explanation of the differences in trade structure among metrics.

Some agricultural commodities were more export-oriented than others, which affected export composition for specialist countries (table 1). For example, high-value crops such as coffee, tea, cocoa, and spices accounted for only 7% of the embodied harvested area, but 69% of this group's global harvested area was devoted to exports. Similarly, although oil palm trade formed a relatively small share of export value (figure 1b), almost half (47%) of its global harvested area was used for exports. In contrast, maize and wheat were among the largest contributors to calorie trade but were geared toward domestic consumption, with only 10% and 23% of their areas used for exports, respectively. A central factor underlying these patterns may be a global shift in diets toward more energy-dense imported foods (Khoury et al. 2014).

In addition to affecting the structure of gross exports, the total mix of commodities traded can lead to different conclusions about net food trade for some countries (i.e., whether a country is a net importer or a net exporter). Table 2 shows countries in which discrepancies between value and calories were particularly influential across their total imports and exports. Such cases often arise when countries export luxury commodities (e.g., coffee, tea, wine) but import lower-value food staples (e.g., wheat, maize), calorie-dense oils (e.g., palm oil), or resource-intensive livestock feeds (e.g., soybean). For example, recent studies have reached different conclusions about China's trade balance in terms of cropland area. Our results indicate that China was a net cropland importer in the 2000s, which agrees with other biophysical accounting studies (Qiang et al. 2013, Kastner et al. 2014b). In contrast, recent value-based MRIO studies indicated that China was a net exporter of embodied cropland (Weinzettel et al. 2013, Yu et al. 2013, Kastner et al. 2014b). We suggest that these disparities may arise, in part, from China exporting relatively higher-value commodities (e.g., apples and other fruit) than it imports (e.g., soybean and palm oil). Such compositional effects could distort the interpretation of trade balance when researchers rely solely on value-based metrics.

**Reexport influence on embodied resource attribution.** Some differences in trade structure among metrics reflect our exclusion of intermediary trade partners to estimate embodied resources (see box 1). To assess the sensitivity of global trade analyses to reexport adjustments, we compared calorie exports among directly reported trade flows (figure 2b) and calorie trade under reexport-adjusted trade flows (i.e., attributing calories only to countries that produced exported crops). We found that 8% of global calorie exports were reallocated from countries that reported crop commodity

*Table 2. Examples of large- and medium-sized countries for which metric choice and trade composition can influence our understanding of trade balance.*

| | Net balance of trade under each metric (largest commodity exported or imported out of total trade) | | |
|---|---|---|---|
| **Country** | **Monetary value**[a] | **Calories**[a] | **Cropland area**[b] |
| India | Exporter (rice) | Importer (oil palm) | Exporter (soybean) |
| Kenya | Exporter (tea) | Importer (oil palm) | Importer (wheat) |
| South Africa | Exporter (grapes)[c] | Importer (wheat) | Importer (wheat) |
| Spain | Exporter (olives) | Importer (wheat) | Importer (soybean) |
| Turkey | Exporter (hazelnuts) | Importer (wheat) | Importer (sunflowerseed) |
| Colombia | Exporter (coffee) | Importer (maize) | Importer (soybean) |
| Vietnam | Exporter (coffee) | Importer (soybean) | Importer (soybean) |
| Poland | Exporter (milk) | Importer (soybean) | Importer (soybean) |

*Note:* All countries listed here have populations of more than 30 million people and more than 3 million hectares of harvested cropland.
[a]Country reported database. [b]Producer-consumer database. [c]Used for wine exports.

exports to countries estimated to have originally grown those crops. Five countries contributed most to reexports: the Netherlands (18% of the total calorie reallocation), Germany (9%), Belgium (9%), the United States (6%), and Malaysia (6%). Using the same approach to assess sensitivity for embodied cropland area, we found that misattribution of production to countries reexporting commodities (often after value-added processing) generates an approximate 7% overestimate of global embodied cropland area. About 9.6 million hectares of cropland would have been incorrectly attributed to EU nations that reexported crop commodities grown in other regions, which would have affected the estimates of domestic cropland dedicated to exports for some countries. Supplemental figure S3 provides a statistical comparison showing the potentially large effects that misattribution can have on the relative estimates of individual bilateral trade flows. Biophysical accounting research should account for reexports to avoid misattribution of embodied resource use in the global trade network.

## Resource-intensity of trade relationships

Export-orientated crop production is a dominant driver of cropland expansion (Huber et al. 2014, Kastner et al. 2014a). When countries import agricultural commodities rather than producing them domestically, they may displace associated environmental problems abroad (Meyfroidt and Lambin 2010). Land-use change in tropical countries related to commodity crop expansion is a crucial example of such displacement (DeFries et al. 2013) and includes large-scale expansion of export-oriented oil palm and soybean production in Indonesia and Brazil, respectively (Carlson et al. 2013, Karstensen et al. 2013).

The degree to which export production is geographically concentrated can have important implications for embodied resources and food security (West et al. 2014). If commodities are sourced predominantly from a single region, this could also concentrate environmental externalities related to export production, such as deforestation (DeFries et al. 2013). Major exporting countries may also produce commodities more efficiently than importers; such a situation would decrease resource use relative to a hypothetical situation with no trade (Kastner et al. 2014a). However, producing countries that specialize in exports of commodity crops (e.g., oilseeds) may need to import food staples despite having large cropland endowments. Concentrated trade relationships could also raise importer susceptibility to price spikes if crop production is disrupted or if governments impose export restrictions following droughts (Headey 2011, Fader et al. 2013).

We assessed the concentration of harvested area for each crop on the basis of the relative share from each producing country, following the inverse Herfindahl index of market concentration described by Andrew and colleagues (2013). We found that the distribution of key exporting and producing countries differed widely among commodities (table 1), with exports typically more concentrated than total production. Just five countries accounted for 97% of the soybean area, 96% of the oil palm area, and 76% of the maize area used for exports. These trends may reflect the biophysical growing conditions for particular crops, especially tropical commodities (e.g., oil palm), for which exports and total production occur in a similarly small number of countries (table 1). Conversely, the embodied wheat area and the total wheat growing area were more distributed across countries, most likely because wheat is a global food staple that is also grown in a range of climates (Mueller et al. 2012). Domestic agricultural policies to promote certain crops could also influence concentration. For example, the total maize producing area was distributed across 11 countries, but 40% of the embodied maize area for exports was concentrated in the United States, where maize production is subsidized.

**Resource-intensive megatrades.** A small number of bilateral trade relationships of certain commodities embodied a disproportionately large amount of cropland and irrigation water. We considered approximately 398,000 bilateral trade

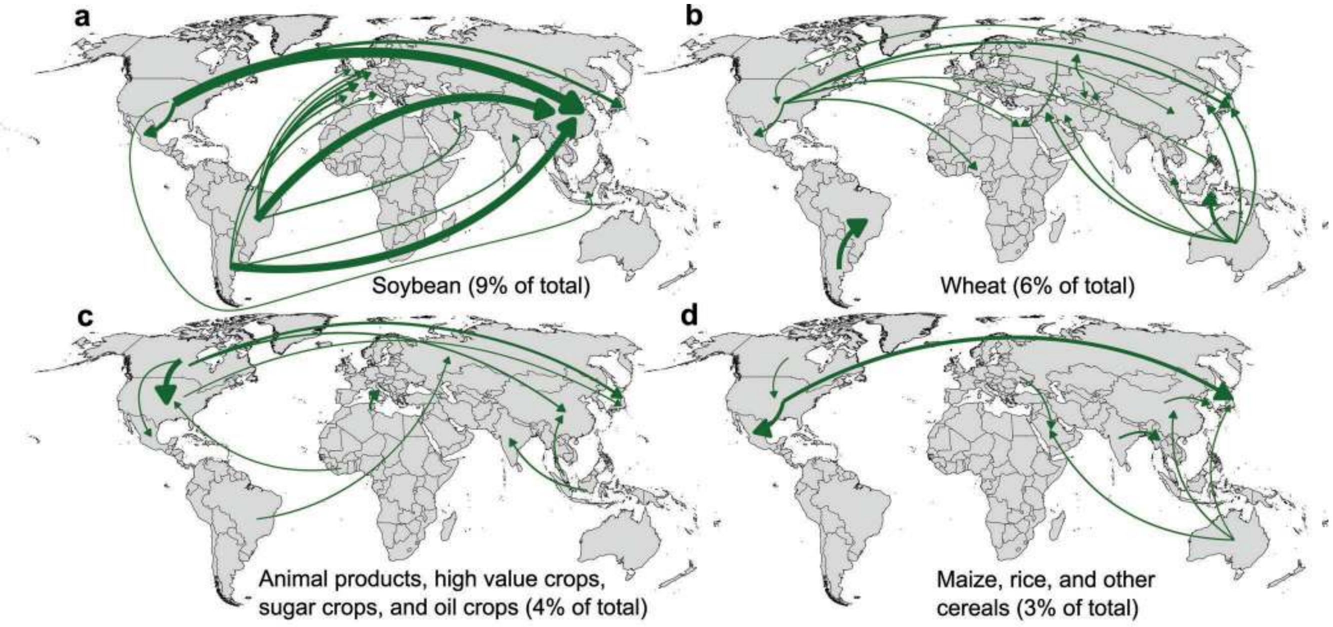

*Figure 6. The 55 largest embodied cropland area megatrades. Each arrow represents a trade for a given commodity or commodity group that used more than 500,000 hectares (see supplemental figure S4a for quantitative depiction). Out of approximately 398,000 bilateral trade relationships for different commodities, these disproportionately large trade relationships represented 22% of the global embodied area (the percentage of this total is shown separately for each commodity group in panels [a] through [d]). The thicker lines indicate relatively larger cropland area use for that trade relationship.*

flows for individual crops and livestock products for the period of 2000 to 2009. From these, we identified a small number that disproportionally influenced global embodied resource use.

For harvested area, trades embodying more than 500,000 ha for a given commodity group were disproportionately large (see supplemental figure S4a for cumulative distribution curves on which this threshold is based). The 55 commodity trades of this size accounted for about 22% of the cropland area embodied in global exports. In particular, the soybean area used for exports was associated with a few extremely large trades, especially from the United States and Brazil, to China (figure 6a). Although most bilateral wheat exports embodied relatively smaller areas, two trades stood out: 2.2 million ha used for wheat exported from Argentina to Brazil and 1.5 million ha for exports from Australia to Indonesia. Such large and land-intensive wheat trades provide a key food staple to countries that specialize in oilseed exports (soybean in Brazil and oil palm in Indonesia).

Irrigation water consumption for trade mostly reflects the interaction of management and climate for specific exporting countries with production in water-limited areas (Brauman et al. 2013). For example, 86% of Pakistan's export production was irrigated, mostly for rice and wheat, compared with 29% of the export production in India, 9% in the United States, and 4% in France. The 101 commodity trades embodying the most irrigation water (with more than 125 billion liters each) accounted for half of the global embodied irrigation consumption (figure S4b). These largest embodied irrigation trades were strongly associated with rice exports, often from relatively less water-rich countries and imported by net food importing developing countries in which rice is an essential food staple (FAOSTAT 2013). The Middle East and parts of sub-Saharan Africa were particularly dependent on foreign irrigation water, associated with rice imports from Pakistan and India (figure 7a). Maize and soybean exports from the United States to Japan, China, and Mexico (figure 7b) also involved extremely heavy irrigation water consumption.

## A synthetic typology of agricultural trade

We propose a simple typology (figure 8) to characterize the relative role that countries play in agricultural globalization. We base our typology on cropland area, which is useful for understanding resource use, because it is highly correlated with total water consumption, offers a straightforward comparison with domestic land use and is more directly linked to food availability than is pasture. We hypothesized that cropland endowment can explain the degree to which countries engage in trade by consuming commodities grown on foreign croplands. Our analysis showed that this is often the case (figure 5b), although some countries engaged more or less in trade than might be expected solely on the basis of their cropland endowments. These typologies compare our embodied cropland results with domestic cropland area across the 193 countries with available data.

*Cropland importer* countries import a minimum of 10% of their cropland requirements (with a mean import share

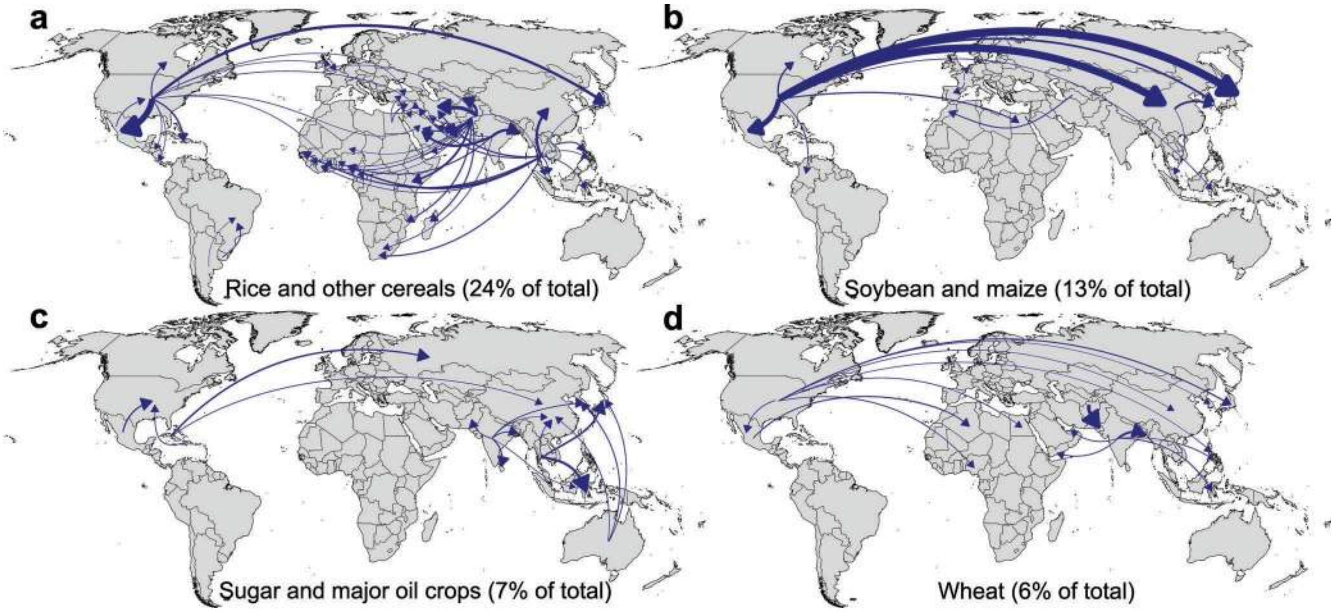

***Figure 7. The 101 largest embodied irrigation water megatrades as a function of commodity or commodity group. Each arrow represents a trade flow that required at least 125 billion liters of water exclusively from the irrigation water component of irrigated production systems for a given commodity or commodity group (see supplemental figure S4b for a quantitative depiction). These disproportionally large trade relationships accounted for half (50%) of the global embodied irrigation water consumption (the percentage of this total is shown separately for each commodity group in panels [a] through [d]).***

of 54%) and devote relatively smaller fractions of domestic cropland to export production. Most cropland importers have per capita cropland endowments below the global mean (87% of these countries had less than 0.2 hectares per capita). In total, 61 countries with a combined population of 700 million people displace more than half of their crop harvested area requirements, with the largest including the Netherlands, Japan, Saudi Arabia, South Korea, Malaysia, the United Kingdom, Italy, and Germany. Some of these countries may be fundamentally reliant on imports because of resource constraints; however, countries such as South Korea and Germany could theoretically reduce their import reliance if more of their domestic resources were devoted to domestic crop production (Fader et al. 2013).

*Cropland exporter* countries are those that use more than 10% of their cropland areas to produce exports (a mean of 44%) while offsetting relatively smaller fractions of their cropland area requirements to other countries. These countries accounted for more than 60% of all cropland area embodied in exports but just 12% of embodied cropland imports. Argentina, Canada, and Australia dedicated particularly large shares of their domestic harvested areas to export production (70–83%). The United States was also export oriented in terms of cropland use (more than 35% of its harvested area used for exports). Although the United States was the third largest importer of harvested area—mostly for fruit, meat, minor cereal crops, and luxury commodities—the area embodied in these imports was less than half of the area that it devoted to exports.

*Cropland exchanger* countries have cropland areas embodied in both imports and exports that are comparable in size. For these countries, imports form more than 10% of the cropland required for domestic consumption, and the cropland area used for exports is more than 10% of that used for domestic use. Countries such as Russia, Indonesia, and France imported roughly the same amount of harvested area as they exported. These relationships often involve trading staple crops for high-value commodities or oil crops, which supports our hypothesis that export specialization influences the degree to which countries import food staples. These cases also support the notion that prevailing diets and consumption patterns have been influenced by globalization (Khoury et al. 2014). For example, Kastner and colleagues (2014a) found that as much as a quarter of the global cropland used for export production was devoted to crops not produced by importing nations (e.g., coffee).

*Primarily domestic cropland use* countries have comparatively little engagement in trade, with less than 10% of their harvested area requirements coming from imports and less than 10% of their domestic harvested area dedicated to export production. These countries were exclusively in Africa and Asia (figure 7d). Most notably, although India contributed a large fraction (about 5%) of the global embodied cropland area, it used only 7% of its own harvested area for export production. Many domestic-oriented countries identified in our study have relatively low crop yields (Foley et al. 2011). Such situations mean that by importing a larger fraction of their calorie consumption from countries with higher yields, these nations may have reduced their total harvested

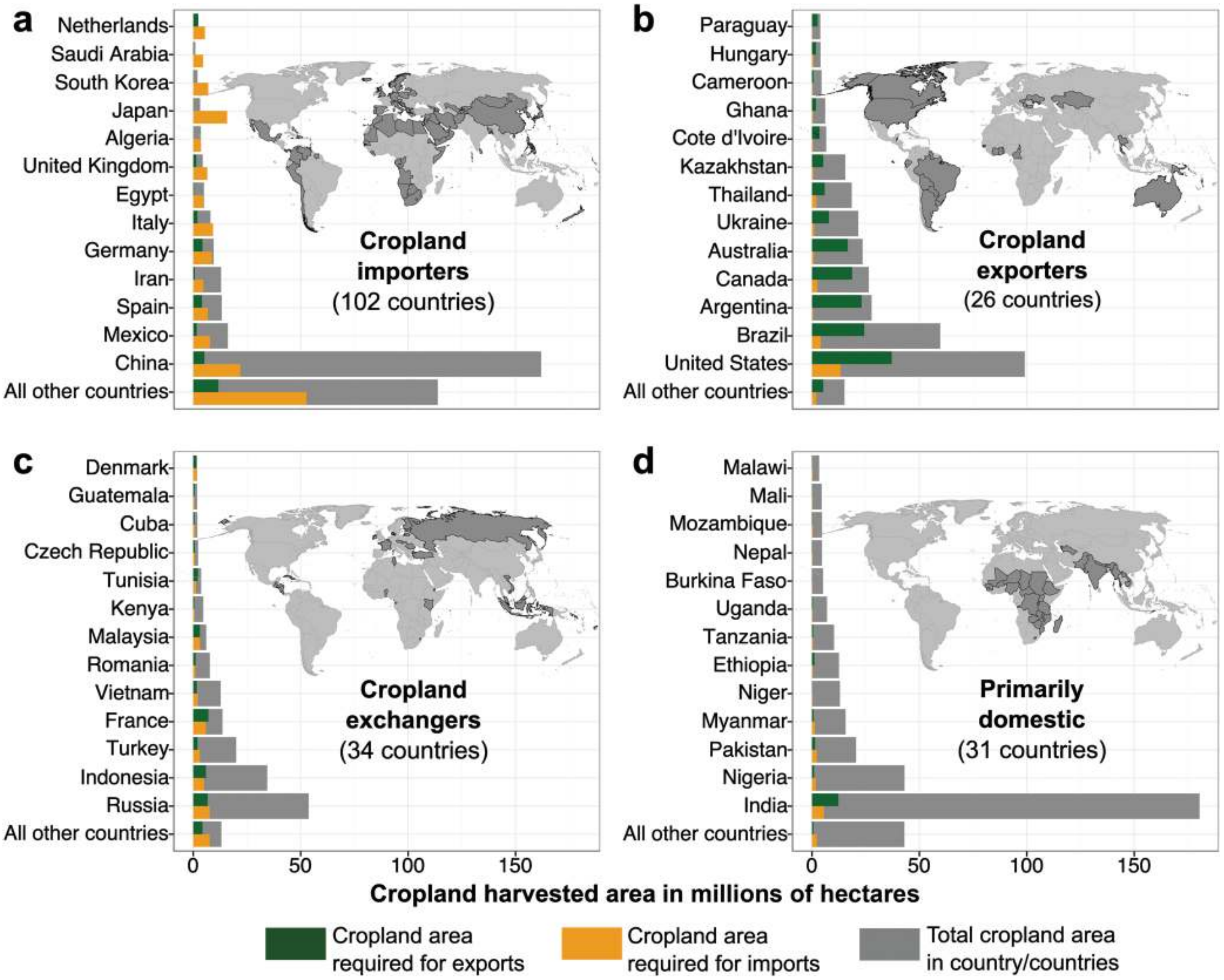

*Figure 8. A typology of trade engagement relating embodied harvested area to total domestic harvested area across 193 countries (the values are means of those for 2000–2009). Cropland (a) importers (e.g., Japan and Mexico) and (b) exporters (e.g., Argentina and Canada) have relatively large fractions of domestic cropland area linked to trade. Cropland (c) exchangers (e.g., Russia, France, and Indonesia) participate widely in trade but with comparable magnitudes of embodied cropland imports and exports. Primarily (d) domestic countries (e.g., India and Nigeria) have less than 10% of their total cropland requirements (production + imports – exports) met by imports and less than 10% of their domestic cropland used for export production. These groupings illustrate how countries allocate resources to domestic and foreign consumption.*

area requirements. These nations may be less integrated in global trade for a variety of reasons, especially a lack of market access based on high trade costs and transport margins (Verburg et al. 2011). How agricultural productivities and transport infrastructure evolve this century could affect the number of countries in this category (Hertel et al. 2014, Laurance et al. 2014), particularly in nations that already have relatively high cropland endowments (figure 5b).

## Alternative typologies

A typology of trade based on embodied irrigation consumption would be distinct from one based on cropland area. Countries that require irrigation because of dry climates may offset the need to irrigate by importing crops grown without the need for irrigation abroad (Dalin et al. 2012, Brauman et al. 2013). For example, we found that one of the largest global wheat exports was from the United States (where 11% of wheat production was irrigated) to Egypt (where 98% of wheat production was irrigated)—theoretically offsetting approximately 1.8 trillion liters of irrigation water in Egypt with US rainwater. However, not all trade structures achieve irrigation savings or enhanced water-use efficiency. If water-scarce countries import from other water-scarce regions, this only shifts the burden of irrigation demand abroad

(Hoekstra and Mekonnen 2012). Appropriate pricing and water markets are one strategy to improve the allocative efficiency of water use in agriculture and among other sectors (Turner 2004). However, low prices for water in most agricultural settings mean that there is generally no economic signal of scarcity to farmers (Tsur 2010). Regardless of price, farmers may improve water-use efficiency but continue to export significant amounts of embodied water if more valuable factors of production are optimized (Tsur 2010).

Demand for foreign livestock products also has complex implications for global resource use, reflecting the diversity of livestock systems and the range in production efficiencies (Galloway et al. 2007, Herrero et al. 2013). Our results indicate that at least 8% of the global agricultural land base was directly linked to exported animal products. Ruminant product imports and their respective source regions substantially influenced the trade position of some countries in terms of total land requirements. For example, we estimated that exported beef from Australia and Brazil was much more likely to be produced on pasture (more than 85% of ruminant feed demand was met by pasture) than beef in the United States (more than 30%). Because the United States also imports beef, it was a net importer of embodied pasture (approximately 58 million hectares), greatly reducing its position as an overall land-use exporter. Japan and China are even more strongly net land importing because of their consumption of ruminants raised on foreign pasture. Including the indirect impact of countries using imported crops to produce livestock for domestic consumption would further emphasize how meat consumption contributes to agricultural globalization (Cassidy et al. 2013).

### Diets and nutritional security via imports

Few empirical estimates exist regarding how many people can be nourished by global trade based on either calories or more complex nutritional metrics (but see D'Odorico et al. 2014). To provide an initial account of how imported calories enter domestic food supplies (either directly as food for people, as livestock feed, or for other industrial nonfood purposes), we used the basic approach of Cassidy and colleagues (2013) with FAOSTAT (2013) data. We found that approximately 66% of imported calories could enter domestic food supplies after accounting for nonfood uses, meaning that approximately 1.7 billion people could be fed each year from agricultural trade (see figure S2). The trade in nonfood calories was greatest for soybean and maize exports from the United States to its key trade partners (Japan, China, and Mexico). The ability of different communities to access food imports (Naylor and Falcon 2010) and food waste along supply chains (Kummu et al. 2012) are other factors affecting nutritional security in importing countries. Quantifying the composition and structure of global trade using alternative metrics of nutritional quality and security, such as vitamins and micronutrients, is a clear research priority. However, value-based aggregations integrate other aspects of nutritional quality and consumer utility not considered here, because prices can reflect a variety of desired characteristics.

### Conclusions

In the present study, we considered the biophysical and economic context of trade relationships and revealed distinct geographies of agricultural globalization. We examined how the metrics used to assess trade relationships can influence the understanding of the major players in agricultural globalization and whether some countries were net food importers or exporters. These multidimensional considerations can be more widely addressed in trade research because differences among metrics often simply reflect the mix of commodities traded. The influence of trade composition on trade structure can therefore be accounted for by considering the differences in embodied values per unit calorie or land (figures 1c and 5a). Although it was implicit in our analyses, we did not examine how commodities are transformed along supply chains and the indirect relationship this could have with other economic sectors, which is a key benefit of value-based MRIO approaches (Lenzen et al. 2012b). However, our findings based on bilateral trade relationships suggested that metric choice is important to consider when designing supply chain research. This is particularly true for high-value crop commodities and animal products, for which value diverges considerably from biophysical characteristics.

Research on agricultural trade can be used to explore hypothetical scenarios, such as how different trade configurations could maximize value and nutritional security while minimizing irrigation consumption and embodied land use. Globalization of agriculture could, in theory, help optimize global resource use while meeting growing food demands, but it could also carry large environmental consequences, depending on the location and efficiency of the new production (Hertel et al. 2014). Several studies have suggested that exports tend to originate in countries with relatively more efficient production than that in importing nations, including land use, water use, and nutrient use (Dalin et al. 2012, Schipanski and Bennett 2012, Kastner et al. 2014a). However, our results also suggest that higher resource endowments in some major exporting countries may facilitate land- or water-intensive exports despite lower efficiency. Research on embodied water trade demonstrates many examples in which trade occurs despite relative disadvantages in terms of water availability, possibly because of inadequate water pricing (Hoekstra 2013).

Given the distinct patterns in embodied cropland, pasture, and irrigation use for trade, considering multiple dimensions of production efficiencies and ecological impacts could help guide more holistic decisionmaking surrounding trade and the environment. For example, we show that the United States imports land-intensive pasture-grazed beef from Australia but simultaneously exports predominantly grain-fed beef to other countries, with complex implications for both domestic and global land use. The degree to which such trade arrangements affect local ecosystems or problems such as greenhouse gas emissions is crucial to determining the environmental costs and benefits of trade. Biologists are well positioned to explore how land use linked to export production could affect ecosystem services and biodiversity worldwide.

Metric choice can lead to divergent interpretations of trade composition and structure that, if they are unacknowledged, could contribute to contrasting policy prescriptions related to agricultural trade. We considered economic, nutritional, and environmental dimensions of globalization, but our analyses did not capture deeper components of individual metrics, including the effects of trade on farmer livelihoods (le Polain de Waroux and Lambin 2012); land tenure rights (Rulli et al. 2013); water scarcity and pollution (O'Bannon et al. 2013); the ecological value of embodied land use (Lenzen et al. 2012a); and differences in management intensities within and among countries (Mueller et al. 2012). Our study suggests that the consideration of multiple metrics—including nutritional and resource-related metrics—could advance research in these interdisciplinary topics related to agricultural trade. The strengths and limitations of particular metrics used to quantify such food and resource interdependencies among nations should be given more consideration in international decisionmaking in this globalizing era.

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## Supplemental material

The supplemental material is available online at *http://bioscience.oxfordjournals.org/lookup/suppl/doi:10.1093/biosci/biu225/-/DC1*.

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*Graham K. MacDonald (graham.k.macdonald@gmail.com), Kate A. Brauman, Shipeng Sun, Kimberly M. Carlson, Emily S. Cassidy, James S. Gerber, and Paul C. West are affiliated with the Institute on the Environment at the University of Minnesota, in St Paul. Shipeng Sun is currently affiliated with the Department of Environmental Studies at the University of Illinois at Springfield. Emily S. Cassidy is currently affiliated with the Environmental Working Group, in Washington, DC.*