RESEARCH ARTICLE

CLIMATE ECONOMICS

Land-use emissions embodied in international trade

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International trade separates consumption of goods from related environmental impacts, including greenhouse gas emissions from agriculture and land-use change (together referred to as "land-use emissions"). Through use of new emissions estimates and a multiregional input-output model, we evaluated land-use emissions embodied in global trade from 2004 to 2017. Annually, 27% of land-use emissions and 22% of agricultural land are related to agricultural products ultimately consumed in a different region from where they were produced. Roughly three-quarters of embodied emissions are from land-use change, with the largest transfers from lower-income countries such as Brazil, Indonesia, and Argentina to more industrialized regions such as Europe, the United States, and China. Mitigation of global land-use emissions and sustainable development may thus depend on improving the transparency of supply chains.

Human land use, while producing vast quantities of agricultural and forestry products, has also disrupted ecosystems (*1*), degraded biodiversity (*2*), and added considerable quantities of greenhouse gases (GHGs) to the atmosphere (*3*). However, as a result of international trade, environmental effects have often occurred in different regions from where products are consumed (*4*, *5*). Previous studies have thus quantified energy-related emissions of CO_2 embodied in global trade (i.e., traded goods and services) (*6*, *7*), as well as air pollution (*8*) and land (*9*–*11*) and water resources (*12*, *13*) virtually embodied in trade. However, previous assessments of land-use GHG emissions embodied in trade have focused on specific regions and commodities such as Brazilian cattle and soybeans (*14*) or meat (*15*), with no comprehensive global analysis of emissions from both agriculture and land-use change.

Global analysis of trade-related land-use emissions has been hindered by a lack of sufficiently detailed estimates of country-, region-, and product-specific land-use emissions [including emissions from both agriculture and land-use change (LUC)] (*14*, *16*, *17*). However, a recent study (*3*) has now supplied the necessary data showing that land-use emissions represent ~25% of net anthropogenic GHG emissions in recent years, about half the amount as methane (CH_4) and nitrous oxide (N_2O) emissions from agricultural production (including both crops and livestock) and half as CO_2 emissions from LUC (*3*, *18*–*21*). These land-use emissions are substantial enough to threaten international climate goals even if fossil fuel emissions are drastically reduced (*3*, *22*). Trade-related accounting of global land-use emissions is needed to reveal the international drivers of land-use emissions and to better target and coordinate mitigation efforts.

We present comprehensive estimates of land-use emissions embodied in international trade. Details of our analytic approach are described in the materials and methods (*23*). In summary, we use a multiregional input-output model to attribute land-use emissions associated with the production of various agricultural and forestry products to final consumption in 141 world regions (most individual countries) in the years 2004, 2007, 2011, 2014, and 2017. Trade data are from the Global Trade Analysis Project (GTAP) and production-based estimates of land-use emissions and agricultural products are from Hong *et al.* (*3*), which are in turn based on agricultural emissions from the United Nations Food and Agriculture Organization (FAO) (*24*) and LUC emissions from a spatially explicit bookkeeping model (BLUE) (*16*, *21*). By using the "base case" accounting assumptions of Hong *et al.* (*3*), we report emissions in units of CO_2 equivalent (CO_2-eq) with the 100-year global warming potentials of CH_4 and N_2O and assign land-use

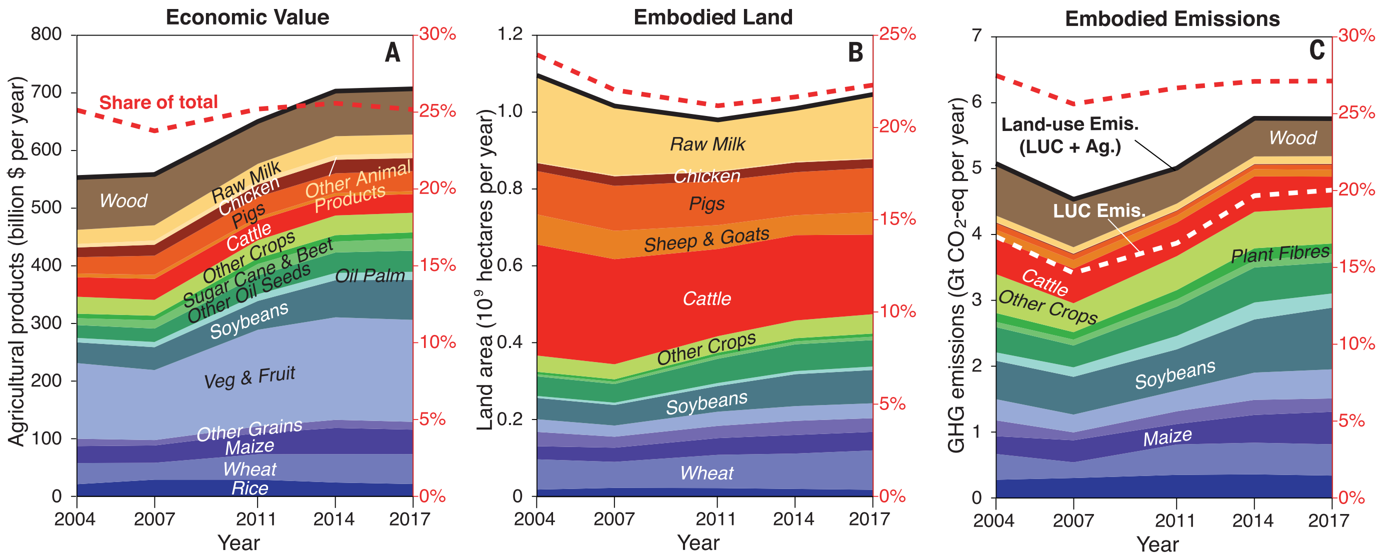

Fig. 1. Agricultural products, land use, and land-use emissions embodied in international trade. (**A**) Global agricultural and forestry products, (**B**) agricultural land use, and (**C**) land-use emissions embodied in trade over 2004 to 2017 by product (sector). In each panel, the global total is indicated by the bold black line. The right *y* axis shows what share of total agricultural value, land use, and emissions are embodied in trade. In (A), the agricultural products traded are in units of constant 2004-2006 billion international dollars. In (C), the subset of land-use change (LUC) emissions is indicated by the dashed white line.

change emissions to the years in which they probably occurred ("legacy" emissions). We exclude carbon uptake related to abandoned agricultural land, as it is not possible to associate such land with a specific product. The input-output approach—widely used for calculating embodied emissions (*6*, *7*)—maps emissions to the region where related goods are ultimately consumed (consumption emissions), even if the products are transshipped through an intermediary region or are intermediate constituents in a multiregional supply chain. Therefore, our trade analysis provides valuable information beyond bilateral trade data, which do not track such re-exports (*12*, *25*). The difference between each region's production emissions and consumption emissions represents the net emissions embodied in trade and is therefore equal to the emissions related to imported goods minus the emissions related to exported goods. Lastly, we analyze the driving factors of country- or region-level changes in embodied emissions from 2004 to 2017 by a structural decomposition analysis. Our analysis is focused on land-use emissions embodied in international trade at the national scale; thus, subnational and smaller-scale details are not well revealed, though such local processes will ultimately be critical to more sustainable global food production and trade.

Land use and emissions embodied in trade

Between 2004 and 2017, we found that roughly 1 billion hectares of agricultural land (both cropland and pasture) were used for traded agricultural products, representing ~22% of agricultural land worldwide (Fig. 1B), a result consistent with previous studies (*11*, *26*). However, a somewhat higher share of global land-use emissions (~27%) are embodied in international trade, ranging between 4.5 and 5.8 billion metric tons (Gt) CO_2-eq per year during the study period (note that carbon uptake from agriculture abandonment is not included in the analysis) (Fig. 1C). Among the traded commodities, cereals (rice, wheat, maize, and other grains) and oil crops (soybeans, oil palm, and other oil seeds) together represent 26 to 35% of the land use of traded products and 45 to 54% of embodied emissions over the study period. Animal products (such as cattle, sheep, pigs, chicken, and raw milk), which generally require more land area per unit produced (*3*, *27*), constitute 55 to 67% of embodied land use but only 14 to 19% of net embodied emissions. By contrast, although vegetables and fruits represent a large share (roughly a quarter) of traded agricultural and forestry products by value (Fig. 1A), their land requirements and emissions are comparatively small (representing <8% of embodied land and emissions).

The dominant global feature of embodied land-use emissions, persistent over time, are large exports of emissions from countries such as Brazil, Indonesia, Argentina, Australia, and Canada to consumers in developed regions such as the US, Europe, and Japan (Fig. 2). However, there were some substantial changes over the study period: although China was an important net exporter of agricultural products in 2004, rapid growth in imports during the study period meant that by 2017 it was an

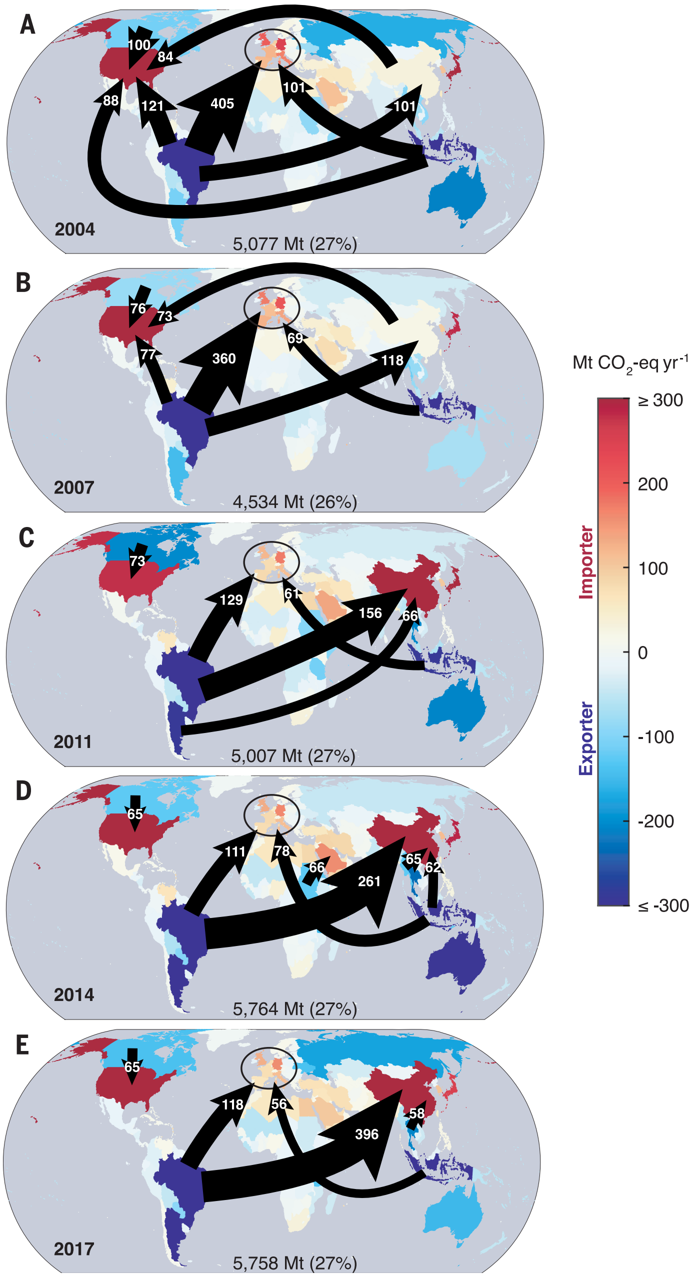

Fig. 2. Global distribution of land-use emissions embodied in trade. (**A** to **E**) Net land-use emissions embodied in trade for each region (shading) and largest net fluxes of embodied emissions between regions (arrows) in 2004 (A), 2007 (B), 2011 (C), 2014 (D), and 2017 (E). Shading indicates the magnitude of net emissions embodied in trade with net exporters blue and net importers red. Fluxes to and from Europe are aggregated to include all 27 member states of the European Union plus the UK. The scale of arrows across the maps is consistent except for arrows with values >200 Mt CO_2-eq year^{-1}, which are drawn at the same size.

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important importer of agricultural products by value, as well as the largest net importer of embodied land use and emissions (Figs. 2 and 3 and figs. S1 and S2). The growth in exports from Brazil to China—one of the most important international trade flows of land-use emissions in 2017—coincided with diminishing Brazilian exports to Europe and the US, one of the most important trade flows in 2004 (Fig. 2). The value of traded products and the land required to produce them (figs. S1 and S2) show similar changes over the decade of study. Figure S1 shows that the US was a net importer of agricultural products by value in 2004 but was a net exporter of agricultural products in 2014. Indonesia, by contrast, was a net exporter of agricultural products by value and embodied emissions but a net importer of embodied land use. Finally, Russia was a net importer of agricultural products by value and embodied land use before 2014 but was a net exporter in 2017, attributable to its changing trade policies (e.g., import bans on certain agricultural products from some Western countries).

We further decompose embodied land-use emissions into those related to land-use change (i.e., CO_2 emissions related to land conversion; LUC) versus agricultural processes (i.e., GHGs emitted directly from the production of crops and livestock; see materials and methods for details) (*23*). Of the total global embodied land-use emissions over the study period, 75 to 81% are related to land-use change (dashed white line in Fig. 1C), particularly conversion to croplands, suggesting that international trade in agricultural commodities (especially crops) is related to substantial land-use change and related CO_2 emissions (*28–31*). Indeed, the major trade flows of land-use emissions (e.g., from Brazil and Indonesia) are also dominated by LUC emissions (Fig. 2 and fig. S3). Of all agricultural emissions embodied in trade, roughly two-thirds are related to CH_4 (from sources such as enteric fermentation, rice cultivation, and manure management) and one-third is related to N_2O (e.g., from fertilizers and manure). The pattern of exporters and importers of agricultural emissions is somewhat similar to that of LUC emissions, but there are also differences (figs. S3 and S4) that reflect considerable variation in emissions intensities across regions.

Regional land-use emissions

Brazil was the largest net exporter of land-use emissions in 2017 [917 million tons (Mt) CO_2-eq], followed by Argentina, Indonesia, Thailand, Russia, and Australia (150 to 330 Mt CO_2-eq each; Fig. 3J). The largest net importer of land-use emissions in 2017 was China (814 Mt CO_2-eq), followed by the US, Japan, Germany, the UK, Italy, South Korea, and Saudi Arabia (100 to 370 Mt CO_2-eq each; Fig. 3G). There is substantial but imperfect overlap between the largest exporters and importers of emissions and the largest exporters and importers of land use. For example, the largest net exporter of agricultural land use in 2017 was Australia [200 million hectares (Mha)], followed by Brazil, Mongolia, Argentina, and Canada (24 to 75 Mha each; Fig. 3K); notably, many of these countries are important exporters of animal products. On a per capita basis, net exports of emissions are largest (5 to 13 tons per capita) in regions where agriculture also accounts for a large share of regional economies and exports (e.g., Paraguay, Australia, and Argentina; Fig. 3L). In these cases, more than half of the land-use emissions produced (and in Australia, more than half of agricultural land use) are related to exports (fig. S5, A and B, and fig. S6B). Similarly, net exports account for 40% of all land-use emissions produced in Brazil, and ~30% of Brazil's agricultural land is used to support exports. By contrast, net imports of emissions are greatest (4 to 8 tons per capita) in affluent regions with little arable land (e.g., United Arab Emirates, Hong Kong, Singapore, Luxembourg, Kuwait; Fig. 3I). In many of these regions, >90% of land-use emissions related to final consumption are embodied in imports (figs. S5D and S6C). The land use embodied in imports to Hong Kong, Singapore, and Bahrain

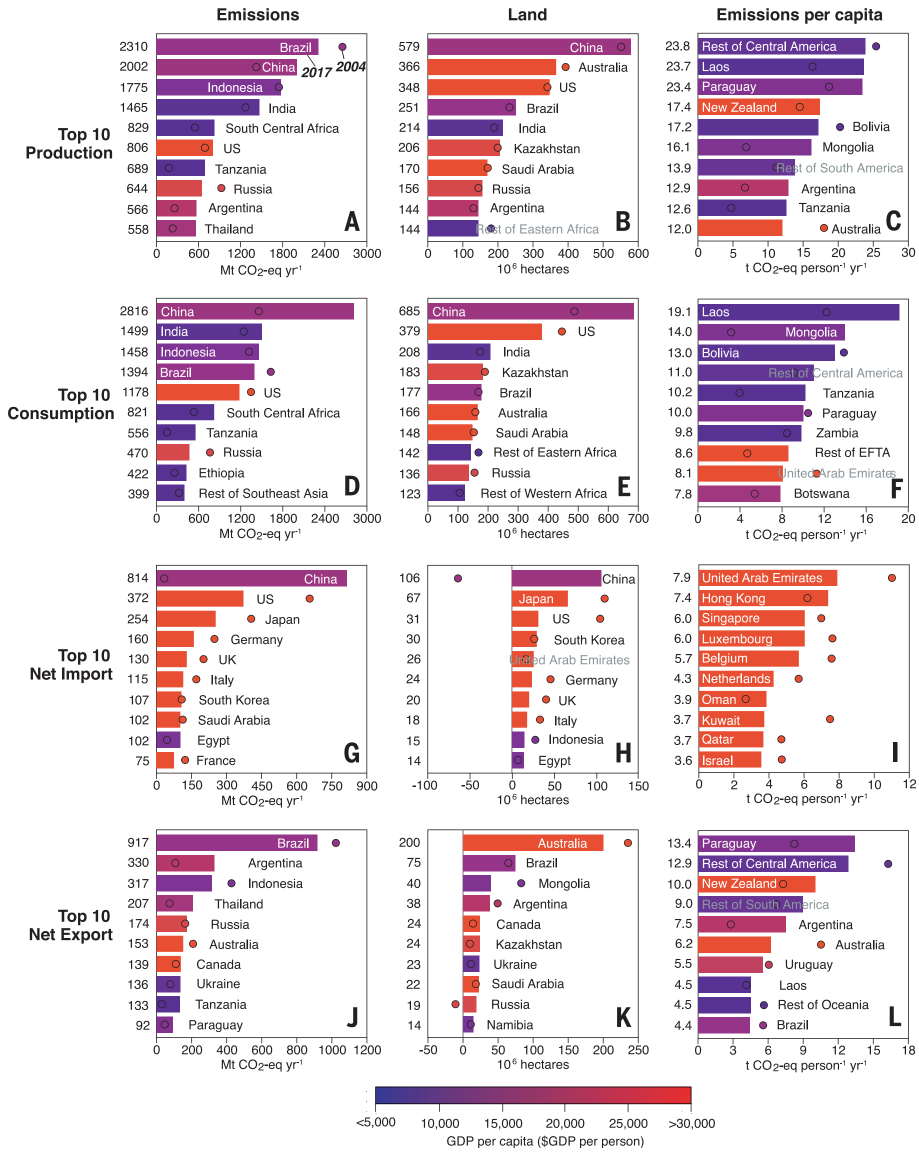

Fig. 3. Top 10 countries or regions by land-use emissions and agricultural land use. (**A** to **L**) Top ten countries/regions in 2017 by production (A) to (C), consumption (D) to (F), net imports (G) to (I) and net exports (J) to (L) of land-use emissions (A), (D), (G), and (J), agricultural land use (B), (E), (H), and (K) and per capita emissions (C), (F), (I), and (L). Data in 2017 are shown as bars shaded by GDP per capita. Data in 2004 are indicated by circles.

is in each case 1 to 2 orders of magnitude as large as the entire area of these regions (fig. S5F).

Exports from Brazil, Indonesia, Argentina, Australia, Thailand, and Tanzania are particularly emissions-intensive (Fig. 4). These agriculturally productive regions have carbon-dense forests (e.g., Brazil and Indonesia) (*32*) and/or produce emissions-intensive products (e.g., sheep and cattle in Australia), and more than three-quarters of their collective land-use emissions are from land-use change. By contrast, the emissions intensity of exports from China, the US, Europe, and Japan is much lower and includes low levels of LUC emissions. Thus, emissions intensity of imports by affluent regions is typically much greater than that of their own exports or domestic production (Fig. 4 and fig. S6D), suggesting that consumption in some affluent regions drives land-use change and emissions in lower-income regions. Indeed, such large differences in emission intensity make the US a net emission importer, although it was a net exporter of agricultural products by value in 2014 (Fig. 2 and fig. S1). China, by contrast, was a net importer of LUC emissions and a net exporter of agricultural emissions from 2004 to 2011. Emission intensity of imports varies much less across regions, though it is noticeably high in China and India (Fig. 4).

The exported land-use emissions from major exporters are usually dominated by a small subset of exported products (Fig. 5). For example, soybeans make up the largest component of emissions exported from Brazil (517 Mt CO_2-eq in 2017) and Argentina (174 Mt CO_2-eq), whereas oil palm makes up the largest component of emissions exported from Indonesia (132 Mt CO_2-eq) and Malaysia (56 Mt CO_2-eq), where agricultural expansion often occurs on peatlands. These products often have a high share of embodied emissions from land-use change to cropland (Fig. 5 and fig. S7). By contrast, animal products such as cattle and sheep represent most of India's exported emissions (~70 Mt CO_2-eq in 2017), with a comparatively large share of the embodied emissions related to agricultural processes [e.g., CH_4 and N_2O from enteric fermentation and manure management (*33*); Fig. 5 and fig. S7]. Rice represents nearly half of the emissions exported by Thailand, with considerable emissions from both land-use change and agricultural processes (CH_4 from rice cultivation). Wheat, cattle, and sheep dominate emissions exported by Australia. Imported emissions are comparatively diversified, though a large share of emissions imported to China are related to oil crops such as soybeans (~600 Mt CO_2-eq in 2017).

Figure S7 shows the 50 largest product-specific trade flows of embodied emissions from 2004 to 2017. This list includes many large trade flows (e.g., Brazil-China, Brazil-Europe, Indonesia-Europe) and major commodity crop and animal products (soybeans, oil palm, cattle, maize), as well as some less recognized sources (e.g., Tanzania-Europe: tobacco, cocoa, coffee, and tea; Cote d'Ivoire-Europe: cocoa; Indonesia/Thailand-China: fiber and rubber). China's soybean imports from Brazil, Argentina, and the US are all among the top 10 trade flows of emissions during the study period. The top flows may thus represent targeted opportunities for efforts to substantially reduce land-use emissions through global supply chains [e.g., expanding the soy moratorium (*34*) to Brazil's Cerrado (*35*) and bolstering and broadening efforts such as the Roundtable on Sustainable Palm Oil (*36*) to include rubber from Southeast Asia and cash crops such as cocoa from Equatorial Africa].

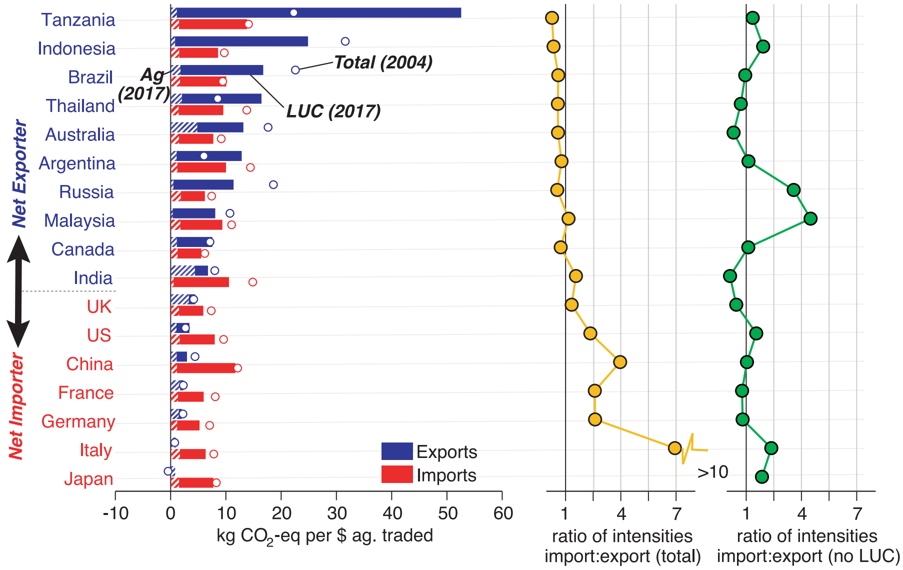

Fig. 4. Land-use emission intensity of exports and imports by major traders. Intensity of total land-use emissions in 2017 is separated into land-use change emissions (LUC; solid bars) and agricultural emissions (Ag; hatched bars). Intensity of total land-use emissions in 2004 is indicated by circles.

Changes and drivers: 2004 to 2017

Land-use emissions embodied in global trade increased by 14% between 2004 and 2017, from 5.1 to 5.8 Gt CO_2-eq per year (Fig. 1C). Meanwhile, the land area supporting traded agricultural products decreased by 5% over the same period, with increases in cropland areas offset by decreases in pasture for livestock (Fig. 1B). Figure 6 decomposes the factors contributing to the changes in annual embodied emissions over the study period, showing that the 0.7-Gt CO_2-eq increase was mostly due to increases in trade volume (+1.6 Gt) partly offset by decreases in emission intensity (–0.9 Gt). In both cases, these changes were dominated by LUC emissions; embodied agricultural emissions changed very little (–0.02 Gt) because steady increases in trade volume (+0.23 Gt) were largely offset by decreases in emission intensity (–0.09 Gt) and changes in trade structure (–0.16 Gt). Although some changes in trade structure—such as the decline in trade of cattle and sheep—reduced embodied agricultural emissions, others acted to increase LUC emissions through expansion of cropland, resulting in an overall small effect on emissions embodied in trade (Figs. 1C and 6A, and fig. S7).

More than half of the increase in annual land-use emissions embodied in trade from 2004 to 2017 were related to exports from Argentina, Thailand, and Tanzania, which together rose by 477 Mt CO_2-eq (+171%), in each case largely driven by increased emission intensity of LUC emissions accompanied with increased volume of agricultural exports (Fig. 6B). Meanwhile, emissions embodied in Brazilian exports decreased by 81 Mt CO_2-eq (–8%), in this case primarily because of decreased emission intensity of LUC emissions related to decreases in deforestation in the Brazilian Amazon between 2004 and 2017 (*34*, *37*, *38*), which offset the growth from increased trade volume (Fig. 6B and fig. S8). By contrast, emissions embodied in imports to China and India increased by 692 Mt CO_2-eq (+206%) and 77 Mt CO_2-eq (+69%), respectively, over the study period, mostly driven by the increasing volume of imports (Fig. 6C and fig. S8). Were it not for the observed changes in emissions intensity (that is, if trade volume and trade structure were the only factors affecting embodied emissions), then annual land-use emissions embodied in trade would have increased by 1.6 Gt CO_2-eq (+31%) from 2004 to 2017, and Brazil would have the largest increase—rather than decrease—in exported emissions (Fig. 6). Similarly, were it not for LUC emissions (that is, if only agricultural emissions were analyzed), there would have been very little change in emissions embodied in trade (–0.02 Gt; Fig. 6).

Further details of changes in embodied land-use emissions from 2004 to 2017 related to specific region and product combinations are shown in Fig. 5 and figs. S7, S8, S9, and S10. In particular, China's soybean imports and the related embodied emissions tripled from 2004 to 2017, reaching 470 Mt CO_2-eq in 2017—mostly related to increases in exported emissions from Brazil, the US, and Argentina. The changes in soybean imports are a large part of the changing trade flows in Fig. 2; soybeans alone represent 46% of the 287 Mt decrease in Brazil's net exported emissions to Europe from 2004 to 2017, whereas Brazil's net exported emissions to China rose over the same period (Fig. 2 and fig. S7).

Discussion and conclusions

Our results reveal that the share of land-use emissions embodied in international trade in recent years is comparable to the relative share of fossil fuel emissions traded internationally (27 and 21% in 2017, respectively; both calculated by this study, see fig. S11 and materials and methods) (*23*). However, unlike fossil fuel CO_2 emissions, the largest net exporters of land-use emissions are concentrated in agrarian regions of the Southern hemisphere, in which the share of agricultural products exported is often high (e.g., Australia and Argentina). Further, carbon-dense and biodiverse ecosystems are often cleared and managed (e.g., tropical forests in Brazil and peatlands in Indonesia) to support exports of agricultural commodities to more affluent and/or populous regions such as Europe, the US, China, and Japan (Figs. 2 and 4, and fig. S6). Consumption-based land-use emissions are considerably lower than production-based emissions in Oceania, Southeast Asia, and Latin America, whereas the opposite is true in Europe, North America, and East Asia (figs. S12 and S13). Meanwhile, Europe, the US, and Japan are major net importers of both land-use emissions and fossil fuel CO_2 emissions, whereas substantial fossil emissions are embodied in China's exports, offsetting China's imports of land-use emissions (fig. S11). Although embodied land-use emissions are comparable in magnitude to embodied fossil fuel emissions in many regions (fig. S11), consumption-based accounting of land-use emissions is not yet required by any national policies or international agreements (*39*–*41*).

One central question is whether trade of agricultural products has inadvertently increased or decreased global emissions relative to a world with no trade or different trade patterns. Although our methods cannot fully evaluate all trade counterfactuals, a simplistic approach that has been applied in the context of water use (*13*, *42*) compares the emissions actually produced by exporters to the emissions that importers would produce if they were to create the imported products domestically (holding all current emissions intensities constant and assuming continued trade in products importers have never produced). This approach suggests that trade of the top 10 net importers of emissions tends to increase global land-use emissions (their imports are more emissions-intensive than domestic production; fig. S6), whereas imports to Latin American and sub-Saharan African regions tend to reduce global emissions (their production is more emissions-intensive than imports). However, this simple method further suggests that in recent years global trade may have both increased and decreased global land-use emissions (by +1.2 Gt CO_2-eq in 2004 and −0.2 Gt CO_2-eq in 2017, respectively). Given the strong assumptions entailed, these results should be interpreted cautiously, but they indicate that a substantial scale of climate mitigation might be possible through strategic trade adjustments. Policy levers that take comparative environmental advantage into account—such as consumption-based accounting and international price adjustments—may help induce such adjustments.

Regardless of the global effect, however, prevailing patterns of trade and land use suggest that at least some trade flows may be exacerbating global GHG emissions and ecological habitat destruction. This conclusion is supported by a large and diverse literature concerned with "displaced land use" and

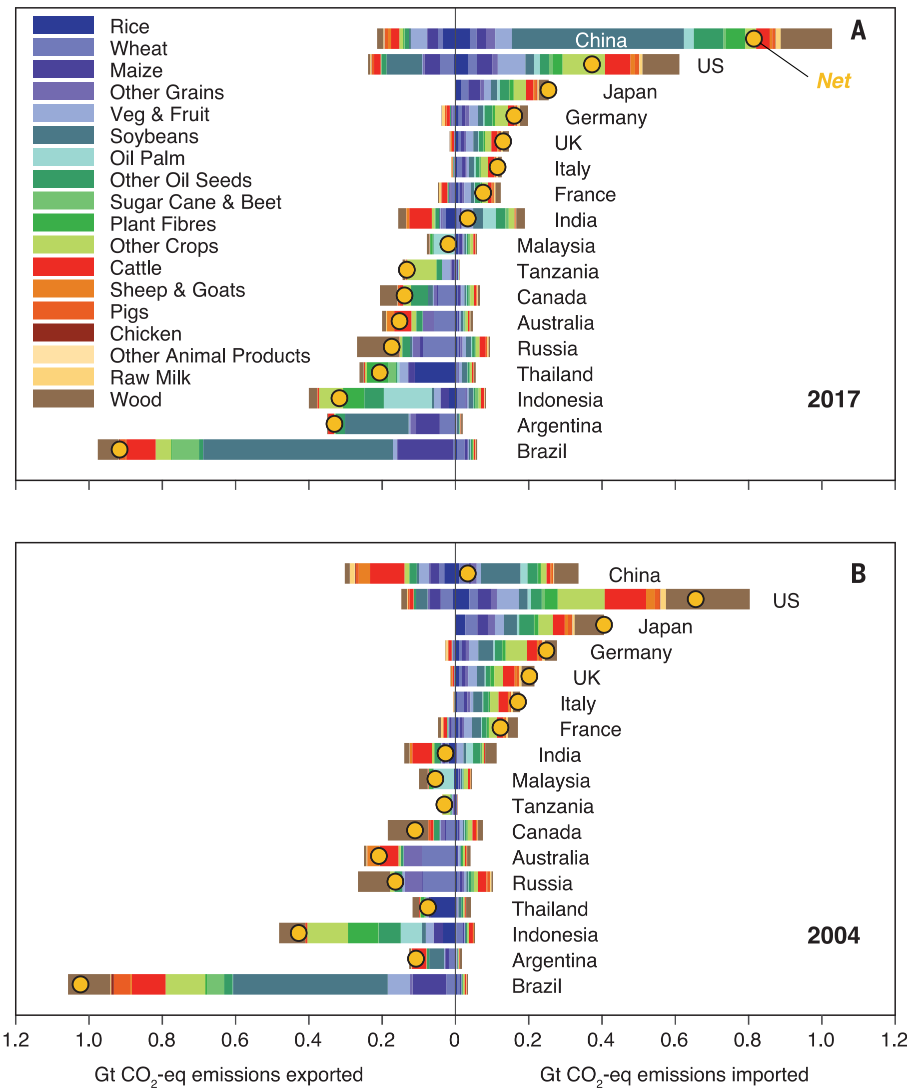

Fig. 5. Balance of land-use emissions embodied in imports and exports of major traders. Trade balance in (**A**) 2017 and (**B**) 2004. The net embodied emissions are indicated by dots.

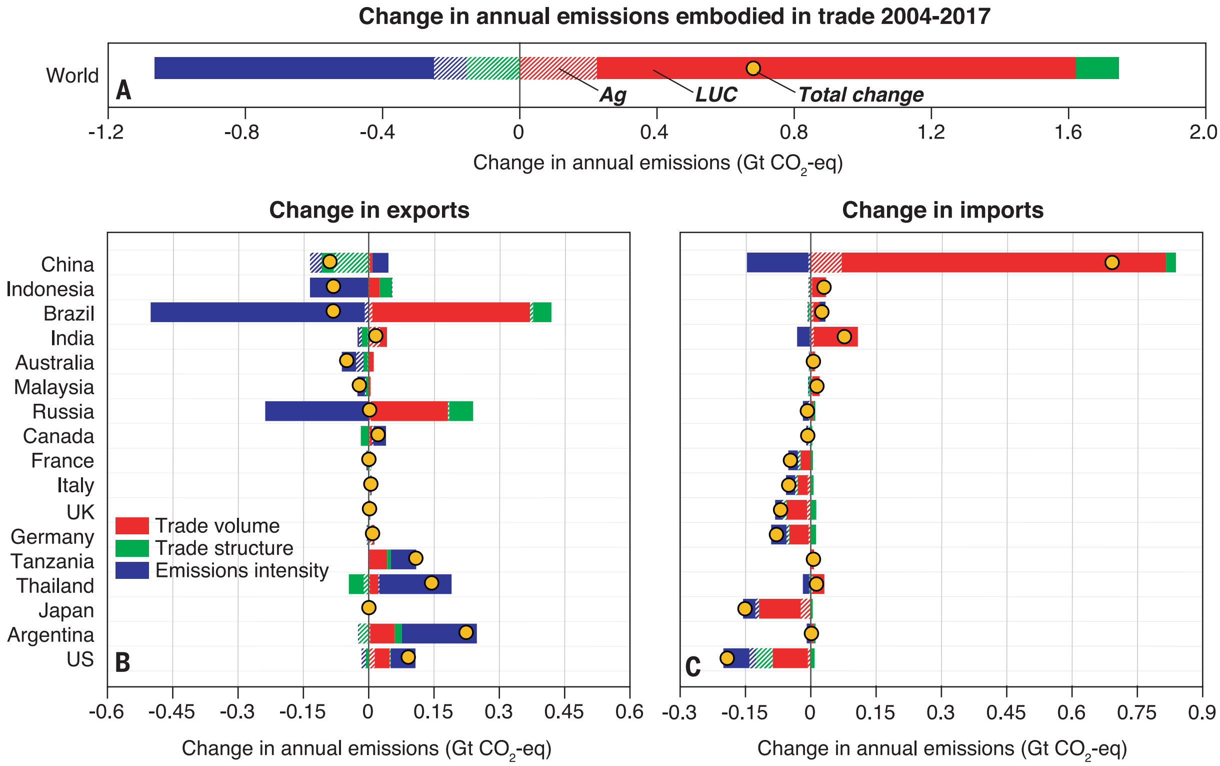

Fig. 6. Drivers of changes in land-use emissions embodied in trade. (**A** to **C**) Contributions of different factors to changes in annual land-use emissions embodied in global trade (A), and exports (B) and imports (C) of major traders from 2004 to 2017. The contributions of each factor (i.e., trade volume, trade structure, and emissions intensity; materials and methods) are shown by bars and total changes over 2004 to 2017 are shown by yellow circles. Total land-use emissions are separated into land-use change emissions (LUC; solid bars) and agricultural emissions (Ag; hatched bars).

"indirect land use change" emissions related to agricultural and forest policies in the US and Europe, particularly related to biofuels and bioenergy (e.g., Europe's decision to phase palm oil out of biofuel markets) (*9*, *43*–*45*). We find that three-quarters of land-use emissions embodied in trade are related to land-use change, which is known to also have considerable ecological impacts (*1*, *2*). If it were possible to produce the same crops by sustainable intensification (*46*–*48*), land-use emissions embodied in trade would be drastically reduced. Despite high LUC emissions, more than a quarter of agricultural land in Brazil and Argentina supports exports, suggesting that targeted zero deforestation agreements among international commodities traders could yield substantial environmental benefits. Policies similar to the Amazon Soy Moratorium (*34*) might be bolstered and expanded to include more regions and commodities such as soy from Brazil's Cerrado [which has been proposed (*35*, *49*)], palm oil from Indonesia and cocoa from Equatoria Africa. Well-crafted policies could help ensure that any additional costs associated with avoiding such land-use change would at least initially be borne by (typically more affluent) importing regions. However, proposals for Europe and the US to adopt border carbon fee adjustments to prevent carbon leakage related to these regions' climate mitigation efforts have rarely extended to land-use emissions (*50*), and care would be needed to ensure that such policies were not implemented in a regressive manner.

Our results, which identify the regions, products, and trade relationships contributing most to the transfer of land-use emissions, may help target efforts to improve the sustainability of land use and agricultural production. In particular, international trade may be used to reduce the emission intensity of agricultural products in the future, on the basis of comparative environmental advantage. For example, China's imports of soybeans from the US are less emissions-intensive than that from Brazil and Argentina (fig. S7), suggesting that global emissions might be avoided if the US were able to produce and export more soy to China (*51*). Of course, it is not quite this straightforward as a result of the dynamism of global trade networks and other environmental factors such as water resources and biodiversity, as well as the influence of various and local social, political, and economic interests (*52*). Indeed, to better support local decision making in the future, datasets and analyses of food production and trade may be extended to resolve food system dynamics at subnational or finer spatial scales; for example, shifts in the use of marginal lands. By the same token, different datasets and accounting schemes can allocate land-use emissions differently among products and across time (materials and methods) (*23*). Nonetheless, our results make the case that policies incorporating environmental externalities could help broaden the notion of comparative advantage, as well as reduce incentives for importers to offshore GHG emissions and for exporters to backslide into environmentally destructive practices. Land-use emissions are expected to be a key challenge in climate mitigation efforts as global population and food demands increase (*3*, *22*). Our results demonstrate the importance of assessing land-use emissions embodied in trade to avoid policy-related leakage and reveal targeted opportunities for international cooperation to reduce emissions and land intensities of global agricultural production.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S17
Tables S1 to S3
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Data S1 to S5

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