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Attribution of CO_2 emissions from Brazilian deforestation to consumers between 1990 and 2010

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Abstract
Efforts to reduce deforestation to mitigate climate change and to conserve biodiversity are taking place on a global scale. While many studies have estimated the emissions occurring from deforestation, few studies have quantified the domestic and international drivers sustaining deforestation rates. In this study we establish the link between Brazilian deforestation and production of cattle and soybeans, and allocate emissions between 1990 and 2010 along the global supply chain to the countries that consume products dependent on Brazilian deforestation. We find that 30% of the carbon emissions associated with deforestation were exported from Brazil in the last decade, of which 29% were due to soybean production and 71% cattle ranching. The share exported is growing, with industrialized nations and emerging markets (especially Russia and China) greatly increasing imports. We find a correlation between exports (and hence global consumption) of Brazilian cattle and soybeans and emissions from deforestation. We conclude that trade is emerging as a key driver of deforestation in Brazil, and this may indirectly contribute to loss of the forests that industrialized countries are seeking to protect through international agreements.

Keywords: deforestation, CO_2 emissions, trade, consumption, consumers, Brazil, Amazon, input–output analysis, land-use change

1. Introduction

Global CO_2 emissions rose nearly 50% over the last two decades (Peters *et al* 2012b), and estimates suggest land-use change (LUC) was one of the largest individual sources, contributing approximately 15% between 1990 and 2010 (Peters *et al* 2012b, Houghton 2012). High emissions from LUC mostly occur in the tropical regions, where forest carbon density is highest (Baccini *et al* 2012). Forest loss releases carbon stored in biomass and soil to the atmosphere, increasing radiative forcing and temperature changes on a global scale (Bala *et al* 2007). Reducing tropical deforestation is desirable, not only because it might be one of the cheapest options to effectively reduce global CO_2 emissions (Kindermann *et al* 2008), but also because it would enhance sinks and protect valuable ecosystems (Canadell and Raupach 2008). Between 1970 and 2010, approximately 18% of the Brazilian Amazon was deforested (Baccini *et al* 2012), with the primary cause being demand for new land for the cultivation of soybeans and expansion of pasture (Barona *et al* 2010, Hosonuma *et al* 2012).

The REDD+ initiative (Reducing Emissions from Deforestation and forest Degradation) is creating incentives for developing countries with large deforestation rates to reduce forest loss and encourage regrowth. However, as industrialized countries are paying to protect tropical forests through mechanisms such as REDD+, the same countries

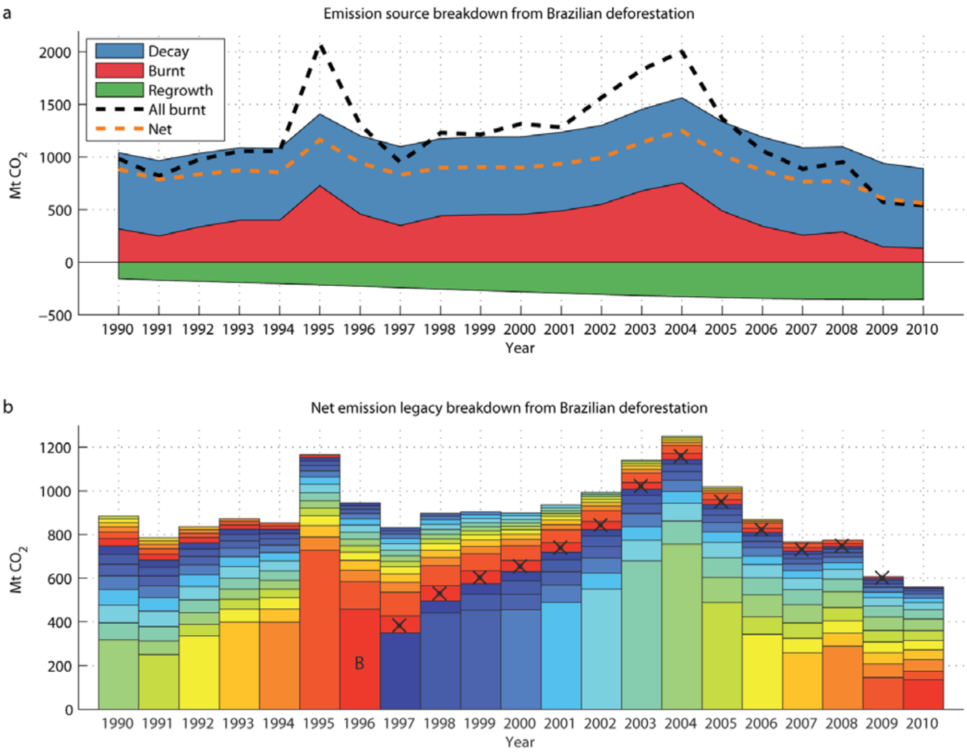

Figure 1. Estimated emissions from Brazilian deforestation, 1990–2010. (a) Estimated burnt and legacy (decay) emission components, and emission absorption from regrowth. The 'all burnt' line is a theoretical scenario where we assume that all deforestation is burnt in the year it was cut down, calculated as deforestation area multiplied by carbon density in biomass per area (by state). We use net emissions (burnt plus legacy less regrowth) in our analysis, divided into year-by-year components. (b) In each year, the component of the vertical bar closest to the horizontal axis represents emissions from deforestation in that year, while legacy emissions from that year's deforestation propagate into later years, represented with the same component color. For example, a part of the forest cleared in 1996 was burnt (the red component in 1996 marked with a 'B'), while the unburnt residual decayed over time (legacy emissions: red components from 1997 to 2009, marked with crosses).

might also indirectly be driving deforestation via consumption of agricultural products from the very countries whose forests they aim to protect (Pacheco *et al* 2010). To uncover these linkages, a model of the global supply chain is necessary to estimate the consumption of goods and services associated with agricultural commodities produced on deforested land in Brazil. Linking deforestation and its associated emissions to agricultural production and international trade can reveal the global socio-economic drivers leading to domestic and international production and consumption.

In recent years, consumer approaches to emission inventories have been emerging, shedding light on the links between geographically separated production and consumption (Davis and Caldeira 2010). In a consumer approach, a proportion of the territorial emissions occurring in producing countries are reallocated from producing to consuming nations (Peters *et al* 2011b). While several ways of sharing allocation among producers and consumers have been explored (Andrew and Forgie 2008, Lenzen *et al* 2007, Zaks *et al* 2009), this study follows the approach of most studies by assuming full allocation to the final consumer. In this view, the consumer is at the end of the global supply chain, creating demand and sustaining/increasing production and international trade of goods and services, leading in turn to deforestation and emissions. Recent studies have shown that a significant share of global CO_2 emissions are embodied in international trade (Peters *et al* 2011b), making consumer approaches increasingly relevant. While there has not yet been a thorough analysis of CO_2 emissions from LUC embodied in international trade, earlier work has indicated the importance of regional forces (Aguiar *et al* 2007) and international trade and consumption (DeFries *et al* 2010, Zaks *et al* 2009) in driving deforestation.

2. Methods

In our analysis we link current and legacy emissions (Ramankutty *et al* 2007) to a detailed model of the global economy for the years 1990–2010 (Peters *et al* 2011b) to quantify the relationship between global consumption and emissions from Brazil's deforestation. Using areas of deforestation estimated in the PRODES project database by the Brazilian National Institute for Space Research (INPE 2012), we estimate continuous net emissions (figure 1(a)). The land-use change and carbon cycle modeling follow Ramankutty *et al* (2007), with updated carbon stock and land-use estimates according to Zaks *et al* (2009) and Galford *et al* (2010).

All model runs over all years were done for each Brazilian state separately, with state-specific carbon density in aboveground biomass, burnt/legacy emission shares, and soybean/cattle land-use shares. State average aboveground live biomass ranges from 95 to 270 Mg ha^{-1} (Saatchi *et al* 2007). The deforested biomass is partitioned into shares with different decay rates: burnt (20% share), slash (70%), products (8%) and elemental carbon (2%) (Zaks *et al* 2009). In the state of Mato Grosso the burnt (70%) and slash (20%) shares are different due to different agricultural practices (Galford *et al* 2010). With only the burnt share releasing emissions the same year the deforestation is occurring, most emissions will usually occur in later years (legacy emissions). Legacy emissions were included from 1977, being INPE's first estimate of deforestation (INPE 2012), resulting in each year having a current emission component and a legacy emission component (figure 1(b)). With this methodology, carbon emissions are allocated when there is a flux from cleared biomass to the atmosphere.

The share of land-use in the year of deforestation in most states is 34.7% for cropland and 65.3% for pastures. This ratio is modeled and found to change over the following years, to be dominated by pastures and secondary forest (regrowth). The emissions are allocated to products from cropland (soybeans) and pasture (cattle meat) according to the land-use following deforestation (Barona *et al* 2010, Fearnside 1996, Galford *et al* 2010, Ramankutty *et al* 2007). Again, shares for Mato Grosso are different: initial share of 65% for cropland and 35% for pastures (Morton *et al* 2006, DeFries *et al* 2010).

Our attribution analysis starts in 1990 and this allows the legacy emissions to accumulate for 13 years (1977–1989) before the analysis begins. For consistency, and with only very minor effects, we therefore only consider legacy emissions for 13 years starting in each year of deforestation. Even though deforestation rates have seen a rapid decline in recent years, probably as a result of strict policy enforcements (Malingreau *et al* 2012), legacy emissions (from gradual decay of wood products and clearance waste) partly sustain emissions over time, creating inertia in the emission trajectories (Aguiar *et al* 2012). Even so, both deforestation rates and net emissions are lower now than at any time in the last 21 years, with 560 $MtCO_2$ estimated in 2010 compared with the 1990–2010 average of nearly 900 $MtCO_2$ (figure 1).

This study does not consider indirect land-use change (e.g. indirect land-use change impacts of biofuels), and only allocates emissions to the primary direct drivers, i.e. cultivation of soybeans and grazing of cattle, according to the literature (Barona *et al* 2010, Houghton 2012, Fearnside 1996).

Each year's emission estimates (both current and legacy emission components) were divided among Brazil and countries importing meat and soybeans according to supply chain shares. The supply chain is modeled using Multi-Regional Input–Output (MRIO) analysis derived from data from the Global Trade Analysis Project (GTAP) (Peters *et al* 2011a, Narayanan *et al* 2012), a database which contains global bilateral trade information for 129 regions and 57 sectors for specific years. Bilateral trade data links the regions at the sector level and additionally separates between intermediate and final consumption (Peters *et al* 2011a). Using 1997, 2001, 2004 and 2007 as base years, we created a full time-series with trade (TSTRD) from 1990 to 2010 based on gross-domestic product (GDP), bilateral trade and emission statistics (Peters *et al* 2011b).

The base years cover different time periods in the TSTRD: 1990–1998 (1997 base year), 1999–2002 (2001 base year), 2003–2005 (2004 base year) and 2006–2010 (2007 base year). Due to issues with the share of consumption in households compared to exports in the 1997 dataset, we excluded it in the analysis of beef. The 1997 version of Brazil's economic structural data in GTAP is based on data from 1985, and shows that a very high share of final consumption going to households compared to the other reference years, which is not consistent with more recent Brazilian data. Because of this, we use the 2001 dataset as a base for the years back to 1990 for calculations relating to beef. The base years are detailed and accurate representations of the global economy, and while the interpolated time-series is less accurate than the data for individual base years, it allows the robust assessment of trends (Peters *et al* 2011b). The MRIO model has a high level of detail on agricultural and food products, and we assume that in Brazil the sector 'Oil seeds' is mostly soybeans, and 'Bovine cattle, sheep and goats, horses' is mostly cattle, which is a reasonable assumption in a Brazilian context.

Using the time-series, we allocate legacy emissions differently based on a trade matrix of the year the legacy emissions belong to. The emissions are allocated to the consuming countries in the year the emissions occur, which in the case of legacy emissions is later than the year of consumption that led to deforestation (figure 1(b)). For legacy emissions connected to a year before 1990 (legacy emissions in 1990–2002), we assumed trade shares equal to those in 1990. The model allocates deforestation emissions to all products of the beef and soybean sectors regardless of whether they were produced on newly deforested land or existing land (which suggests that consumers do not know the source of production). This can be justified since most soybean production and cattle ranching in Brazil occurs on newly or previously deforested land (Barona *et al* 2010).

3. Results

Including the entire supply chain, Brazilian consumption has led to the largest share of emissions from its own deforestation: on average over the two decades, 85% of the emissions embodied in Brazilian beef products and 50% of Brazilian soybean products have been driven by domestic consumption. Due to the rapid growth in international trade in recent decades, Brazilian shares of these emissions are generally decreasing over time. The exported CO_2 emissions from all Brazilian deforestation over 1990–2010 averaged 25% (with a minimum of 18% in 1990, and a maximum of 37% in 2004). For beef products the average exported was 15% (ranging from 12% in 1998 to 19% in 2008), while for soybean products the average exported was 50% (ranging from 33% in 1996 to 69% in 2004) (figure 2).

Particularly in the last decade, greater imports by emerging markets and industrialized countries have led to an increasing share of the exported emissions (figure 3). While

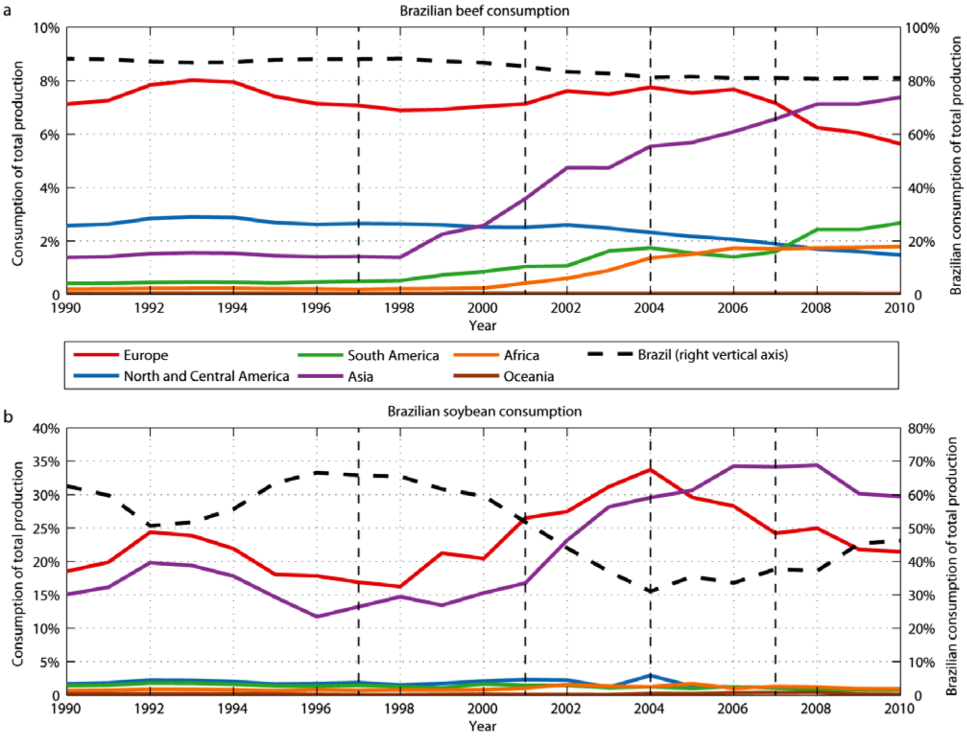

Figure 2. Export shares of Brazilian (a) beef and (b) soybeans to regions. The share of emissions linked to beef that was exported to Europe has fallen slightly, while Asian consumption (driven mainly by Russia) has been steadily rising over the last decade. A similar development can be seen in emissions linked to soybean production exported to the European and Asian markets. According to our estimates, Asia (mainly due to China) now consumes more than the European market. Brazil's meat consumption (right vertical axis) has seen a more steady development than soybean consumption, while being the dominant consumer of both products. Vertical dashed lines indicate the base years of our analysis (see section 2).

the largest share of exported emissions from Brazilian beef production in 1990 were embodied in trade to the USA and the UK, Russia has recently increased its share from very low levels to becoming the world's largest importer of emissions embodied in Brazilian beef in 2010 (from 0.1% of production in 2000, to 2.8% in 2010), with 15% of total exported beef. China's share of emissions linked to soybeans has increased from 7% of total production emissions in 2000 to 22% in 2010, equivalent to about 41% of the emissions embodied in exported soybeans in 2010. While consumption by most regions has been very stable over the last two decades, the Asian and European markets have seen large changes. Our study indicates that the Asian market now has a larger share of beef and soybean emissions than the European market (figure 2): Asia is now allocated 7% of total beef emissions (driven mainly by Russia and the Middle East) and 30% of total soybean emissions (driven mainly by China).

The increase of emissions from 1998 to 2004 (355 $MtCO_2$) coincided with the growth of the total exported share from 18% to 37%. So while domestic consumption grew slightly from 730 to 790 $MtCO_2$, exports almost tripled, growing from 165 to 460 $MtCO_2$. Due to the large inter-annual variability of the deforestation rates, the share exported is a better metric to portray the drivers of deforestation. Our analysis suggests that, in recent years, there is a positive correlation between high deforestation emissions and high proportions of production exported, giving additional support to the hypothesis that deforestation is increasingly connected to international trade (DeFries *et al* 2010). We split the analysis into multiple time periods as these time periods cover different data sources, and while there is no apparent correlation in the first time periods between emissions from deforestation and the share of the emissions exported, there is correlation in the later time periods (figure 4). Although we find a correlation between emissions from deforestation and export share, we do not attempt to isolate the direction of the causation, which would require different analytical approaches.

Assuming causation in one direction would mean that increases in the share exported would lead to increased deforestation rates and growth in emissions. For example, following the trends from 2003 to 2010, if the export share of soybeans were to increase by 10 percentage points (e.g. from 60% to 70%), the deforestation emissions would be expected to rise by about 160 $MtCO_2\ yr^{-1}$. Similarly, if the export share of beef were to increase by 10 percentage points (e.g. from 20% to 30%), the emissions from deforestation would be expected to rise by 480 $MtCO_2\ yr^{-1}$. Causation in this direction implies deforestation is driven by market demand.

In contrast, if one views the causation in the opposite direction, then if emissions from deforestation due to soybeans were to increase by 100 $MtCO_2\ yr^{-1}$, the export share of soybeans would be expected to increase by 6 percentage points (e.g. from 60% to 66%). For emissions related to beef, an increase of 100 $MtCO_2\ yr^{-1}$ would lead to an increase of the share exported by 2 percentage points

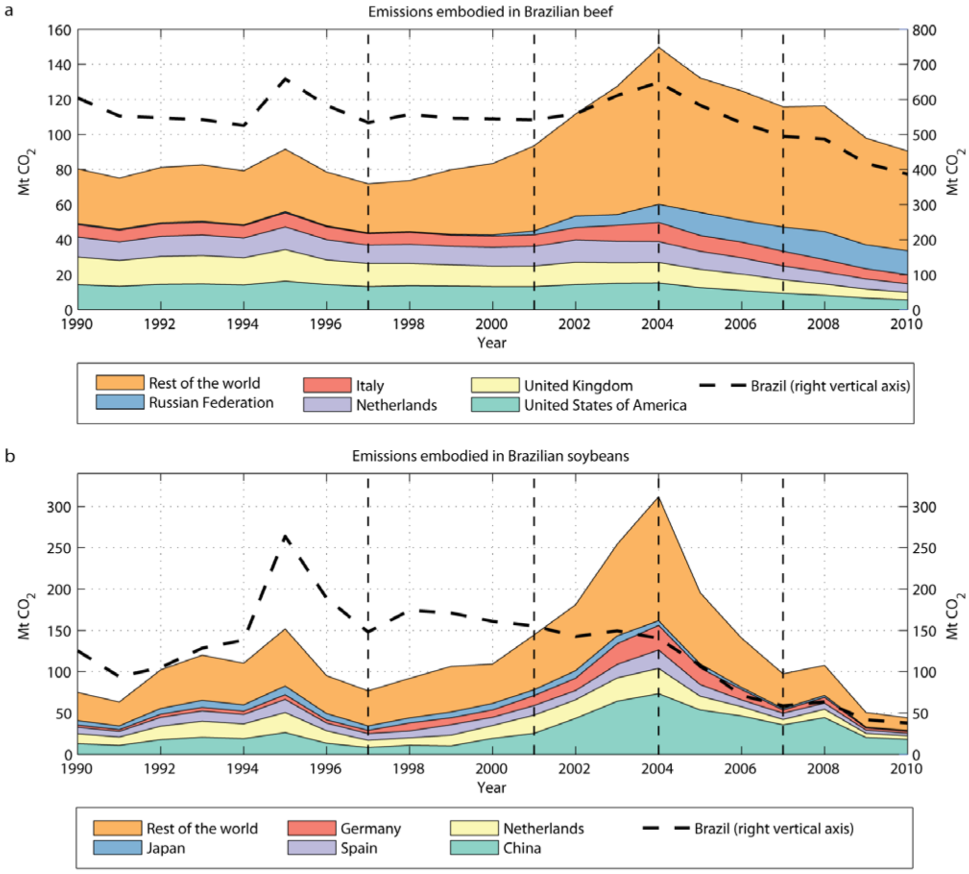

Figure 3. Deforestation emissions in trade distributed among top importers of (a) beef and (b) soybeans from 1990 to 2010. In total, Brazil (right vertical axis) is responsible for about 85% of the emissions from cattle, and 50% of the emissions from soybeans. Deforestation rates do have an important impact on the emissions embodied in trade, as low deforestation rates imply less emissions allocated to consumption. However, legacy emissions and high export shares counter that trend. Vertical dashed lines indicate the base years of our analysis (see section 2).

(e.g. from 20% to 22%). Causation in this direction implies deforestation and increased cultivation occur first and markets are then found for new production.

4. Discussion and conclusion

There are large uncertainties in current LUC emissions estimates, and the estimates are strongly affected by parameter choices (Ramankutty *et al* 2007, Aguiar *et al* 2012). Many of the parameters are hard to constrain due to lack of data, suggesting that the share of emissions allocated to particular economic sectors is uncertain. To reduce uncertainty we have used recent land-use transition data (Galford *et al* 2010, Zaks *et al* 2009) and INPE's updated dataset from 1977 to 2010, consistently used legacy emissions for all years in the analysis, and allocated legacy emissions to the year the legacy emissions are released and according to the trade shares from the year the deforestation originates.

Global economic and trade data come with uncertainties as they require the merging and harmonization of conflicting datasets (Lenzen *et al* 2012a). While the uncertainty of the data is difficult to estimate, previous authors have found the robustness of consumption-based estimates to be relatively high, as the uncertain data tend to be small and generally uncorrelated errors in individual data points tend to cancel (Peters *et al* 2012a, Lenzen *et al* 2010, Lenzen 2011, Peters *et al* 2011b). Thus, the long-term trends of regions are considered more accurate representations of the global situation than specific data points.

Trade is emerging as a key driver of agricultural expansion and therefore deforestation in Brazil, with two key implications. First, consumption of Brazilian soybeans and beef by countries who are already seeking to protect Brazilian forests (e.g., via REDD+), are driving demand and therefore indirectly increasing the deforestation they are seeking to prevent. With these indirect links quantified, measures can be taken in the consuming countries to limit the pressure on Brazil's forests using, for example, policies to influence consumption patterns or regulation of products originating from deforested land. Second, the recent land-use change trend in Brazil might not continue, as production (FAO 2012) and export shares have largely been increasing while deforestation rates have seen a dramatic decrease over recent years (figure 4). With increasing global pressure on Brazilian agriculture to increase production (Nassar 2009), desire for continued economic growth, and emerging changes to the Brazilian Forest Code (Tollefson 2012), it appears unlikely that Brazilian deforestation rates will continue to decrease

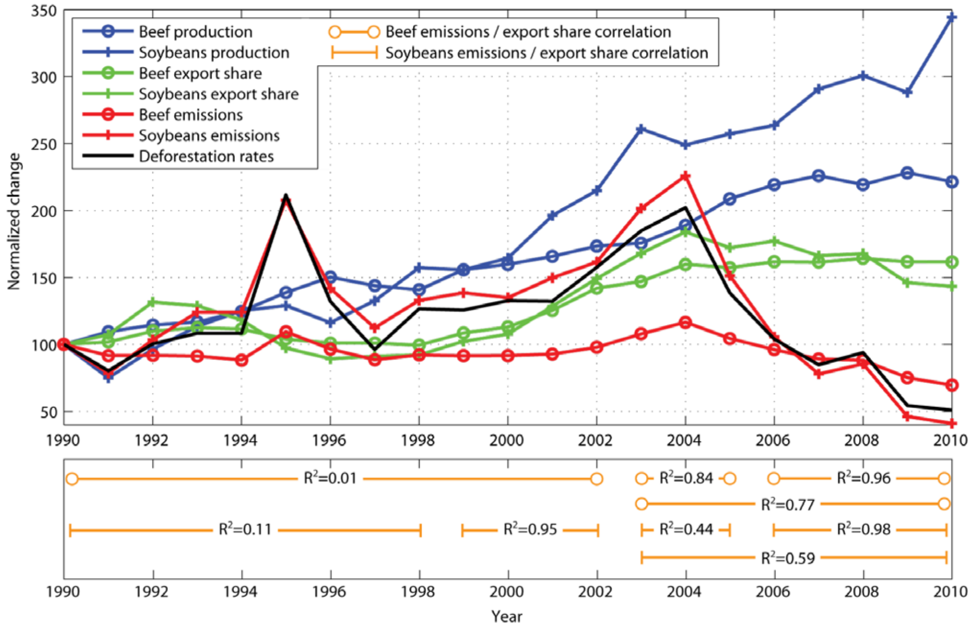

Figure 4. Changes to production, trade shares, emissions and deforestation rates (normalized to 100 in 1990), and R^2 values from correlation of emissions linked to beef and soybeans and export shares of production. Production (FAO 2012) and export shares of beef and soybeans have increased over 21 years, while value added from the agriculture sector in Brazil has doubled (measured in constant 2000 US$) (World Bank 2012). Emissions linked to soybeans follow deforestation rates more closely than emissions linked to beef due to different land-use transitions (Ramankutty *et al* 2007), however, both deforestation rates and emissions have decreased since 2004. Because of these recent contrasting trends, the development of deforestation rates or production of agricultural products may change. To sustain the increasing demand for products (and the economic growth that it brings), it is likely that land-use expansion will continue (Malingreau *et al* 2012). The R^2 values show increasing correlations between emissions and export shares from 1990 to 2010, implying a connection between deforestation and global trade in recent years. To show how the correlations change over time, we do the regressions on the time periods based on when different base years are used in the time-series (see section 2), in addition to a correlation between 2003 and 2010.

at the current rate without strengthening measures to protect forests (Malingreau *et al* 2012).

To sustain and increase the current level of production and exports, Brazil would need to either intensify agricultural production or use more land (which may lead to additional deforestation). Agriculture in Brazil has seen a dramatic increase in productivity since 1960 (155% for cattle and 300% for cropland), but the projections for the next decade show much lower expected gains (24% for cattle and 23% for cropland, from 2010 levels to 2021) (Mapa a, Mapa b). The hypothesis that deforestation rates might rise is strengthened by a recent study concluding that the current yield of soybeans in Brazil is in most places very close to the climatic potential yield, indicating low potential for further increase in agriculture production without the use of additional land (Licker *et al* 2010). Another study suggests that, in the event that deforestation rates level out, emissions will remain high as loggers move into more dense forests, where carbon density is higher (Loarie *et al* 2009).

Our analysis suggests that Brazil's deforestation cannot be considered in isolation from the global supply chain. Similar conclusions have recently been highlighted for the rapid growth of CO_2 emissions in emerging economies (Peters *et al* 2011b), for global biodiversity loss (Lenzen *et al* 2012b) and water consumption (Hoekstra and Mekonnen 2012). Since global drivers contribute to Brazil's deforestation, they should also be seen as a part of the solution. A first step in this direction is a full assessment of the consumption patterns that indirectly lead to deforestation and agricultural expansion, building on studies such as this analysis. The complexity of the global supply chain in transforming agricultural output into everyday commodities may make regulation difficult, suggesting regulation is required at several points in the supply chain. Examples of potential regulation points are deforestation itself (e.g., REDD+), importers of agricultural commodities, and consumers who have the ability to change behavior away from particular products (e.g., via labeling or information campaigns). Such distributed regulation can facilitate the use of a wide range of complementary mitigation policies and measures, potentially increasing effectiveness.

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