

Producer and consumer responsibility for greenhouse gas emissions from agricultural production—a perspective from the Brazilian Amazon

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Abstract

Greenhouse gases from the combination of land use change and agriculture are responsible for the largest share of global emissions, but are inadequately considered in the current set of international climate policies. Under the Kyoto protocol, emissions generated in the production of agricultural commodities are the responsibility of the producing country, introducing potential inequities if agricultural products are exported. This study quantifies the greenhouse gas emissions from the production of soybeans and beef in the Amazon basin of Brazil, a region where rates of both deforestation and agricultural exports are high. Integrating methods from land use science and life-cycle analysis, and accounting for producer–consumer responsibility, we allocate emissions between Brazil and importing countries with an emphasis on ultimately reducing the greenhouse gas impact of food production. The mechanisms used to distribute the carbon emissions over time allocate the bulk of emissions to the years directly after the land use change occurred, and gradually decrease the carbon allocation to the agricultural products. The carbon liability embodied in soybeans exported from the Amazon between 1990 and 2006 was 128 TgCO₂e, while 120 TgCO₂e were embodied in exported beef. An equivalent carbon liability was assigned to Brazil for that time period.

Keywords: Amazon, deforestation, carbon emissions, producer–consumer responsibility, life-cycle assessment, land use, Kyoto protocol

1. Introduction

Agriculture is now recognized as one of the dominant transformative forces in the global environment (Foley *et al* 2005). By the year 2000, croplands and pastures accounted for ~40% of the ice-free land surface on Earth and provided food,

feed and fuel to meet the demands of the current population (Monfreda *et al* 2008, Ramankutty *et al* 2008). Global agriculture is also a powerful economic force: according to the Food and Agriculture Organization (FAO) of the United Nations, the value of exported agricultural products increased from \$32 to \$720 billion between 1961 and 2006, with the fastest rate of increase in the last decade (FAOSTAT 2009).

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The current production methods of the global food system help sustain our livelihoods, but the extent and intensive practices of modern agriculture have substantial negative environmental consequences (Foley *et al* 2005, Roy *et al* 2009, Schau and Fet 2008). For example, agricultural land use is responsible for the release of greenhouse gases (GHG), biodiversity loss, eutrophication of waterways, emergence of disease and changes in local and regional climates, all of which detract from human health and security (MEA 2005). In economic terms, the extent and severity of these negative consequences are typically externalities of the economic system, because they are rarely communicated to the consumer or accounted for in the price of agricultural products (Pretty *et al* 2000).

In addition, agricultural products are part of an increasingly globalized food system that separates producers and consumers by thousands of kilometers and lengthy supply-chains. The impacts of production span from local (e.g. air and water pollution) to global (e.g. greenhouse gas emissions) scales (Tilman 1999, Smith *et al* 2008) and the mechanisms to track and account for these impacts are poorly developed.

As markets become more globalized, the production of cash crops and other export commodities is expected to increase. This will likely lead to expansion of agricultural land in the tropics, the region that has the most arable land not currently in production (Alexandratos *et al* 2006, Barbier 2000). Such expansion could have serious implications for GHG emissions, as did land use emissions from tropical regions in the 1990s (Houghton 2003). Moreover Gibbs *et al* (2010) found that more than half of new agricultural land in the tropics originated from intact forest with another third coming from previously cleared forests. Although signatories to the Kyoto protocol are working to reduce their GHG emissions from within-country fossil fuel sources, they have neglected land use emissions, including those stemming from their agricultural imports.

Rising concern about GHG emissions, an increasingly informed public, and the threat of regulatory action have prompted producers in the global food system and other energy intensive sectors to measure the energy life cycles of their products (Brentrup *et al* 2004, Jolliet *et al* 2003, Goleman 2009). Some producers are voluntarily providing consumers with estimates of the life-cycle energy costs of the production, distribution and consumption of their products, to enable consumers to choose goods with the smallest energy footprints (Gallastegui 2002). Current proposals suggest that carbon will become a regulated commodity under future global climate agreements and the disclosure of the energy used in the production of commercial goods, including agricultural products, will be necessary (Bodansky *et al* 2004).

Previous analyses have estimated the carbon contained in internationally traded crop biomass (Ciais *et al* 2007) and the embodied emissions from industrial production (Peters and Hertwich 2008b), and have highlighted the importance of producer and consumer responsibility for carbon emissions (Bastianoni *et al* 2004). Recent studies have explicitly called for the inclusion of land use related greenhouse gas impacts of soybean and beef production (Garnett 2009, Lehuger *et al*

2009). This study extends previously developed methods by aggregating new land use datasets and models to track carbon emissions from land use to the resulting agricultural commodities.

This study aims to quantify the hidden GHG emissions of food production from the Amazon basin of Brazil, a region where rates of both deforestation and agricultural production for export are high, and to develop mechanisms to quantify and ultimately reduce the GHG impact of food production. Specifically, our study provides an analysis of GHGs embodied in exported beef and soybeans from the Brazilian Amazon, explicitly accounting for land use. We also propose an approach to allocate GHG emissions associated with agricultural land use change between producers and consumers, by integrating methods from land use science and life-cycle analysis.

2. Producer versus consumer

In the current Kyoto protocol, GHG emissions are allocated to the country in which the emission occurred. Future internationally-binding agreements are likely to incentivize countries to reduce GHG emissions throughout the life cycles of the goods they produce (Bodansky *et al* 2004). When goods are destined for consumption in other countries, the emissions generated in their production are referred to as the 'emissions embodied in trade' (Ahmad and Wyckoff 2003). This can be a significant fraction of global carbon emissions: using a global trade model, Peters and Hertwich (2008a, 2008b) estimated that in 2001, roughly 23% (or ~ 5.7 Gt CO₂) of energy related emissions were embodied in trade.

'Carbon leakage' occurs when a country opts to limit its own carbon emissions by importing goods from a country that does not participate in carbon-reduction agreements. Carbon leakage is a noted problem of the current Kyoto protocol, and has been estimated to comprise 11% of production emissions (Peters and Hertwich 2008b). Consumption-based GHG inventories account for emissions from production *and* imports, and subtracts embodied emissions exported in trade (Peters and Hertwich 2008a). Allocating embodied emissions to the consumer avoids carbon leakage, amongst other deficiencies of production-based greenhouse gas inventories.

Assigning the responsibility for carbon emissions to either producers or consumers should not be a binary decision; a fairer allocation scheme is needed (Munksgaard and Pedersen 2001, Gupta and Bhandari 1999). If responsibility is given to the producer, carbon leakage can occur, and if it is assigned to the consumer not participating in a global GHG-reduction agreement, the responsibility for the emissions are not taken (Andrew and Forgie 2008). Hence, several authors have put forth allocation schemes in which carbon emissions are shared between producers and consumers (Lenzen *et al* 2007, Rodrigues and Domingos 2008, Bastianoni *et al* 2004). These shared allocation schemes provide economic incentive to the consumer nation to favor products with the smallest environmental impacts, and thereby push producers to reduce the carbon emissions embodied in their products.

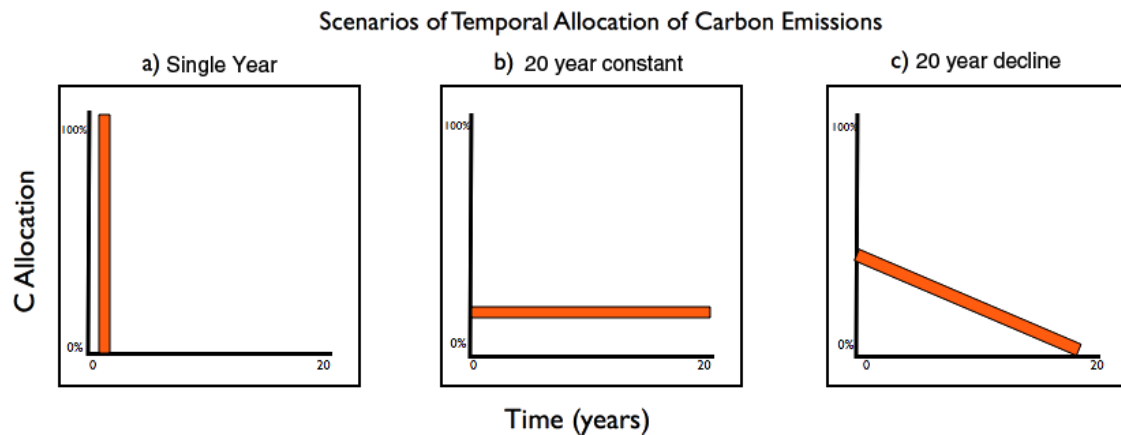


Figure 1. The ‘pulse’ of GHG emissions from land use can be amortized over (a) a single year, (b) 20 years constant, or (c) 20 years linearly declining.

To date, calculations of emissions embodied in trade have only been completed for manufactured products, where data on emissions from fossil fuels are readily available. Life-cycle emissions embodied in agricultural products require a different set of methodologies that have recently been highlighted by the agro-fuels community (Gibbs *et al* 2008, Panichelli *et al* 2009, Reijnders and Huijbregts 2008). Quantifying the GHG emissions embodied in a product is a necessary step to distribute the responsibility for the impacts between the producers and consumers.

3. Allocation of land use emissions

Life-cycle assessments (LCAs) have helped to illuminate the ‘cradle to grave’ ecological impacts for a select number of manufactured and agricultural products. The LCAs of agricultural products are markedly different from those of manufactured products, especially if the product originated from an area that recently underwent land use change. With every transformation of land for agricultural use, biophysical impacts occur over various spatial and temporal scales (Foley *et al* 2005). When the conversion process includes removing aboveground biomass from the site, a large ‘pulse’ of GHGs is released to the atmosphere by burning or decay of the removed vegetation (Ramankutty *et al* 2007). Sometimes the pulse of GHG emissions is nearly instantaneous (from burning biomass) or it may decay slowly as forest slash or secondary products (e.g., paper, wood products). When considering agricultural life-cycle assessments, the analysis domain must include impacts from ‘field to fork’, since activities such as land clearing can overshadow efficiency gains in other areas of the product life-cycle (Gibbs *et al* 2008, Fargione *et al* 2008).

The time frame of land use varies greatly. Cleared land can transition between forest, agriculture, fallow and bare ground as the fertility of the land changes, or changes to the cropping system are introduced. Depending on the location and intensity of the new agricultural operation, the land may remain in production for as little as a single season or as long as several millennia. Each of these states have different net carbon balances as vegetation biomass regrows or is cleared

(Ramankutty *et al* 2007). Therefore the GHG liability from the initial transformation needs to be tracked over time and allocated to the appropriate user.

Several amortization schemes can be used to distribute the ‘pulse’ of GHG emissions over the duration of subsequent land use, although none have been widely adopted. Here, we briefly describe current methodologies and present a new hybrid approach that combines the best features from other described methods.

4. Methods

The approach taken in the Ecoinvent LCA database (www.ecoinvent.ch/) assigns all land use emissions to the product that is harvested in the year of land conversion, without consideration of the ultimate duration of agricultural production (Jungbluth *et al* 2007) (figure 1(a)). The rationale for this approach is that since deforestation causes irreversible damage, its impacts should not be amortized over a long period (Jungbluth 2009). If these impacts are monetized on a carbon cost-basis and conferred to the importing country, the resulting elevated price of goods becomes a disincentive for the future conversion of land with large stocks of carbon. If the land is used for agricultural production in later years, the successive products would not incur any carbon debt, and would be ‘free-riding’ on the price paid in the initial year.

While assigning all emissions to the first year is not an optimal solution, dispersing the cost of the emissions over a very long time horizon (e.g. 500 years) is also untenable, and a middle ground needs to be explored (Canals *et al* 2007a). An analog can be found in international accounting standards, which assign ‘useful lives’ for products (Canals *et al* 2007b). Several LCAs and carbon footprinting standards (Muys and García Quijano 2002, BSI 2008) have adopted methods that amortize emissions uniformly over a 20 yr time horizon (figure 1(b)). This time frame is practical for continued occupation before the land is abandoned, does not confer an undue economic burden on the producer, and still values the carbon emitted in the land conversion process.

However, neither of these methods satisfies the goal of sending a price signal to reduce deforestation without applying disproportional financial pressure on either the producer or consumer. A hybrid approach would allocate the bulk of emissions to the years directly after the land use change occurred, and gradually decrease the carbon allocation to the agricultural products derived from the cleared land as time went on (figure 1(c)). With higher additional costs for the first several years, a disincentive signal is introduced into the market, but not with disproportionate force. In later years, the remainder of the carbon costs are captured, but at a reduced amount per year. Similar to the previous case, the time horizon over which the cost of the carbon is collected is arbitrary, but is a length that can be societally determined. All three cases assume that the land would stay in agricultural production for the entire duration of the allocation period, which may not be realistic in a market and environmentally sensitive area such as the Brazilian Amazon.

These amortization schemes are designed with inherent flexibility that makes them applicable across a range of local to global carbon-trading mechanisms. Proposed programs, have taken a broad-brush approach to monetizing carbon emissions from deforestation and agricultural production, and are important building blocks in accounting for the life-cycle environmental impacts of agricultural production. The reduced emissions from deforestation and degradation (REDD) mechanism would compensate tropical developing countries for reducing deforestation rates (Mollicone *et al* 2007, Gullison *et al* 2007). On a smaller scale, groups such as Alianca da Terra in Brazil (www.aliacadaterra.org.br/) provide payments to farmers for more sustainable production methods by selling their products at a premium. These programs rely on the monetization of carbon emissions that is currently determined by regional carbon markets. These examples assume that the price of carbon emissions are enough to reduce profit margins and create a disincentive to production on newly cleared land.

5. Case study

5.1. Deforestation in the Amazon

While land use/land cover change and deforestation are growing concerns in all tropical regions, the Brazilian Amazon has been under intense pressure from national colonization and agriculture programs, and more recently due to increased production of soybeans and cattle for export (Barreto *et al* 2006). The Amazon is the largest contiguous tropical forest on the planet, with vast stores of biodiversity and carbon, and provides essential ecosystem services to people within the basin and around the world (Foley *et al* 2007), but also accounted for more than half of global deforestation from 2000 to 2005 (Hansen *et al* 2008), and thus for a substantial portion of carbon emissions to the atmosphere. 'Business as usual' scenarios of future demand for goods and governmental policies suggest that deforestation and its attendant problems will continue (Soares Filho *et al* 2006).

By 2007, 18% of the Legal Amazon had been deforested by smallholder as well as large holder mechanized agricultural

operators, loggers and cattle ranchers, among other actors (Barreto *et al* 2006). In the last decade, mechanized agriculture (primarily soybean cultivation) and intensive cattle grazing have been the dominant drivers of land clearing (Simon and Garagorry 2006, McAlpine *et al* 2009). Between 1990 and 2006, the cattle herd in the Amazon almost tripled in size and the area used for soybean cultivation quadrupled, so that by 2006 cattle occupied 95% of the pastoral landscape and soybeans had more than doubled their share of land (IBGE 2009).

5.2. Transition to an export market

When large-scale deforestation in the Amazon began in the 1970s, the resultant agricultural products were mostly consumed within the region. The Amazon did not produce enough beef to feed its own population until 1991 (Kaimowitz *et al* 2004). Since that time, national incentives and global demand have transformed Brazil into the world's largest exporter of soybeans and beef, among other commodities (Nepstad *et al* 2006). Most exports are in the form of fresh or frozen beef, although there is an increasing trend of live cattle exports (ALICEweb 2009). Between 1990 and 2006, market and trade reforms in addition to the eradication of foot-and-mouth disease helped exports of beef from the Amazon to grow over 500% (IBGE 2009, Walker *et al* 2008). This growth has had environmental consequences, such as carbon emissions from deforestation, nutrient pollution, biodiversity loss and displacement of local people (Betts *et al* 2008, Fearnside 2008, Gibbs *et al* 2010, Foley *et al* 2007).

While cattle production is the predominant land use in the Amazon, soybeans have recently begun to encroach from the southern and eastern boundaries and are responsible for new land clearing and displacement of cattle pastures (Vera-Diaz *et al* 2008). Several factors, ranging from development of moisture-tolerant soybean varieties to increasing global demand for animal rations, have led to the dramatic increase in soybean production, and its rising percentage of the global grains market (Nepstad *et al* 2006). The Brazilian agricultural complex is highly integrated into the global market system, as Brazil exports more than 10% of the internationally traded crop biomass (Ciais *et al* 2007).

Here we present an illustrative example that distributes the responsibility for GHG emissions from deforestation between Brazil and the eventual importing nation of commodities produced in the Amazon (figure 2). While the data and methods presented here are considered to be the 'state of the science', the exact parameters allocating emissions between international actors were chosen to exemplify the importance of GHG emissions embodied in internationally traded agricultural commodities, as a template for future policies. Future work can build upon this framework, making different policy assumptions as appropriate.

5.3. Model description

Here we use a land use transition and carbon emission model, described in detail by Ramankutty *et al* (2007), to estimate the fate of deforested land and the associated carbon dioxide

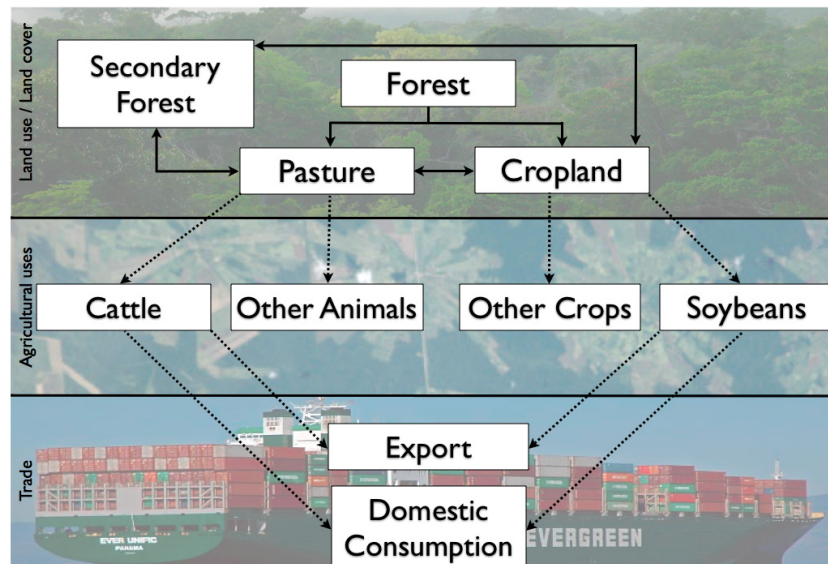


Figure 2. Three major phases in the process of converting forests for the production and eventual consumption of beef and soybeans: (1) land use/land cover change, (2) agriculture, and (3) trade.

Table 1. Average biomass, mean annual deforestation and change in deforestation rate between 1990 and 2006 for the nine states within the Brazilian Amazon. (Sources: INPE 2009, Saatchi *et al* 2007.)

State	Mean biomass value (Mg ha ⁻¹)	Mean annual deforestation 1990–2006 (km ²)	Increase (+) or decrease (–) in deforestation rate between 1990 and 2006
Acre	204	583	+
Amazonas	270	861	+
Amapá	263	75	–
Maranhão	125	910	+
Mato Grosso	164	6781	+
Pará	230	5703	+
Rondônia	211	2633	+
Roraima	215	246	–
Tocantins	95	331	–

equivalent (CO₂e) emissions (figures 3(a) and (b)). While the previously published model is robust, several key changes were made to incorporate the latest published data and changing agricultural practices in the Brazilian Amazon. The model was run for each of the nine states in the legal Amazon from 1990 to 2006 using (time-smoothed) annual deforestation rates provided by Brazil’s National Institute for Space Research (INPE) (2009). Initial aboveground forest biomass values for land identified as intact forest by Brazil’s program to calculate the deforestation of the Amazon (PRODES) were summarized by state from Saatchi *et al* (2007) (table 1). In each year, carbon emissions from deforestation are calculated as the sum of combusted biomass (20%), and the decay of biomass remaining in the slash (70%), product (8%) and elemental (2%) pools (Ramankutty *et al* 2007) (figures 4(a) and (b)). For the state of Mato Grosso, the percentages of biomass allocated to the slash and burn pools were set to 20% and 70%, respectively, to reflect the trend of highly mechanized agriculture where most limbs and stumps are removed and burned after forest clearing (Galford *et al* 2010). The model partitions deforested land between cropland, pasture and secondary forest using

transition rates initially described by Fearnside (1996), but land transition rates for the state of Mato Grosso, a hotspot of deforestation, were updated according to the patterns reported in Morton *et al* (2006) and Defries *et al* (2008). In addition to carbon emissions from deforestation, added methane emissions from enteric fermentation in cattle were included in the total CO₂ equivalent (CO₂e) flux, and were computed with IPCC values for tropical cattle assuming a 100 yr global warming potential (IPCC 2007, Robertson and Grace 2004). GHG emissions from the application of fertilizer were found to be negligible compared to fluxes from deforestation and methane production.

5.4. Carbon allocation methods

The model distributes deforested land as it shifts between cropland, pasture and secondary forests, computing the GHG emissions (or sequestration, for the secondary forests) of each land use type. While the model estimates the net emissions for new pastures and croplands, the major export commodities (cattle and soybeans) only occupy a percentage

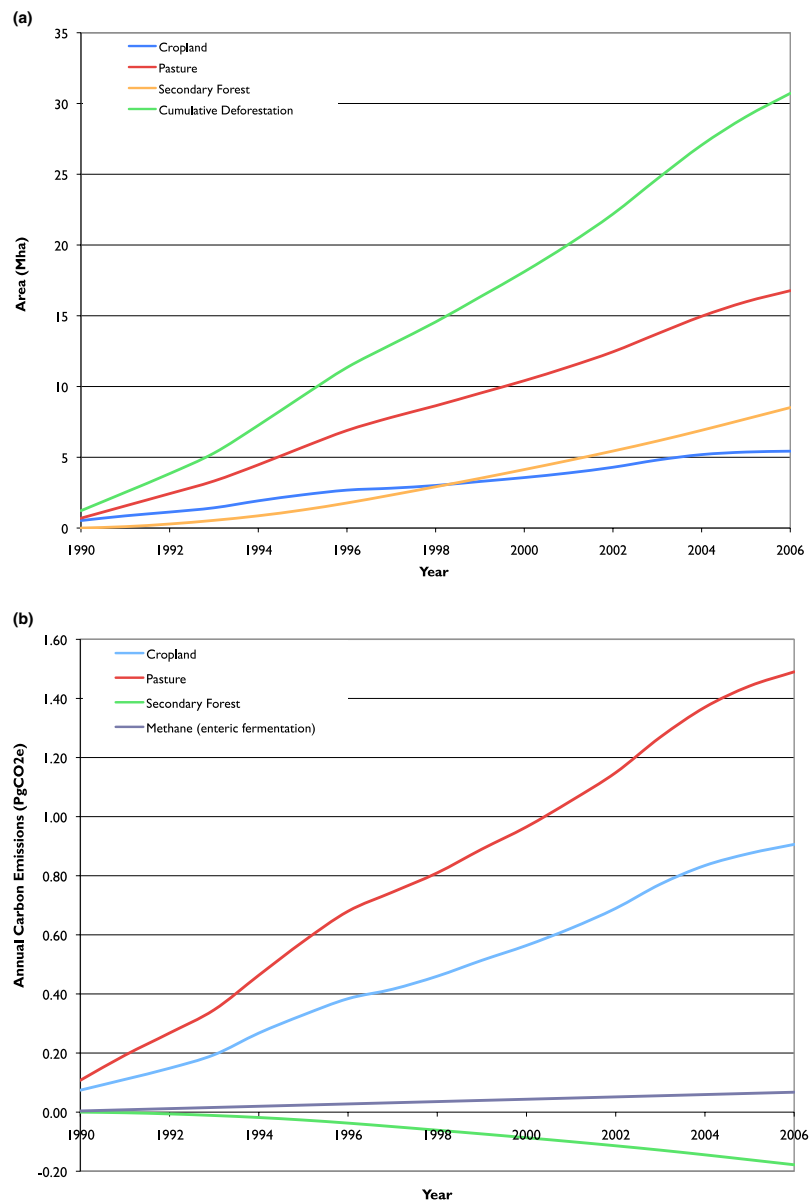


Figure 3. Model simulation of the legal Amazon (a) land use and (b) carbon emissions from 1990 to 2006. The model distributes deforested land (and resulting carbon emissions) between farms, pastures and secondary forests. Methane emissions from enteric fermentation in cattle are included within the emissions from ‘pasture’.

of the agricultural landscape. For each product, the relative dominance on the landscape each year is calculated, using the ratio of area planted in soybeans to total agricultural area, and a similar ratio of pasture area for cattle to buffalo, horses, sheep and other pastured animals (IBGE 2009). The landscape dominance modifiers were applied to each state’s carbon emissions in every year of the model.

Export modifiers are calculated by dividing the amount of soybeans exported by the amount produced. For cattle, approximately 10% of the herd is slaughtered every year, and the average carcass yield is used to calculate the beef and associated products for a given year (IBGE 2009, FAOSTAT 2009). Live cattle exports are incorporated with the beef export data using average carcass yields (FAOSTAT 2009). The ratio of beef exported to beef produced was then estimated

(ALICEweb 2009). The export modifiers were applied over the aggregate Amazon to avoid data inconsistencies resulting from interstate trade for each year of the model.

The emissions calculated for each year are the sum of burnt, decay, slash and elemental carbon from land deforested in previous years minus land that transitioned to secondary forest. The allocation of carbon emissions over time were calculated using three scenarios: (1) emissions were allocated to the year they occurred, (2) equally distributed over 20 years and (3) linearly decreasing over 20 years (figure 1). Carbon fluxes from deforestation prior to 1990 were not included, and emission rates should therefore be seen as underestimates. Also, as future land use, agricultural production and export patterns are unknown; carbon from recent deforestation events cannot be definitively allocated, but must be tracked in order to assign future responsibility.

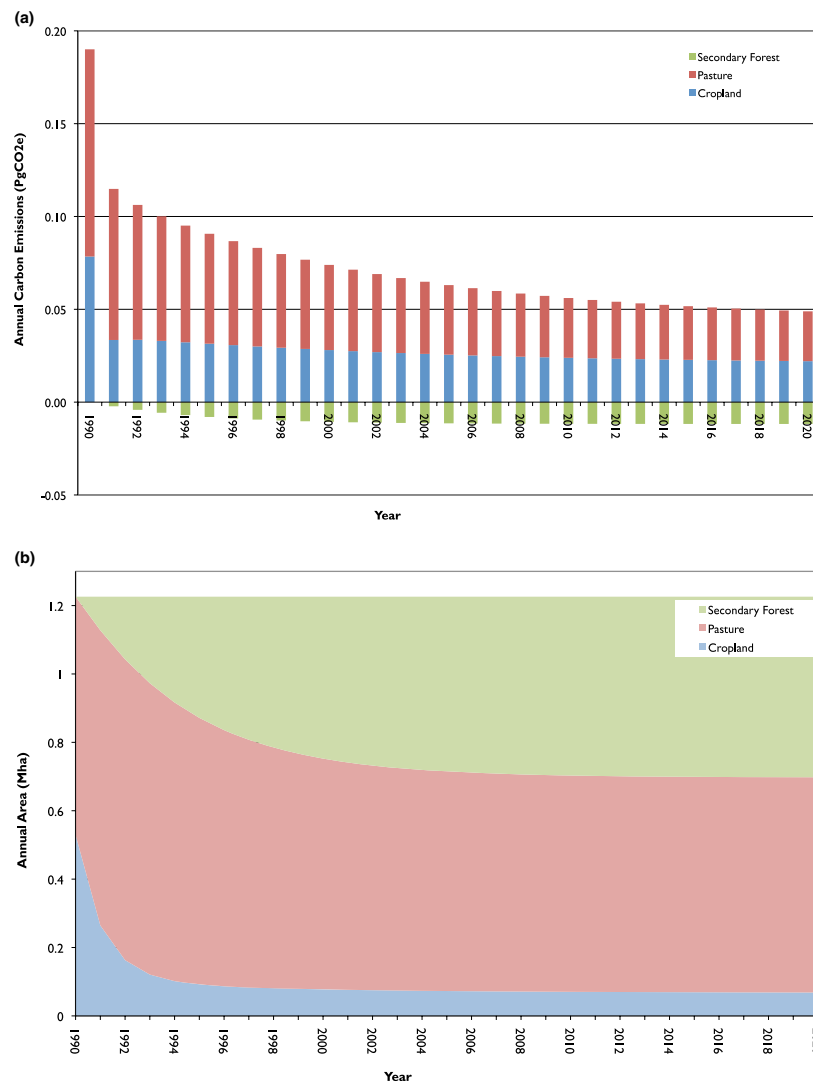


Figure 4. Model representation of the fate of land deforested in the legal Amazon in 1990 (b), as the cohort of land progresses through time and (a) fluxes of carbon from deforestation in 1990 assigned to each land use class. The initial pulse of emissions in the first year is from the burning of biomass, while the remaining fluxes are from the decay of slash, product and elemental pools. Carbon sequestration from secondary forests is also included.

5.5. Producer–consumer

Following the example of Gallego and Lenzen (2005), the final responsibility for the carbon emissions was divided 50:50 between producer and consumer (where Brazil is the ‘producer’ and importing countries are ‘consumers’). Because assigning the entire responsibility for carbon emissions to either the producer or consumer has been shown to be a suboptimal solution (Peters 2008, Peters and Hertwich 2008a), sharing the responsibility between both parties is preferred (Lenzen *et al* 2007). While the 50:50 division of emissions liability between producer and consumer is arbitrary, and would need to be negotiated by the importing and exporting parties, it serves to illustrate how emissions can be fairly divided along the supply chain. In the present case, the allocation of GHG responsibility between Brazil and the country importing the agricultural goods would remain the same in all three scenarios, but the length of time needed to

complete the carbon debt obligation and annual distribution of carbon liability would vary.

5.6. Results

Exports of beef and soybeans from the Brazilian Amazon increased dramatically between 1990 and 2006. As increased exports coincided with increases in deforestation in the Amazon, carbon emission liability increased for both beef and soybeans. The emissions embodied in exported beef and soybeans can be compared using the three temporal allocation scenarios from figure 1 (figures 5(a) and (b)). Model results between 1990 and 2006 are derived from deforestation and commodity export data; results for later years depend on this data and assumptions about future land use and export patterns.

Carbon emissions liability from recent deforestation events continue into the future due to decaying biomass and to amortization by the 20 yr allocation scenarios. Here we

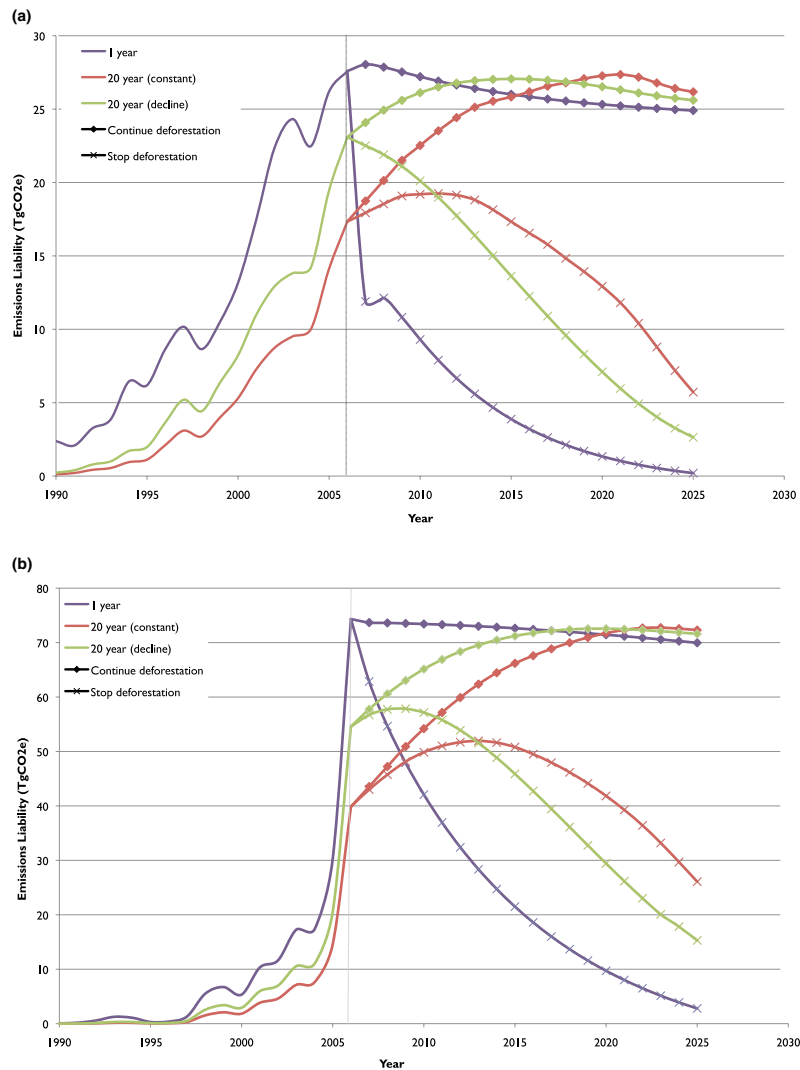


Figure 5. Comparison of carbon liability for (a) soybeans and (b) beef exported from the legal Amazon between 1990 and 2006 using the 1 yr, 20 yr and 20 yr decline allocation methods. Carbon emissions between 2006 and 2025 assume that rates of export continue at 2006 levels and deforestation either continues at 2006 levels, or ceases.

assumed that export rates for the future were equal to the export rate of 2006 and either no further deforestation took place or deforestation took place at the same annual rate as in 2006. While the probability of realizing these scenarios is small, they illustrate the envelope of possibilities that land use could have on the allocation of carbon emissions embodied in soybeans and beef into the future.

The total amount of carbon to be allocated is equal for the three scenarios, although the annual distribution varies according to each scenario. The annual allocation of carbon is most greatly influenced by annual deforestation and export rates. Between 1990 and 2006, the annual carbon liability from the 1 yr allocation scenario is greater than either 20 yr allocation (figures 5(a) and (b)). After 2006, whether deforestation is halted or continues, carbon liability is generally less than either 20 yr allocation scheme, as most carbon is allocated soon after the deforestation event. Comparing the 20 yr allocation schemes, the annual allocation to the 20 yr decline scenario is greater than the 20 yr constant scenario before 2006, while the trend reverses after 2006.

The temporal patterns for carbon emissions export liability are similar for both soybeans and beef.

Using the 20 yr decline allocation scenario, 128 TgCO₂e embodied in soybeans were exported from the Amazon between 1990 and 2006. If deforestation and exports continue at 2006 levels until 2025, an additional 499 TgCO₂e would be embodied in soybean exports, while 236 TgCO₂e would be exported if deforestation ceased. For beef, 120 TgCO₂e were exported from 1990 to 2006, and an additional 822–1369 TgCO₂e could be exported by 2025, as calculated using our chosen envelope of future land use and export patterns. The relatively low embodied emissions from the early 1990s are due to minimal exports, and ignoring decay emissions from deforestation previous to 1990. Increasing embodied carbon emissions between 1990 and 2006 are the result of rising exports and the distribution of decay emissions over time.

Using the 20 yr decline allocation scenario, emissions from deforestation were assigned to importing regions according their percentages of the total global imports. Assuming imports for each region remained constant between

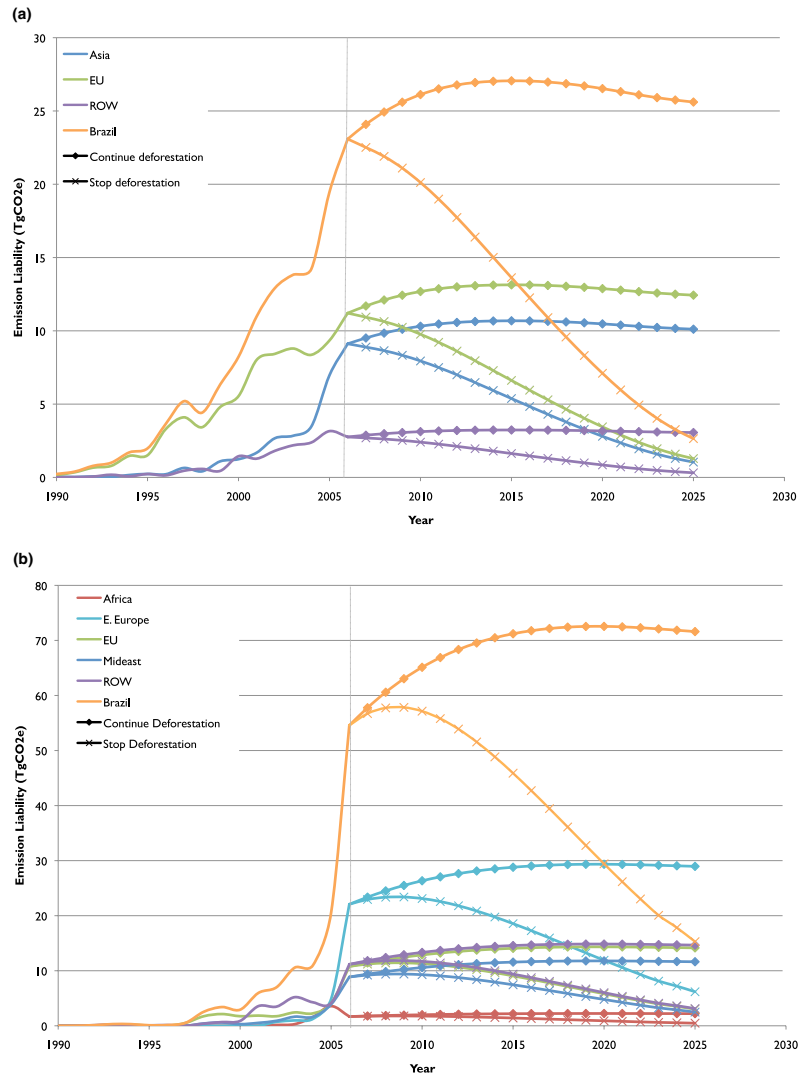


Figure 6. Annual carbon emissions liability for major importing regions of soybeans (a) and beef (b) from the Brazilian Amazon using the 20 yr decline allocation method. Carbon emissions between 2006 and 2025 assume that rates of export continue at 2006 levels and deforestation in the Amazon either continues at 2006 levels, or ceases.

2006 and 2025, the envelope of carbon liability is shown based on the continuation or cessation of deforestation in the Amazon. The major beef importing regions during the study period were Eastern Europe, the EU, Middle East, Africa, South America and Asia. The EU and Asia were the major soybean importers during this time period (figures 6(a) and (b)). Between 1990 and 2006, the EU was the largest importer of soybeans from the Amazon, importing 31.2% of the emissions embodied in soybeans during that time. Major imports from Asia began around 2000, with the largest single year increase between 2004 and 2005. Between 1990 and 2000 the EU imported the majority of beef from the Amazon, comprising 61.8% of embodied emissions during this time. After 2000, imports by Eastern Europe, the Middle East and other areas in South America rapidly increased, as imports by the EU decreased. In the mid-1990s, live cattle were exported exclusively to other countries in South America, while after 2000, exports shifted to the Middle East. The total carbon liability for soybeans and beef between 1990 and 2006 is shown in figure 7.

The 20 yr decline scenarios suggest important outcomes of such an allocation scheme (figures 6(a) and (b)). First, the carbon emissions liability of importing countries decreases dramatically if they import from regions where deforestation ceased decades ago. This is by design; the relative impact of the allocation policy then depends on the price of carbon. Second, the deforestation status of the exporting region can have a greater effect on the carbon emissions liability of the importing country than does the amount of commodity imported. This could confer a significant trade advantage on exporting countries that avoid new deforestation, and intensify production on already cleared land.

6. Conclusions

In this paper we present the methodologies necessary to calculate the embodied GHG emissions due to land conversion in agricultural products, and compare three schemes for shifting some of the responsibility for these emissions from

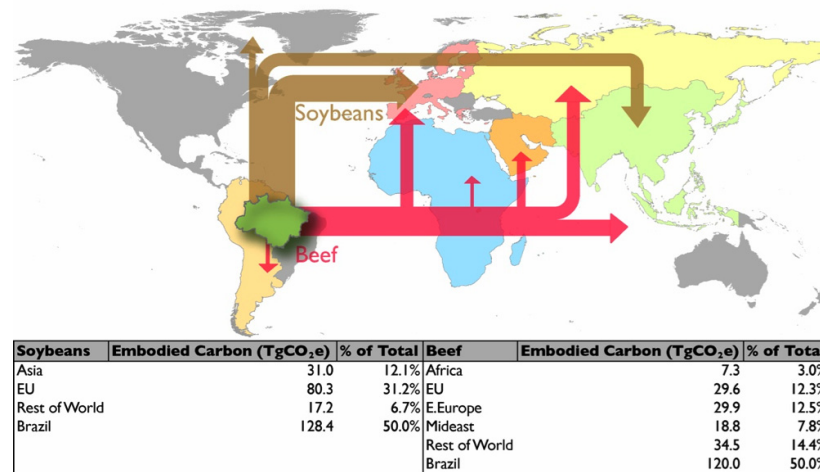


Figure 7. Cumulative carbon emission liability (1990–2006) for countries importing soybeans and beef from the Amazon. The total carbon emissions liability of importing countries is equal to the liability assigned to Brazil.

producer to consumer. While many mechanisms have been proposed to decrease rates of deforestation in the Amazon, very few of them include the ultimate drivers of deforestation: consumers of agricultural products. Prior to 2000, exports from the Amazon minimally contributed to the environmental footprints of importing countries, but increasing exports have thrust the idea of embodied carbon onto the global stage. If greenhouse gas mitigation becomes globally and consistently valued, then distributing the responsibility for GHG emissions will be a practical and feasible instrument to incentivize alternatives to deforestation.

The Amazon case study presented here tracked the GHG emissions of land use and land cover change due to farming soybeans and beef for export. The study required a fusion of techniques, including calculating emissions from deforestation, life-cycle analysis of agricultural systems and allocating emissions between producers and consumers. While the best available data were used in this case study, the input data place several constraints on the analysis, such as the inability to distinguish between exports from newly cleared land and exports from previously cleared land. For this reason, we used the commodity production data as relative modifiers of the carbon emission model. It would have been inappropriate to assume the carbon emissions embodied in soybeans and cattle could be inferred from the production statistics alone due to varied production practices. Also, decay related emissions from later years of deforestation (e.g. post-2000) must be allocated using assumptions, as future production and export quantities are unknown.

In addition to bypassing the current drawbacks of the Kyoto protocol, allocating emissions between producers and consumers would incentivize both parties to adopt less polluting production practices. Production practices in the Amazon, which is increasingly becoming integrated into globalized markets, can be leveraged to decrease rates of deforestation and increase yields on already-established farms. If buyers must pay for the carbon embodied in the products they purchase, economic logic dictates that they will buy

items whose prices are lower due to lower carbon intensity of production. In turn, producers will change their practices to compete with producers with lower costs, in this case by changing management and land use practices.

While land use can make up a considerable portion of the life-cycle impacts from tropical agriculture, additional components need to be considered. Emissions related to consumption of beef, including production of feed grains, transportation and processing must be quantified. Soybeans, on the other hand, are used as an input for animal feed and industrial processes (e.g. biodiesel production), while humans only directly consume a small proportion of soybeans (mostly as soybean oil). In the case of soybeans, emissions from processing and transportation need to be assessed in addition to emissions from the combustion of biodiesel or impacts of livestock rearing. Some of the methodologies required to assess these additional impacts have been considered in other studies (e.g. Roy *et al* 2009, Dalgaard *et al* 2008).

This study helps to lay the foundations for a much-needed global analysis of embodied emissions from agricultural production and to develop methodologies needed to assign responsibility for the impacts. While a global analysis is feasible for a selection of agricultural products, as illustrated in this case study, there are many uncertainties and unknown parameters needed to perform full GHG accounting for other managed agricultural systems. Future research in this highly interdisciplinary arena must take advantage of recently released research using remote sensing platforms (Palace *et al* 2008, Wang and Qi 2008), field studies (Davidson *et al* 2008) and RFID technology (Kelepouris *et al* 2007) in order to make progress toward full ‘field to fork’ life-cycle assessments for agricultural products.

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