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Including Carbon Emissions from Deforestation in the Carbon Footprint of Brazilian Beef

Christel Cederberg,*,† U. Martin Persson,‡,⊥ Kristian Neovius,§ Sverker Molander,⊥ and Roland Clift||

†SIK, the Swedish Institute of Food and Biotechnology, 402 29 Göteborg, Sweden

‡Center of Globalization and Development, Department of Economics, University of Gothenburg, 405 30 Göteborg, Sweden

§Department of Public Health Sciences, Karolinska Institute, 171 76 Stockholm, Sweden

⊥Department of Energy and Environment, Chalmers University of Technology, 412 96 Göteborg, Sweden

||Centre for Environmental Strategy, University of Surrey, Guildford, Surrey GU2 7XH, U.K.

S *Supporting Information*

ABSTRACT: Effects of land use changes are starting to be included in estimates of life-cycle greenhouse gas (GHG) emissions, so-called carbon footprints (CFs), from food production. Their omission can lead to serious underestimates, particularly for meat. Here we estimate emissions from the conversion of forest to pasture in the Legal Amazon Region (LAR) of Brazil and present a model to distribute the emissions from deforestation over products and time subsequent to the land use change. Expansion of cattle ranching for beef production is a major cause of deforestation in the LAR. The carbon footprint of beef produced on newly deforested land is estimated at more than 700 kg CO_2-equivalents per kg carcass weight if direct land use emissions are annualized over 20 years. This is orders of magnitude larger than the figure for beef production on established pasture on non-deforested land. While Brazilian beef exports have originated mainly from areas outside the LAR, i.e. from regions not subject to recent deforestation, we argue that increased production for export has been the key driver of the pasture expansion and deforestation in the LAR during the past decade and this should be reflected in the carbon footprint attributed to beef exports. We conclude that carbon footprint standards must include the more extended effects of land use changes to avoid giving misleading information to policy makers, retailers, and consumers.

INTRODUCTION

Greenhouse gas (GHG) emissions resulting from land use change (LUC) have been estimated at around 17% of total anthropogenic GHG emissions in 2004.[1] A key driver of deforestation is the expansion of pastures for beef production in South America and estimates indicate that LUC, mainly deforestation, caused by the growing livestock sector is the source of approximately 6% of global GHG emissions.[2]

Brazil is the world's second largest beef producer, with exports having increased 7-fold during the past decade, and the world's top exporter of beef. In 2006 production totaled 8.6 million tons (MT) carcass weight (CW), of which 24% was exported.[3] The Legal Amazon region (LAR, an administrative unit which includes the nine states of Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Tocantins, Mato Grosso and most of Maranhão state) is of growing importance for Brazilian beef production (see Supporting Information, SI). In 2006, nearly 25% of Brazil's beef production came from the nine states of the LAR where continuous grazing all year around is the predominant feeding strategy.[4,5] There has been a steady expansion of pasture area in the LAR over recent decades,[6] at the expense of natural forests;[7] gross deforestation rates in this region averaged ~1.9 million hectares (Mha) per year in the period 1986−2005[8] and several studies show that pasture is the main subsequent land use occupying 60−75% of newly deforested land.[9−11]

At present, there is widespread interest in better understanding various products' life cycle GHG emissions, so-called "carbon footprints" (CF), a term used for example by the British Standards Institution and in International Organization for Standardization (ISO) working documents to describe the GHG emissions attributable to providing a specific product or service. The main purpose of estimating CFs is to provide information for policy-making, for supply chain management, and to facilitate a shift by retailers and consumers toward low-carbon products.[12]

Examples of CF reporting standards include The British PAS 2050:2008 which sets out a prescriptive method for assessing CFs of goods and services[13] and ongoing work to develop international standards for CF calculations by the ISO[14] and World Resources Institute & World Business Council for Sustainable Development.[15] These initiatives build on existing life cycle assessment (LCA) methods. However, while LCA has already been used extensively to assess the environmental performance of food including GHG emissions, emissions from LUC are not routinely included.[16] Their omission leads to substantial underestimates of food products' total impact on climate change, and this is especially the case for beef.[2]

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In assessing GHG emissions from LUC, it is conventional to distinguish between direct LUC, which can be attributed directly to a product from a specific piece of land following a change of use, and indirect LUC, where changes in agricultural activity or aggregate demand induce land-use changes that cannot be associated directly with a specific product. The CF reporting standards currently under development include only emissions from direct LUC.[13−15]

Here, we present a method for attributing greenhouse gas emissions from deforestation to beef produced on the resulting pasture, using the example of the Legal Amazon region in Brazil. We have estimated total GHG emissions from LUC along with pasture productivity and distributed emissions over products and time. The research outcomes are intended to inform environmental policy and regulatory bodies on the importance and feasibility of including LUC in carbon footprint estimates and also on the very high carbon footprint associated with beef production on newly deforested land.

METHODS

Estimates of Land Productivity. Cattle for beef production is the predominant utilization of Brazilian pastureland, comprising close to 160 Mha in 2006.[6] Milk production was estimated to use around 20 Mha in the late 1990s[17] but of this total area only a small part is within the LAR. According to the latest census, two-thirds of Brazil's total milk production comes from the south and south-eastern regions whereas less than 10% comes from the nine states of the LAR.[6] From statistics on beef production and agricultural land used for beef production,[3,6] we calculated indicative values for land productivity in beef production, defined as beef production per hectare and year; see further details in the SI.

Estimates of Greenhouse Gas Emissions from Deforestation. The GHG emissions from deforestation were calculated using a method referred to as "net committed emissions" (NCE)[7,18,19] in which emissions are calculated from the net difference in carbon stock between the original and the replacement land-cover, including emissions from decay of biomass residuals that can continue for more than a decade after the actual deforestation. Land use changes following deforestation in the Brazilian Amazon are dynamic and complex and involve different cycles of clearing, grazing, cultivation, and forest regeneration.[20] A common progression is that after some years as cropland, as the nutrients left from the burning of forest become depleted, a piece of land is abandoned or transferred into pasture. Pasture can stay productive if well managed or may turn into degraded pasture (often due to overgrazing) and eventually be abandoned. On abandoned land, forest regenerates into secondary forest, but is normally cleared within a decade to begin a new cycle, see Figure 1. A result of these complicated land use transitions is that more than one hectare of forestland is cleared to provide one new hectare of land in permanent agricultural production. In the nine states of the LAR, the accumulated deforestation amounted to 37.3 Mha from 1986 to 2005[8] while land in agricultural production (cropland, pasture, agroforestry) increased by only 20.8 Mha between the two agricultural censuses in 1985 and 2006.[6]

Fearnside[21] developed a Markov model of agricultural land use in the LAR that considered the land-use states "Productive Pasture", "Degraded Pasture", "Cropland", "Secondary Forest from Pasture", "Secondary Forest from Cropland", and "Regenerated Forest", and gave the annual transition probabilities between these land-use states,[21] described in detail in SI Table S5. The model gives final land use (stabilized after ∼50 years; i.e., the "equilibrium landscape") after deforestation as 51% pasture (including degraded pasture), 5% cropland, and 44% secondary forest; see SI Table S6.

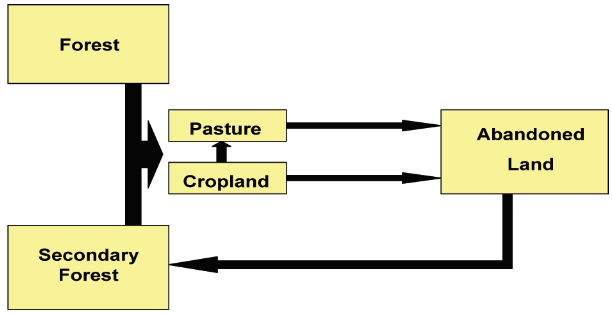

Figure 1. Typical cycle of land use in the Legal Amazon Region.

Carbon stocks take the forms of biomass, both above and below ground, and Soil Organic Carbon (SOC), and their size determines possible emissions after LUC. Values used for carbon stocks in the biomass for different vegetation types and associated uncertainties are described in SI and summarized in Table S6.

Forest is typically cleared by fire in the Amazon.[22] However, the forest is not completely burned: some carbon is left on the ground as dead organic matter, decaying over a period of years and thus included in the NCE calculations, while some is partially combusted and released as methane and nitrous oxide, see further discussion in SI.

Distribution of Emissions over Products and Time. A critical issue is how to attribute the emissions to subsequent products from the deforested land, since it may yield food, feed, or bioenergy products over a long period. Also, the calculated carbon footprint will be sensitive to the time period selected for accounting, i.e. the production period over which the emissions from the initial deforestation are amortized.

First, 11 t C ha^{-1} of the total carbon emissions from land clearing, corresponding to 6% of above and below ground biomass, were allocated to timber products on the basis of carbon removal in the timber. While only part of the total area deforested in the LAR is logged prior to conversion into agricultural land, loggers practice high-impact selective logging, removing only a few marketable timber species but causing canopy damage resulting in carbon emissions beyond the biomass removed from the forest as product. Based on remote sensing and inventory data from Asner and colleagues,[23,24] we assume that on average 22% of land clearing for cattle ranching is preceded by selective logging and that the net committed emission from logging is 50 tC ha^{-1}, the latter based on average timber harvest of 23 m^3 ha^{-1} (or 8 tC ha^{-1}) and the remainder coming from fine and coarse debris (residual stumps, branches, foliage, and roots) left in the forest after harvesting. While the resulting carbon output in timber products is relatively low, it is in accordance with other estimates, e.g., values given by Keller et al.[25]

A second critical methodological issue is that, in a CF analysis or an LCA, the environmental impact from an event, in this case LUC must be distributed over a subsequent activity period since a new piece of agricultural land can generate economic products indefinitely. If a long period of agricultural production is chosen, the emissions per product unit will be low. Unless land is

Table 1. Areas of Pasture and Fodder Production (Mha year^{-1}), Beef Production (Mton CW year^{-1}) and Indicative Values for Land Productivity (as kg CW ha·year^{-1}). Total Brazil and the Legal Amazon Region

year	pasture and roughage fodder crops, total, Mha	pasture and roughage fodder crops allocated to beef[b], Mha	beef production, Mton CW year^{-1}	productivity, kg CW ha·year^{-1}
		Brazil total		
1996[a]/97[c]	177.7[a]	151	6.444[c]	43
2006	168.9	144	8.6	60
		nine states of the Legal Amazon Region		
1996[a]/97[c]	51.2[a]	46	1.095[c]	24
2006	56.8	51	2.155	42

[a] Mha (million hectares), data from 1996 only including pasture; data from 2006 also include cut roughage fodder from cropland and agroforesty, see further SI.[6] [b] Area for milk production and other grazing livestock deducted before calculating land productivity in beef production, see further SI. [c] Mton ((million ton carcass weight) (CW)), data from 1997.[3]

abandoned after some known time span, there is no single obvious value for what can be called the amortization period; it is therefore a matter of choice or general convention. When calculating the emissions associated with beef production, we varied the amortization period to illustrate the outcome of different choices. Besides annualizing the emissions over a number of production years, changes in use between pasture and cropland also must be allowed for. This was done based on Fearnside's values[21] for the transformation factors describing land use following deforestation (see SI Table S5). The resulting allocation factor between pasture and cropland stabilizes at just over 90% after approximately ten years.

The above approach leads to eq 1 for calculating the GHG emissions from LUC attributed to beef production (as kg CO_2e kg carcass weight^{-1}, CW^{-1}) with the amortization period as a variable factor:

$$\text{GHG emissions}_{\text{beef}} = \frac{\text{GHG emissions ha}^{-1} \times \text{pasture factor}_n}{\sum_{y=1}^{n} (\text{prop pasture}_y \times (1+\text{rate})^{y-1} \times \text{prod start ha}^{-1})} \quad (1)$$

GHG emissions$_{\text{beef}}$	GHG emissions from LUC (deforestation) allocated to beef production (as kg CO_2e kg CW^{-1})
GHG emission ha^{-1}	Total net committed emissions (NCE) from deforestation allocated to agriculture
pasture factor	The relative share of pasture in the n years following deforestation, calculated as the sum of pasture area (productive and degraded) divided by the total agricultural area (pastures + crop) during n years
n	Amortization time, years
prop pasture	Proportion of land remaining as pasture (included degraded pasture), n years after deforestation
rate	Annual fractional increase in pasture productivity
prod start ha^{-1}	Average production per ha pasture (kg CW ha^{-1}) used for beef production during year 1 (y=1)
y	Years after deforestation

RESULTS

Net Committed Emissions. We estimated total GHG emissions from deforestation in the LAR at 612 ± 212 ton CO_2e ha^{-1} ($CI_{95\%}$) with the uncertainty estimated using simple error propagation equations.[26] The relatively high uncertainty results primarily from the uncertainties in carbon content of the original forest (compare Table S6 in SI). Allocating 6% of the carbon to the timber product from logging activity before clearing the forest for agriculture (see above) leaves 572 ± 198 ton CO_2e ha^{-1} allocated to agricultural activities, of which 21 ton CO_2e ha^{-1} is trace gases from the initial burn, see SI Table S6. This emission estimate can be compared with estimates of 604−824 ton CO_2e ha^{-1} by Searchinger et al.[27] for conversion of tropical forest into cropland and the default LUC value of 740 ton CO_2 ha^{-1} recommended in PAS 2050[13] for conversion of Brazilian forest into cropland. The lower estimate of GHG emission per hectare obtained here reflects the increase in SOC in well-managed pasture, as distinct from cropland, following deforestation, and the recognition in the NCE method that some of the deforested land reverts to secondary forest which acts as a carbon sink and allocation of some of the emissions to timber products.

Pasture Productivity. The indicative values for pasture productivity suggest that during the past decade productivity has increased from ∼43 to ∼60 kg carcass weight (CW) per hectare per year as an average for the whole of Brazil. For the nine states of the LAR, the increase has been from ∼24 to ∼42 kg CW per hectare per year, see Table 1 and SI. Based on this historical development, pasture productivity is assumed to increase by 4% per annum.

Lower productivity is reasonable in the LAR because it is less developed in terms of management, breeding, and advisory service, etc. However, although land productivity has increased over the past decade, Brazilian production is still land-inefficient: beef production per hectare is substantially higher in Europe (in the range of 230−580 kg CW per ha and year depending on production system)[28] compared with Brazil (around 60 kg CW per ha and year, see Table 1). Improving pasture productivity is crucial since pasture is the dominant fodder in Brazilian beef production. Pasture degradation is a severe problem in Brazilian agriculture mostly due to overgrazing and lack of nutrient replacement.[4,29,30]

Attribution of LUC Emissions to the Beef Product. In eq 1, total NCE was taken as 572 ± 198 ton CO_2e ha^{-1}, annual pasture productivity increase (rate) as 4%, and average pasture production per hectare at start was taken as 42 kg CW ha^{-1}, results are shown in Figure 2. As expected, the carbon footprint values depend strongly on the amortization period chosen. If the carbon footprint indicator is to be used in policy making or for consumer information aiming at substantial short-term reduction

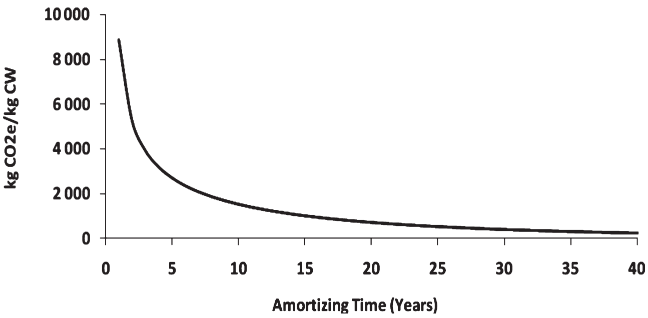

Figure 2. Influence of amortization on GHG emissions (kg CO_2e per kg carcass weight (CW) beef) from direct land use change of beef produced on pasture from deforested land in the Legal Amazon Region.

of GHG emissions, the choice of a short amortization period emphasizes the importance of deforestation. Therefore, if near-term greenhouse gas abatement is the aim, carbon footprint standards should favor shorter amortization periods. The carbon footprint standards now under development[13−15] suggest that emissions should be annualized over 20 years of production.

Using a 20-year amortization period, we calculated the CF of beef as a result of LUC at 726 ± 252 kg CO_2e per kg (CW) ($CI_{95\%}$) while amortization over 50 years leads to a CF of 156 ± 54 kg CO_2e per kg CW. The 20-year figure is used in the subsequent discussion.

Carbon Footprints of Beef. Life cycle GHG emissions of Brazilian beef *not* including LUC, i.e., comprising methane, nitrous oxide, and fossil CO_2, have been estimated at around 28 kg CO_2e per kg CW at the farm-gate as a national average.[5] Methane from enteric fermentation represents around 75% of this estimate and depends mainly on current breeding practice of the livestock population and its feed intake. Data for beef production systems in different climatic regions over an area as large as Brazil are inadequate to give a fair representation, leading to uncertain estimates of methane from enteric fermentation. According to Lassey,[31] national enteric fermentation inventories rarely have less than ∼20% uncertainties. Based on an assumption of 25% uncertainty in the methane calculations, results in a national average CF of Brazilian beef (LUC not included) fall in the range 23−34 kg CO_2e kg CW^{-1}.

Carbon footprints in the range 16−27 kg CO_2e kg CW^{-1} have been reported in European studies,[28,32−34] i.e., somewhat lower than the Brazilian average of around 28 kg CO_2e kg CW^{-1}. The difference is to be expected. The dominant cattle production system in Brazil is extensive with calving intervals of around 20 months and 3−4 years to slaughter,[4] compared to calving intervals around 12 months and slaughter ages between 18 and 24 months in more intensive European production systems. Furthermore, more than half of current beef production in Europe is derived as coproducts from dairy production (surplus calves and culled cows); consequently part of the total GHG emissions can be allocated to dairy products.[5]

Comparing the average emissions of methane, nitrous oxide, and fossil CO_2 for beef production in Brazil (∼28 kg CO_2e kg CW^{-1}) with emissions arising from direct LUC (amortized over 20 years) in the LAR of around 726 kg CO_2 per kg CW reveals how LUC dominates the carbon footprint when production takes place on newly deforested land. Even using the lowest value within the uncertainty range, the resulting CF of 474 kg CO_2e per kg CW is still more than an order of magnitude higher than the sum of emissions of methane, nitrous oxide, and fossil CO_2.

The next question is to determine the share of the beef production that should be associated with these GHG emissions from LUC. Or, more specifically, beef from what areas should carry the burden of the emissions? We estimated beef production in 2006 on land converted from forest in the 20 years preceding 2006 as approximately 0.51 MT CW, based on the net increase of land for cattle (+13.5 Mha) in the LAR between 1985 and 2006,[6] average land productivity in the LAR in 2006 (Table 1), and the assumption that 90% of pasture in the LAR is used in beef production.[5] Total production in the LAR was around 2.16 MT CW in 2006; thus ∼25% was produced on land deforested within the preceding 20 years. Averaging the LUC emissions over the whole production in the LAR in 2006 results in an average CF of ∼180 kg CO_2e per kg CW, which still is a very high value. Total Brazilian production was around 8.6 MT CW beef in 2006; thus close to 6% was produced on the recently deforested land in the LAR. Averaging the LUC emissions (annualized over 20 yrs) for the total Brazilian production in 2006 results in an average carbon footprint around 44 kg CO_2e per kg CW. Thus GHG emissions from LUC allocated to beef production and annualized over the 20 years following deforestation are about 25 to 1.5 times greater than the emissions of methane, nitrous oxide, and fossil CO_2 from beef production from established pasture land (around 28 kg CO_2e kg CW^{-1}) and depends on the allocation of the LUC emissions to (a) beef directly produced on newly (20 years) deforested land in the LAR (∼726 kg CO_2e per kg CW), (b) beef production in the whole of LAR (∼180 kg CO_2e per kg CW), or (c) beef production in the whole of Brazil (∼44 kg CO_2e per kg CW). The way in which the LUC should be allocated over beef production in Brazil is a matter for further debate, but these figures illustrate how misleading CF values can be if land use change is not included, irrespective of the boundaries chosen.

■ DISCUSSION

Brazil's strong growth in beef production during the past decade has been achieved by intensification and pasture expansion in the LAR but mainly by intensification in the rest of Brazil; see Table 1. The growth of the cattle herd in the LAR was particularly strong between 1996 and 2006 (see Table S2 in SI) and according to Nepstad et al.,[35] the high deforestation rates in 2002, 2003, and 2004 were primarily related to this. Brazilian exports also grew substantially during the period. The dominant share of the production increase since 1996 has been exported, while the national consumption has been rather stable[3] (Figure 3). The expansion of production was dependent on control of foot-and-mouth disease (FMD) enabling more beef to be exported, and driven by growing demand for beef on the world market, aided by devaluation of the Brazilian currency and outbreaks of BSE, reducing production in Europe.[35] Until the first years of 2000, FMD control was more effective in the states of the South, Southeast, and Centre-West, thus qualifying these regions to export while the LAR supplied only the national and the regional markets.[36] Between 2001 and 2003, Mato Grosso and Rondônia became disease-free zones and beef from these states now provides an increasing share of total export.[5] However, over the decade, beef for export was mostly sourced from non-deforestation states. Although export growth cannot be said conclusively to have been the sole driver for LUC in LAR, it

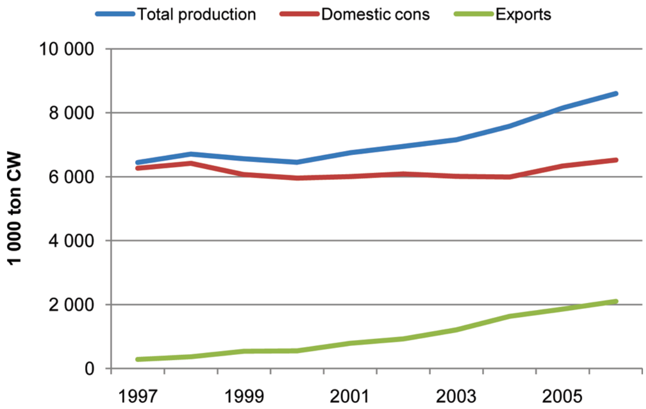

Figure 3. Development of production, domestic consumption, and exports (1 000 tons carcass weight, CW), 1997−2006.

does appear that growing international demand for beef at a time of relatively stable domestic demand (Figure 3), has led to the overall growth in production and hence induced the ongoing process of pasture expansion in the LAR.

A prerequisite for adequate market responses is that market actors are correctly informed. During recent years, environmental certification schemes have become increasingly important as tools to inform retail purchase and to guide consumers toward more environmentally benign products.[37] The ongoing work to develop carbon footprint accounting standards is yet another step in this process. However, we question some aspects of the detailed methodological proposals for estimating carbon footprints, for example PAS 2050:2008[13] and ongoing working documents by ISO and World Resource Institute & World Business Council for Sustainable Development.[14,15] For LUC calculation, these guidelines propose supply chain analysis considering solely the specific land associated directly with the product labeled. We argue that including only these proposed direct LUCs will in some cases fail to inform consumers that their purchases can have a strong impact on changes with large associated GHG emissions, along with other environmental impacts. The LUCs in the Brazilian Amazon in the period 1996−2006 exemplify this. Our results indicate that beef production in the LAR on newly deforested land has a CF many times higher than the CF from methane, nitrous oxide, and fossil CO_2. So, even if the production from this land is small (around 6% of total Brazilian), its contribution to GHG emissions is very large and therefore the inclusion of these emissions will greatly influence the final CF, regardless of whether it is calculated as a LAR or a Brazilian mean CF. If the methods for LUC calculations in CF reporting standards are applied as proposed in prestandards, findings like the ones presented here would not be reflected in the carbon label on exported beef because it is mainly sourced from states without recent deforestation. As a consequence there would have been no label information to support pressure against deforestation from meat importers and consumers.

A further complication is that exported beef is not the only agricultural commodity driving the conversion of forest into pasture in the LAR. Increased global demand for soymeal and bioethanol from sugar cane is raising land prices, which contributes to the migration of cattle production to the north of Brazil. Livestock farmers in the South who sell their land to soya and cane farmers and move to the northern region can multiply their pasture area: the average land price is seven times lower than in the south and the differential is increasing.[38] Studies in the areas with major expansion in sugar cane (state of São Paolo and neighboring states) confirm that the bioethanol expansion has not affected food crop production in these regions but has impacted on pasture area, with cattle production discontinued on pasture which has been converted to sugar cane plantations.[39]

The high deforestation rate in the Amazon region in the early years of 2000, possibly fueled by a favorable world market for beef and soy,[35] has been followed by a significant decline: from July 2005 to July 2009, deforestation decreased to 36% of the average clearing rate which was 1.95 Mha yr^{-1} during the period 1996−2005. The reduced rate is a result of federal campaigns aiming to eliminate illegal operators as well as putting pressures on buyers of products from the Legal Amazon Region.[40] Brazil's ambitious program to reduce deforestation may also have been helped by the worldwide economic recession but a long-term prognosis is for a doubling of world meat consumption from 2000 to 2050.[2] Brazil's leading role in the global meat trade is indisputable and the Brazilian Ministry of Agriculture has announced aspirations to almost double exports in the coming decade.[41] To accomplish this without further expansion of pasture leading to deforestation, pasture management and animal husbandry must be improved so that more beef can be produced on the land already in production. This is indeed a challenge but the current low land productivity in Brazil suggests that there is scope for substantial increase in beef production without further increase in pasture land.

However, even if the envisioned increases in Brazilian beef exports are to be realized through improved productivity rather than area expansion, the forests of the Amazon will need stronger protection due to the generally expected growth in global demand for agricultural products. Consumer-driven changes of agricultural practices can support the changes called for, but environmental certification schemes that do not include more extended effects of LUC will not help to reduce the pressure for changes like deforestation since current export production often is sourced from non-newly deforested land. Methods to incorporate LUC in the calculations of carbon footprint will always struggle to find agreement on what exactly to include. The Brazilian beef example developed here illustrates the need to maintain the search for methodology to include LUC in estimating the environmental impacts associated with agricultural and forest products.

We conclude that carbon footprint standards that do not include more extended effects of land use changes risk providing policy makers and consumers with misleading information, concealing the links between agricultural expansion, deforestation, and global trade.

■ ASSOCIATED CONTENT

Supporting Information. Further information on cattle production and land use in Brazilian agriculture together with information on how GHG emissions from deforestation were calculated is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author
*E-mail: christel.cederberg@sik.se.

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