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Abstract

We couple a global agricultural production and trade model with a greenhouse gas model to assess leakage associated with modified beef production in the United States. The effects on emissions from agricultural production (i.e., methane and nitrous oxide emissions from livestock and crop management) as well as from land-use change, especially grazing system, are assessed. We find that a reduction of US beef production induces net carbon emissions from global land-use change ranging from 37 to 85 kg CO_2-equivalent per kg of beef annualized over 20 years. The increase in emissions is caused by an inelastic domestic demand as well as more land-intensive cattle production systems internationally. Changes in livestock production systems such as increasing stocking rate could partially offset emission increases from pasture expansion. In addition, net emissions from enteric fermentation increase because methane emissions per kilogram of beef tend to be higher globally.

Keywords: land-use change, greenhouse gas emissions, pasture expansion, beef production

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1. Introduction

With climate change becoming an increasingly pressing issue together with a world population of 7 billion people in 2011, significant pressure is put on global agriculture and forestry.

The two sectors (including deforestation) are responsible for 13.5% and 17.4% of global anthropogenic greenhouse gas (GHG) emissions, respectively [1]. Although treated separately in national GHG inventories, there is little doubt that both categories are closely linked and climate policies targeting agriculture will have spillover effects on forestry and vice versa. Hence, the implementation of large-scale agricultural policies is prone to unintended consequences.

In this paper, we analyze the hypothesis that a reduction of cattle in the US causes a net increase in GHG emissions

on a global scale. A decrease in US cattle numbers increases production in other countries to compensate for the reduction in US beef production, leading to pasture expansion and, thus, an increase in GHG emissions [2]. We refer to this production shift as 'leakage'.

Previous literature on the effects of livestock and agricultural production on GHG emissions varies in scope and geographic extent. Many studies focus on land-use in Brazil [3–6] or on a subset of countries in the tropics [7, 8] because agricultural production is close to carbon-rich forests. Global studies analyze the implications of increased livestock demand and biofuels on land-use and greenhouse gas emissions [9–11]. We extend the previous research by combining the regional and global approaches and quantifying global GHG emissions from a US policy.

The initial idea for calculating leakage from a decrease in US beef production associated with a cattle tax is based on an Advance Notice of Proposed Rulemaking by the US Environmental Protection Agency (EPA) from 30 July 2008 to regulate greenhouse gas emissions under the Clean Air Act [12]. The American Farm Bureau voiced opposition to the proposal and claimed that a potential consequence would be the regulation of GHG emissions from livestock production, e.g., a so-called 'cow tax'[6].

In the EPA's response to the public comments, the agency '... assures commenters that it is not proposing a cow tax. [...] EPA has proposed a rule focusing on large facilities emitting more than 25 000 tons of GHGs a year. Small farms [...] are projected to be below this threshold'[7]. The proposal as well as the Farm Bureau's comments serve as a starting point to calculate leakage from US beef production. The policy used in this article reduces beef production by imposing a tax on fed steer prices and, thus, is only a hypothetical policy with similar effects in terms of herd size to a 'cow tax'. In addition, the policy does not include any border adjustments for imported beef even if it has higher CO_2 emissions associated with its production.

We couple a GHG model that calculates non-CO_2 emissions from agriculture and carbon emissions from land-use change with an agricultural production and trade model to assess a scenario that results in a reduction of US beef production. We do not include energy related emissions such as fossil fuel use or wastewater treatment but use the model output to assess potential impacts of differences in production systems among countries. Different energy intensities associated with livestock production on pasture and in feedlots result in trade-offs between the production systems in terms of lifecycle emissions [13–15].

We pay particular attention to global pasture and Brazilian agriculture. The global expansion of livestock is a pressing issue, especially in view of a growing human population and increased demand for livestock products [16]. Population growth, urbanization, and increasing income levels are key drivers of livestock product demands [9, 8, 3]. Over the last two years, almost 486 000 ha of the Paraguayan Chaco thorn forest has been cleared due to increasing cattle herds[8]. Although intensification of grazing systems in developing countries is expected in the long run, especially in Latin America [16, 17], the extent of these productivity gains remains uncertain. Brazil deserves attention because of its large cattle herd of 200 million head, expanding agricultural production, and vast areas of tropical rainforest storing a significant amount of carbon. Brazil encompasses widely varying ecosystems, ranging from grassland and cropland associated with temperate climates in the south to tropical forests in the north and semiarid areas in the northeast. In addition, Brazilian pasture not only provides feed for livestock but is also the easiest way to claim land ownership and to avoid rapid forest re-growth [5]. A low stocking rate of less than 1 head per ha exacerbates the problem of pasture expansion in the Legal Amazon [18]. Emission from beef production has been estimated to be 700 kg of CO_2-equivalents per kg carcass weight for newly deforested land in Brazil [4]. In the Brazilian state of Mato Grosso, pasture remains the dominant use of land brought into production after forest is cleared [6, 7]. Thus, if a US policy causes leakage in countries such as Brazil, the carbon impact can potentially be very significant.

We find that a reduction of beef production in the US would in part be offset by an increase in production elsewhere. The reduction of methane and nitrous oxide emissions in the US is offset by an expansion of pasture into grassland and forest because more land-intensive grazing systems are used in some large livestock producing countries. Annualized over a period of 20 years [4], emissions from land-use change increase between 37 and 85 kg of CO_2-equivalent per kg reduction of beef production in the United States. The results suggest that it is important from a GHG perspective to consider the implications of agricultural policies broadly, in terms of both direct and indirect emissions as well as the global market. It underlines the suggestion of previous research [19] to focus on agricultural policies that reduce conversion of land from native vegetation or that increase the productivity of existing crop or livestock production systems.

2. Methods

For the baseline and policy evaluation, we use an existing econometric trade and production model for global agriculture developed at the Center for Agricultural and Rural Development (CARD) at Iowa State University. The GHG model takes the output from the production model and calculates the emissions associated with land-use change (CO_2) and agricultural production (N_2O, CH_4). Figure 1 represents a simplified model structure.

2.1. Agricultural production model

The model provides projections of crop and livestock production, commodity prices, utilization, and crop area

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[6] Greenhouse Gas Regulation, the Clean Air Act and Potential Implications for Production Livestock.

[7] EPA Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act: EPA's Response to Public Comments.

[8] New York Times, Vast tracts in Paraguay forest being replaced by ranches.
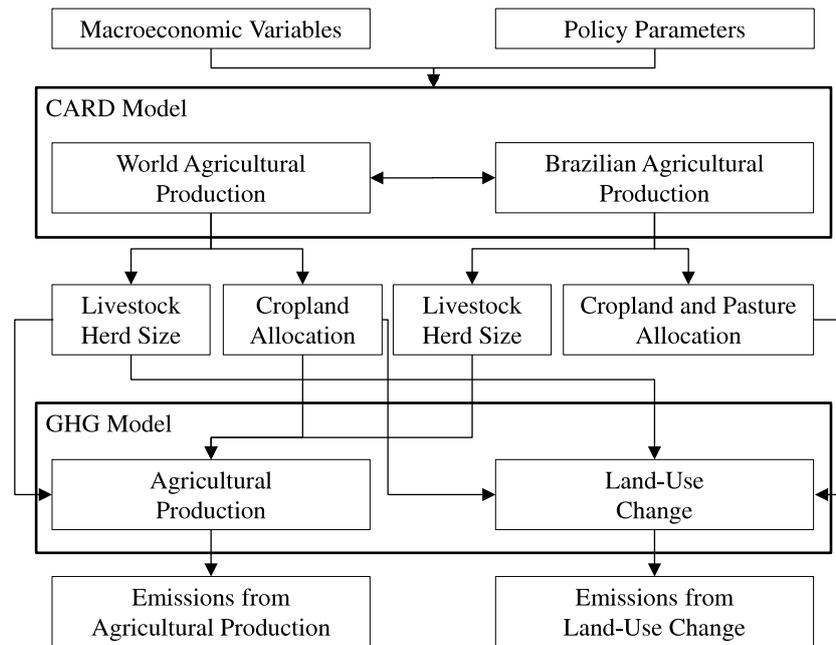
Figure 1. Model structure. The agricultural trade and production model ('CARD model') provides projections about herd size, cropland allocation, commodity prices, biofuel production, etc on a global scale. In Brazil agricultural production is modeled at the sub-national level. In addition, the Brazil model provides pasture allocation explicitly. The output of the trade and production model is then used by the GHG model to calculate emissions from agricultural production and assess carbon emissions associated with land-use change.

until 2023. The partial equilibrium model covers 14 major crops and three major livestock categories (cattle, swine and poultry) as well as the biofuel and dairy industries. The model is non-spatial in the sense that trade relations between specific countries are not analyzed but there exists a price that clears the import and export markets globally, i.e., total imports equal total exports. The model solves for a market clearing world price and includes macroeconomic variables such as population growth and policy parameters such as price supports and/or import tariffs. Long-term changes in technology and preferences such as yield increases and dietary shifts in developing countries are included in the model. The long-run equilibrium is characterized by a zero economic profit condition for the crop, livestock, and biofuel sectors. Although the model's output includes consumption by sector, prices, and quantities of processed crop and livestock commodities such as cheese, butter and biofuels, we focus on crop area allocation and livestock herd size because those values are pertinent for our GHG calculations. The model has been used to analyze the land-use change impacts of biofuels [10, 20, 21], the effect of trade barriers on ethanol markets [22], and the effect of high crude oil prices on commodity prices and biofuels [23]. The structure of the model is described in more detail in the referenced publications.

Agricultural production in Brazil is modeled at a sub-national level dividing the country into six regions to present developmental disparities in terms of infrastructure, logistics, and strategies available to increase production. The model captures regional differences in terms of capabilities and consequences of area expansion, so that the impact of land-use changes derived from increasing demand for agricultural products can be more precisely established. Note

that the Brazil model computes the stocking rate explicitly and reports the pasture use as an output.

2.2. Greenhouse gas model

The GHG model encompasses two large categories: agricultural production and land-use change (figure 1). Emissions from agricultural production focus on three categories: enteric fermentation (CH_4), manure management (CH_4, N_2O) and agricultural soil management (N_2O). Emissions from land-use change focus on biomass and soil carbon. We use the spatial distribution of cropland, landcover and biomass/soil carbon to determine the difference in the carbon pool between the baseline and the scenario. The calculations are based on tier 1 emission factors from the Intergovernmental Panel on Climate Change (IPCC) [24].

Given the spatial distribution of livestock and pasture, we can implicitly calculate the stocking rates and, hence, the pasture requirement for the year 2000. This is not necessary for Brazil because pasture is an output of the model. The global coverage makes it possible to account for leakage in terms of area allocation and crop production as well as GHG emissions from land-use change and agricultural production. For the land-use as well as the agricultural production component of the GHG model, we focus only on comparison between the baseline and the scenario in emissions for the year 2023, which represents the long-run equilibrium of the model.

One important driver of emissions is the future evolution of the stocking rate. To simplify our model and to limit assumptions, we first model emissions using a constant stocking rate between the base year and 2023 in all countries, except Brazil. This assumes that land is currently at the carrying capacity and cannot be intensified. We then provide
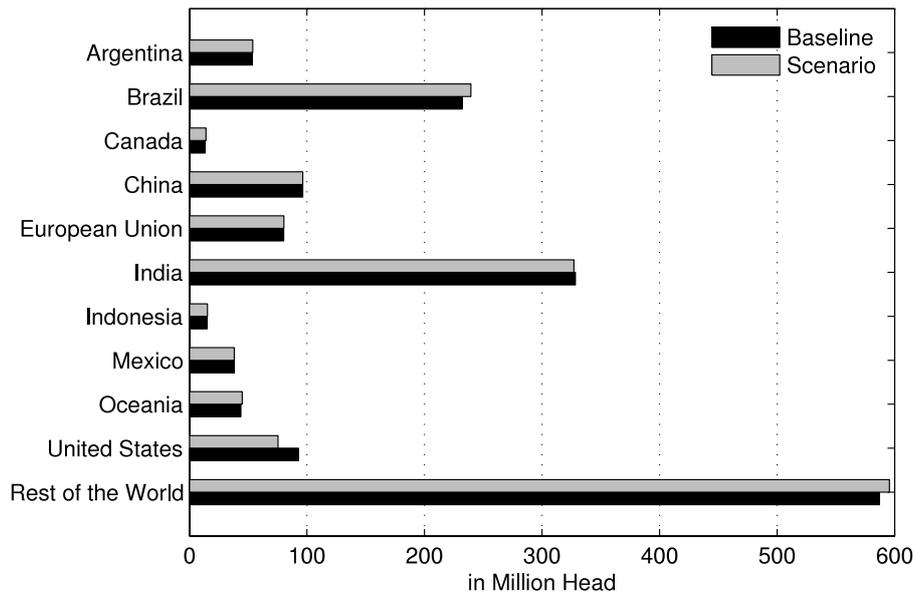
Figure 2. Comparison in cattle herd size between the baseline and the scenario by 2023. Cattle herd in the US decreases by 17.3 million head whereas Brazil and the rest of the world increase their cattle herd by 7.4 and 10.3 million head, respectively.

a sensitivity analysis for major livestock producing countries to identify the carbon savings that could potentially be achieved between the baseline and the scenario by allowing for intensification, i.e., an increase in the stocking rate of up to 50% compared to the base year. This is consistent with estimates from the late 1990s where the national average stocking rate for Brazil was 0.54 animal units per ha and could be raised to 0.72 (+33.3%) and 0.96 (+77.7%) by improved systems and high technology systems, respectively [25].

3. Policy impact on beef production and consumption

The scenario analyzed with the agricultural production model imposes a 10% tax on US fed steer prices. Beef cow and total cattle numbers are reduced by 26.06% and 18.62% respectively in the United States by 2023 (figure 2). US beef production is reduced by 17.06% from 12.61 to 10.46 million tons. This is a reduction of 2.15 million tons. On a global scale, beef cow herd is reduced by 0.91% or 2.87 million head. Although the policy results in a small net decrease in beef numbers, the increase of herd sizes in countries with low stocking rates results in pasture expansion. An increase in cattle herd is observed in large livestock producing countries such Brazil (6.31%), Australia (4.04%), India (3.51%) and Indonesia (7.11%). On average, global net export of beef and veal increases by 17.3% to compensate for the reduction in US beef production. The increase in net exports is particularly high in Brazil with an increase of 24.75% (figure 3). Table 1 illustrates the change in diet from beef to pork and broiler due to the increase in beef prices. Note that the own-price elasticities reported for beef demand are inelastic, i.e., small changes in demand in response to price, which is generally true for food demand [10].

Although beef production in the US is reduced significantly, demand is not reduced by the same amount

because imports compensate partly for the reduction in the United States. The market price for beef and veal increases by 3.68% and the imports increase by 6.95% in the scenario. The higher price results in a reduction of domestic beef consumption from 13.08 to 12.61 billion tons or a decrease of 3.61 per cent. This translates into a per capita reduction in beef consumption of nearly 1 kg, from 25.98 to 25.04 kg. The demand for beef consumption in the United States is inelastic (-0.73) with respect to its own price and, hence, consumption of beef is maintained despite the price increase in the United States. The inelastic demand in the agricultural production model is consistent with other estimates in the literature such as [26] with values ranging from -0.26 to -0.41 depending on the household income levels. Table 2 shows how the beef production changes and how this increase in production translates into the demand for feed. In the United States, the decrease in feed demand decreases prices and, thus, makes it cheaper to feed livestock. The reduction in prices increases the use of feed in other livestock sectors resulting in a decrease of US feed demand by less than 17%. Globally, if all beef were raised on feedlots, we would expect an increase in feed demand in equal proportions. If the feed demand increases at a lower pace than the beef production, then we have the indication that some of the additional beef production is raised on pasture and, hence, potentially causing an increase in pasture area.

4. Changes in greenhouse gas emissions

The results are presented separately for methane and nitrous oxide emissions from agricultural production and carbon emissions from land-use change. In our model, the emissions from agricultural production are not influenced by land-conversion decisions. All the emission numbers are based on the comparison between the baseline and the scenario.
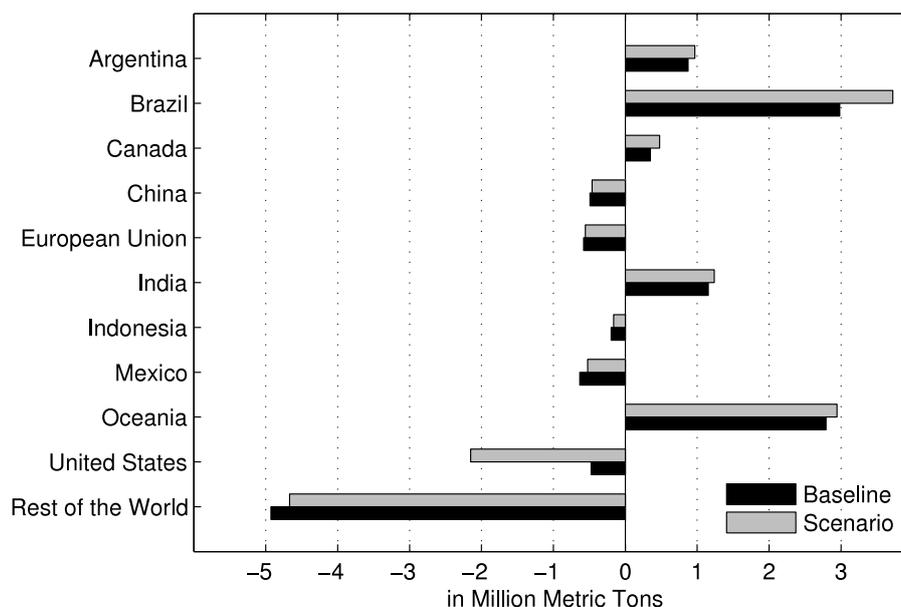
Figure 3. Net exports in 2023 for select countries. Because of higher global beef prices, countries either increase their beef exports due to profitability or decrease their exports because of reduced consumption.

Table 1. Per cent difference between the baseline and the scenario in beef, pork, and broiler consumption and prices and own-price beef demand elasticities for select countries in the year 2023. The feed demand for Oceania includes only Australia.

	Consumption			Price			
	Beef	Pork	Broiler	Beef	Pork	Broiler	Beef demand elasticity
Argentina	−1.29	0.26	0.34	7.79	0.39	0.00	−0.17
Australia	−1.34	0.49	0.46	6.48	0.31	0.00	−0.22
Brazil	−2.02	0.31	0.65	12.54	0.57	−0.19	−0.15
Canada	−2.13	0.60	0.94	11.56	0.64	−0.14	−0.23
China-mainland	−0.19	0.01	0.01	0.31	−0.39	−0.32	−0.37/ − 0.5
European Union	−0.21	−0.06	0.09	0.56	0.63	0.00	−0.40
India	−1.49	0.00	0.11	8.81	n/a	0.02	−0.18
New Zealand	−2.59	1.22	0.56	9.98	0.00	0.27	−0.22
United States	−3.61	1.62	0.25	3.68	0.22	0.18	−0.73
Indonesia	−1.86	0.14	0.82	8.51	0.40	0.02	−0.25
Mexico	−1.69	0.51	0.73	10.04	0.58	0.03	−0.20

Table 2. Per cent difference in meat production and feed demand in selected countries between the baseline and the scenario in 2023. The feed demand for Oceania includes only Australia.

	Production			Feed demand				
	Beef	Pork	Broiler	Barley	Maize	Sorg.	Soya	Wheat
Argentina	4.82	0.84	0.20	1.45	1.76	1.38	0.28	1.40
Brazil	4.88	0.41	0.23		0.57		0.41	0.52
Canada	6.69	0.71	0.83	1.12	2.07		0.61	2.06
China	0.11	0.02	0.02	−0.33	0.08		−0.78	−0.01
EU	0.09	0.32	0.11	−0.15	−0.11		0.17	−0.07
India	1.40		0.11		1.56	1.35	0.15	1.32
Indonesia	3.98	0.14	0.41		2.64			
Mexico	2.01	0.51	0.42	0.26	0.60	0.74	0.27	0.72
Oceania	3.73	0.61	0.09	3.10	3.43	3.52		3.30
United States	−17.06	1.26	0.58	5.40	−3.17	−9.56	−0.79	−19.41

4.1. Emissions from agricultural production

The inclusion of N_2O emissions from cropping systems is important because US cattle feed is heavily crop dependent.

A reduction in US beef production induces changes in crop area and trade patterns.

By 2023, the emissions from US enteric fermentation fall by 15.72%, or 19.1 Mt of CO_2-equivalent relative to the
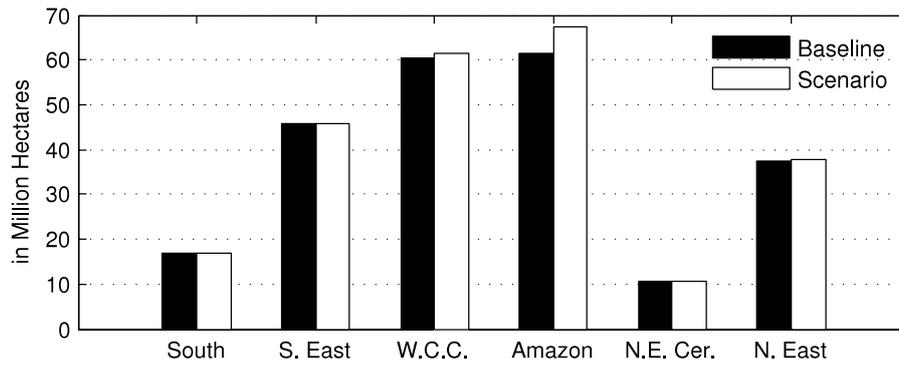
Figure 4. Pasture in Brazil. Between the baseline and the scenario, total pasture in Brazil increases by 3.56% and pasture in the carbon-rich Amazon region increases by 9.93%. The second largest per cent increase is observed in West Central Cerrado (WCC) which covers most of the state of Mato Grosso.

baseline, as shown in figure 5. The decrease in emissions from manure management in the US is more moderate and falls by 4.42%. In isolation, these numbers are consistent with the idea of reducing emissions from enteric fermentation and manure management. Although emissions in the US decline as a result of reduced livestock production, emissions in other countries increase because of expanded herd size. Combined emissions from enteric fermentation and manure management increase by 10.94 and 13.83 Mt CO_2-e in Brazil and the rest of world, respectively, with negligible changes in China, the EU and India. Overall, livestock emissions increase slightly by 3.22 Mt CO_2-e, which is very small compared to total US emissions from agriculture. The increase in emissions from enteric fermentation is due to a difference in meat production per head in the United States compared to other countries. The higher energy diet of intensive livestock in the US results in lower emissions of methane per unit of meat. The more intensive livestock management in the US results in quicker fattening and, thus, more beef per year. A similar trade-off is observed when emissions from agricultural soil management are taken into account. Although total global emissions increase slightly by 2.25 Mt CO_2-e, the effect is negligible. Ignoring land-use change, a reduction in US beef production has almost no effect on global non-CO_2 emissions because of the relative price inelastic demand for beef in the United States.

Emissions not explicitly taken into account in our model are CO_2 emissions associated with the different energy intensities of the livestock production system. A complete lifecycle assessment is beyond the scope of this paper but would include CO_2 emissions from agricultural fossil fuel combustion, upstream emissions from the production of agricultural inputs, and downstream emissions from wastewater treatment. Methane emissions from industrial wastewater alone are estimated to be 3.6 Mt of CO_2-equivalent for the US meat and poultry sector in 2009 [15]. Embodied fuel and other energy related inputs in feedlot production systems can be more CO_2-intensive than for a pastoral system depending on the location [13, 27]. For example, whereas US feedlot raised beef has emissions of 5.5 kg CO_2-e per kg of beef, African pastoral systems have only 0.1 kg CO_2-e per kg of beef [13]. This is consistent

with the difference of 4.4 kg CO_2-e per kg of beef between pasture and feedlot systems in the United States [27]. Hence a decrease in US beef production by 2.15 billion kg can result in emission savings of up 11.825 Mt CO_2-e. This amounts to approximately 2.77% of US agricultural emissions, which were 427.5 Mt of CO_2-equivalent in 2008 [15]. However, in light of the results that follow, it is difficult to compare intensive livestock production with pastoral systems in general in terms of CO_2 emissions. For countries with a high land carbon pool, it might be advantageous to have intensive livestock production in order to avoid CO_2 emissions from forest clearing. In light of our results, the findings from Subak (1999) comparing US feedlot systems and African pastoral systems might need modification to incorporate the emissions from the shift in production. Although pastoral systems are low in energy use, their emissions from land-use change can be significant.

4.2. Emissions from land-use change

Figure 6 shows the increase in global pasture due to a reduction of US cattle herd. Pasture in Brazil increases by 6.85 million ha (figure 4). The increase in Brazil is not proportional to the herd size because the stocking rate increases across regions by on average 1% in the scenario when compared to the baseline. Seemingly small, it should be kept in mind that an increase in the stocking rate of 2% in Brazil could accommodate all of the US biofuel production [28]. Pasture in the United States is reduced by 33.90 million ha. However, this area is mostly found in the west of the country with low precipitation and low carbon stocks. On a global scale (including the US), almost 10 million ha less pasture land would be used.

Total emissions from land-use change are summarized in figure 7. Note that the emissions refer to the difference between unmanaged vegetation and cultivated vegetation. Because the carbon stock in the western part of the United States is very low, the increase in carbon sequestration is moderate. For medium carbon coefficients, the carbon sequestered in the US is almost exactly offset by an increase in the category 'rest of the world'. However, as stated before, the significant carbon pool found in the Brazilian Amazon
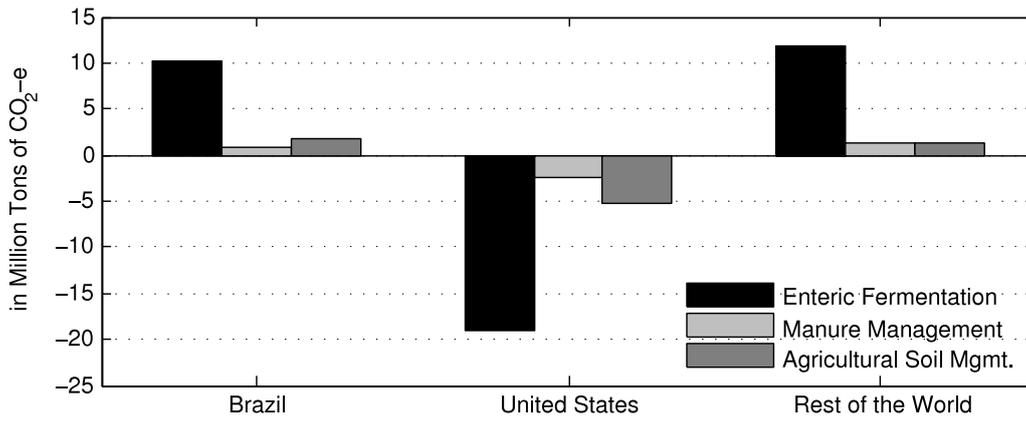
Figure 5. Changes in emissions relative to the baseline from agricultural production.
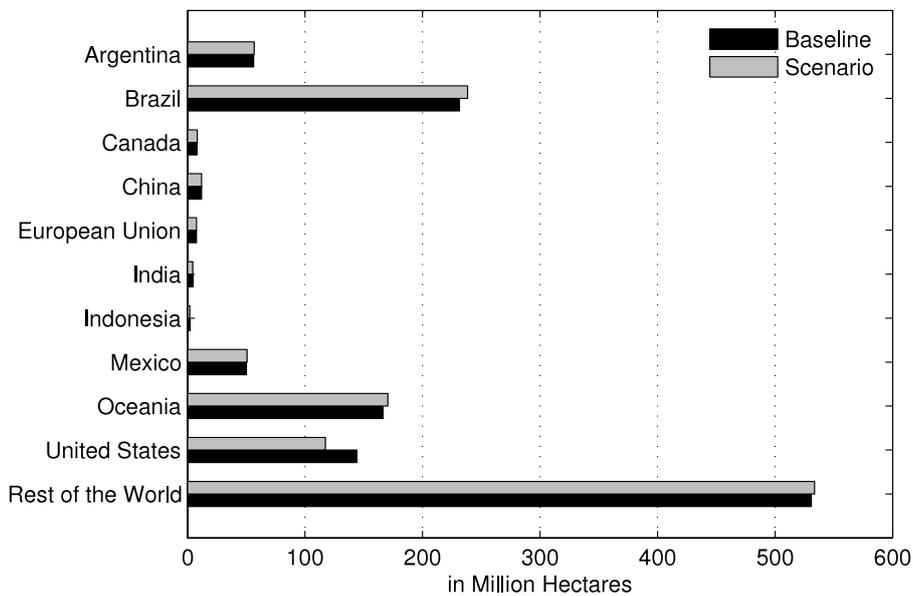

Figure 6. Global pasture. In countries other than the United States, pasture increases by 14.82 million ha with the largest shares in Brazil (6.85 million ha), Oceania (4.07 million ha) and 'rest of the world' (2.61 million ha).
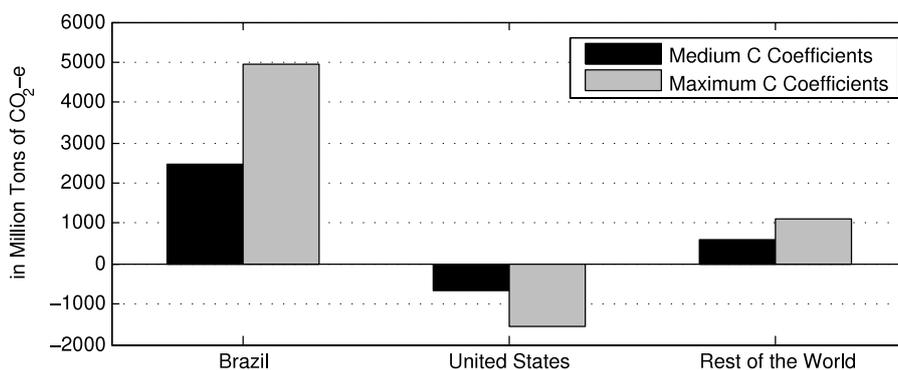

Figure 7. Emissions from land-use change. Almost no change occurs in China, the European Union and India and, thus, the emissions from these countries are in the category rest of the world.

together with the expected increase in pasture under the policy scenario leads to a significant release of carbon in Brazil. Given the median and maximum carbon coefficients, 1961 or 3641 Mt CO_2-e is emitted from land-use change (cropland and pasture combined), respectively. Assuming an amortization period of 20 years and given the reduction of US beef by 2.15 million tons, emissions of 45.6 and 84.68 kg CO_2-e per kg reduction of US beef can be calculated. This is lower
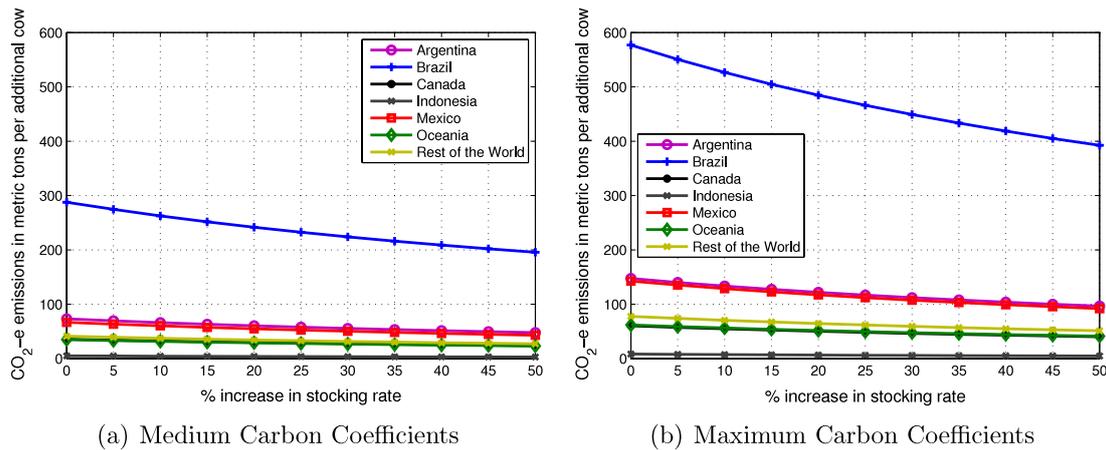
Figure 8. Sensitivity analysis for selected countries. The CO_2 emissions represent the emissions from land-use change over the additional number of cattle in the scenario compared to the baseline. (a) Medium carbon coefficients and (b) maximum carbon coefficients.

than the previously estimated 700 kg of CO_2-equivalents per kg carcass weight for newly deforested land in Brazil [4] because we take the average over all countries. Our results are lower because Brazil represents an extreme case whereas the emission coefficients from other countries where pasture expansion takes place have lower carbon coefficients.

4.3. Sensitivity analysis

In the previous analysis, we held stocking rates constant except in Brazil, where stocking rates were allowed to increase based on historical stocking rate increases in the period from 2000 to 2006 from 0.74 to 1.17 head ha^{-1} [3]. Projecting the stocking rate in each grid cell globally is very difficult and, hence, we provide a sensitivity analysis by country over a range of possible stocking rate improvements.

Figure 8 represents the carbon savings that can be achieved in the scenario for each additional cow for a countrywide increase in stocking rates. The lower range for our analysis is represented by an increase in stocking rate by 50% until 2023 which would result in emissions of 1593 and 2488 Mt CO_2-e for the medium and maximum carbon coefficient scenarios, respectively. This leads to emissions of 37 and 58 kg CO_2-e per kg reduction of US beef. Note that there are significant differences in the reductions that can be achieved across countries. Brazil has the largest potential but Argentina and Mexico remain critical as well.

With respect to Brazil, the last few years (2005–10) have shown stocking rate growths that are much lower than those observed in the early 2000s. Estimates based on the early period stocking rate changes may result in projections of changes in stocking rates that are too high given data from more recent years. Partial explanations behind the reduction in the pace of livestock intensification can be attributable to a slowdown in the growth of areas for crops and of the number of animals in the last few years. Elasticities estimated using the data of the early to mid-2000s would result in much higher stocking rate estimates than those utilizing the second half of the decade [29]. On the other hand, if animal numbers are driving the stocking rates, then new beef demand caused by

the US policy could increase stocking rates to the levels seen in the first half of the last decade. As seen in figure 8, those stocking rate increases would have to be significant in order to reduce the net emissions of this policy to zero.

The policy analyzed is a unilateral implementation by the US and the question of a broader adoption of GHG policies remains. In general, GHG regulation causes a decrease in production in the regulated countries and an increase in countries not subjected to the policy [30, 2]. A broader adoption would have two opposing effects: (1) emissions in adopting countries would decrease. In the case of agriculture, this would put pressure on prices and, in the absence of a border adjustment policy, increase production and (2) increase emissions in non-adopting countries. Depending on the emissions associated with production in those countries, emissions may increase globally. Previous research suggests that as an increasing number of countries adopt GHG policies the emission reductions in the adopting countries are not equally matched by the increased emissions from leakage in other countries [30]. We hypothesize, however, that the sequence or group of countries is a large determinant of leakage, e.g., as long as carbon-rich countries such as Brazil are not part of an agreement, emissions from leakage are going to be present.

5. Summary and conclusions

We examine the impact of a policy change on beef herd output or productivity in the United States. The carbon impact of a reduction in US beef production depends heavily on the breadth of framework that is used. Evaluating the impact on US agricultural emissions only results in an emission reduction whereas including the price-induced response in other countries results in a net increase in emissions due to land-use change. This finding is important because it suggests that in a world where prices adjust to policy changes, and other sectors respond to these price changes, one can obtain very misleading conclusions from analysis that is specific to one country or one industry.

The key results from this study are as follows. First, there are dramatic differences in the carbon efficiencies of different beef production systems, with the more extensive systems having the worst carbon efficiencies. Second, among counties and products where international trade is allowed, any attempt to reduce output in one sector in one country will be mitigated by an increase in output in other sectors and in other countries. This suggests a need for a global carbon accounting of any carbon-based policy proposal. Third, where trade works to create the described carbon leakages, costs associated with unilateral restrictions on output could more wisely be spent on increasing agricultural productivity in the developing world. More broadly, the results show that an increase in productivity, e.g., stocking rate, can have very beneficial global impacts.

Acknowledgments

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