Supporting Information

Cohn et al. 10.1073/pnas.1307163111

SI Text

Policy Context. This analysis examines the potential for cattle ranching intensification interventions to achieve the greenhouse gas (GHG) mitigation targets put forth in the Brazil National Climate Policy (PNMC) (1). The PNMC does not define mitigation strategies, but the Brazil Nationally Appropriate Mitigation Activities (NAMAs) are mitigation targets for the year 2020 that may be the best hint thus far of how the PNMC might develop.

The NAMAs commit just 10% of total mitigation to come directly from changes in cattle ranching practices. However, roughly 90% of the mitigation proposed in the NAMAs would come from reduced land use change and changes in output and production practices in agricultural systems that would hinge on increased cattle ranching productivity (2). As a related report describes the mechanism, "Increasing . . .intensification of livestock-raising can play an essential role in reducing the need for land. . . while releasing the land required for expansion of other activities" (3). Table S3 details the content of the NAMAs proposed by the government of Brazil (4).

Methods Supplement. ***Model description.*** This analysis uses the Global Biosphere Management Model (GLOBIOM), an economic partial equilibrium model of the competition for global land use. In GLOBIOM, the demand for land stems from exogenously specified regional drivers, including gross domestic product (GDP) growth, population growth, evolution of food diets and global bioenergy demand, and local characteristics of the land. The present analysis uses the most recent projections developed by the climate change community for GDP and population growth (Table S4) (5). We use the shared socioeconomic pathways 2 scenario (SSP2), a so-called, "middle of the road" scenario. Results are reported using indicators calculated from model output (Table S7).

Agricultural and livestock productivity. Spatially explicit yields for each crop and each management system, as well as input requirements, have been estimated using the biophysical crop growth model EPIC (6, 7). Livestock management systems have been defined according to the livestock production systems classification developed by the International Livestock Research Institute and the Food and Agriculture Organization (8, 9). Input-output coefficients have been computed with the RUMINANT model for ruminants (bovines, sheep, and goats) and derived from a literature review for monogastrics (pigs and poultry) (10).

Productivity change. Productivity change arises in the model as a combination of exogenous productivity growth over time and endogenous yield change. The latter comes about through management system changes and movement of crop production to relatively more or less suitable areas. The analysis distinguishes four crop management systems—subsistence agriculture, low-input rain-fed agriculture, high-input rain-fed agriculture, and high-input irrigated agriculture (11).This analysis assumes exogenous productivity growth as detailed in Table S4. Exogenous productivity growth is coupled with crop-specific management intensification, including increased use of fertilizer.

Transportation costs model. The transportation costs model uses ArcMap 10.0 to estimate agricultural input and output transportation costs across Brazil. The output is a set of cost maps, expressed in year 2000 US dollars, depicting crop-specific input and output costs for each 1-km^2 grid cell in Brazil. Each of these maps is then aggregated to the level of GLOBIOM simulation units and used to determine agricultural production costs in the model. The first step was to assemble a raster map of land cover and of road, river, and rail transportation networks (data were accessed at http://www.diva-gis.org/gdata and the Brazilian Environmental Ministry website). Next we developed a transportation friction raster, a map depicting the cost per meter of traversing each surface type in the raster map. Costs were adapted from travel times in Farrow et al. (12) and from data and modeling on Brazilian agricultural logistics (13–15). In cells with overlapping features, we prioritize the lowest cost alternatives as would users of transportation services. Next we multiplied the land cover raster by a slope adjustment raster (16). Then we assembled a set of points of origin for agricultural inputs (fertilizer, lime, and pesticides) and a set of destinations for agriculture and ranching outputs (beef, milk, eggs, soy, corn, sugar, and generic domestic crops). These origins and destinations were identified based on publicly available accessed from a variety of web sources. Then we used the cost-distance feature of ArcMap Spatial Analyst to compute the least cost path for inputs to each point on the map and the least cost path from each point on the map to crop-specific, market-specific infrastructure.

Thus, for cattle ranching systems, for example, total logistics costs are the sum of input logistics costs (primarily fertilizer) and output logistics costs. Outputs costs are computed as a market share weighted average of local market, national market, and export market logistic costs. Market shares are estimating in the following fashion. First, we use a Brazilian state level 50 sector input output table to distinguish sector output for consumption within the state from sector output that leaves the state (17). We then use Brazil Trade Ministry data from http://aliceweb.mdic.gov.br/ to calculate the proportion of output leaving the state that is exported internationally. These market shares are used to weight the output costs based on the differential transport costs to local, domestic, and export markets.

Intervention scenarios: Policies targeting semi-intensive cattle system adoption in Brazil. In the analysis, two interventions are modeled: a land tax on extensive cattle ranches and a subsidy for adoption of semi-intensive cattle ranching technologies. Taxes are levied on all simulation units that fail to adopt or maintain semi-intensive pasture in the time step. Subsidies are provided to all simulation units that adopt or maintain semi-intensive ranching in the time step. For any given grid cell, the subsidy and the tax have an equal impact on the relative cost of the conventional and the semi-intensive pasture systems.

We are interested in how livestock intensification interventions in Brazil affect net global land use and land cover and net land use GHG emissions relative to a counterfactual baseline in which all else is equal except for the livestock intensification intervention. In the baseline scenario, the model is calibrated for the year 2000. It simulates global land use and land cover for three time steps: 2000–2010, 2010–2020, and 2020–2030. We use these land use and land cover values to calculate the overall deforested area over each modeled period, the annual deforestation rate, and the forest that regenerates on surplus land. The deforested area is given as the area of mature forest at time step t_0 minus the area of mature forest at time step t_1. We presume that the deforestation is evenly spaced across the 10 y of the time step. Because the carbon sequestered by regenerating forest follows a different profile than the carbon emitted by deforestation, we account regeneration separately from deforestation. The area under regeneration is computed directly by the model. The models also conducts similar tabulations for savannahs because savannahs also have an asymmetric profile of carbon emissions and sequestration. Grasslands are considered to regrow over a sufficiently short period that the model computes their net area. The model contains spatially explicit $CO_2eq \cdot ha^{-1} \cdot y^{-1}$ estimates of the emissions from deforestation, savannah loss, and grassland loss. It also contains $CO_2eq \cdot ha^{-1} \cdot yr^{-1}$ sequestration values for reforestation and savannah regrowth.

Semi-intensive cattle ranching. Brazil has the largest commercial cattle herd in the world at roughly 200 million head, but the productivity per head is less than many other nations. Productivity gains have occurred over the last few decades with the stocking rate per hectare of pasture increasing 80% over the period of 1950–2006 (18). However, gains have not been uniform across the industry, but rather stem from a vanguard of advanced pockets where improved technologies, including those developed by the Brazilian Agricultural Research Corporation, have been adopted (3). In these regions, stocking rates are up and direct GHG emissions are down due to pasture management practices, animal diets, genetic advances, and herd management practices. Together, these factors reduce cattle life spans, enteric fermentation per unit feed consumed, and GHG emissions per unit weight gained (19). They afford the possibility of semi-intensive systems with substantially lower direct emissions and higher land intensity than typical production systems (20).

In our model analysis, we introduce a semi-intensive production pathway representative of a system already found in Brazil (18, 20). The production pathway is developed as a set of additional inputs to a conventional cattle system that would result in doubled pasture productivity per hectare of pasture. As additional inputs, the semi-intensive pasture production pathway requires fertilizer, lime, pasture seed, and labor. The costs of using these inputs depend on the location of the pasture in question because of logistics costs.

The average annual cost differential between the conventional pasture and the semi-intensive pasture averages 80 USD/ha. The semi-intensive system is adopted on less than 1% of land in the baseline simulation scenario. The cost of production will vary according to the local land rent, a value computed in the model. In turn, as is the case for all cattle pasture in the model, producers are free to adopt any 1 of 12 cattle production systems on the newly improved land. These systems have differing inputs and costs. Broadly, they are divided into mixed systems and pasture-only systems. The mixed system derives a maximum of 4% of animal calories from animal feed. Holding pasture productivity constant, the most productive livestock system is 33% more productive per hectare than the least productive system.

In our modeling framework, the necessary conditions for adoption of the semi-intensive, pasture-based cattle technology, in simulation unit i in time step j are that (i) no other land use is more competitive than cattle ranching and (ii) the cost per unit output of the semi-intensive system, o_2, is less than the cost per unit output of the conventional cattle system, o_1. The adoption of the semi-intensive system is determined by the spatiotemporal flux of land and agricultural prices. These depend on the land productivity potential, the spatially explicit costs of transporting inputs to agricultural regions, the costs of transporting agricultural goods to markets, and the policy intervention scenarios.

GHG accounting. GLOBIOM accounts for the major GHG emissions and sinks related to agriculture and forestry. Soil N_2O emissions from application of synthetic fertilizers are calculated according to the 1997 International Panel on Climate Change (IPCC) guidelines on the basis of fertilizer use as simulated in EPIC.

Coefficients for methane (CH_4) emissions from rice production are derived from the Environmental Protection Agency (21); CH_4 emissions from enteric fermentation and N_2O emissions from manure management are estimated with the RUMINANT model.

Land use change GHGs are calculated as the differences between the equilibrium carbon embodied in the investigated land cover classes. Carbon content in above- and below-ground living forest biomass is taken from Kindermann et al. (22), and carbon content in the biomass of short rotation plantations is calculated based on the present study's estimates of the plantation productivity. For parameterization of carbon in grasslands and in other natural vegetation, the biomass map of Ruesch and Gibbs (23) is used. CO_2 coefficients for emissions and sinks due to land use change are calculated as the difference between the carbon content of the initial land cover class and that of the new class.

We only consider carbon in the above- and below-ground living biomass because global spatially resolved reliable data on current soil organic carbon levels and a comprehensive set of carbon response simulations are scarce.

GLOBIOM Regions. The GLOBIOM regions include the following—Australia and New Zealand; Brazil; Canada; China; Congo Basin: Cameroon, Central African Republic, Congo Republic, Democratic Republic of Congo, Equatorial Guinea, Gabon; European Union Baltic: Estonia, Latvia, Lithuania; European Union Central East: Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia; European Union Mid West: Austria, Belgium, Germany, France, Luxembourg, Netherlands; European Union North: Denmark, Finland, Ireland, Sweden, United Kingdom; European Union South: Cyprus, Greece, Italy, Malta, Portugal, Spain; Former Union of Soviet Socialist Republics: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan; India; Japan; Mexico; Middle East and North Africa (MENA): Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, United Arab Emirates, Yemen; Pacific Islands: Fiji Islands, Kiribati, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu; Caribbean: Bahamas, Barbados, Belize, Bermuda, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Netherland Antilles, Panama, St Lucia, St Vincent, Trinidad and Tobago; Rest of Europe: Albania, Bosnia and Herzegovina, Croatia, Macedonia, Serbia-Montenegro; Rest of Western Europe: Gibraltar, Iceland, Norway, Switzerland; Rest of South America: Argentina, Bolivia, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela; Rest of South Asia: Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka; Rest of Pacific Asia: Brunei Daressalaam, Indonesia, Singapore, Malaysia, Myanmar, Philippines, Thailand; Rest of Southeast Asia: Cambodia, Korea DPR, Laos, Mongolia, Viet Nam; South Africa; South Korea; Sub Saharan Africa (SSA): Angola, Benin, Botswana, Burkina Faso, Burundi, Cape Verde, Chad, Comoros, Cote d'Ivoire, Djibouti, Eritrea, Ethiopia, Gambia, Ghana, Guinea, Guinea Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Martinique, Mauritania, Mozambique, Niger, Nigeria, Rwanda, Sao Tome Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe; Turkey; and United States of America.

Responsiveness of Beef Demand to Beef Price. Beef demand elasticities with respect to price of beef are shown by the major world regions. Elasticities are unitless values that show the responsiveness of one variable y, to another x. They are computed as the percentage change in y divided by the percentage change in x. They are exogenously specified in the model and are taken from ref. 24. Elasticities assumed: Mideast and North Africa, −0.496; sub-Saharan Africa, −0.572; North America, −0.25; South Asia, −0.548; Brazil, −0.469; Europe, −0.3; Oceania, −0.25; Eastern Asia, −0.475; Southeast Asia, −0.513; Other Latin America, −0.478.

1. Federal Government of Brazil (2008) *National Action Plan For Climate Change (PNMC)* (Interministerial Committee for Climate Change, Brasilia, Brazil).
2. Cohn A, Bowman M, Zilberman D, O'Neill K (2011) *The Viability of Cattle Ranching Intensification in Brazil as a Strategy to Spare Land and Mitigate Greenhouse Gas Emissions* (CCAFS, Copenhagen), p 43.
3. Gouvello C (2010) *Brazil Low Carbon Country Case Study* (World Bank: Sustainable Development Department of the Latin America and Caribbean Region, Washington, DC), p 286.
4. Embassy of Brazil (2010) *Brazil's Nationally Appropriate Mitigation Activites* (Embassy of Brazil, Brasilia, Brazil).
5. O'Neill BC, et al. (2014) A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Clim Change* 122(3):387–400.
6. Izaurralde R, Williams JR, McGill WB, Rosenberg NJ, Jakas M (2006) Simulating soil C dynamics with EPIC: Model description and testing against long-term data. *Ecol Modell* 192(3):362–384.
7. Williams J (1995) The EPIC model. *Computer Models of Watershed Hydrology*, ed Singh V (Water Resources Publications, Highlands Ranch, CO), pp 909–1000.
8. Kruska R, Reid R, Thornton P, Henninger N, Kristjanson P (2003) Mapping livestock-oriented agricultural production systems for the developing world. *Agric Syst* 77(1): 39–63.
9. Wint W, Robinson T (2007) *Gridded Livestock of the World, 2007* (United Nations Food and Agriculture Organization, Rome), p 131.
10. Herrero M, Thornton P, Kruska R, Reid R (2008) Systems dynamics and the spatial distribution of methane emissions from African domestic ruminants to 2030. *Agric Ecosyst Environ* 126(1):122–137.
11. You L, Wood S (2006) An entropy approach to spatial disaggregation of agricultural production. *Agric Syst* 90(1):329–347.
12. Farrow A, Risinamhodzi K, Zingore S, Delve RJ (2011) Spatially targeting the distribution of agricultural input stockists in Malawi. *Agric Syst* 104(9):694–702.
13. de Castro N, Carris L, Rodrigues B (1999) Custos de transporte ea estrutura espacial do comércio interestadual brasileiro. *Pesqui Planej Econ* 29(3):447–500.
14. Bowman MS, et al. (2011) Persistence of cattle ranching in the Brazilian Amazon: A spatial analysis of the rationale for beef production. *Land Use Policy* 29(3):558–568.
15. University of São Paulo-ESALQ System of Freight Information (2012) *Soybean Logistics Costs from Farm to Port* (Univ of São Paulo-ESALQ, Piraçicaba, Brazil).
16. Wagtendonk JW, Benedict JM (1980) Travel time variation on backcountry trails. *J Leis Res* 12(2):100–106.
17. Haddad EA, Domingues EP, Perobelli FS (2002) Regional effects of economic integration: The case of Brazil. *Journal of Policy Modeling* 24(5):453–482.
18. Martha GB, Alves E, Contini E (2012) Land-saving approaches and beef production growth in Brazil. *Agric Syst* 110:173–177.
19. Thornton PK, Herrero M (2010) Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *Proc Natl Acad Sci USA* 107(46):19667–19672.
20. Euclides V, et al. (2010) Brazilian scientific progress in pasture research during the first decade of XXI century. *R Bras Zootec* 39:151–168.
21. Scheehle E, Godwin D, Ottinger D (2006) Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2020 (U.S. Environmental Protection Agency, Washington D.C.).
22. Kindermann GE, McCallum I, Fritz S, Obersteiner M (2008) A global forest growing stock, biomass and carbon map based on FAO statistics. *Silva Fennica* 42(3):387–396.
23. Ruesch A, Gibbs HK (2008) *New IPCC Tier-1 Global Biomass Carbon Map For the Year 2000* (Oak Ridge National Laboratory, Oak Ridge, TN).
24. Seale JL, Regmi A, Bernstein J (2003) *International Evidence on Food Consumption Patterns* (Economic Research Service, US Department of Agriculture, Washington, DC.

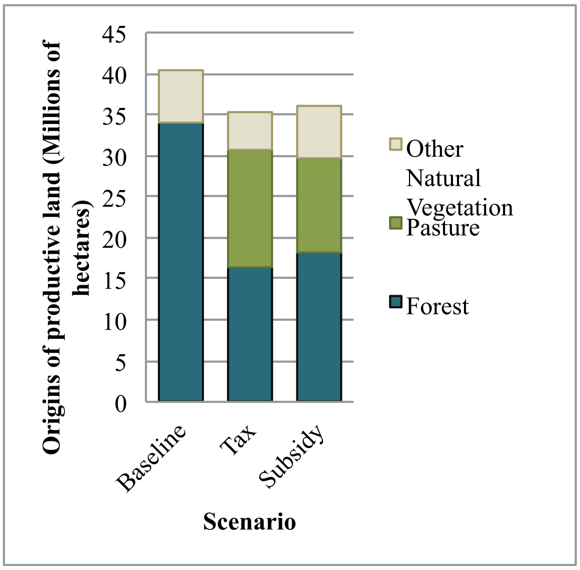

Fig. S1. Effects of tax policy (*T*) and subsidy policy (*S*) on origins of productive land in Brazil. Since the 1980s, forests have been the primary origin of new productive land across much of the tropics including Brazil (1). We find that either *T* or *S* could halt this trend. Whereas 84% of new productive land (intensive pasture, cropland, and managed forest) in Brazil from 2010 to 2030 would originate as forest under scenario *B*, just 46% and 50% would originate as forest under *T* and *S*, respectively.

1. Gibbs HK, et al. (2010) Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proc Natl Acad Sci USA* 107(38):16732–16737.

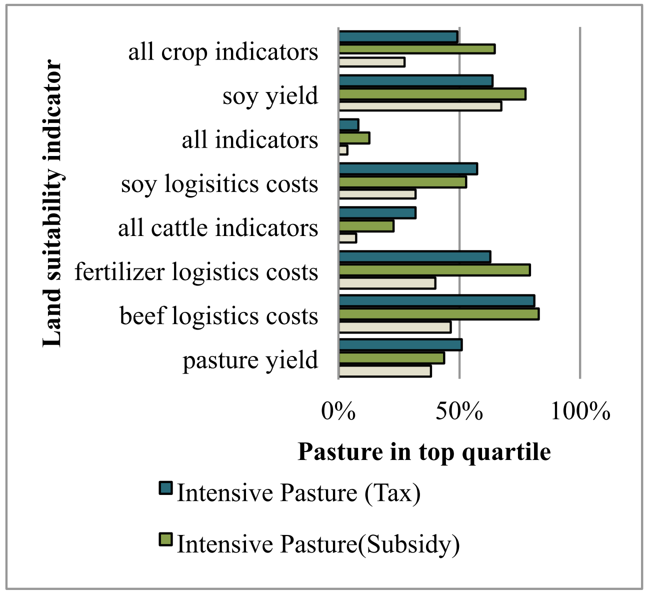

Fig. S2. Land suitability is a strong predictor of adoption of intensive cattle ranching. Intensive pasture, whether triggered by S_a or T_a, is more than three times as likely as conventional pasture to be found on the land in Brazil that is most suitable for livestock. The most suitable land ranching land is land that is in the best quartile of for pasture productivity potential (>75th percentile), fertilizer and lime transport costs (<25th percentile), and beef transport costs (<25th percentile). Under both policies, intensive pasture is also twice as likely as conventionally pasture to be found in locations that are highly suitable for soybeans, i.e., the best quartile of soy productivity potential (>75th percentile) and soy logistics costs (<25th percentile).

Analysis	Scenario	Baseline deforestation rate (mha/yr)	Total avoided deforestation hectares (in 2020)	Percent deforestation reduced (area)	Total avoided deforestation in 2020 (Gt)	CO2e/ha
PNMC	n.a.	1.95	1.5	80.0%	0.56	0.38
Nepstad et al.	n.a.	1.95	1.95	100.0%	0.70	0.36
GLOBIOM1	tax	1.13	0.69	61.1%	0.14	0.20
GLOBIOM2	tax	1.13	0.69	61.1%	0.20	0.29
GLOBIOM3	tax	1.13	0.69	61.1%	0.22	0.32
GLOBIOM4	tax	1.13	0.69	61.1%	0.16	0.23
GLOBIOM1	subsidy	1.13	0.46	40.7%	0.12	0.25
GLOBIOM2	subsidy	1.13	0.46	40.7%	0.17	0.37
GLOBIOM3	subsidy	1.13	0.46	40.7%	0.19	0.41
GLOBIOM4	subsidy	1.13	0.46	40.7%	0.14	0.29

Fig. S3. Sensitivity of GLOBIOM results to forest carbon maps and a comparison with the National Climate Plan of Brazil and Nepstad et al. (1) are shown. GLOBIOM1 uses FRA2005 downscaled to the 0.5° grid (2), GLOBIOM 2 uses Saatchi et al. (3) for the tropics, GLOBIOM 3 uses Baccini et al. (4) biomass map for the tropics, and GLOBIOM 4 uses FRA2005 downscaled to 0.5° grid adjusted to match FRA2010 national values (5).

1. Nepstad D, et al. (2009) Environment. The end of deforestation in the Brazilian Amazon. *Science* 326(5958):1350–1351.
2. Kindermann GE, McCallum I, Fritz S, Obersteiner M (2008) A global forest growing stock, biomass and carbon map based on FAO statistics. *Silva Fennica* 42(3):387.
3. Saatchi SS, et al. (2011) Benchmark map of forest carbon stocks in tropical regions across three continents. *Proc Natl Acad Sci USA* 108(24):9899–9904.
4. Baccini A, et al. (2012) Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nat Clim Change* 2(3):182–185.
5. Valin H, et al. (2013) Agricultural productivity and greenhouse gas emissions: Trade-offs or synergies between mitigation and food security? *Environ Res Lett* 8(3):035019.

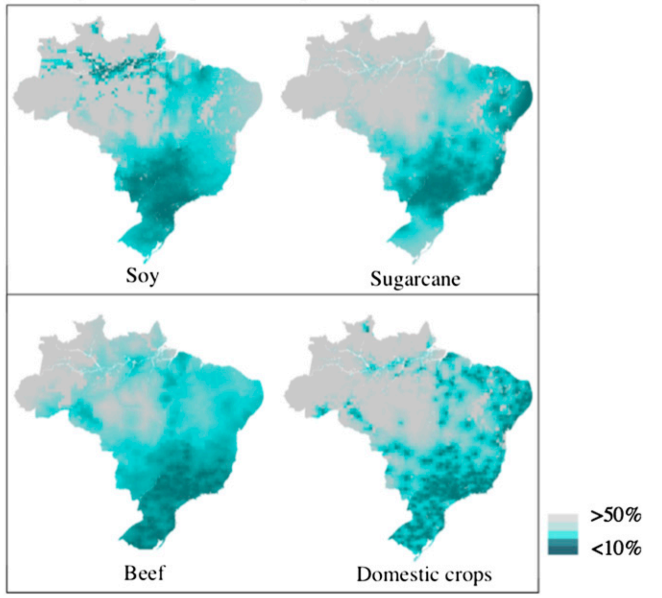

Fig. S4. Agricultural logistics costs as a percentage of market prices. Maps depict the costs of transporting agricultural products to points of market access within Brazil. The costs are expressed as a percentage of the market price for each commodity.

Table S1. Results by scenario

Trade scenarios	Results	Policy scenarios: Subsidy	Tax	Baseline
Trade as usual (trade and consumption adjust in response to policies modeled)	Abbreviation	S_{TAU}	T_{TAU}	B_{TAU}
	Adoption % area	40	17	0
	BeefBr (mt)	11.4	9.3	10.4
	ExportsBr (mt)	1.8	3.4	2.7
	BeefPriceBr (USD)	1,462	1,215	1342
	BeefROW (mt)	74.0	73.0	73.4
	PastureBr (mha)	182.4	177.5	198.1
	ForestBr (mha)	345	347	329
	ForestROW (mha)	2,600	2,598	2599
	Cost (billion USD)	30	48	n/a
	GHGs (mtCo2e/y)	328	261	540
No trade (policies modeled have no effect on trade in cattle products between Brazil and ROW)	Abbreviation	S_{NT}	T_{NT}	same as B_{TAU}
	Adoption % area	34	20	
	BeefBr (mt)	10.9	10.1	
	ExportsBr (mt)	2.7	2.7	
	BeefPriceBr (USD)	1,498	1,208	
	BeefROW (mt)	73.4	73.4	
	PastureBr (mha)	182.3	179.2	
	ForestBr (mha)	345	346	
	ForestROW (mha)	2,599	2,599	
	Cost (billion USD)	26	48	
	GHGs (mtCo2e/y)	317	296	
No consumption, no trade (policies modeled have no effects on trade in cattle products between Brazil and ROW and no effects on amount of cattle products consumed in Brazil or in ROW)	Abbreviation	S_{NCNT}	T_{NCNT}	same as B_{TAU}
	Adoption % area	30	21	
	BeefBr (mt)	10.4	10.4	
	ExportsBr (mt)	2.7	2.7	
	BeefPriceBr (USD)	1,503	1,204	
	BeefROW (mt)	73.4	73.4	
	PastureBr (mha)	181.8	179.9	
	ForestBr (mha)	346	345	
	ForestROW (mha)	2,599	2,599	
	Cost (billion USD)	23	48	
	GHGs (mtCo2e/y)	308	304	

Select agriculture, land use, and GHG outcomes are shown across the policy scenarios and trade scenarios simulated. All values are for the year 2030 unless otherwise stated. "Adoption %" refers to the proportion of total pasture in Brazil on which semi-intensive cattle ranching systems are adopted over the period of 2010–2030. Cost is the cumulative amount distributed under the subsidy by the government or the cumulative amount collected under the tax over the period of 2010–2030. "BeefBr" is amount of beef produced in Brazil in carcass weight equivalent. BeefPriceBr is the producer price of beef in Brazil per ton. ROW, rest of the world.

Table S2. Baseline projections for beef production and exports

Beef production exports	2000	2010	2030
World supply (Mt)	66.3	74.8	83.9
Brazil supply (Mt)	7.0	8.1	10.4
World exports (Mt)	3.2	5.1	8.8
Brazil exports (Mt)	0.6	0.9	2.7
Brazil exports/world exports	18%	18%	31%
Brazil supply/world supply	11%	11%	12%
World exports/world supply	5%	7%	10%

Table S3. Brazil's pledged emissions reductions in the year 2020

Mitigation source	Mitigation potential (Mt CO_2eq)	Percent of total mitigation
Restoration of grazing land	83–104	9–11%
Integrated crop livestock systems	18–22	2%
Reduction in Amazon deforestation	564	54–58%
Reduction in *cerrado* deforestation	104	10–11%
No-till farming	16–20	2%
Biological N_2O fixation	16–20	2%
Biofuels use	48–60	5–6%
Energy efficiency	12–15	1%
Hydroelectric power production	79–99	8–10%
Other alternative energy	26–33	3%
Grand total	966–1,041	100%

Table S4. Assumed growth in crop yields, GDP, and population

Crop	Region	2010	2020	2030
	Increased productivity for select crops			
Barley	World	9%	8%	8%
Cassava	World	10%	7%	5%
Corn	World	17%	10%	6%
Cotton	World	38%	27%	12%
Rape	World	29%	9%	8%
Rice	World	8%	6%	6%
Soy	World	12%	12%	7%
Sorghum	World	27%	23%	18%
Sugarcane	World	21%	5%	7%
Sunflower	World	8%	8%	6%
Barley	Brazil	20%	11%	8%
Cassava	Brazil	−7%	8%	10%
Corn	Brazil	20%	11%	7%
Cotton	Brazil	41%	5%	14%
Rice	Brazil	14%	12%	7%
Soy	Brazil	9%	7%	6%
Sorghum	Brazil	−3%	33%	7%
Sugarcane	Brazil	40%	11%	5%
Sunflower	Brazil	6%	6%	5%
Wheat	Brazil	−5%	−34%	5%
	GDP (trillions of USD)			
		2010	2020	2030
	MidEastNorthAfr	2.4	3.6	4.9
	SubSaharanAfr	0.9	1.4	2.4
	NorthAmerica	14.4	18.5	22.1
	SouthAsia	1.5	3.0	5.7
	Brazil	1.1	1.6	2.2
	Europe	16.5	19.6	22.6
	Oceania	1.0	1.3	1.6
	EasternAsia	9.5	15.8	24.0
	SouthEastAsia	1.2	2.0	3.2
	OtherLatinAmerica	2.1	3.0	4.2
	Population (billions)			
		2010	2020	2030
	MidEastNorthAfr	0.5	0.5	0.6
	SubSaharanAfr	0.9	1.1	1.4
	NorthAmerica	0.4	0.4	0.4
	SouthAsia	1.6	1.8	2.0
	Brazil	0.2	0.2	0.2
	Europe	0.8	0.8	0.8
	Oceania	0.0	0.0	0.0
	EasternAsia	1.5	1.6	1.6
	SouthEastAsia	0.6	0.7	0.7
	OtherLatinAmerica	0.4	0.4	0.5

Table S5. Exogenously specified model parameters

Parameter	Spatial scale	Unit	Notes
Technical and cost parameters			
Pasture productivity potential (conventional)	Simulation unit	t DM·ha^{-1}·y^{-1}	Productivity potentials are estimated by EPIC (1).
Agricultural output transportation costs	Simulation unit	USD·t agricultural $product^{-1}$	Transport costs from farm gate to market were estimated using a GIS-based modeling approach for agricultural products beef, dairy, soy, sugar, corn, and primarily domestically used crops.
Agricultural input transportation costs	Simulation unit	USD·t agricultural $product^{-1}$	Transport costs from input facility to farm were estimated using a GIS based modeling approach for agricultural inputs.
Conventional pasture, feed, and mixed livestock production systems	Simulation unit	t CWE·ha^{-1}·y^{-1}	Feeding requirements—fodder and crops—and output quantity per livestock unit are defined for each country and each production system using the RUMINANT model (2).
Pasture productivity (semi-intensive pasture management)	Simulation unit	t CWE·ha^{-1}·y^{-1}	We develop a semi-intensive, pasture-based system where boosted inputs and management combine to double the amount of usable pasture fodder output per year. As a consequence, any given livestock production system will see double the output per hectare.
Production cost (semi-intensive pasture management)	Simulation unit	USD·t^{-1}	The cost of inputs to semi-intensification includes logistics costs. These are computed as a weighted average of all of the physical inputs per hectare associated with the Semi-intensive cattle production system. These consist primarily of lime and fertilizers.
Crop production systems	Simulation unit	t·ha^{-1}	Productivity potentials, phosphorous, nitrogen and water requirements are estimated for eighteen crop types by EPIC (3).
Technological change in crop sector	Model region	Percent	Yield growth for crops are assumed to follow recent historical trends derived from the analysis of past FAOSTAT yields between 1980 and 2010.
Timber harvesting potentials and harvesting costs	Simulation unit	m^3·ha^{-1}·y^{-1}	Managed forests and short rotation tree plantations are used for wood production. Five primary products can be harvested from managed forests: saw logs, pulp logs, other industrial logs, firewood, and energy biomass. The Global Forestry Model (G4M) is the basis for annual wood estimates (4).
Bioenergy technical coefficients and production costs	Model region	GJ·t $feedstock^{-1}$	Energy feedstocks are sourced from crops, managed forests, and short rotation tree plantations. These can be used to produce ethanol, methanol, heat and power, and biogas mixes. Bioenergy representation is elaborated in Havlik et al. (5)
Fertilizers production	Global	CO_2e·ha^{-1}	Fertilizer use per hectare are compiled from EPIC (1). Emissions per fertilizer use are calculated using a standard approach detailed by the IPCC (6).
Crop soil nitrous oxide	Global	CO_2e·ha^{-1}	Calculated using a standard approach detailed by the IPCC (6).
Rice methane	Global	CO_2e·ha^{-1}	Calculated using a standard approach detailed by the IPCC (6).

Table S5. Cont.

Parameter	Spatial scale	Unit	Notes
Enteric fermentation methane	SimU	$CO_2e \cdot ha^{-1}$	Computed by the RUMINANT model for each production system and each country (2). Emissions sources are enteric fermentation methane, manure management nitrous oxide, and manure management methane.
Manure management nitrous oxide	SimU	$CO_2e \cdot ha^{-1}$	Calculated using a standard approach detailed by the IPCC (6).
Manure management methane	SimU	$CO_2e \cdot ha^{-1}$	Calculated using a standard approach detailed by the IPCC (6).
Fuel displacement by bioenergy	SimU	$CO_2e \cdot MJ^{-1}$	Calculated using a standard approach detailed by the IPCC (6).
Base year values (2000)			
Land cover	1 km	Global land cover 2000 classes	The base land cover map is largely comprised of the Global Land Cover 2000, a European Commission project to interpret satellite data to classify each $1km^2$ grid cell on the globe as major land cover classification types.
Livestock number by system			Definition of production systems by the United Nations Food and Agriculture Organization is used (7).

1. Williams J (1995) The EPIC model. *Computer Models of Watershed Hydrology*, ed Singh V (Water Resources Publications, Highlands Ranch, CO), pp 909–1000.
2. Herrero M, Thornton P, Kruska R, Reid R (2008) Systems dynamics and the spatial distribution of methane emissions from African domestic ruminants to 2030. *Agric Ecosyst Environ* 126(1):122–137.
3. Williams J (1995) The EPIC model. *Computer Models of Watershed Hydrology*, ed Singh V (Water Resources Publications, Highlands Ranch, CO), pp 909–1000.
4. Kindermann GE, McCallum I, Fritz S, Obersteiner M (2008) A global forest growing stock, biomass and carbon map based on FAO statistics. *Silva Fennica* 42(3):387.
5. Havlík P, et al. (2011) Global land-use implications of first and second generation biofuel targets. *Energy Policy* 39(10):5690–5702.
6. Penman J, et al. (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (Institute for Global Environmental Strategies, Tokyo).
7. Sere C, Steinfeld H (1996) *World Livestock Production Systems: Current Status, Issues and Trends* (FAO, Rome).

Table S6. Endogenously computed variables

Endogenous variable	Spatial scale	Unit	Notes
Land cover	30 ArcMin in Brazil (~50 km)	ha	Land cover possibilities are cropland, managed forest, unmanaged forest, short rotation coppice, pasture (conventional and semi-intensive), other natural vegetation
Area of crop, livestock, and forestry by management type	30 ArcMin in Brazil (~50 km)	ha	Each production type has fixed input and outputs; the model has multiple production types for individual products
Trade flows	Model region to model region	tons or m^3	Trade flows are such that consumer and producer surplus maximizing equilibrium prices evolve in each region, given the cost of shipment between regions and given known barriers to trade
Prices of crops, livestock products, and forestry products	Model region	Year 2000 USD	

Table S7. Definitions of select indicators of model output

Indicator	Spatial scale	Unit	Notes
AFOLU GHG emissions	World, Brazil	t CO_2eq	AFOLU GHG emissions are computed using production type-specific emissions summarized in Table S1 and endogenously computed land use change and activities. In policy scenario i for region j, and trade scenario k, emissions, $G_{i,j,k} = \sum_{2000}^{2030}(P_{i,j,k} + Q_{i,j,k})$ where $P_{i,j,k}$ are emissions from land use change, and $Q_{i,j,k}$ are direct emissions from the agricultural sector.
AFOLU GHG mitigation world	World, Brazil	t CO_2eq	GHG mitigation, $M_{i,j,k} = \sum_{2000}^{2030} G_{i,j,k} - G_{0,j}$ where $G_{i,j,k}$ is defined in row 1 above, and $G_{0,j}$ are the AFOLU GHG emissions for region, j, associated with the baseline scenario policy and trade scenario. In this way, mitigation from each policy is the difference between total regional emissions under the policy and emissions absent the policy.
Semi-intensive cattle system adoption	30 ArcMin in Brazil (~50 × 50 km)	Percent	Percentage of cattle pasture area devoted to semi-intensive ranching in Brazil.
Cattle density	30 ArcMin in Brazil (~50 × 50 km)	AU·ha^{-1}	Given as the number of animal units (AU) per hectare of pastureland. AUs scale with the metabolic requirements of livestock.
World market share	World	Percent	The proportion, by weight of the world market
Deforestation	World, Brazil	ha·y^{-1}	The area of forest lost relative to the base year
Avoided deforestation	World, Brazil	ha·y^{-1}	The difference between deforestation in the baseline scenario and deforestation in each policy scenario.
Tariff GHG mitigation effect	World, Brazil	t CO_2eq·time $step^{-1}$	The tariff GHG effect for region, j, policy scenario i, in year l is $T_{i,j,l} = \sum_{2000}^{2030}(M_{i,j,k,l} - M_{i,j,o,l})$, where M_k is the AFOLU GHG mitigation under flexible trade and M_o is the AFOLU GHG mitigation under the imposition of trade restrictions. Positive values means that the tariff is enhancing the GHG mitigation of a policy.
Cost of policies	World, Brazil	USD·t CO_2eq^{-1}·time $step^{-1}$	The cost of each policy scenario is defined as the difference between the sum of consumer, producer and Brazilian government surplus, under the policy scenario vs. the sum of consumer, producer, and Brazilian government surplus in a baseline simulation. For example, the land use taxes are a direct source of government revenue and lost profitability for the cattle sector. They also reduce the surplus of consumers of cattle products, but may increase the consumer surplus for other consumers and producers.
Beef	World, Brazil	Billions of kcal	An aggregation, on an energy basis, of all beef products marketed for human consumption.
Animal products	World, Brazil	Billions of kcal	An aggregation, on an energy basis, of all meat, eggs, and dairy products.
Vegetal products	World, Brazil	Billions of kcal	An aggregation, on an energy basis, of all 18 crop products represented in the model.
Brazilian beef exports	Brazil	t CWE	An aggregation, on a mass basis, of all exported nondairy, nonleather cattle products
Agricultural Intensification	World, Brazil	$(t_1 - t_0)$·ha^{-1}	The change in crop yield over time
Cattle ranching intensification	World, Brazil	$(t_1 - t_0)$·ha^{-1}	The change in livestock yield over time