Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation

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This study examines whether policies to encourage cattle ranching intensification in Brazil can abate global greenhouse gas (GHG) emissions by sparing land from deforestation. We use an economic model of global land use to investigate, from 2010 to 2030, the global agricultural outcomes, land use changes, and GHG abatement resulting from two potential Brazilian policies: a tax on cattle from conventional pasture and a subsidy for cattle from semi-intensive pasture. We find that under either policy, Brazil could achieve considerable sparing of forests and abatement of GHGs, in line with its national policy targets. The land spared, particularly under the tax, is far less than proportional to the productivity increased. However, the tax, despite prompting less adoption of semi-intensive ranching, delivers slightly more forest sparing and GHG abatement than the subsidy. This difference is explained by increased deforestation associated with increased beef consumption under the subsidy and reduced deforestation associated with reduced beef consumption under the tax. Complementary policies to directly limit deforestation could help limit these effects. GHG abatement from either the tax or subsidy appears inexpensive but, over time, the tax would become cheaper than the subsidy. A revenue-neutral combination of the policies could be an element of a sustainable development strategy for Brazil and other emerging economies seeking to balance agricultural development and forest protection.

agricultural intensification | land sparing | climate policy

Brazil is one of many emerging economies developing policies to balance greenhouse gas (GHG) mitigation, forest protection, and agricultural growth by promoting agricultural intensification (1). By enrolling agriculture to fight deforestation, these land sparing policies (LSPs) may be politically and organizationally advantageous complements or substitutes to policies to prevent deforestation through payments to forest owners and/or command and control of illegal deforestation (2).

Successful LSPs must make higher productivity agricultural systems more competitive than lower productivity agricultural systems such that GHG emissions and/or deforestation decline. LSPs can either limit lower productivity agriculture with disincentives or stimulating higher productivity agriculture with incentives. In both cases, LSPs rely on market-mediated changes to production, consumption, and trade (3). Disincentive-based LSPs must raise agricultural commodity prices to stimulate new, higher productivity agriculture that outcompetes lower productivity agriculture. However, by raising agricultural commodity prices, disincentive-based LSPs risk stimulating additional production both locally and offshore. To spare land, incentive-based LSPs must increase the output from higher productivity systems to depress the prices of agricultural commodities such that some lower productivity agriculture is no longer viable. However, by lowering consumer prices of goods composed of agricultural commodities, incentive-based LSPs risk triggering increased consumption. These risks of LSPs, known as leakage, can undermine their land sparing and GHG benefits. Additional unintended consequences of LSPs include migration, environmental impacts, and food insecurity.

The amount and location of land spared from LSPs depends on a complex array of factors including the policy instrument used, farmer technology adoption propensity, the efficiency of the newly adopted production systems relative to the ones replaced, economy-wide producer and consumer responses to changing prices, and effects on agricultural input markets. Estimating the effects of LSPs requires not only monitoring land use across many regions and tracking production across many sectors, but also using modeling to compare the world with the LSP to an unobservable baseline—a counterfactual world identical except for the policy and its effects (4).

This study asks whether cattle ranching intensification in Brazil can reduce global deforestation and mitigate global GHG emissions. Using an economic model of global land use, it examines the potential GHG emissions, land use, agriculture, and commodity market impacts of two cattle ranching intensification policies. The case is salient because Brazilian agriculture makes major contributions to the global food system and the Brazilian economy (5–7), Brazil had the largest net forest loss of any country over the period of 1990–2010 (8), a tremendous stock of carbon still remains in the forests of the Brazilian

Significance

Could the intensification of pasture-based cattle ranching allow Brazil to protect its forests and reduce its greenhouse gas (GHG) emissions while increasing its agricultural production? Would these benefits be substantially undermined by increased deforestation and GHGs triggered abroad? We model two policies for increasing cattle ranching productivity in Brazil: a tax on conventional pasture and a subsidy for semi-intensive pasture. Either policy could considerably mitigate global GHGs by limiting future deforestation in Brazil. The GHG benefits would be roughly ten times greater than the emissions triggered by policies stemming from (*i*) increased cattle production abroad (under the tax) and (*ii*) increased beef consumption (under the subsidy). Agricultural intensification policies may help emerging economies to balance agricultural development and forest protection.

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Amazon (9), and cattle ranching is intertwined with the deforestation process in Brazil (10, 11). Agricultural forestry and other land use (AFOLU) is central for Brazilian climate mitigation (12, 13). Balancing climate change mitigation and agricultural development (14) could make Brazil a template for the many other emerging economies where AFOLU is the primary source of GHG emissions (15).

We use an economic optimization model representing land use activities in the agricultural, forestry, and bioenergy sectors. The model consists of (*i*) spatially explicit estimates of the productivity of global crops, pasture, and timber; (*ii*) spatially explicit transportation costs for agricultural inputs and outputs in Brazil; (*iii*) economic optimization representing the competition for land among the forestry, agriculture, and livestock sectors; and (*iv*) international trade for crops, livestock, and forestry products.

The model includes the ability to adopt a semi-intensive alternative cattle ranching production system on pasturelands. Through better land management, the alternative system enables productivity of pasturelands to double relative to output if the land were managed conventionally. Producers may also adopt improved breeding, feeding, and other management practices. In combination, the pasture management and the cattle management components can increase cattle product output per unit pasture by as much as 2.5 times over conventional systems. Known as *boas práticas* (best practices) cattle ranching, the system has been extensively researched and developed by the Brazilian Agricultural Research Corporation (Embrapa). It is already deployed commercially on some ranches in Brazil (16, 17). It is not yet widely cost competitive due in part to high upfront costs (see *SI Text* for further details on semi-intensive pasture management systems).

We investigate the market-mediated GHG and land use impacts of two policies to promote the adoption of *boas práticas* semi-intensive cattle ranching in Brazil. The land tax policy (T) is a per hectare fee charged annually to all ranchers who do not adopt the semi-intensive system; the cattle ranching subsidy policy (S) is an annual per hectare payment to all ranchers who do adopt the semi-intensive system. For a given cattle ranch, S and T have equal effects on the relative cost of production of a given unit of semi-intensive beef vs. a unit of conventional beef. Because the payments and fees are distributed on an area basis, the value of the policies is highest for the lowest productivity systems and lowest for the highest productivity systems. The value of the policies ranges from roughly 5% to 105% of production costs, with an average value of 15%.

We compare both a simulated world under T and a simulated world under S to a counterfactual baseline simulation scenario (B) in which all else is equal except for the policy. The effect of each policy is computed as the emissions in each of the two policy scenarios minus the emissions in the baseline scenario. Scenario B contains no AFOLU GHG mitigation policies other than S or T. GHG emissions accounted are the sum of emissions of carbon dioxide, nitrogen oxide, and methane from AFOLU.

We also use trade scenarios to examine whether leakage from market-mediated changes to beef consumption and trade unduly limit GHG abatement. The primary focuses of the analysis are the trade as usual scenarios (*TAU*), in which international trade in cattle products and cattle product consumption adjust in response to price changes from the policies. In the no trade scenarios (*NT*), international trade in cattle products does not adjust in response to S or T; in the no trade, no consumption scenarios (*NCNT*), neither international trade of cattle products nor consumption of cattle products adjust as a result of the price effects of the policies. A full description of all scenarios investigated can be found in Table S1.

Results

Fig. 1 presents GHG, land use, and agricultural outcomes in Brazil and the rest of the world (ROW) for S_{TAU} vs. the counterfactual baseline scenario, B_{TAU} and for T_{TAU} vs. B_{TAU}. Table S1 presents the GHG impacts of leakage from price-responsive trade and consumption (S_{TAU} vs. S_{NT} vs. S_{NCNT} and T_{TAU} vs. T_{NT} vs. T_{NCNT}). Fig. S1 shows the effect of the policies on the origin of productive land in Brazil. Fig. S2 shows how and where the policies would change Brazilian land use.

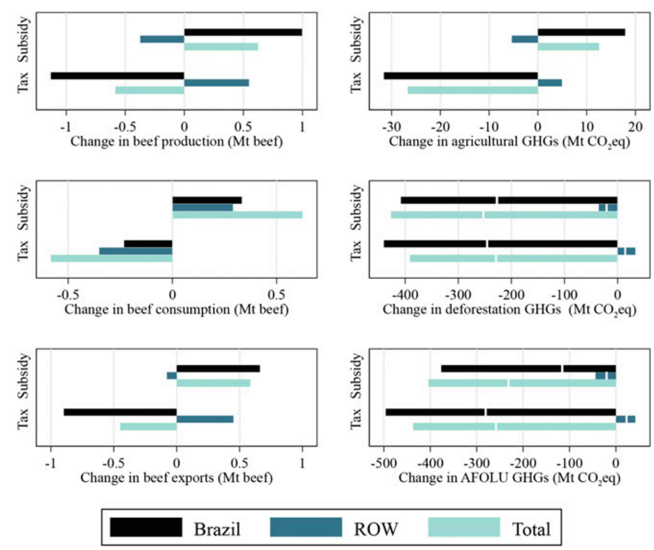

Fig. 1. Changes in agricultural output (*Left*) and AFOLU GHGs (*Right*) in the year 2030 caused by the tax and subsidy policy scenarios. AFOLU GHG emissions are agricultural GHG emissions plus deforestation GHG emissions. Emissions reductions are reported as negative numbers. Emissions increases are reported as positive numbers. For the AFOLU GHGs and the deforestation GHGs, the bars and the break lines, respectively, represent the upper bound and the lower bound of four distinct maps of the carbon density of vegetation cover investigated (9, 35–37). Either a tax on beef from conventional pasture in Brazil (*T*) or a subsidy for beef from semi-intensive pasture in Brazil (*S*) could substantially alter production and consumption of beef in Brazil and in the rest of the world (ROW). These changes are associated with considerable reductions in AFOLU GHGs. *T* reduces Brazil AFOLU emissions by 52% and total global deforestation GHGs by 24%. *S* reduces Brazil AFOLU emissions by 41% and total global deforestation emissions by 26%. In 2005, AFOLU GHG emissions constituted roughly 30% of global anthropogenic emissions and roughly 75% of Brazil anthropogenic emissions (15, 68).

Substantial Abatement of Brazilian AFOLU GHGs Is Possible Through Either the Tax or Subsidy (Fig. 1). For both T_{TAU} and S_{TAU}, the net of all market effects in Brazil and the ROW is a substantial reduction of AFOLU emissions. In Brazil, S_{TAU} would reduce GHGs by 212 Mt CO_2eq in 2030, an amount equivalent to roughly 40% of projected national AFOLU emissions under our baseline simulation of Brazil for that year. Cattle product output would increase by 9.5%, but agricultural emissions (a subset of AFOLU emissions) would increase by just 5.5%, because of efficiency gains. With pasture area reduced by 16 million hectares (mha), 15 mha of forest would be spared from deforestation. The decline in deforestation would be associated with a 75% reduction in deforestation emissions (another subset of AFOLU emissions). An additional 20 Mt CO_2eq per year in abatement from reduced agricultural emissions would occur in the ROW. In Brazil, T_{TAU} would mitigate 278 Mt CO_2eq during the year 2030. Cattle production and agricultural emissions would both decline by 10%, and pasture area would drop by 21 mha. The reduced pasture area would be associated with a 17-mha decline in deforestation and an 80% drop in emissions from deforestation. Increased production in the ROW would increase ROW agricultural emissions by 24 Mt CO_2eq per year. The GHG abatement reported above can be considered conservative because it is based on the lowest density carbon map of the four datasets investigated. Fig. 1 reports the full range of results across carbon densities. Fig. S3 reports results for each carbon scenario.

Deforestation Reduced by Either the Tax or Subsidy Modeled Would Achieve More than Half of Brazilian Deforestation Policy Targets. Enacted in 2008, the National Climate Action Plan of Brazil (PNMC) pledges to reduce the rate of deforestation in Brazil's Legal Amazon to 80% of historical rates by 2020 using a mixture of agricultural interventions and command and control efforts to directly protect forests (18). Even without direct deforestation prevention, by 2020, S_{TAU} would reduce the Brazilian Amazon deforestation rate by 41% and T_{TAU} would reduce it by 61%.

Leakage Would Weakly Reduce GHG Abatement Under the Subsidy, but Weakly Enhance GHG Abatement Under the Tax (Table S1). Using trade scenarios, no trade and no consumption, no trade, we estimate how much of the abatement under S_{TAU} and T_{TAU} is enhanced or diminished by trade and consumption leakage. By reducing costs of intensive cattle ranching in Brazil, S_{TAU} would increase cattle products exported from Brazil by 7% and reduce cattle product costs to consumers by 2%. The results would be decreased beef production offshore and increased beef consumption in both Brazil and in the ROW. In total, the leakage effects under S_{BAU} would diminish GHG abatement by 20 Mt CO_2eq, or 6%. By contrast, T_{BAU} would make Brazilian cattle products more expensive, increasing consumer prices by 2% and decreasing exports by 5%. The result would be increased production offshore and reduced beef consumption in Brazil and the ROW. Under T_{TAU}, leakage is the source of 43 Mt CO_2eq per year of the modeled GHG abatement, or 16% of the total.

Global Beef Production and Consumption Effects Are Considerable. Under S_{TAU}, a 2% decrease in the world average beef price would lead to a 1% increase in global beef consumption. Under T_{TAU}, a 2% increase in the world average beef price would lead to a 1% reduction in global beef consumption. However, much larger shifts would occur between regions. Under S_{TAU}, changes in cattle pasture area in the ROW would be limited, but a shift to lower output production systems concentrated in Oceania and Australia would account for 28% of the global supply response. Under T_{TAU}, changes to pasture area in the ROW would also be small. Increased output from intensification of existing pasture in the ROW would constitute 27% of the global supply response. Forty-seven percent of the consumption response to S_{TAU} would occur outside of Brazil, and 61% of the consumption response to T_{TAU} would occur in the ROW, with much of this concentrated among the poorest beef consumers, i.e., sub-Saharan Africa. Overall, the supply effects are three times larger than the demand effects. This result is explained by the regional discrepancies in the supply and demand responsiveness to price (see *SI Text* for the responsiveness of beef demand to price) and to model constraints on the most dramatic of changes in bilateral trade flows.*

GHG Abatement from Either of the Policies Would Be Cost-Effective but, Over Time, a Tax Might Have Lower Impacts to Government Budgets than a Subsidy. Over the period of 2010–2030, S_{TAU} can abate GHGs at a cost to the Brazilian government of \$8.50 per ton CO_2eq and T_{TAU} can abate at a cost to producers of \$11.80 USD per ton CO_2eq. These amounts are slightly higher than several previous cost estimates of livestock-based intensification in Brazil (20–22), but these estimates would fall by up to 40% if less conservative carbon maps were used for estimating mitigation (see *Discussion* and Fig. 1 for upper and lower bound deforestation GHG abatement estimates). Even with the conservative mitigation estimates, the total annual costs of S_{TAU} are in line with existing government expenditures to reduce the environmental impacts of agriculture in Brazil (23). However, because the cost of the tax to Brazilian suppliers is tied to the area of conventional pasture and because this area would diminish over time, the cost of the tax would also diminish. In contrast, because the cost of the subsidy to the government is tied to the area of semi-intensive pasture and this area would increase over time, the cost of the subsidy would also increase.

Either a Tax or a Subsidy Would Substantially Alter Beef Production Geography and Technology in Brazil. Over the period of 2010–2030, S_{TAU} would cause cattle ranchers to adopt 72 mha of semi-intensive ranching in Brazil, an area constituting 40% of the projected pasture area. The payments would reduce semi-intensive cattle production costs by as little as 3% to as much as 86%. On average, the reduction would be 14%. Disbursement to producers who adopt semi-intensive cattle systems would cost 30 billion USD. However, net pasture area in Brazil would fall by 16 mha because S_{TAU} would also prompt abandonment of 88 mha of conventional cattle production. T_{TAU} would amount to a tax of between 4% and 108% of production costs. On average, the tax would be equivalent to 14% of conventional production costs. T_{TAU} would cause abandonment of 50 mha of conventional ranching and the adoption of 30 mha of semi-intensive cattle ranching, an area constituting 17% of all pasture area. The remaining conventional producers would pay 48 billion USD in taxes. Whereas 84% of new productive land in Brazil from 2010 to 2030 would be sourced from forest under baseline scenario B, just 46% and 50% would be sourced from forest under T_{TAU} and S_{TAU}, respectively (Fig. S1).

Potential Pasture Yield and Distance to Markets Strongly Predict Adoption of Intensive Ranching in Brazil (Fig. S2). Under both S_{TAU} and T_{TAU}, intensive pasture is more than three times as likely as conventional pasture to be planted on land that is high quality and accessible to markets (i.e., the first quartile in terms of pasture productivity potential, fertilizer and lime transport costs, and beef transport costs). This intensive pasture is also twice as likely as conventional pasture to be found in locations that are highly suitable for soybeans, i.e., the first quartile of soy productivity potential and soy logistics costs. Thus, intensive pasture may be more likely than conventional pasture to compete with crop agriculture expansion. Because some cattle ranching produces substantially less protein per unit area than crop agriculture, the land-sparing effect might be enhanced if it were possible to induce intensive cattle ranching on land not well suited to cropping.

Discussion

We find that cattle ranching intensification policies in Brazil can cost-effectively abate GHGs by limiting deforestation. These results are in line with previous studies suggesting that regional agricultural productivity gains can reduce global GHGs and can help to limit deforestation (4).

Our investigation contributes to the land sparing literature—a body of research on whether increased agricultural productivity can reduce agricultural area or at least limit the expansion of agricultural area (24–26).† Many early land-sparing analyses provided rough retrospective estimates of how much more land would have been required for agriculture if not for yield increases (24, 25, 27). These studies obtained data on crop yields and crop area at time, t, and data on crop yields at time, $t-1$. They then estimated how much more land would have been required for agriculture at time t if crop yields had been held constant from $t-1$ to t. The presumptions were that (i) the decrease in crop area would be proportional to the increase in yield from $t-1$ to t and (ii) changes to agricultural prices would not change levels of agricultural consumption to significantly offset the direct effects on agricultural area.

*Rapid increases in trade between nations is rarely observed because trade requires infrastructure and relationships that cannot be instantaneously created. For more see, ref. 19. In the model, bilateral trade cannot increase by greater than 7.5 times from year to year. This constraint binds on cattle ranching output. It has minimal effects on GHGs, but it does increase global trade by triggering re-exporting.

†Borlaug N (1987) Making institutions work: A scientist's viewpoint. Conference on Water and Water Policy in World Food Supplies, May 26–30, 1985, Texas A&M University, College Station, TX.

SUSTAINABILITY SCIENCE

Later studies tested the presumption that crop area indeed varies in an inverse proportion with changes in crop yields. Critiques focused especially on the potential for increased productivity to increase agricultural extent by increasing the area over which agriculture is profitable (28, 29). Other studies have sought to identify correlations between periods of increasing productivity and declining agricultural area within a particular region or nation (30, 31). The rationale has been that such correlations are necessary evidence of land sparing.

However, empirical analyses linking increases in agricultural productivity with increases in area do not rule out land sparing. Neither do analyses linking increases in agricultural productivity with decreases in agricultural area necessarily show land sparing. First, changes in agricultural area are primarily caused by factors besides changes in agricultural productivity. Land-sparing analyses must control for these other drivers. Second, as long as the region of analysis participates in agricultural trade, some portion of the effects of the productivity change can be expected to occur extralocally. It is therefore necessary to trace the effects of a regional productivity shock across all trade-connected regions. Third, it is possible that productivity changes observed are not independent of changes in agricultural area (32). Statistical techniques may be required to account for the influence of agricultural area on agricultural productivity.

Model-based land-sparing analyses are another approach used to overcome the abovementioned hurdles to empirical land-sparing analysis. One recent model-based land-sparing study, using similar methods to our study, coined the term "land saving" to describe the land changes investigated (4). The authors use land saving as opposed to land sparing to contrast the measurement of changes in land use relative to a modeled counterfactual baseline vs. empirical land sparing studies that test for correlations between productivity and area (30, 33). We agree that this distinction is important methodologically, but Stevenson et al. still address the same fundamental question as the wider land-sparing literature.

Modeled land-sparing results are highly sensitive to the simulated counterfactual baseline. Although the GHG abatement and deforestation that we find is, as a percentage of our baseline, in line with PNMC targets, it is substantially lower than the PNMC abatement pledged in absolute terms. A part of the discrepancy is that our GHG abatement relies on a terrestrial carbon map with relatively low carbon values. In alternative model scenarios, with four other higher carbon maps, abatement reached 436 Mt CO_2eq for the tax and 404 Mt CO_2eq for the subsidy (Fig. 1 presents both the lower and upper bounds of deforestation GHG and AFOLU GHG abatement) (9, 34–36). In addition, the PNMC baseline rate of deforestation is 75% higher than the baseline deforestation rate that we simulate. The higher PNMC baseline creates more mitigation potential. The PNMC baseline is a constant rate of deforestation extrapolated[‡] from an average of past deforestation. Our baseline is a simulation of the deforestation rate that increases as a function of increasing food, feed, fiber, and fuel production. A wide variety of extrapolation and simulation baselines can be found in deforestation science and policy (37).

Meanwhile, the rate of deforestation in Brazil has declined since peaking in 2004 (38). The permanence of this decline—and how much of it is caused by policies to prevent deforestation—is a subject of active research (39–41). Nevertheless, we expect that the production and productivity of globally traded commodities will affect deforestation rates regardless of whether these commodities are produced in a nation with an active forest frontier. Investigating the extent to which the impacts of productivity gains on land cover are locally concentrated is an urgent research priority.

More broadly, both physically and politically, LSPs can act as both substitutes and complements for other deforestation reduction policies. Golub et al. (21) showed that forest protection efforts complement GHG mitigation from climate policies targeting livestock systems. However, because Golub et al. investigated policies targeting the reduction of direct agricultural emissions, it is ambiguous whether LSPs would also be enhanced by payments for avoided deforestation. Whereas most GHG abatement in Golub et al. stems from reduced agricultural emissions, we primarily find abatement from avoided deforestation. It is inevitable that some land spared from deforestation could be spared either by LSPs or policies that directly intervene in forest systems. Meanwhile, Nepstad et al. (2) argued for LSPs as politically and organizationally advantageous substitutes for policies that pay forest owners to avoid deforestation, although they stop short of arguing that deforestation policy requires agricultural interventions (2). It is evident that political expediency is a strong determinant of LSP adoption as policies are proliferating (1) even without substantial evidence that they can reduce deforestation or GHGs. Disincentive-based LSPs may face political headwinds relative to LSPs that support agricultural development.

The tax and subsidy also contrast in land, GHG, and financial magnitude. The choice of policy determines the relationship between agricultural productivity gained, the area of land spared from conversion, and the associated GHG abatement. Land spared is not proportional to productivity gained. Under S_{TAU}, we find up to 71% less GHG abatement, and under T_{TAU}, up to 35% less GHG abatement than if land sparing was proportional to productivity (16). We also observe much greater abatement under T_{TAU} than under S_{TAU}, despite a much larger area of adoption of intensive production under S_{TAU}. This is because T_{TAU}, by raising beef prices, lowers consumption of beef, the most GHG intensive food (42, 43). S_{TAU} increases beef consumption by lowering beef prices.

Even though S_{TAU} and T_{TAU} have equal effects on the cost differential between conventional and semi-intensive pasture systems in a given place, over the period of 2010–2030, the amount of revenue collected under T_{TAU} (48 billion USD) would be much greater than the amount of support distributed under S_{TAU} (30 billion USD). This is because adoption effects are not symmetrical and because the output from the conventional cattle ranching subsector under T_{TAU} would be larger than the semi-intensive cattle subsector under S_{TAU}. However, the GHGs abated per dollar in S_{TAU} are greater than the GHGs abated per dollar in T_{TAU}. These values are not straightforwardly commensurate because the private sector would pay for the tax, whereas the public sector would bear the cost for subsidy. Over time, revenues collected under tax would decline as conventional ranching is supplanted by semi-intensive ranching. In contrast, the payments to semi-intensive ranchers under the subsidy would grow as semi-intensive ranching supplants conventional ranching. Combining taxes and subsidies that update could provide a cattle ranching intensification strategy that is revenue neutral, price-effect neutral, and might also avoid cost overruns and declining revenue (44).

Our results contrast with previous studies warning that land-consuming leakage from LSPs might eclipse land-sparing benefits (45, 46). Ranging from 6% to 16%, our leakage rates are low compared to much of the GHG mitigation policy modeling literature (47). Two plausible explanations are (*i*) our approach estimated market-mediated avoided deforestation that was not accounted in previous investigations of direct local land use effects of LSPs and (*ii*) the large magnitude of GHG abatement relative to the price impacts of the policies helped to ensure that the leakage[§] was relatively small. International leakage would also be low because, although Brazilian beef production

[‡]The PNMC defines mitigation targets sector by sector relative to reference emissions projections. Avoided deforestation targets under the PNMC were set as a percentage of a baseline deforestation rate. The baseline deforestation rate assumed for the PNMC is an average of the deforestation rate over the period from July 1995 to July 2005. The location of deforestation under the baseline and reduction scenarios was simulated, and GHG abatement was estimated based on the difference between the baseline and the policy emissions. For more, see refs. 18 and 20.

[§]Price effects mediate various leakage mechanisms. One example is that local price increases decrease demand, reduce prices elsewhere, and increase consumption elsewhere. Another is that a constraint on supply increases prices and increases production elsewhere.

comprises a considerable share of the global market, only a small portion of all beef is internationally traded (see Table S2 for the evolution of Brazilian and global beef production and trade in our results).

Nevertheless, our modeling framework does not represent all salient leakage channels (28, 48). Local and regional household, migration, and nonland economy effects are beyond the scope of our analysis. We also do not model induced technological change, i.e., when prices rise, we would expect the creation of technological innovations that can increase efficiency and decrease GHGs globally, and when prices fall, we would expect a slowing of technological innovation, decreased efficiency, and higher GHG emissions per unit production globally (49). Policies to directly prevent deforestation could serve as safeguards against many of these uncertainties.

Our model represents land use activities as motivated primarily by food, feed, fiber, and fuel production. This is accurate, but people also cattle ranch for other reasons. Cattle ranching is valuable as a hedge against inflation, a land tenure-securing activity, a tax shelter, and a status symbol (11). Each of these factors favors extensive ranching over intensive ranching and could limit adoption of semi-intensive cattle systems. Because the magnitudes of these effects are unknown, future empirical research is warranted on the utility of extensive ranching.

We showed that either a tax on conventional cattle pasture systems in Brazil or a subsidy for semi-intensive cattle pasture production in Brazil can reduce global GHG emissions by sparing land from deforestation. The policy effects are subject to some uncertainty, but they appear considerable relative to total Brazilian GHG emissions, large relative to leakage, and small relative to the GHG effects expected if land sparing was proportional to the increase in productivity. A revenue neutral combination of tax and subsidy policies could help to balance agricultural growth, land use conservation, and global GHG mitigation. Such an approach, when combined with land conservation policies, holds promise for sustainable development.

Methods

Model Framework. This analysis uses the Global Biosphere Management Model (GLOBIOM), a bottom-up economic partial equilibrium model of the global land use economy that depicts the competition for land between the forestry, crop, and livestock sectors (50–52). Demand for food and wood is determined by exogenous population and gross domestic product (GDP) per capita projections and by projections of dietary patterns and trends (53). Equilibrium prices are the result of a simulation to maximize the sum of the producer and consumer surpluses (54). The maximization problem is subject to resource, technological, and policy constraints (55). Prices vary across regions according to transport costs (56) and a database of trade tariffs (57). GLOBIOM has mostly constant elasticities, is solved with linear programming, is arrayed in 28 regions, and is run at an ~50-km^2 resolution in Brazil (0.5° grid). Production types are detailed, geographical, and Leontief type (i.e., have fixed input and output ratios) (58). Changes in the technological characteristics of primary product production can occur because multiple production types are available for each product. In cattle systems, the model differentiates between dairy- and meat-based systems, three climate zones, and between grass-based systems and mixed systems with varying feeding requirements, product outputs, and direct GHG emissions. Incremental demand for primary products elicits intensification and or extensification. Some of the extensification requires land use/cover change that is associated with conversion costs. Intensification can occur through the increase in animal density on pasture and/or through switching from grass-based systems to mixed systems with greater meat production per animal.

Input Data. Agricultural market balance data are compiled by the United Nations Food and Agriculture Program (59). Landcover data comes from Global Landcover 2000 (60). The biophysical model EPIC is the source for crops and pasture productivity (61, 62), and G4M (63) simulates production possibilities for forests in each pixel. They draw on global maps of soil types; climate; topography; land cover; crop area and management; and livestock systems (60, 64). Livestock production systems for five different animal species are populated with data using a process-based model for ruminants and using literature review and expert knowledge for the monogastrics (65, 66). Eighteen crops, five forestry products, and six livestock products (four types of meat, eggs, and milk) are included in the model.

We modify the GLOBIOM Brazil region with improved representation of agricultural logistics costs, grassland productivity potential, and pasture intensification pathways. Using the cost-distance function in ArcMap 10.0 Spatial Analyst, we estimate logistics costs for each simulation unit in Brazil for each of the agricultural inputs and outputs present in GLOBIOM (see Fig. S4). Spatial Analyst computes the least cost path to transport inputs to rural properties and to transport agricultural products to market. Our transportation cost methodology is patterned on an approach to estimate minimum travel time to cities (67) and is described in further detail in *SI Text*. Baseline grassland productivity was calculated with EPIC. Conventional ranching productivity in a given simulation unit is a function of these baseline grassland productivity estimates and the blend of the 12 possible cattle production pathways that is used. Where semi-intensive alternative systems are adopted, grassland productivity is assumed to be double the EPIC conventional grassland productivity estimates. Semi-intensive output is often slightly more than double conventional production because it depends on the blend of the 12 cattle production pathways used in the simulation unit. This blend typically shifts under the adoption of semi-intensive pasture management. It is a function of the location-specific costs and benefits of land, feed, and fodder as system inputs.

Intervention Scenarios for Semi-Intensive Cattle System Adoption. In our modeling framework, the necessary conditions for adoption of the semi-intensive, pasture-based cattle technology in any simulation unit at any time step is that (*i*) cattle ranching is the most profitable land use and (*ii*) the cost per unit output of the semi-intensive system is less than the cost per unit output of the conventional cattle system. 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.

Two policies, a tax on conventional ranching and a subsidy for semi-intensive ranching, are investigated. Both the tax and the subsidy reduce 80% of the average cost advantage of conventional beef production over semi-intensive beef production at the beginning of the simulation period. Adoption can be expected in any simulation unit where the cost gap is less than either the tax or the subsidy.

We sum the AFOLU GHG emissions over each simulation unit and each time step for each policy scenario. The components emissions come from land use change, direct emissions from the agricultural sector, and total indirect emissions from the agricultural sector. To compute the mitigation from each policy scenario, we subtract the cumulative AFOLU GHG from the baseline scenario. We also distinguish and report the subset of the mitigation that occurs within Brazil. Fig. S3 shows the comparison with PNMC deforestation GHG mitigation targets (as indicated by the Government of Brazil in a 2010 Nationally Appropriate Mitigation Activities pledge to the United Nations Framework Convention on Climate Change; Table S3).

Model Calibration. GLOBIOM is calibrated with data from the year 2000. We run our simulation from the year 2000 to the year 2030 to allow a period for model validation over the period from 2000 to 2010. Our global level validation uses the same sources used for calibration. For some Brazil-level variables, we also use statistics collected by the Brazilian government. For the most part, the simulated trends broadly agree with observed trends over 2000–2010. Tables S4–S7 provide a complete list of data sources.

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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.

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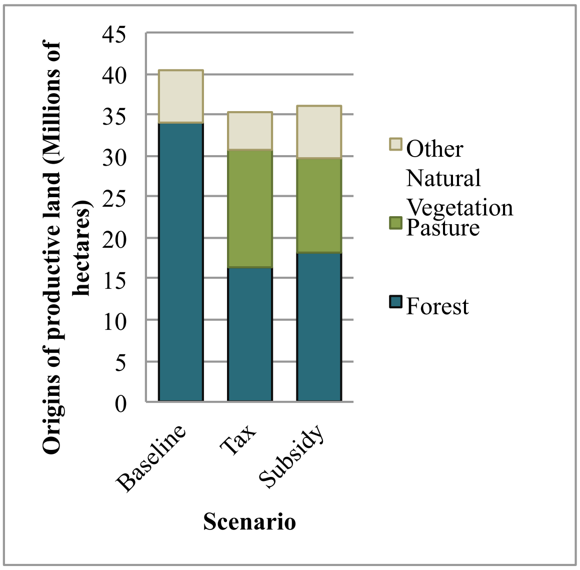

Fig. S1. Effects of tax policy (*T*) and subsidy policy (*S*) on origins of productive land in Brazil. Since the 1980s, forests have been the primary origin of new productive land across much of the tropics including Brazil (1). We find that either *T* or *S* could halt this trend. Whereas 84% of new 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.

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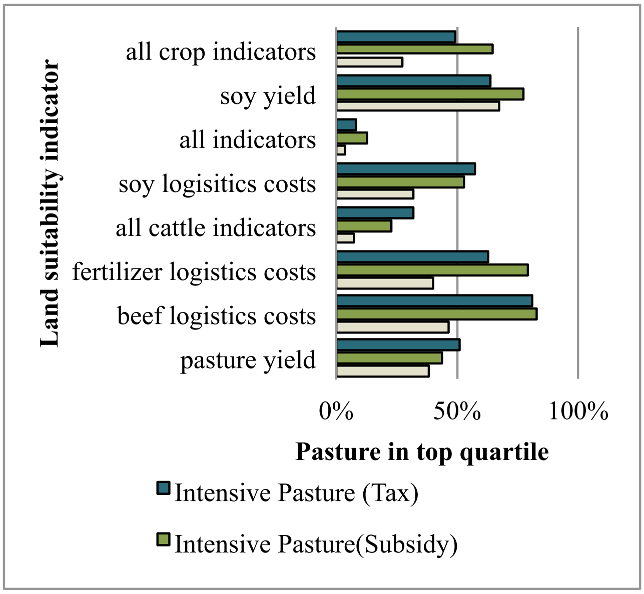

Fig. S2. Land suitability is a strong predictor of adoption of intensive cattle ranching. Intensive pasture, whether triggered by S_a or T_a, is more than three times as likely as conventional pasture to be found on the land in Brazil that is most suitable for livestock. The most suitable land ranching 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).

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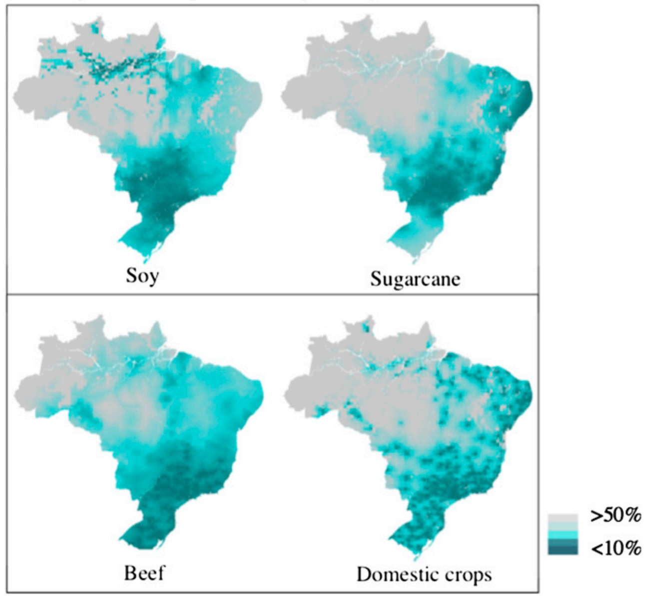

Fig. S4. Agricultural logistics costs as a percentage of market prices. Maps depict the costs of transporting agricultural products to points of market access within Brazil. The costs are expressed as a percentage of the market price for each commodity.

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).

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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)	$AU \cdot ha^{-1}$	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	$ha \cdot y^{-1}$	The area of forest lost relative to the base year
Avoided deforestation	World, Brazil	$ha \cdot y^{-1}$	The difference between deforestation in the baseline scenario and deforestation in each policy scenario.
Tariff GHG mitigation effect	World, Brazil	t $CO_2eq \cdot$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_0 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 $CO_2eq^{-1} \cdot$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	$(t_1 - t_0) \cdot ha^{-1}$	The change in crop yield over time
Cattle ranching intensification	World, Brazil	$(t_1 - t_0) \cdot ha^{-1}$	The change in livestock yield over time