Global climate policy impacts on livestock, land use, livelihoods, and food security

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Recent research has shed light on the cost-effective contribution that agriculture can make to global greenhouse gas abatement; however, the resulting impacts on agricultural production, producer livelihoods, and food security remain largely unexplored. This paper provides an integrated assessment of the linkages between land-based climate policies, development, and food security, with a particular emphasis on abatement opportunities and impacts in the livestock sector. Targeting Annex I countries and exempting non-Annex I countries from land-based carbon policies on equity or food security grounds may result in significant leakage rates for livestock production and agriculture as a whole. We find that such leakage can be eliminated by supplying forest carbon sequestration incentives to non-Annex I countries. Furthermore, substantial additional global agricultural abatement can be attained by extending a greenhouse gas emissions tax to non-Annex I agricultural producers, while compensating them for their additional tax expenses. Because of their relatively large emissions intensities and limited abatement possibilities, ruminant meat producers face the greatest market adjustments to land-based climate policies. We also evaluate the impacts of climate policies on livelihoods and food consumption in developing countries. In the absence of non-Annex I abatement policies, these impacts are modest. However, strong income and food consumption impacts surface because of higher food costs after forest carbon sequestration is promoted at a global scale. Food consumption among unskilled labor households falls but rises for the representative farm households, because global agricultural supplies are restricted and farm prices rise sharply in the face of inelastic food demands.

Recent research on livestock's role in climate change (1–7) has raised awareness about the potential contribution that livestock can make to global greenhouse gas (GHG) abatement.

Where reducing agricultural emissions comes second to other development objectives, the challenge for policy makers wanting to address this issue is to design incentive packages to capitalize on this potential without jeopardizing food security and livelihoods. One important input for this process is information on abatement opportunities and costs for the various livestock sectors. A small number of studies provides bottom-up engineering-type marginal abatement cost estimates for livestock and other land use sectors globally (7–9). These studies incorporate detailed information on specific abatement technologies but ignore market interactions, including competition for land and international commodity trade; they are all critical for understanding climate policy impacts, because they alter the global allocation of cost-efficient abatement and can lead to emissions leakage.

Furthermore, climate policies in agriculture will certainly not be implemented in isolation from climate policies in forestry, energy, transport, and other sectors with large abatement potential, and these policies may have large impacts on agriculture. For example, carbon sequestration incentives in forestry will increase the scarcity and cost of agricultural land, and taxes on fossil fuel emissions will also raise the costs of producing, transporting, and processing agricultural commodities. Given their economy-wide scope, computable general equilibrium (CGE) models provide a useful framework for quantifying these interactions. However, few CGE models incorporate spatially explicit land use data along with associated emissions and carbon stocks either in a unified model framework or by linking with a detailed geographical/biophysical model (10).

The work edited by Hertel et al. (11) offers an overview of the approaches to incorporating land, land-using sectors, and associated GHG emissions into CGE models. The volume highlights the Global Trade Analysis Project (GTAP) –agro-ecological zone (AEZ) –GHG model (12, 13), which uses an AEZ database to capture the heterogeneous environmental and economic characteristics of land use activities. The integration of these data with estimates of the potential for forest carbon sequestration (14) and agricultural abatement (8) provides a comprehensive framework for the rigorous accounting of opportunity costs of land-based mitigation.*

This study extends the GTAP-AEZ-GHG model by disaggregating the ruminant sector into dairy and ruminant meat sectors, expanding regional coverage well beyond the three regions of the initial model, incorporating additional emissions information, and disaggregating household impacts. The extended model includes CO_2 emissions from fossil fuel combustion (15) in addition to CH_4, N_2O, fluorinated gases emissions, and forest carbon stock data that were used in the work by Golub et al. (13).† The model is used to evaluate market-based policies that are broadly aligned with the different mitigation responsibilities of Annex I, non-Annex I, and Annex II countries specified under the United Nations Framework Convention on Climate Change (16).‡ Particular emphasis is placed on livestock given its importance as a source of GHG emissions and a source of income and nutrition in developing countries.

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*Agricultural mitigation includes noncarbon dioxide (non-CO_2) emissions [methane (CH_4) and nitrous oxide (N_2O)] and cropland soil carbon but excludes soil carbon from other agricultural land uses. For forestry, carbon sequestration responses are derived from a model that incorporates all potential activities for sequestering carbon, including afforestation, avoided deforestation, and forest management.

†Note that we use the global warming potentials from the Intergovernmental Panel on Climate Change Second Assessment Report to convert non-CO_2 gases into CO_2 equivalent terms, because these calculations are required for the purpose of official submissions of national GHG inventories under the United Nations Framework Convention on Climate Change.

‡Annex I Parties to Convention are industrialized countries that have commitments to mitigate emissions. Annex II Parties to Convention are a subset of these countries with obligations to facilitate mitigation in developing countries through the provision of financial resources and transfer of technology (16).

Results

The global impacts of market-based mitigation policies on livestock and other land-using sectors are estimated under three GHG price scenarios, each reflecting successively greater levels of participation by countries and sectors. As outlined in Table 1, scenario A applies a GHG emissions tax and forest carbon sequestration incentive in Annex I countries. Scenario B extends the forest carbon sequestration incentive to all countries. Finally, scenario C applies the GHG emissions tax and forest carbon sequestration incentive in all countries; however, non-Annex I producers receive a refund for their tax expenses. Given our interest in the implications of the different policy scenarios, we focus on only one GHG tax/incentive: 27 \$US/tCO_2eq (or 100 \$US per ton carbon). This price is consistent with current market prices and policy discussions.[§]

A regional breakdown of emissions changes within each land use category for the three policy scenarios is provided in Fig. 1, where results reflect average annual changes in GHG emissions in millions of metric tons of CO_2-equivalent units over the medium term (20-y period) relative to 2001 base year emissions and forest carbon stocks. In Fig. 1*A*, crop and livestock emissions are grouped together under agriculture and contrasted with the dominant forest carbon sequestration category. In Fig. 1*B*, the agricultural category is disaggregated into crops and livestock. Detailed model results by individual livestock sectors and the 19 model regions are available in *SI Appendix*, Table S10*B*.

When Climate Policies Are Limited to Annex I Countries (Scenario A), a Portion of Land-Based Abatement in Annex I Countries Is Lost Through Increased Emissions (Leakage) in Unregulated Non-Annex I Countries. About 1 GtCO_2eq is abated annually in land use sectors in this scenario. Leakage in agriculture as a whole sums to 25%, and it is highest for livestock (35%) (Fig. 1, positive black bars).[¶] Moreover, an expansion of agricultural land in non-Annex I countries causes some increased emissions from deforestation (Fig. 1, positive light gray bars). If these emissions are also attributed to agriculture, then the leakage of Annex I agricultural abatement increases from 25% to 55%.

The regional breakdown of emission changes in scenario A shows comparatively large livestock abatement in the United States, European Union 27, and Oceania (*SI Appendix*, Table S10*B*) when only Annex I emissions are regulated. Crop and forestry sectors in the United States deliver significantly more abatement than the other Annex I regions (Fig. 1). Agricultural emissions leakage is apparent in all non-Annex I regions, particularly in the livestock sectors of China and Latin America; these areas are increasingly integrated into the global economy and share relatively close trade relations with Europe, Australia, New Zealand, and North America.

Extension of the Forest Carbon Sequestration Incentives to Non-Annex I Countries (Scenario B) Nearly Eliminates Leakage and Boosts Global Agricultural Abatement. The carbon-based increase in economic returns to forests under this second scenario enables this sector to bid land away from agriculture in non-Annex I countries, thereby reducing emissions and possibly limiting the need for the direct regulation of agricultural emissions in these countries.[‖] This outcome is most notable in regions with large areas of tropical forests, such as Latin America, but also in Sub-Saharan Africa and India (*SI Appendix*, Table S10*B* offers a detailed breakdown). Moreover, global application of the forest carbon sequestration incentive generates a sixfold increase in global land-based abatement, most of which occurs in forestry (*SI Appendix*, Table S10*A*). Agricultural abatement also increases by 50%, with livestock contributing the largest share.

Table 1. Description of mitigation policy scenarios A, B, and C

	Forest carbon sequestration incentive		Carbon tax in emitting sectors, including agriculture		Compensation for carbon tax payment	
Scenario	Annex I	Non-Annex I	Annex I	Non-Annex I	Annex I	Non-Annex I
A	✓	—	✓	—	—	—
B	✓	✓	✓	—	—	—
C	✓	✓	✓	✓	—	✓

Rows correspond to the three scenarios considered in this paper. Columns correspond to policy instruments used in the Annex I and non-Annex I regions, respectively. The check marks denote the presence of a given regional policy in each scenario.

Application of the GHG Emissions Tax and the Forest Carbon Sequestration Incentive to All Countries (Scenario C) Doubles Global Agricultural Emissions Abatement. Virtually all of this additional abatement occurs in non-Annex I countries. Large increases in abatement from livestock are observable in Brazil and Sub-Saharan Africa, whereas China experiences a significant increase in abatement from its crop sector, mostly because of reduced CH_4 emissions from the paddy rice sector.

Under this scenario, non-Annex I producers are compensated for their emissions tax expenses. In addition, we explicitly avoid taxing emissions from agricultural products sold in informal markets or consumed directly by households in non-Annex I countries (*SI Appendix*, section 4). Below, we will assess the effectiveness of this combination of policy incentives in balancing both environmental and social objectives.

Ruminant Meat Sector Production Is the Most Strongly Affected by a GHG Emissions Tax That Encompasses Agriculture Globally (Scenario C), Because This Sector Has a High Emissions Intensity and Limited Abatement Potential. Together, the three livestock sectors are responsible for the abatement of 0.3 GtCO_2eq in scenario C, with 58% achieved by the ruminant meat sector, 18% achieved by the dairy sector, and the remaining 24% achieved by the nonruminant meat sector. The economic impacts of market-based climate policies on the different livestock sectors depend on abatement opportunities, which are embodied in their marginal abatement costs as well as the emissions intensity of their outputs, and they affect profitability in the wake of a tax. Although there is great variation in emissions intensities across countries within a given sector, they are by far highest in the ruminant meat sector (*SI Appendix*, Fig. S5). The capacity of sectors to abate emissions without sacrificing output also varies, being higher in nonruminant sectors and smaller in dairy and ruminant meat sectors (*SI Appendix*, Fig. S6*A*).

These differences in abatement possibilities and emission intensities are reflected in the emission changes, which can be decomposed into changes in output and changes in emissions intensity for each livestock sector: ruminant meat, dairy, and

[§]Europe has been at the forefront of carbon pricing, and as of this writing, the futures price for carbon in the European Energy Exchange was about 17 €tCO_2eq or roughly, 24 \$UStCO_2eq (17). A 2008 review commissioned by the Australian Government recommended the implementation of an emission trading scheme in 2010 with a permit price equal to 20 \$AU/tCO_2eq. (18). Japan recently entertained a carbon tax of roughly 20 \$US/tCO_2eq. (19). Sweden has had a carbon tax on fossil fuels in place since 1991, which was recently assessed to be equal to about 100 €/tCO_2eq. (20).

[¶]Assumptions about the trade elasticities are critical for the leakage rates in the model. The 95% confidence interval with respect to uncertainty in trade elasticities for leakage in livestock sectors is 16–56%. The corresponding confidence interval for agriculture as a whole is 12–40%] (*SI Appendix*, section 8.2 has details).

[‖]Unfortunately, in this version of the CGE model, there is no scope for conversion of currently unmanaged lands, which means that the model may overstate intensification of existing agricultural lands and overestimate conversions from agriculture to forestry when carbon sequestration incentives are applied. Detailed discussion is in *SI Appendix*, section 2.4.

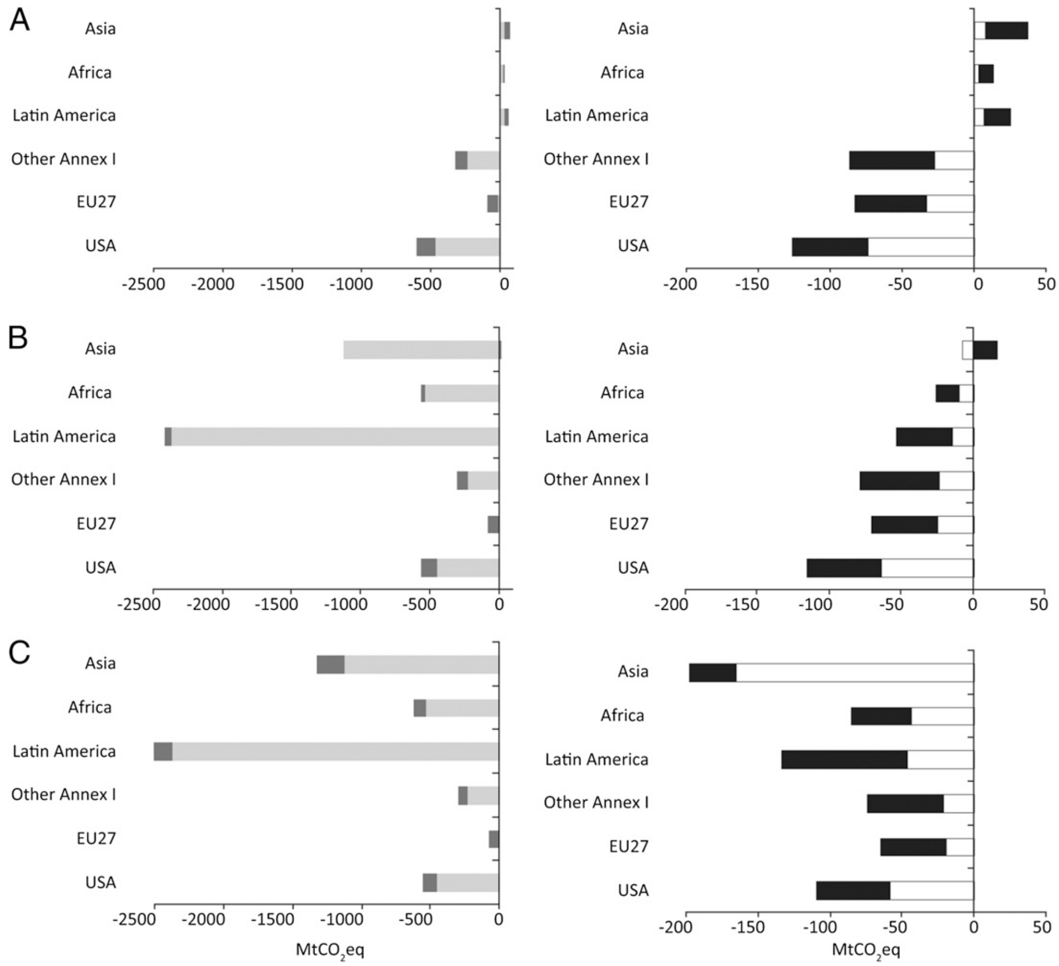

Fig. 1. Emission changes in $MtCO_2eq$ are reported by region and land using sector for each of the scenarios (A, B, and C) described in Table 1. Emissions reductions and forest carbon sequestration are reported as negative numbers, whereas leakages (increased emissions in response to carbon policies) are reported as positive numbers. The light gray and dark gray bars on the left represent forestry and agriculture (crops + livestock), respectively. The black and white bars on the right represent livestock and crops, respectively.

nonruminant meat. These changes are reported in aggregate for both Annex I and non-Annex I regions in Fig. 2 and the 19 model regions in *SI Appendix*, Fig. S9. In Annex I countries, output in all three livestock sectors under all scenarios is scaled back (Fig. 2, dark gray portion of the three rightmost bars). The output reduction is particularly pronounced for ruminant meat producers given their high emissions intensity coupled with limited abatement opportunities. By contrast, dairy and nonruminant meat producers in Annex I regions are able to deliver sizeable emission reductions (Fig. 2, combined light and dark gray bars), while experiencing minimal reductions in output. In scenario A, livestock sectors in non-Annex I countries experience increases in emissions driven by a growth in output, which is additional evidence of the emissions leakage discussed above. Leakage is particularly marked in the ruminant meat sector, because production in the non-Annex I countries expands to fill the global shortfall created by the contraction in Annex I output.** The extension of the global GHG emissions tax to all regions in scenario C significantly increases the percentage reductions in non-Annex I livestock emissions. Furthermore, the compensation of non-Annex I producers for their emissions tax expenses enables many of the non-Annex I sectors to simultaneously expand output even as they reduce overall emissions by using less emissions-intensive practices and technologies (*SI Appendix*, Fig. S9*C*). Under scenario C, the non-Annex I livestock sectors contribute just over one-half of global livestock abatement (Fig. 1*C*, *Right*).

Livelihoods of Farm and Nonfarm Households in Non-Annex I Countries Are Differentially Affected by Land-Based Climate Policies. It has long been understood among agricultural economists that direct or indirect efforts to restrict agricultural production can benefit farm asset owners. This finding is because food demand is price-inelastic, meaning that the potential revenue loss of any reduction in quantity is more than offset by the ensuing rise in price. Indeed, this knowledge has been implicit in many of the historical attempts at agricultural supply control as a vehicle to transfer income to the farm sector—particularly in the United States (21). With globalization of the farm and food sectors, national supply control policies have gone out of fashion, because the production deficit resulting from a single country's restrictions is now readily filled by foreign competitors.

The climate policies considered here indirectly achieve the same type of farm supply restriction but at global scale. Table 2

**Tariff rate quotas as well as disease restrictions represent significant barriers to trade in livestock products. The presence of restrictions on trade because of disease is implicitly captured in the model's geography of bilateral trade. However, because tariff rate quotas are not explicitly modeled, trade growth from South to North and therefore, leakage rates may be overestimated when policies are implemented in Annex I countries only (scenario A).

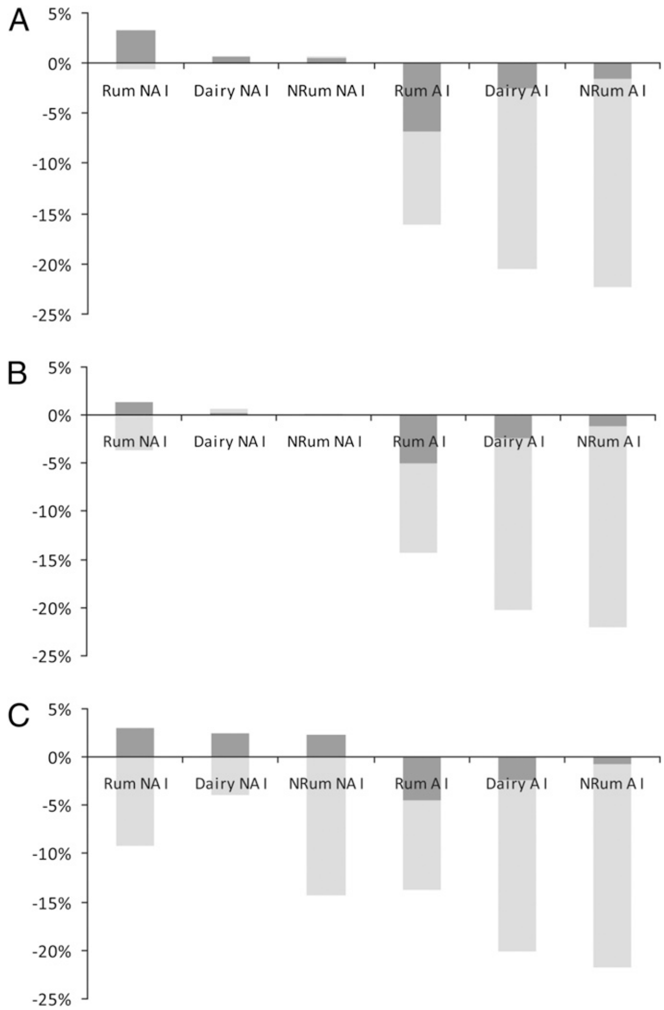

Fig. 2. Percentage changes in total emissions for the three scenarios (A, B, and C) are decomposed into the portion attributable to the change in sector output (dark gray portion of the bars) and the portion attributable to the change in emissions per unit of output (light gray portion of the bars). The sum of the two gives the change in total sector emissions. A I, Annex I; NA I, non-Annex I; NRum, nonruminant meat; Rum, ruminant meat.

reports changes in real income and food consumption separately for representative unskilled labor and farm households by region and policy scenario. Because these scenarios involve multilateral supply restrictions (particularly in scenario C, where all regions participate), the rise in farm prices offsets the decline in production in nearly every case—even after we deflate by the farm household consumer price index to take account of the change in food and nonfood prices (farm household real income column in Table 2).

The outcome for farm households stands in sharp contrast to the impact on landless farm workers and unskilled urban households because of their own unskilled labor being the sole source of income. The first group of columns in Table 2 reports the change in real income for unskilled labor households. In the case of scenario A, unskilled households in the Annex I regions experience a reduction in welfare as the rise in food, energy, and other goods prices exceeds the rise in wages. In contrast, unskilled labor households in non-Annex I regions generally experience a modest gain in welfare, because production in these regions become more competitive, increasing labor demand, production, and exports. However, after the forest carbon sequestration policy becomes global in scope (scenario B), the rise in food prices in non-Annex I regions dominates, and real incomes fall for unskilled labor households. Finally, when the economy-wide GHG mitigation policy in non-Annex I is coupled with subsidies from the Annex II regions (scenario C), the subsidy transfers are sufficient to increase real incomes for unskilled labor households in all but two of the non-Annex I regions.

Food Consumption Impacts of Climate Policies Tend to Mirror the Livelihood Outcomes and also, Are Heterogeneous. Table 2 also reports changes in overall food consumption by the two household groups.[††] Income changes are an important driver of these consumption changes. Accordingly, household/region/scenario combinations with positive income changes are expected to experience positive changes in food consumption. However, higher food prices associated with land-based mitigation strategies work to reduce food consumption for many of the regionally representative unskilled labor households. In the case of the representative farm households, the effect of rising food prices on food consumption offsets the income effect in a number of countries when abatement efforts are restricted to Annex I countries (scenario A). However, after payments for sequestration (scenario B) and agricultural abatement (scenario C) are included, rising farm incomes are sufficient to boost real farm household consumption expenditures in most non-Annex I regions. Clearly, land-based mitigation policies are beneficial for households controlling assets in agriculture.[‡‡]

Discussion

Although recent research has shed light on the cost-effective contribution that livestock can make to global GHG abatement, there is still much to be learned about the policy options available to exploit this potential. This study has shown that the design and coverage of climate policy options matter a great deal in terms of environmental effectiveness and their impacts on agricultural production, producer livelihoods, and food security.

Our work underscores the heterogeneity of sector responses to global, land-based mitigation policies. In the case of livestock producers, we find that the most important emitters of GHGs—namely, ruminant meat producers—are required to make greater market adjustments to the land-based climate policies than nonruminant meat producers and dairy farms, because they have higher emission intensities and face more limited abatement possibilities. For non-Annex I countries, the enforcement of the emissions tax coupled with the compensation of these tax expenses enabled the simultaneous reduction of emissions and expansion of output for nonruminant meat and dairy producers.

There is the temptation to try to address concerns about food security and agricultural development by exempting non-Annex I regions from climate policies. However, this exemption can lead to high emissions leakage rates in livestock sectors and agriculture as a whole. The prospect of large leakages because of expansion in non-Annex I production could easily derail the inclusion of agriculture in future mitigation strategies.

Extension of the forest carbon sequestration incentive to all regions, while still exempting non-Annex I producers from the GHG emissions tax (scenario B), was shown to eliminate this leakage and boost livestock abatement by 80% and agricultural

[††]While not presented in Table 2, Food and Agriculture Organization food security statistics were used to construct baseline per capita calories and protein profiles for each of the non-Annex I regions. Using these profiles, percent changes in consumption of different food categories predicted by the model are translated into changes in per capita calories and protein intake. Percent changes in calories and protein consumption in each non-Annex I region because of the three scenarios are reported in *SI Appendix*, Table S9.

[‡‡]Table 2 reports a very large negative impacts on real income and food consumption in Russia. This finding is because of high fossil fuel emission intensity of the Russian economy (*SI Appendix*, section 5.2 has more details).

Table 2. Percentage changes in real income and consumption by region, household type, and scenario (A, B and C; details in Table 1)

Countries/region	Unskilled labor households						Farm households					
	Real income (percent change)			Food consumption (percent change)			Real income (percent change)			Food consumption (percent change)		
	A	B	C	A	B	C	A	B	C	A	B	C
Annex I												
Canada	−0.9	−0.9	−0.6	−1.0	−1.2	−1.2	5.5	7.1	8.0	2.4	3.1	3.5
European Union 27	−0.9	−1.0	−1.1	−1.0	−1.2	−1.3	−0.3	0.3	0.7	−0.7	−0.5	−0.4
Japan	−0.5	−0.6	−0.7	−0.6	−0.9	−1.0	4.8	5.1	5.4	2.0	2.0	2.1
Oceania	−2.6	−2.6	−2.5	−2.9	−3.0	−3.1	8.9	10.9	12.4	3.1	4.0	4.6
Rest of European countries	−0.5	−0.6	−0.7	−0.6	−0.8	−1.0	−0.2	0.5	1.1	−0.4	−0.2	0.0
Russia	−18.1	−18.2	−18.1	−15.2	−15.4	−15.4	−13.7	−13.8	−13.4	−11.2	−11.5	−11.1
United States	−1.0	−1.1	−1.2	−1.5	−1.7	−1.9	11.3	13.4	14.7	5.7	6.7	7.3
Non-Annex I												
Brazil	0.4	−0.4	0.8	0.2	−1.5	−0.4	1.1	39.2	38.3	0.7	27.8	27.4
Other South America	0.3	−0.9	0.5	0.1	−2.2	−1.3	1.4	58.2	56.9	0.9	36.6	36.8
Central and Caribbean Americas	0.1	−0.1	0.7	−0.2	−0.8	−0.2	1.8	20.7	20.8	1.1	13.7	13.8
Sub-Saharan Africa	0.6	−1.1	1.1	0.3	−1.3	0.8	0.1	21.0	21.4	−0.1	15.7	16.5
Middle East and North Africa	0.1	0.0	1.6	−0.1	−0.3	0.7	0.3	1.5	1.8	0.1	0.9	0.9
China and Hong Kong	0.1	−0.5	0.1	−0.0	−0.8	−0.2	0.3	10.5	10.0	0.2	8.0	7.9
East Asia	0.0	−0.7	−0.3	−0.2	−1.4	−1.4	1.2	22.3	22.7	0.5	11.0	11.0
Malaysia and Indonesia	0.4	0.0	−0.3	0.0	−0.7	0.3	−0.2	13.5	11.3	−0.4	10.1	9.7
Rest of Southeast Asia	0.1	0.0	1.8	−0.0	−0.4	1.0	1.1	6.7	4.7	0.8	4.9	3.4
India	0.3	−1.4	0.3	0.1	−1.7	−0.4	0.8	17.9	17.4	0.4	11.9	11.7
Rest of South Asia	0.0	−0.1	0.3	−0.1	−0.4	−0.0	0.6	6.9	7.7	0.4	4.9	5.5

Changes are expressed relative to base year levels. Columns (A, B, and C) refer to the three scenarios outlined in Table 1. The real income of unskilled workers is calculated by deflating unskilled wages by a household-specific consumer price index. The real income of farm households is calculated in a similar fashion. However, farm income is based on earnings of the land, labor, and capital used in farming, with proportions based on the earnings shares of these factors in agricultural gross domestic product. Quantity changes in food consumption are obtained by aggregating disaggregated consumption changes, which are determined by expenditure functions that vary by household type and region.

abatement by 50%. Indeed, the potential efficacy with which forest carbon sequestration incentives can contain the leakage of non-Annex I agricultural emissions is an important finding. Thus, non-Annex I agriculture-specific climate policies may not be needed to control the leakage if such sequestration incentives could be implemented in these countries. Needless to say, this result bears closer scrutiny to assess its robustness to alternative specifications (*SI Appendix*, section 8) as well as likely implementation constraints in developing countries. Substantial additional global agricultural abatement was also shown to be possible by extending the emissions tax to non-Annex I producers (scenario C).

In evaluating the impacts of climate policies on livelihoods and nutritional attainment in non-Annex I countries, we find that the outcomes are quite heterogeneous. Although modest when climate policies are not imposed on non-Annex I countries, as soon as forest carbon sequestration is induced on a global scale, the income and nutritional impacts begin to surface more strongly. Food consumption among unskilled labor households falls in almost all regions under all scenarios, whereas real income impacts are mixed. In contrast, real incomes of representative farm households rise sharply in each scenario in nearly every region. This outcome is driven by the strong rise in farm prices, because global agricultural supplies are restricted in the face of inelastic food demands. Of course, many farm households also work off-farm, and the impact on their well-being will be more nuanced, while the same is true for nonfarm households that obtain a share of their income from agriculture.

Finally, the feasibility of these policy interventions hinges largely on their costs. The forest carbon sequestration incentive in non-Annex I countries, which accounts for 80% of land-based mitigation in scenario B, would cost Annex II countries just over 100 billion $US per year. For comparison, the Green Climate Fund, established at the 16th session of the Conference of the Parties, will disperse 100 billion $US per year from 2020 for sector-wide support of mitigation and adaptation in developing countries. Thus, the policies packages examined in this study would require additional funds from industrialized countries beyond those funds committed at the 16th session of the Conference of the Parties.

Materials and Methods

Modeling Framework. The GTAP-AEZ-GHG model used in this paper is a modified version of the GTAP comparative static general equilibrium global trade model used in conjunction with recently developed land use and emissions modules (12, 13, 22, 23). It builds on the work by Golub et al. (13) by disaggregating regions, agricultural sectors, and households. The model incorporates detailed non-CO_2 GHG and CO_2 emissions mapped directly to countries and economic sectors and a forest carbon stock database (15, 24, 25). The associated non-CO_2 marginal abatement cost curves have also been updated for this work (26). Additional details are provided in *SI Appendix*, section 2.5. The forestry component of the model is calibrated to outputs from a partial equilibrium global forestry model derived from the model developed in the work by Choi et al. (27). This model shares the same land endowments and land supply functions that are used in the GTAP-AEZ-GHG model. Forest extensification (more hectares) and intensification decisions (more carbon per hectare) are modeled separately to better isolate the land competition between agriculture and timber products (13).

Competition for Land. A critical feature of this analysis is the treatment of land use and the competition for land within regions. We follow the approach in the work by Hertel et al. (12), which introduces AEZs into the GTAP model. Within each model region we distinguish 18 AEZs, which differ along two dimensions (growing period and climatic zones) using the work of Monfreda et al. (28). These same AEZs are also incorporated into the forestry model underpinning the forest carbon sequestration analysis. *SI Appendix*, section 2.3 has a detailed discussion about the representation of land market in the model.

Mitigation Options. Marginal abatement costs in agriculture are derived from the US Environmental Protection Agency global mitigation work (26). *SI Appendix*, section 2.5 has more details on the emission sources and mitigation options incorporated into the model.

Evaluation of Livelihood and Food Consumption Impacts. To assess the disaggregated impacts of climate policy on farm and unskilled labor households, we construct representative households for these two subgroups in each region. Both are assumed to be characterized by the same consumer preferences that apply at the national level in the GTAP model. These disaggregated households differ, however, in their income sources. The representative farm household is assumed to earn its entire income from the farming activity in that region, with earnings shares for land, labor, and capital reflective of the shares in national agricultural value-added. The unskilled labor household is assumed to earn all of its income from unskilled wage labor. It is, therefore, indicative of the impacts of climate policies on the nonfarm poor.

Rationale for Policy Scenarios. Non-Annex I countries have no mitigation obligations under the United Nations Framework Convention on Climate Change. Annex II countries are required to provide them with financial resources to meet mitigation commitments to which they voluntarily agree. In this study, wherever climate policies are imposed on non-Annex I countries, their abatement costs are subsidized. For example, when the emissions tax is extended to non-Annex I producers in scenario C, an output subsidy is used to offset the tax expenses that these producers face for their unabated emissions. Annex II countries cover the cost of this subsidy and the forest carbon sequestration incentive provided to non-Annex I countries. Furthermore, both scenarios B and C acknowledge the potential provision of significant funds for mitigation by forestry, which is mentioned in the Copenhagen Accord (29).

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1. Steinfeld H, et al. (2006) *Livestock's Long Shadow: Environmental Issues and Options* (Food and Agriculture Organization of the United Nations, Rome).
2. Steinfeld H, Wassenaar T (2007) The role of livestock production in carbon and nitrogen cycles. *Annu Rev Environ Resour* 32:271–294.
3. Smith P, et al. (2008) Greenhouse gas mitigation in agriculture. *Philos Trans R Soc Lond B Biol Sci* 363:789–813.
4. Rose SK, et al. (2012) Land-based mitigation in climate stabilization. *Energy Econ* 34: 365–380.
5. Bellarby J, Foereid B, Hastings A, Smith P (2008) *Cool Farming: Climate Impacts of Agriculture and Mitigation Potential* (Greenpeace International, Amsterdam).
6. CAST (2004) *Climate Change and Greenhouse Gas Mitigation: Challenges and Opportunities for Agriculture. Task Force Report 141* (Council for Agriculture Science and Technology, Ames, IA).
7. McKinsey & Company (2009) *Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve* (McKinsey & Company, London).
8. USEPA (2006) *Global Mitigation of Non-CO_2 Greenhouse Gases.* Available at http://www.epa.gov/climatechange/Downloads/EPAactivities/GlobalMitigationFullReport.pdf. Accessed January 7, 2011.
9. Smith P, et al. (2007) Agriculture. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (Cambridge Univ Press, Cambridge, UK).
10. van der Werf E, Peterson S (2009) *Modeling Linkages Between Climate Policy and Land Use: An Overview. Open Access Publications from Kiel Institute for the World Economy Info: Agricultural Economics* 40:507–517.
11. Hertel TW, Rose S, Tol R, eds (2009) *Economic Analysis of Land Use in Global Climate Change Policy* (Routledge, London).
12. Hertel TW, Lee H-L, Rose S, Sohngen B (2009) Modeling land-use related greenhouse gas sources and sinks and their mitigation potential. *Economic Analysis of Land Use in Global Climate Change Policy*, eds Hertel T, Rose S, Tol R (Routledge, London).
13. Golub A, Hertel TW, Lee H, Rose S, Sohngen B (2009) The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry. *Resour Energy Econ* 31:299–319.
14. Sohngen B, Mendelsohn R (2003) An optimal control model of forest carbon sequestration. *Am J Agric Econ* 85:448–457.
15. Lee H-L (2007) *An Emissions Data Base for Integrated Assessment of Climate Change Policy Using GTAP. GTAP Resource #1143, Center for Global Trade Analysis, Purdue University*. Available at https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=1143. Accessed January 7, 2011.
16. United Nations Framework Convention on Climate Change, opened for signature on May 9 1992, (entered into force March 21, 1994).
17. European Energy Exchange (2011) Available at http://www.eex.com/en/Market%20Data/Trading%20Data/Emission%20Rights/European%20Carbon%20Futures%20%7C%20Derivatives. Accessed May 27, 2011.
18. Garnaut R (2008) *The Garnaut Climate Change Review Final Report* (Cambridge Univ Press, Cambridge, UK).
19. Reuters (2009) *Japan Industry Unites Against Carbon Tax*. Available at http://uk.reuters.com/article/idUKTOE5B609U20091207. Accessed May 27, 2011.
20. IEA (2008) *Energy Policies of IEA Countries—Sweden—2008 Review. International Energy Agency.* Avaiable at http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=2023. Accessed May 27, 2011.
21. Hertel TW, Tsigas ME (1991) General equilibrium analysis of supply control in U.S. agriculture. *Eur Rev Agric Econ* 18:167–191.
22. Dimaranan BV, ed (2006) *Global Trade, Assistance, and Production: The GTAP 6 Data Base* (Center for Global Trade Analysis, Purdue University, West Lafayette, IN).
23. Hertel TW (1997) *Global Trade Analysis* (Cambridge Univ Press, Cambridge, UK).
24. Rose S, Lee H-L (2009) Non-CO2 greenhouse gas emissions data for climate change economic analysis. *Economic Analysis of Land Use in Global Climate Change Policy*, eds Hertel TW, Rose S, Tol R (Routledge, London).
25. Sohngen B, Tennity C, Hnytka M, Meeusen K (2009) Global forest data for the economic modeling of land use. *Economic Analysis of Land Use in Global Climate Change Policy*, eds Hertel TW, Rose S, Tol R (Routledge, London).
26. Rose SK (2011) *Agricultural Non-CO2 Greenhouse Gas Abatement Supplies for Global CGE Modeling, GTAP Technical Note* (Center for Global Trade Analysis, Purdue University, West Lafayette, IN).
27. Choi S, Sohngen B, Rose S, Hertel T, Golub A (2011) Total factor productivity change in agriculture and emissions from deforestation. *Am J Agric Econ* 93:349–355.
28. Monfreda C, Ramankutty N, Hertel TW (2009) Global agricultural land use data for climate change analysis *Economic Analysis of Land Use in Global Climate Change Policy*, eds Hertel TW, Rose S, Tol R (Routledge Press, UK), Chapter 2.
29. Accord C, Decision D (2009) *15th Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change*. Available at http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf. Accessed May 27, 2011.