2010

Toward a whole-landscape approach for sustainable land use in the tropics

R. DeFries
Columbia University

C. Rosenzweig
National Aeronautics and Space Administration Goddard Institute of Space Studies, cynthia.rosenzweig@nasa.gov

Toward a whole-landscape approach for sustainable land use in the tropics

R. DeFries[a,1] and C. Rosenzweig[b]

[a]Department of Ecology, Evolution, and Environmental Biology, Columbia University, New York, NY 10027; and [b]National Aeronautics and Space Administration Goddard Institute of Space Studies, New York, NY 10025

Increasing food production and mitigating climate change are two primary but seemingly contradictory objectives for tropical landscapes. This special feature examines synergies and trade-offs among these objectives. Four themes emerge from the papers: the important roles of both forest and agriculture sectors for climate mitigation in tropical countries; the minor contribution from deforestation-related agricultural expansion to overall food production at global and continental scales; the opportunities for synergies between improved food production and reductions in greenhouse gas emissions through diversion of agricultural expansion to already-cleared lands, improved soil, crop, and livestock management, and agroforestry; and the need for targeted policy and management interventions to make these synergistic opportunities a reality. We conclude that agricultural intensification is a key factor to meet dual objectives of food production and climate mitigation, but there is no single panacea for balancing these objectives in all tropical landscapes. Place-specific strategies for sustainable land use emerge from assessments of current land use, demographics, and other biophysical and socioeconomic characteristics, using a whole-landscape, multisector perspective.

Tropical landscapes lie at the nexus of two of the most pressing concerns for a globally sustainable future. First, future food demand is projected to increase by at least 50% by 2050 in response to growing levels of per capita consumption, shifts to animal-based diets, and increasing population (1–3). Improving agricultural productivity in the tropics is critical to meet this demand (4, 5) as well as to alleviate chronic food insecurity currently afflicting nearly 1 billion undernourished people (2). The second pressing concern is the need to reduce atmospheric concentrations of greenhouse gases to address climate change that is progressively affecting agriculture, coastal areas, human health, and many other sectors (6). International policy discussions have focused on reducing emissions from tropical deforestation and degradation (REDD) for climate mitigation (7). To date, this is one of the few strategies that has gained wide acceptance among parties to the United Nations Framework Convention on Climate Change in the Copenhagen Agreement.

These two concerns—food production and climate mitigation through reduced deforestation/degradation—are interconnected in tropical landscapes. Tropical forests and woodlands are the only remaining biomes where large tracts of land are available for additional expansion of agricultural production. Agricultural expansion is the primary cause of deforestation, often preceded by logging. As forests are cleared to make room for croplands and pastures, combustion and decay of biomass contribute to the accumulation of greenhouse gases in the atmosphere. Recent estimates indicate ≈1.2 Pg C/y (4.8 Pg CO_2/y) for 1997–2006 (12% of all anthropogenic CO_2 emissions) (8) and 1.5 Pg C/y (6.0 Pg CO_2/y) for 2000–2006 (9) were emitted from deforestation and forest degradation. Pressures to expand agriculture, including augmented production of bioenergy crops, are likely to lead to further tropical deforestation over large areas in the absence of incentives to counter these driving forces (10).

Whereas reducing deforestation caused by agricultural expansion is a focus for climate mitigation in the tropics, agricultural intensification (increased output per area) is the primary focus for increasing food production. Seventy percent of the increase in crop production in developing countries over the last four decades has occurred through intensification from high-yield seed varieties, synthetic fertilizer and other chemical inputs, irrigation, mechanization, multiple cropping, and shorter fallow periods (4). The remaining increase in production occurred from expansion of agricultural lands. Projections suggest that 80% of future production increases need to result from intensification (4). In tropical landscapes with low-yield smallholder agriculture and rangelands, the need for intensification is a key ingredient to overcome food insecurities, particularly with looming impacts of climate change (11).

Intensification of food production potentially reduces pressure for agricultural expansion in active deforestation frontiers, thereby reducing forest conversion and resulting carbon emissions. On the other hand, intensification could involve higher livestock densities and chemical inputs that contribute other greenhouse gases, notably methane (CH_4) and nitrous oxide (N_2O). These non-CO_2 greenhouse gases contributed over half of all agriculture-related greenhouse gases emissions since 1960, although the net effect of intensification has been a substantial reduction in total emissions relative to counterfactual scenarios in which historical food demands were met solely through agricultural expansion (12). Future agricultural intensification will play a major role in meeting food demands, but is also likely to contribute a substantial portion of future greenhouse gases.

This special feature examines the linkages between food production and climate mitigation, two seemingly contradictory objectives for tropical landscapes. We address the following questions:

> What are the trade-offs between climate mitigation by reducing greenhouse gas emissions from tropical deforestation/degradation and food production? Can agricultural intensification alleviate these trade-offs?
> What policy and management options are most promising for synergistically mitigating climate change and enhancing food production in tropical landscapes?
> How do the trade-offs and synergies between climate mitigation and food production vary in different land use settings, in different regions, and at different scales of analysis?

The papers in this special feature address these questions from perspectives that vary according to the scale of analysis. Thomson et al. (13), Angelsen (14), and West et al. (15) take global-scale views of the linkages between food production and climate mitigation. Thomson et al. use an integrated modeling approach to understand potential outcomes from climate

Author contributions: R.D. designed research; R.D. analyzed data; and R.D. and C.R. wrote the paper.

The authors declare no conflict of interest.

[1]To whom correspondence should be addressed. E-mail: rd2402@columbia.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1011163107/-/DCSupplemental.

mitigation policies combined with scenarios of growth in agricultural productivity. Angelsen addresses policy options that affect both deforestation and food production. West et al. (15) analyze carbon stocks and current crop yields globally to assess the trade-offs in different regions. Galford et al. (16) and Murdiyarso et al. (17) address the linkages between deforestation and agricultural production at regional scales in today's major deforestation frontiers, the southern Amazon and southeast Asia, respectively. Palm et al. (18) address the linkages at local scales in two villages in East Africa. Finally, Thornton and Herrero (19) examine options for achieving the dual objectives in agricultural landscapes from livestock management. Other literature (20, 21) examines the options for managing agricultural soils.

In this paper, we identify the major themes that emerge from the collection of papers in the special feature and the implications for land use policies. We emphasize the need to view landscapes from a cross-sectoral, integrated perspective to identify opportunities that maximize synergies and minimize trade-offs between food production and climate mitigation.

Theme 1

Most greenhouse gas emissions in tropical countries are currently related to land use in forests and agriculture, implying that the main opportunities to mitigate climate change currently arise in these sectors. In contrast, in the rest of the world, climate mitigation opportunities occur mainly in the energy sector.

Globally, carbon dioxide (CO_2) emissions from fossil fuel combustion are overwhelmingly responsible for the increase in atmospheric greenhouse gas concentrations since the industrial revolution (22). Only ≈14% of global CO_2 emissions from fossil fuels and other nonorganic sources came from tropical countries in 2005 (Table 1). However, when considering additional emissions of the two other major greenhouse gases, methane (CH_4) and nitrous oxide (N_2O), and CO_2 from fires and decomposition related to land-use activities, the contribution of tropical countries to the global total increases to 31%.

Land use-related activities constitute a larger share of greenhouse gas emissions in tropical countries than they do in the rest of the world. Fires (including those fires purposefully used to clear biomass in the deforestation process, fires for agricultural management, and uncontrolled fires) and decay contributed >35% of all tropical emissions (<1% in the rest of the world) in 2005. CH_4 resulting primarily from enteric fermentation in livestock and rice cultivation, contributed 23% of all tropical emissions (16% in the rest of the world). N_2O resulting from a range of sources including forest and savanna fires, fertilizer use, and manure, contributed almost 10% of all tropical emissions (4% in the rest of world). At a global scale, land use activities including deforestation and agricultural emissions contribute 36% of all anthropogenic emissions. Approximately 60% of these land-use related emissions arise in tropical countries.

Table 1. Greenhouse gas emissions from tropical countries in 2005 calculated from EC-JRC/PBL (34) in Pg CO_2-eq

		Tropical countries in			
	World	Latin America	Africa	Asia	Total tropical countries (% of world total)
CO_2 (excluding organic carbon)*	30.09*	1.25	0.69	2.39	4.33 (14.39)
CO_2 (fires and decay)	5.44	1.85	2.04	1.43	5.32 (97.7)
N_2O	2.84	0.39†	0.50‡	0.52§	1.41 (49.75)
CH_4	8.71	1.01¶	0.90‖	1.53**	3.44 (39.44)
Total	47.09	4.60	4.13	5.86	14.50 (30.79)

CO_2 equivalents are calculated from global warming potentials for a 100-y time horizon, methane (CH_4) = 25 and nitrous oxide (N_2O) = 298 (35). Tropical countries are defined as those with a majority of their land area between the Tropic of Cancer and the Tropic of Capricorn (see Table S1 for list of countries).

*Includes fossil fuel combustion and other industrial sources excluding combustion of biofuels, field burning of agricultural waste, savanna burning, grassland fires, forest fires, and waste incineration of renewable wastes.

†Main sources of N_2O in tropical Latin America are manure in pasture/range/paddock (0.12), forest fires (0.09), and direct soil emissions from fertilizer (0.05).

‡Main sources of N_2O in tropical Africa are forest fires (0.17), savanna burning (0.13), and manure in pasture/range/paddock (0.11).

§Main sources of N_2O in tropical Asia are direct soil emissions (0.15), forest fires (0.13), and manure in pasture/range/paddock (0.07).

¶Main sources of CH_4 in tropical Latin America are: enteric fermentation (0.52), fugitive emissions from oil and gas (0.14), and forest fire (0.13).

‖Main sources for CH_4 in tropical Africa are enteric fermentation (0.26), fugitive emissions from oil and gas (0.23), and savanna burning (0.12).

**Main sources for CH_4 in tropical Asia are enteric fermentation (0.43), rice cultivation (0.39), and wastewater handling (0.21).

Emissions of all greenhouse gases are increasing at a more rapid rate in tropical Asia and Latin America relative to the rest of the world despite the lower absolute concentration (Fig. 1). CH_4 emissions have increased most rapidly in Latin America since 1990 where enteric fermentation by ruminant animals is the largest source. N_2O emissions have increased most rapidly in tropical Asia where the primary source is direct emissions from soil due to fertilizer applications.

These substantial contributions and increasing trends of land use-related emissions from tropical countries suggest that tropical landscapes can play a role in climate mitigation. Policy discussions have recognized the climate mitigation potential of REDD in tropical landscapes (7). These discussions have reached high levels of United National Framework Convention on Climate Change (UNFCCC) negotiations, and many related activities are underway in multilateral, bilateral, and private initiatives outside the UNFCCC process. This special feature explores the additional important role that agricultural landscapes can play in reducing greenhouse gas emissions, particularly in light of the potential for synergies that both mitigate climate change by reducing pressure on forests (*Theme 2*) and improve food production (*Theme 3*).

Theme 2

At continental and global scales, agricultural expansion into tropical forests in this decade has traded off small increases in food production for large increases in greenhouse gas emissions from forest clearing. Agricultural intensification to increase food production (as opposed to expansion) can help balance this trade-off to meet multiple objectives for climate mitigation, increased food production, and food security for smallholder farmers.

One of the key questions motivating this special feature is whether policies to reduce deforestation could negatively affect food production as land to conserve carbon competes with land for agricultural expansion. We find, for the first half of this decade, only a minor contribution of deforested lands to food production at global and continental scales. Angelsen (14) reports that agricultural production in developing countries taken as a group has increased by 3.3–3.4% annually over the last two decades, whereas gross deforestation has increased agricultural area by only 0.3%. He concludes that future agricultural production will be more sensitive to improvements in yields than to reduced deforestation. West et al. (15) underscore the need to increase yields in the tropics to alleviate the current situation in which a unit of cleared land in the tropics loses nearly twice as much carbon and produces less than half the crop yield compared with temperate regions. A notable exception to this general conclusion is the high-input farming practices in the southern Amazonian agricultural frontier (16, 23).

Thomson et al. (13) use a global integrated assessment model to examine future sensitivity of tropical forest lands and crop prices to demand for bioenergy and food under scenarios of agricultural productivity and climate mitigation policy that places a value on terrestrial carbon. They project that without mitigation strategies large areas of tropical and temperate forests will become deforested over the 21st century. Both crop prices and emissions from deforestation are highest in a scenario with low growth in agricultural productivity. These results reiterate the important role of agricultural intensification to meet dual objectives of satisfying future food demands and mitigating climate change through forest preservation and bioenergy production.

As an additional approach to addressing this question, we use various data sources to compare relative contributions of deforestation to agricultural land and to emissions at a continental scale (*Methods* and Table S2). Deforestation in dry and humid tropical forests between 2000 and 2005 increased agricultural land by a maximum of 4.3, 1.3, and 2.6% in tropical countries in Latin America, Africa, and Asia, respectively. For this time period, we estimate that deforestation from the three continents contributed 53, 29, and 31% of their total CO_2 emissions, respectively (Fig. 2). For the tropics as a whole, deforestation from 2000 to 2005 added a maximum of only 2.5% of agricultural area relative to 2000 while contributing 39% of CO_2 emissions.

Results indicate a large increase in emissions from deforestation for a very modest gain in agricultural area at global and continental scales. Despite this conclusion, food security for the rural poor depends on local production regardless of the global-scale dynamics. Palm et al. (18) analyze the impacts of three scenarios for nitrogen additions (mineral fertilizer, green manure, and agroforestry) on food production in two East African villages. They calculated effects on greenhouse gas emissions from fertilizer application and carbon sequestration by reforestation in land not required for agriculture. They conclude that intensification is required at the local scale to promote both food security and climate mitigation in both villages.

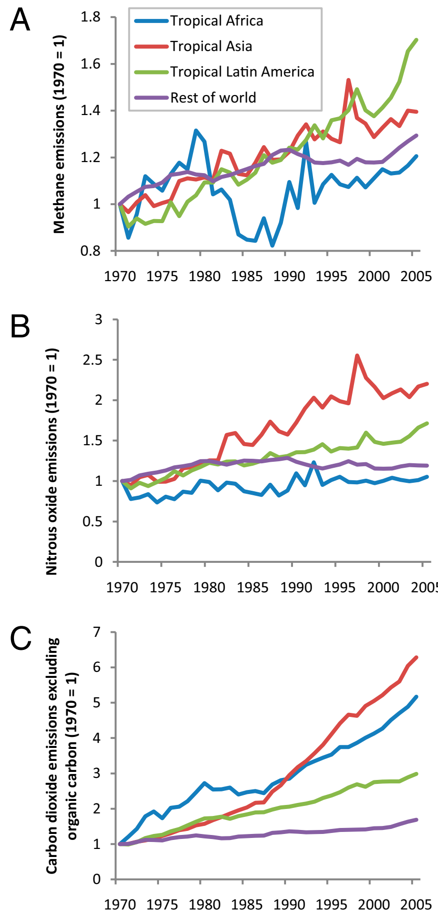

Fig. 1. Changes in emissions of methane (*A*), nitrous oxide (*B*), and carbon dioxide (*C*) in tropics from 1970 to 2005 calculated from European Commission–Joint Research Center/Netherlands Environmental Assessment Agency (EC-JRC/PBL) (42). Values are normalized to 1970. Carbon dioxide is nonorganic sources only and does not include fires that have high interannual variability. See Table S1 for a list of countries included in each continent.

The papers in this special feature and our results reinforce the oft-stated conclusion that addressing both food security and reduced deforestation lies in agricultural intensification rather than agricultural expansion into forested lands (24, 25). The analyses do not support an argument that reducing deforestation will lead to decreased food production and increased food prices due to foregone agricultural expansion. We conclude that tropical deforestation has generally involved an imbalanced trade-off between small increases in agricultural area for food production and a large increase in greenhouse gas emissions at global and continental scales. However, the past may not be a predictor of the future. If international investors purchase large tracts of tropical forest and other lands and grow crops with high-yield farming techniques (this process is already underway in some parts of Africa) (26), deforestation could lead to significant contributions to both food supply and greenhouse gas emissions.

The trade-offs and appropriate options to reduce emissions vary between large-scale commercial and small-scale agriculture. Currently the major foci for deforestation are two frontier regions with commercially driven agricultural expansion in the southern Amazon (16) and southeast Asia (17). With urbanization and international trade, future deforestation is likely to be similarly driven largely by demands for commercial production (24). The increasing importance of large-scale commercial agriculture presents an opportunity for policy incentives to locate new production on land that has already been cleared or land with relatively low carbon stocks. Such policies would likely be more difficult to implement for small-scale agriculture where farmers are not able to shift locations as readily as newly establishing commercial enterprises.

For smallholder subsistence farmers where food security depends on local production, overall global food production is not directly relevant (27). For these agricultural systems, other options to synergistically reduce emissions from agricultural management and improve food production arise from soil and livestock management, including conservation tillage, mulching, improved manure and pasture utilization, and composting (*Theme 3*).

Theme 3

Several synergistic opportunities exist to improve food production and mitigate climate change, including diversion of agricultural expansion to already-cleared lands, restoration of carbon in agricultural soils, and agroforestry. The effectiveness and appropriateness of these management options in a particular setting vary with current land use, demographics, socioeconomic conditions, and other site-specific characteristics.

Management options commonly involve trade-offs among multiple objectives, such as the trade-off occurring when deforestation provides agricultural expansion but increases emissions or conversely when policies reduce emissions from deforestation but curtail agricultural expansion. Synergistic options are less common but, when and where they do exist, can meet multiple objectives. In this special feature, we assess several potential options that synergistically improve food production and mitigate climate change in tropical landscapes.

Murdiyarso et al. (17) examine oil palm production in peat swamp forests of Indonesia. They conclude that intensifying

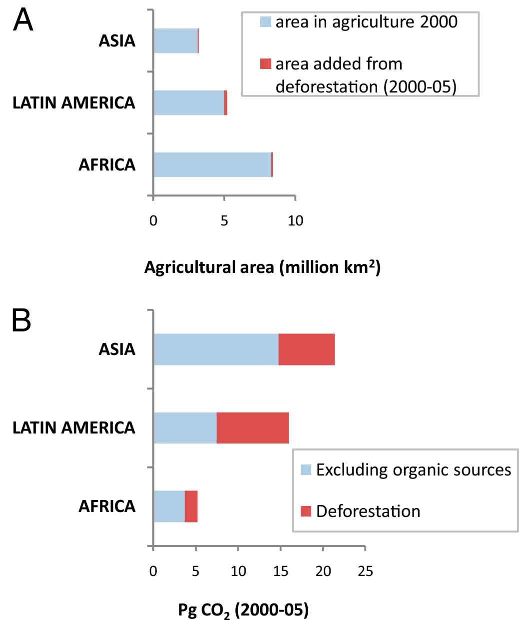

Fig. 2. The trade-off between maximum area added for agricultural expansion from deforestation in 2000–2005 (*A*) and carbon dioxide emissions (*B*). See Table S2 for datasets used for the estimates.

existing production and locating new plantations in degraded secondary forests and grasslands can both satisfy demands and reduce greenhouse gas emissions. A carbon market is unlikely to provide adequate incentives for avoided deforestation for high value oil palm, so policies for land use allocation are needed to locate new plantations on previously cleared land (28).

Thornton and Herrero (19) consider extensive tropical livestock systems and conclude that management options could mitigate a maximum of ~7% (417 Mt CO_2-eq or 0.417 Pg CO_2-eq) of the global agricultural mitigation potential to 2030 without reducing production. Mitigation options include intensifying rangeland productivity in the neotropics via adoption of improved pastures, livestock diet intensification in sub-Saharan Africa and Asia so that fewer animals are required to satisfy milk and meat demands, carbon sequestration in degraded rangelands and adoption of agroforestry, and shifts in breeds of ruminant livestock to improve animal productivity. Other authors (20, 21) conclude that soil carbon sequestration in tropical agroecosystems could be a small but partial offset of emissions from deforestation and degradation. More importantly, management practices aimed at soil carbon sequestration enhance food production and reduce pressure for cropland expansion.

The effectiveness and appropriateness of these options vary along a continuum of land use intensification from frontier clearing to extensive small-scale farming to intensive agriculture (29). In agricultural frontiers, such as described in Murdiyarso et al. (17) and Galford et al. (16), CO_2 emissions from deforestation are the primary concern. Incentives to locate agriculture on already cleared land promote production while curtailing emissions. Reliable data on the extent of abandoned and degraded lands are scarce but estimates indicate ≈385–472 million ha of abandoned agriculture globally (30). In extensive small-scale agriculture, soil carbon sequestration and agroforestry are often promoted as management options that achieve both food security and climate mitigation concerns. In rangeland systems where livestock perform multiple functions in addition to meat and milk production, cultural aspects of livestock ownership and whether fewer but more productive livestock would be acceptable require further understanding (19). At the other extreme of intensification with highly mechanized production, efficient fertilizer application and energy conservation are highlighted as options for synergistically addressing multiple goals (31).

Options for achieving dual goals for food production and climate mitigation also vary with particular demographic and land use settings, even within the same region. Palm et al. (18) report that within two locations in East Africa, effective options differ between a location with high population density and small farms and a location with low population density and abundant land availability. In the former, only mineral fertilizers allowed yield to increase enough to meet caloric requirements and allow land for reforestation. In the latter, mineral fertilizer, green manure, and agroforestry all achieved the dual objectives. Devising local strategies to mitigate climate change and improve food security requires analysis of options that accounts for site-specific conditions that vary across demographic and biophysical settings.

We emphasize in this special feature that analyses of options at local, national, continental, or global scales require a whole-landscape approach that incorporates the full spatial, temporal, and socioeconomic domains. Spatially, the unit of analysis has often been confined to either agricultural or forested systems, whereas the linkages between these systems are critical to assess dual outcomes for climate mitigation and food security. Similarly, in the temporal domain, Galford et al. (16) examine not only deforestation but also postclearing activities to estimate that land uses following clearing account for 24–49% of the net greenhouse gas budget. From a socioeconomic perspective, the trade-offs and opportunities for synergistically increasing food production and reducing emissions vary between and within large-scale commercial and small-scale agricultural systems.

Theme 4

Synergistic opportunities for improving food production and mitigating climate change do not occur spontaneously and require targeted policies to become a reality.

A common notion asserts that agricultural intensification leads to cropland abandonment and land sparing (32, 33). If this were the case, policies to promote intensification would spontaneously lead to forest regrowth and carbon sequestration as occurred, for example, in eastern North America beginning in the 1890s (34). Other analyses conclude that cropland abandonment occurs only with food imports, political upheaval, or specific, targeted conservation set-aside programs (35). Angelsen (14) reports that increases in local yield in many contexts stimulate rather than reduce agricultural encroachment because increasing local profits promote expansion, contrary to assumptions about land sparing. These results suggest that intensification is necessary, but not sufficient, to reduce pressures on forests for conversion to agriculture. Carefully designed policies that explicitly consider deforestation and agriculture are required to achieve the dual goals of climate mitigation and food security. REDD is one policy that addresses climate mitigation, but leaves aside concerns for food security, and does not address the need to promote alternatives to agricultural expansion through intensification.

We argue that international, national, and local policies will be most fruitful for promoting synergistic options if multiple goals are explicitly factored into policy formulation. At the international scale, many have called for investments to improve productivity of long-neglected tropical agriculture (36–38). We support this conclusion and add a call for including synergies between climate mitigation and food security in these discussions.

International policies to promote such synergies between reduced deforestation and enhanced agricultural production are, for example, the inclusion of agricultural soil carbon sequestration credits in the compliance carbon market, development assistance for projects that explicitly link avoided deforestation and improved agricultural productivity, and guidelines for participation in global markets and trade policies that encourage the production of agricultural commodities on land that has already been cleared. Such global policies and development-assistance projects in turn encourage national policy and local management options.

Conclusions

The four themes that emerge from the papers in this special feature reinforce the need for an integrated, whole-landscape perspective for tropical landscapes to achieve multiple objectives. In this collection of papers, we consider only two objectives for tropical landscapes, climate mitigation and food production. Tropical landscapes provide many other services that equally require a whole-landscape perspective, including conservation of biological and cultural diversity; watershed protection; a range of provisioning services such as timber, nontimber forests products, and medicinal plants (39); and management that contributes to poverty alleviation and climate adaptation (40).

The many objectives for tropical landscapes can be identified and achieved only through a lens that encompasses multiple sectors including forests and agriculture. In this special feature, we focus on options that maximize synergies and minimize negative trade-offs between these two sectors. The whole-landscape perspective encompasses both forest and agricultural lands (including crops, pastures, and rangelands) and the links between them. The need to incorporate multiple sectors applies at all spatial scales, whether pantropical (13), regional (16, 17), or local (18) scales.

Linkages between forests and agricultural lands take several forms. First, the pressure for deforestation arises squarely from the agricultural sector to expand productive land area. We find that the contribution of deforested lands to agricultural area at global and continental scales is modest, but deforestation persists in frontier areas where expansion is possible (although rates have fallen in the Brazilian Amazon since 2005). Second, whether agricultural intensification reduces or increases pressure on forests is not a straightforward question. On one hand, higher productivity agriculture in the absence of price declines can create additional pressure for clearing by making expansion more profitable. On the other hand, higher yields can enable increased production without new deforestation provided incentives are in place. Abandoned agricultural and degraded lands offer a large opportunity for agricultural expansion without additional deforestation, although it cannot be assumed that all abandoned land is suitable for production. The potential for climate mitigation from reduced deforestation and degradation is now widely recognized, but the ability to realize this potential through addressing these linkages with the agricultural sector has not yet received a similar level of attention.

Tropical agricultural lands also hold potential for synergies that mitigate climate and increase food production in their own right, irrespective of the links with deforestation. Enhanced soil carbon, agroforestry, and livestock management are among the options discussed in this special feature and other literature (19–21). The rising call for increased investments to intensify tropical agriculture to meet future food demands, if viewed from a whole-landscape perspective, potentially provides a platform for meeting the dual objectives of climate mitigation and food production.

The framework for this special feature has several limitations. We address the potential for climate mitigation in tropical landscapes but we do not address the important impacts of climate change on food production and food security that are projected to occur in the coming decades (11, 41). We have not addressed the costs of climate mitigation options or of agricultural intensification measures. Nor do we consider the trade-offs in intensive agriculture with emissions related to use of fossil fuel energy, especially for fertilizer production. Further, we have not included the potential for pressure on future agricultural production through conversion of existing high-quality farmland in areas adjacent to expanding urban areas to residential, industrial, and recreational uses (4).

We recognize the many considerations for tropical landscapes besides climate mitigation and food production, including biodiversity conservation, watershed protection, provisioning ecosystem services, and social and cultural aspects that need to be included in a whole- landscape approach, although we focus on only two aspects here. In addition, recognizing the distinction between food production and food security, with crucial dependence of the latter on access, income, and distribution in addition to food production, is important for meeting sustainable development objectives for tropical landscapes although we have not directly addressed this topic in this special feature.

The issues addressed in this special issue give rise to a number of research questions, including the following:

(*i*) What are the relative roles of international food prices, domestic policies, yield gains, and climate variability in driving deforestation?

(*ii*) What management options are effective to achieve multiple goals for increasing crop yields, optimal soil and water management, reduction in greenhouse gas emissions, and maintenance of other ecosystem services such as biodiversity and watershed protection? How does the effectiveness of options vary in different biophysical and socioeconomic settings?

(*iii*) What is the extent of abandoned agricultural lands? Are these lands suitable for cultivation? What investments and policies are required to make these lands useful for agricultural production?

(*iv*) How will a changing climate affect the intertwined dynamics of deforestation and agricultural production in the tropics? How might climate change coupled with economic factors and policies outside the tropics alter the demands on tropical agriculture and pressures for deforestation?

(*v*) How do national and global policies affect local land use decisions? Which policies at which scales can effectively promote a whole-landscape approach for balancing multiple objectives?

To answer these and related questions, an integrated whole-landscape approach is needed—one that links the goals of climate change mitigation and adaptation with agricultural production and food security. Such an approach can then contribute to the development of effective policies at local, national, and global scales that address synergies and trade-offs for meeting multiple objectives in tropical landscapes.

Methods

To estimate greenhouse gas emissions in 2005 (Table 1), country emissions for each gas were obtained from the Emission Database for Global Atmospheric Research v. 4.0 (42). Countries included for each continent were those with a majority of land area between the Tropic of Cancer and the Tropic of Capricorn (Table S1). Global warming potentials for a 100-y time horizon (43) were used to convert to CO_2 equivalents.

The trade-off between agricultural area and carbon dioxide emissions in Fig. 2 was estimated by assuming that all loss of dry and humid tropical forest from 2000 to 2005 (44) was converted to either cropland or pasture within the boundaries of the countries listed in Table S1. This conversion represents a maximum estimate of agricultural expansion. Areas in cropland and pasture in the year 2000 were determined from the updated dataset at www.geog.mcgill.ca/landuse/pub/Data/Histlanduse/ on the basis of ref. 45. Carbon dioxide emissions excluding organic carbon were derived from ref. 42. Emissions from deforestation were estimated by assuming biomass using average values for each forest type in each continent in ref. 46 and assuming that a fraction of 0.6 was lost through combustion and decay on the basis of ref. 47. Emissions of peat were added for Asia, using values from ref. 8.

ACKNOWLEDGMENTS. We are grateful to the authors of the papers in this special feature for their contributions and comments on an earlier draft of this paper. We thank David Lobell, Ken Cassman, and Eric Lambin for constructive comments. Remaining errors are our responsibility. We also thank the anonymous reviewers for reviewing all of the papers, as well as PNAS staff Meredith Jones and David Stopak.

1. Godfray HC, et al. (2010) Food security: The challenge of feeding 9 billion people. *Science* 327:812–818.
2. Nelleman C, et al. (2009) The Environmental Food Crisis—The Environment's Role in Averting Future Food Crises. *A UNEP Rapid Response Assessment* (United Nations Environment Program, GRID-Arendal, Arendal, Norway).
3. Royal Society of London (2009) *Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture* (Royal Society of London, London).
4. Food and Agriculture Organization (FAO) (2002) *World Agriculture: Towards 2015/2030* (Food and Agriculture Organization of the United Nations, Rome).
5. Fedoroff NV, et al. (2010) Radically rethinking agriculture for the 21st century. *Science* 327:833–834.
6. United Nations Framework Convention on Climate Change (2009) *Draft Decision CP 15* (Conference of the Parties, 15th session, 7–18 December, Copenhagen).
7. Angelsen A ed (2008) *Moving Ahead with REDD: Issues, Options and Implications* (CIFOR, Bogor, Indonesia).
8. van der Werf G, et al. (2009) CO2 emissions from forest loss. *Nat Geosci* 2:1–2.
9. Canadell JG, et al. (2007) Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proc Natl Acad Sci USA* 104:18866–18870.
10. Melillo JM, et al. (2009) Indirect emissions from biofuels: How important? *Science* 326:1397–1399.
11. Schmidhuber J, Tubiello FN (2007) Global food security under climate change. *Proc Natl Acad Sci USA* 104: 19703–19708.
12. Burney JA, Davis SJ, Lobell DB (2010) Greenhouse gas mitigation by agricultural intensification. *Proc Natl Acad Sci USA* 107:12052–12057.
13. Thomson AM, et al. (2010) Climate mitigation and the future of tropical landscapes. *Proc Natl Acad Sci USA* 107:19633–19638.
14. Angelsen A (2010) Policies for reduced deforestation and their impact on agricultural production. *Proc Natl Acad Sci USA* 107:19639–19644.
15. West P, et al. (2010) Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. *Proc Natl Acad Sci USA* 107:19645–19648.
16. Galford GL, et al. (2010) Greenhouse gas emissions from alternative futures of deforestation and agricultural management in the southern Amazon. *Proc Natl Acad Sci USA* 107:19649–19654.
17. Murdiyarso D, Hergoualc'h K, Verchot L (2010) Opportunities for reducing greenhouse gas emissions in tropical peatlands. *Proc Natl Acad Sci USA* 107:19655–19660.
18. Palm CA, et al. (2010) Idenifying potential synergies and trade-offs for meeting food security and climate change objectives in sub-Saharan Africa. *Proc Natl Acad Sci USA* 107:19661–19666.
19. Thornton PK, Herrero M (2010) Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *Proc Natl Acad Sci USA* 107:19667–19672.
20. Smith P, et al. (2008) Greenhouse gase mitigatioin in agriculture. *Philos Trans R Soc B* 363:789–813.
21. Wassman R, Vlek P (2004) Mitigating greenhouse gas emissions from tropical agriculture: Scope and research priorities. *Environ Dev Sustain* 6:1–9.
22. Houghton RA (2007) Balancing the global carbon budget. *Annu Rev Earth Planet Sci* 35:313–347.
23. Cassman K (2005) Soybean production and expansion in Mato Grosso, Brazil. *Nebraska Soybean Review* (Nebraska Soybean Association, Lincoln, NE), pp 10–15.
24. DeFries R, Rudel TK, Uriarte M, Hansen M (2010) Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nat Geosci* 3:178–181.
25. Matson PA, Vitousek PM (2006) Agricultural intensification: Will land spared from farming be land spared for nature? *Conserv Biol* 20:709–710.
26. Friis C, Reenberg A (2010) Land grab in Africa: Emerging land system drivers on a teleconnected world. *GLP Report No. 1* (GLP-IPO, Copenhagen).
27. Coomes OT, Grimard F, Potvin C, Sima P (2008) The fate of the tropical forest: Carbon or cattle? *Ecol Econ* 65: 207–212.
28. Koh LP, Ghazoul J (2010) Spatially explicit scenario analysis for reconciling agricultural expansion, forest protection, and carbon conservation in Indonesia. *Proc Natl Acad Sci USA* 107:11140–11144.
29. DeFries R, Foley J, Asner GP (2004) Land use choices: Balancing human needs and ecosystem function. *Front Ecol Environ* 2:249–257.
30. Campbell JE, Lobell DB, Genova RC, Field CB (2008) The global potential of bioenergy on abandoned agriculture lands. *Environ Sci Technol* 42:5791–5794.
31. Cassman KG (1999) Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proc Natl Acad Sci USA* 96: 5952–5959.
32. Green RE, Cornell SJ, Scharlemann JP, Balmford A (2005) Farming and the fate of wild nature. *Science* 307:550–555.
33. Kauppi PE, et al. (2006) Returning forests analyzed with the forest identity. *Proc Natl Acad Sci USA* 103: 17574–17579.
34. Pfaff A, Walker R (2010) Regional interdependence and forest "transitions": Substitute deforestation limits the relevance of local reversals. *Land Use policy* 27:119–129.
35. Rudel TK, et al. (2009) Agricultural intensification and changes in cultivated areas, 1970–2005. *Proc Natl Acad Sci USA* 106:20675–20680.
36. International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), (2009) *Agriculture at a Crossroads: International Assessment of Agricultural Knowledge, Science, and Technology for Development, Synthesis Report*, eds McIntyre B, et al. (Island Press, Washington, DC).
37. Sanchez PA (2009) A smarter way to combat hunger. *Nature* 458:148.
38. Von Braun J, Swaminathan MS, Rosegrant MW (2004) *Agriculture, Food Security, Nutrition, and the Millennium Development Goals* (International Food Policy Research Institute, Washington, DC).
39. Hassan R, Scholes R, Ash N, eds (2005) *Ecosystems and Human Well-Being: Current Status and Trends* (Island Press, Washington, DC), Vol 1.
40. Campbell B (2009) Beyond Copenhagen: REDD+, agriculture, adaptation strategies and poverty. *Glob Environ Change* 19:397–399.
41. Parry M, Rosenzweig C, Livermore M (2005) Climate change, global food supply and risk of hunger. *Philos Trans R Soc Lond B Biol Sci* 360:2125–2138.
42. European Commission and Joint Research Center (JRC)/Netherlands Environmental Assessment Agency (PBL) (2009) Emission Database for Global Atmospheric Research (EDGAR), release version 4.9. Available at http://edgar.jrc.ec.europa.eu.
43. Intergovernmental Panel on Climate Change (IPCC) (2007) *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (Cambridge Univ Press, Cambridge, UK, and New York).
44. Hansen MC, Stehman SV, Potapov PV (2010) Quantification of global gross forest cover loss. *Proc Natl Acad Sci USA* 107:8650–8655.
45. Ramankutty N, Foley J (1999) Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochem Cycles* 13:997–1027.
46. Gibbs H, Brown S, Niles JO, Foley J (2007) Monitoring and estimating tropical forest carbon stocks: Making REDD a reality. *Environ Res Lett* 2:045023.
47. van der Werf G, et al. (2010) Global fire emissions and contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009). *Atmos Chem Phys* 10:16153–16230.

Supporting Information

DeFries and Rosenzweig 10.1073/pnas.1011163107

Table S1. Countries used to calculate greenhouse gas emissions in Table 1

ISO	Country name
Tropical Africa	
AGO	Angola
BEN	Benin
BWA	Botswana
BFA	Burkina Faso
BDI	Burundi
CMR	Cameroon
CAF	Central African Republic
TCD	Chad
CIV	Cote d'Ivoire
DJI	Djibouti
GNQ	Equatorial Guinea
ERI	Eritrea
ETH	Ethiopia
GAB	Gabon
GMB	Gambia
GHA	Ghana
GIN	Guinea
GNB	Guinea-Bissau
KEN	Kenya
LBR	Liberia
MDG	Madagascar
MWI	Malawi
MLI	Mali
MRT	Mauritania
NER	Niger
NGA	Nigeria
OMN	Oman
COG	Republic of Congo
MOZ	Mozambique
NAM	Namibia
RWA	Rwanda
SDN	Sudan
TZA	Tanzania
COD	Democratic Republic of the Congo
TGO	Togo
UGA	Uganda
ARE	United Arab Emirates
ESH	Western Sahara
YEM	Yemen
ZMB	Zambia
ZWE	Zimbabwe
SAU	Saudi Arabia
SEN	Senegal
SYC	Seychelles
SLE	Sierra Leone
SOM	Somalia
Tropical Asia	
BGD	Bangladesh
BRN	Brunei
KHM	Cambodia
IND	India
IDN	Indonesia
LAO	Laos
MYS	Malaysia
PNG	Papua New Guinea

Table S1. Cont.

ISO	Country name
PHL	Philippines
MMR	Myanmar
LKA	Sri Lanka
THA	Thailand
TLS	East Timor
VNM	Vietnam
SGP	Singapore
Tropical Latin America	
BLZ	Belize
BOL	Bolivia
BRA	Brazil
COL	Colombia
CRI	Costa Rica
CUB	Cuba
ECU	Ecuador
SLV	El Salvador
GTM	Guatemala
GUY	Guyana
GUF	French Guiana
HND	Honduras
MEX	Mexico
NIC	Nicaragua
PAN	Panama
PRY	Paraguay
PER	Peru
SUR	Suriname
VEN	Venezuela

Countries are those with the majority of land area between the Tropic of Cancer and the Tropic of Capricorn.

Table S2. Comparison of maximum land area gained for food production from deforestation (gross forest loss) and estimated carbon emissions for 2000–2005

	Change in gross forest area 2000–2005 from ref. 1, km^2		Agricultural area in 2000 based on ref. 2, km^2*		Estimated deforestation emissions (2000–2005), Pg CO_2[†]		CO_2 emissions excluding organic sources from ref. 3 (2000–2005), Pg
	Dry tropical forest	Humid tropical forest	Crop area	Pasture area	Dry forest	Humid forest	
Tropical Latin America	53,959	159,427	1,187,396	3,797,626	0.98	7.52	7.44
Tropical Africa	94,088	14,494	1,820,616	6,470,506	1.00	0.52	3.70
Tropical Asia	8,766	72,194	2,928,100	187,070	0.21	6.43[‡]	14.73
Total tropics	156,813	246,115	5,936,113	10,455,202	2.20	14.47	25.87

Countries included within each continent are listed in Table S1.

*The data set used is available at www.geog.mcgill.ca/landuse/pub/Data/Histlanduse/.

[†]Emissions were estimated from mean biomass values reported in Table 2 in ref. 4 for forest type and continent and a conservative estimate of 0.6 fraction of biomass lost from combustion and decay (5).

[‡]Includes 2.88 Pg CO_2 from peat using annual estimate of 0.12 Pg C/y from ref. 6.

1. Hansen MC, Stehman SV, Potapov PV (2010) Quantification of global gross forest cover loss. *Proc Natl Acad Sci USA* 107:8650–8655.
2. Ramankutty N, Foley J (1999) Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochem Cycles* 13:997–1027.
3. European Commission and Joint Research Center (JRC)/Netherlands Environmental Assessment Agency (PBL) (2009) Emission Database for Global Atmospheric Research (EDGAR), release version 4.9. Available at http://edgar.jrc.ec.europa.eu.
4. Gibbs H, Brown S, Niles JO, Foley J (2007) Monitoring and estimating tropical forest carbon stocks: Making REDD a reality. *Environ Res Lett* 2:045023.
5. van der Werf G, et al. (2010) Global fire emissions and contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009). *Atmos Chem Phys* 10:16153–16230.
6. van der Werf G, et al. (2009) CO2 emissions from forest loss. *Nat Geosci* 2:1–2.