Agricultural intensification escalates future conservation costs

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The supposition that agricultural intensification results in land sparing for conservation has become central to policy formulations across the tropics. However, underlying assumptions remain uncertain and have been little explored in the context of conservation incentive schemes such as policies for Reducing Emissions from Deforestation and forest Degradation, conservation, sustainable management, and enhancement of carbon stocks (REDD+). Incipient REDD+ forest carbon policies in a number of countries propose agricultural intensification measures to replace extensive "slash-and-burn" farming systems. These may result in conservation in some contexts, but will also increase future agricultural land rents as productivity increases, creating new incentives for agricultural expansion and deforestation. While robust governance can help to ensure land sparing, we propose that conservation incentives will also have to increase over time, tracking future agricultural land rents, which might lead to runaway conservation costs. We present a conceptual framework that depicts these relationships, supported by an illustrative model of the intensification of key crops in the Democratic Republic of Congo, a leading REDD+ country. A von Thünen land rent model is combined with geographic information systems mapping to demonstrate how agricultural intensification could influence future conservation costs. Once postintensification agricultural land rents are considered, the cost of reducing forest sector emissions could significantly exceed current and projected carbon credit prices. Our analysis highlights the importance of considering escalating conservation costs from agricultural intensification when designing conservation initiatives.

swidden | slash and burn | land use change | payment for ecoysystem services | biodiversity

Novel conservation policies for Reducing Emissions from Deforestation and forest Degradation and through the conservation, sustainable management, and enhancement of carbon stocks (REDD+) have been deployed in more than four dozen tropical developing countries (1, 2). These propose to financially compensate countries that improve forest conservation and management to reduce emissions and mitigate against climate change. The pantropical initiative has the potential to recruit billions of dollars in annual conservation finance (3) and is the focus of United Nations negotiations and multi- and bilateral agreements between industrialized and developing nations (2). Moreover, REDD+ interventions have the potential to yield knock-on effects, including cobenefits for biodiversity conservation and poverty alleviation (3). These incipient REDD+ schemes involve a broad range of conservation interventions, ranging from protected areas establishment, improved environmental governance, and agricultural intensification to motivate land sparing.

Intensification to Reduce Deforestation

Agricultural intensification—increasing agricultural inputs to improve per-hectare yields rather than expanding land under cultivation—is often posited as a strategy for reducing agriculture encroachment into forest, while satisfying agricultural demand (*SI Text*) (4–8). Intensification purportedly creates a "virtuous cycle of poverty reduction and reduced forest pressures," where it increases yields while limiting expansion, attracts labor away from forested areas, and/or facilitates reinvestment into already degraded lands (9, 10). As a result, agricultural intensification has become central to REDD+ policy formulation across the tropics (11, 12). For example, the Democratic Republic of Congo (DRC) seeks to "increase productivity and sedentary lifestyle" of 50% of its subsistence farmers by 2030 to reduce pressures on forests (13). Similarly, Nepal, Liberia, Mozambique, Madagascar, Argentina, Kenya, and Indonesia are adopting agriculture intensification policies to discourage "slash-and-burn" agriculture (also swidden, shifting, or rotational agriculture; 11–14). These extensive farming systems are prevalent across the tropics, but are being widely replaced by more intensive agriculture, often spurred by government policies (15). Policies that restrict extensive farming in an effort to curb deforestation may essentially impose an intensification agenda (13).

However, empirical analyses show a weak or nonexistent relationship between intensification and land sparing for conservation (16–19), for which there are diverse plausible explanations (4, 16, 19–23). Notably, intensification changes future agricultural land rents as yields and surpluses increase, creating financial incentives for agricultural expansion, including into forests (11, 20). Agricultural rents may further increase if conservation reduces land available for farming (11), compounded with increasing commodity prices and economic globalization (7, 10). Agricultural intensification is also associated with in-migration, road construction, and increased economic activity (4), themselves leading causes of deforestation (20, 24). Moreover, intensification can facilitate greater consumption (Fig. 1) (10, 18), and can also free up land for economic diversification and export production, driving deforestation without actualizing conservation benefits (11, 16, 17, 19).

Payment for ecosystem services (PES) schemes that leverage incentives to spur voluntary conservation, such as REDD+, have the potential to compete with escalating incentives to clear forest for agriculture. However, the relationships between future agricultural yields and conservation incentives have been little addressed in policy or literature. We propose a conceptual framework for exploring the agricultural intensification–land sparing debate within the context of PES and REDD+ policies. To illustrate the interaction between increasing farm yields (land rent) and conservation incentives (forest rent), we used a von Thünen model (20) with geographic information systems (GIS) mapping to explore possible effects on forest cover in the DRC, a leading REDD+ country (13). The model considers hypothetical scenarios involving step-wise increases in crop yields, and highlights possible changes to future break-even costs of conservation. Our framework and model can help decision-makers visualize unintended consequences of contemporary conservation policies, such as land sparing and REDD+, which could jeopardize long-term conservation outcomes.

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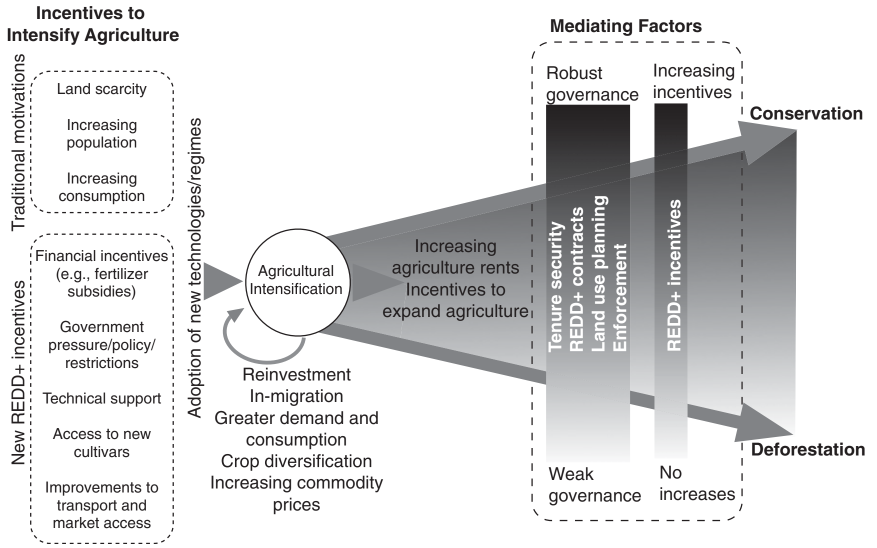

Fig. 1. Relationship between REDD+ policies, agricultural intensification, and deforestation. New REDD+ policies drive agricultural intensification, which increases future agricultural rents and incentivizes forest clearing for agricultural expansion. A number of feedbacks (e.g., reinvestment, in-migration) create further incentives for expansion. Whether these result in deforestation or land sparing for conservation depends on two mediating factors (1): robust forest sector governance and (2) whether REDD+ payments match future agricultural rents. Macroeconomic contexts not depicted.

Framework: Relationship Between Intensification and Conservation Interventions

The conceptual framework (Fig. 1) depicts how traditional drivers such as new agribusiness models, land scarcity, increasing demographic pressure, and increasing consumption have stimulated farmers to adopt new agricultural technologies resulting in intensification (25). REDD+ policies may further drive agricultural intensification through provision of technical support and subsidies, and may even impose intensification on extensive farmers. Resulting increases in agricultural rents incentivize agricultural expansion, as well as diverse feedbacks (e.g., in-migration, reinvestment) that are likely to further increase intensification and motivate agricultural expansion. The framework considers these drivers in the context of PES/REDD+ policies, and depicts two complementary factors through which to mitigate incentives for deforestation: strengthened forest governance and escalating conservation incentives.

First, avoiding deforestation relies on robust forest sector governance, a proxy for a range of institutional factors including tenure security, coherent land use planning, policy harmonization, and enforcement (26) (Fig. 1). Limiting agricultural expansion into forestlands may further necessitate new limits on deforestation and restrictions on farming to within already-deforested and degraded lands (e.g., outlawing extensive agriculture or implementing "fortress conservation" measures). Indeed, several developing countries have successfully leveraged policy instruments to simultaneously protect forests and increase agricultural production (10). However, a heavily enforcement-based approach to governing REDD+ raises serious social equity issues (27), and potentially represents an economically inefficient approach to conservation. Nevertheless, improving broader forest sector governance is widely considered central to REDD+ implementation (2).

Crucially, mitigating future deforestation also depends on conservation incentives remaining competitive against rising agricultural land rents. Across much of the tropics, landholder opportunity costs are comparatively low, and modest incentives are capable of promoting voluntary conservation (28). However, should conservation incentives fail to match future agricultural rents, particularly in a landscape characterized by intensive agriculture, projects could face local rule and contract breaking, resistance, and conflict, potentially leading to deforestation. For example, the emergence of high-value oil palm agriculture across Southeast Asia has substantially increased local agricultural rents, spurring deforestation despite environmental regulations, and to the point where conservation incentives may be insufficient to stimulate voluntary conservation (29, 30). We explore this part of the framework—changing agricultural yields and conservation incentives—in the context of REDD+ implementation in the DRC.

Agricultural Intensification and REDD+ in the DRC

The DRC is a priority REDD+ country, host to the largest forest tracts in Africa (13, 31), and among the highest forest carbon emitters between 2000 and 2005 (32). Small-scale and subsistence agriculture are reportedly the principle drivers of deforestation (31, 33), with business-as-usual projections forecasting a 3–4% increase in forest-based emissions by 2030 (28). The country is seeking to support forest conservation alongside economic and agricultural development (28, 31). Smallholder agricultural intensification, particularly within high population density forest border regions, is a central approach to reducing deforestation (34).

In addition to traditional drivers of intensification, REDD+ planning documents outline additional measures for actively promoting intensification (Fig. 1; *SI Text*). Policies include a US$2.2 billion, 15-y plan to cover ~50% of the territory to improve agricultural techniques, yields and income affecting ~3 million rural households (28). The plan draws on a range of strategies, including improved crop varietals, agricultural inputs, credit access, and transportation (*SI Text*). Moreover, it proposes to accompany intensification with improved administration of services, land tenure allocation, and national land use planning (35). These strategies are poised to significantly transform smallholder agriculture, and propose to reduce 184MtCO_2 through agricultural reform, at a one-time abatement cost of US$11.80/t$CO_2$ (28).

Model Scenarios

In light of these policies, a model was built to illustrate the dynamics between agricultural intensification and increases in conservation incentives, under different macroeconomic conditions (governance factors were not modeled). We modeled stepwise increases in yields of key crops and of REDD+ payments per avoided ton of carbon dioxide (tCO_2) emissions. We focused on cassava and maize as the most widely cultivated staple crops in the DRC (36) that constitute the basis of the national diet and are targeted by REDD+ intensification efforts (28).

Prices, input costs, original and improved yields, and other parameters for the scenarios are provided in Tables S1 and S2 (37, 38). The intensification scenarios were as follows: scenario 1, monoculture of improved cassava results in stepwise increases in cassava yields (14.75–39.2 t/ha); scenario 2, use of improved cassava varieties, intercropped with maize with increased fertilizer input results in stepwise increases of cassava yields (10.35–20.70 t/ha), and increases of maize yields (2.55–3.83 t/ha); and scenario 3, monoculture of maize with increases in fertilizer input results in stepwise increases in maize yields (2.85–4.28 t/ha). Scenarios were further modeled within three different macroeconomic contexts based on Organisation for Economic Co-Operation and Development, and Food and Agriculture Organization forecasts (39): macroeconomic context 1, food price inflation with a 20% agricultural commodity price increase between 2011 and 2020; macroeconomic context 2, market flooding with a 20% reduction in agricultural commodity prices due to the increases in supply; and macroeconomic context 3, oil price increase and a 25% increase in transport costs, 14% increase in price of fertilizer, and 4% increase in agricultural commodity prices.

Model Results

Intensification resulting in surplus agricultural production would increase agricultural land rents. Despite high transport costs across much of the DRC (Table S2), intensification would substantially expand the primary and secondary forest area over which agricultural production would be profitable (Fig. 2).

To promote forest conservation, REDD+ incentives would need to increase over time to match increasing agricultural rents, and could reduce the area for which agricultural rents exceed forest rents (example from scenario 1, Fig. 2 *D–F*; other scenarios in Figs. S2–S12). For instance, a strategy aimed at limiting deforestation to below 10 million hectares under intensification scenarios 1 and 2 would require annual payments of, or nonfinancial incentives equivalent to, \$2/tCO2 to match yield increases of 40%, and \$3/tCO_2 per year to compete with yields increases of 60% (Fig. 2 *A* and *B*). In scenario 3, intensified maize agriculture would likely outcompete REDD+ payments of \$1/tCO_2 per year (Fig. 2*C*), at even small yield increases. However, small increases in REDD+ payments (\$3/tCO_2 per year) would potentially prevent significant deforestation (Fig. 2*C*, area of forest at risk limited to below 20 million ha for a 50% yield increase). Overall, annual payments of ~\$5/tCO_2 appeared to be the most cost-effective for the three scenarios—they attained the maximum forest conservation at the lowest REDD+ payment, even after intensification (Fig. 2 *D–F*).

Crucially, however, payments must recur to offset annual agricultural rents, such that the modeled \$5/tCO_2 represents a discounted net present cost of \$98/tCO_2 for a 30 y time horizon at a 3% discount rate. This contrasts with the average one-time \$5.5/tCO_2 value of forestry sector carbon credits across voluntary and regulated markets in 2010, for contract of varying lengths (40). Annual conservation payments of \$2/tCO_2 (net present cost of \$39/tCO_2) might be capable of protecting against deforestation under a scenario involving half of the potential maximum yield increase, and are closer to the \$25/tCO_2 median of peer-reviewed carbon price estimates with a 3% pure rate of time preference (41). Both differ considerably from the government-proposed, one-time US\$11.80/tCO_2 emissions abatement cost (28).

REDD+ break-even points were similar across the three macroeconomic contexts. Predictably, increases in agricultural prices increased the risk of deforestation, while price decreases due to market flooding and increased oil prices decreased deforestation risk. However, the effect was not symmetrical, with price increases endangering greater areas of forest than might be spared by comparable falls in price for scenarios 1 and 2; the opposite was true for scenario 3 (Fig. 2 *D–F*).

The model showed a nonlinear relationship between REDD+ incentives and conservation outcomes, with the marginal costs of conservation dramatically increasing as more area is protected (Fig. 2). For instance, halting deforestation altogether is prohibitively expensive, requiring annual payments of \$100/tCO_2. However, annual payments of \$15/tCO_2 would potentially increase forest rents above agricultural rents in most areas of the DRC, even after intensification (Fig. 3). A price of \$10/tCO_2 per year could increase the area under conservation from 10 to 90 million hectares (Fig. 2 *D–F*).

Discussion

REDD+ conservation policies in a number of tropical developing countries portend to transition extensive farmers toward more intensive production. This has the potential to result in conservation and emissions reductions through land sparing. However, policies have ill considered the impacts of intensification on future conservation efforts. As suggested by the conceptual framework and model, intensification will significantly affect future conservation costs, and has implications for the timing and nature of incentives, their cost-effectiveness, and spatial variability.

Intensification Increases Break-Even Points for Conservation. Increasing agricultural rents are likely to incentivize future agricultural expansion, including through forest encroachment.

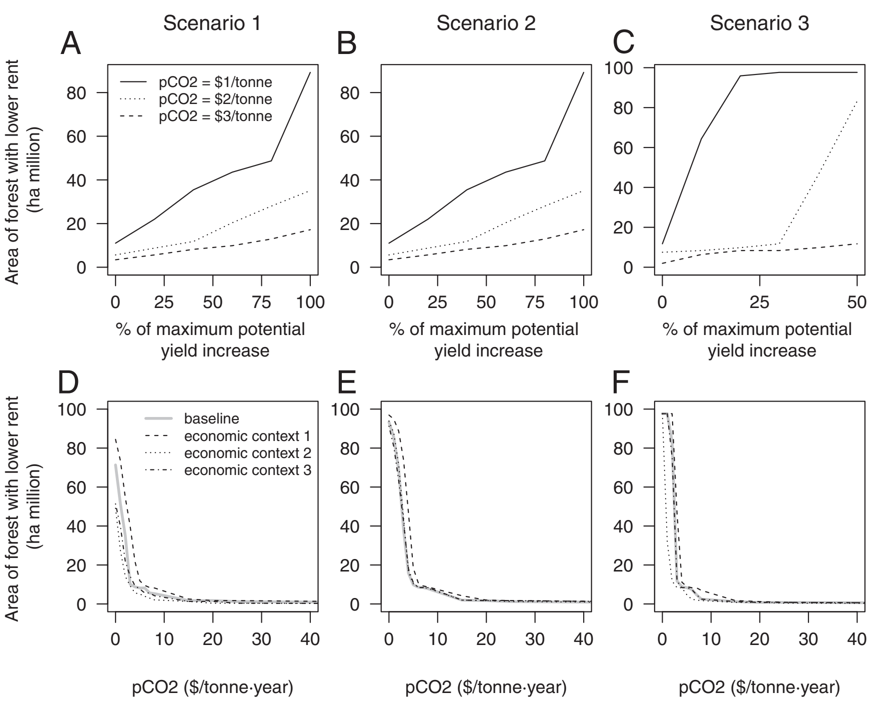

Fig. 2. Area of forest with rent lower than agricultural rent for proportional increases in yield under intensification policies (*A–C*), and proportional increase in the price of CO_2 emissions per year• (p_{CO2}) under the maximum potential yield after intensification (*D–F*). Scenario 1, improved cassava in monoculture; scenario 2, improved cassava intercropped with maize and fertilizer input; scenario 3, maize monoculture with fertilizer input. Macroeconomic context 1 and 2, increase and decrease of 20% in agricultural commodity prices, respectively; and macroeconomic context 3, increase in transport cost (25%), fertilizers (14%), and agricultural commodity prices (4%).

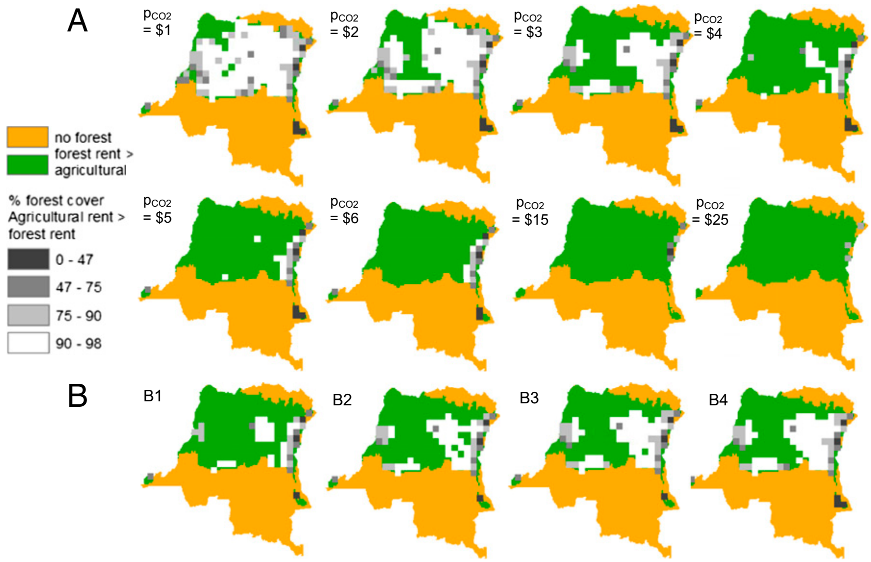

Fig. 3. (*A*) Forest with rent below agricultural rents under scenario 1 baseline context (maximum expected yield increase under intensification, doubling cassava yields) for different annual payments per ton of CO_2 emitted (p_{CO2}). (*B*) Forest with rent below agricultural rents under increasing cassava yields in the baseline context; B1, 20% increase; B2, 40% increase; B3, 60% increase; and B4, 80% increase of the maximum potential yield.

Conservation incentives can potentially counteract future deforestation incentives. However, conservation agreements may result in short-term protection while incentives are attractive, but could be followed by future deforestation when increasing agricultural rents exceed unadjusted conservation incentives. Our analysis strongly suggests that future conservation costs will concomitantly increase with intensification. Indeed, the Congo Basin is currently an attractive conservation target not only for its extensive forests and high biodiversity, but for its comparatively low opportunity costs (31, 42). In the context of policies to intensify agriculture, however, the model anticipates dramatically increased break-even points for conservation.

Not only must conservation schemes respond to increasing yields, but our analysis highlights the importance of the timing and nature of incentives. Notably, incentives must account for recurring, annual benefits from agriculture. In comparison, one-time conservation incentives may be inadequate to spur voluntary land sparing. Similarly, policy makers need to ascertain the differences between leveraging direct payments versus nonfinancial benefits to promote conservation. For example, existing policy formulations in the DRC do not prescribe cash payments to households as incentives to reduce deforestation, but rather focus on nonfinancial incentives such as livelihood development (34). This approach differs significantly from model projects such as Brazil's ProAmbiente (43), where households are directly and monetarily rewarded for conservation. It remains uncertain how most countries will distribute REDD+ finances to incentivize local conservation, and the effectiveness, efficiency, and equity impacts of different benefit distribution strategies remain unclear (44). Regardless of benefit mechanism, the model highlights that incentives will need to increase to counteract intensification.

Diminishing Returns and Cost-Effectiveness of Conservation. However, the nonlinear relationship between conservation incentives and forest conservation suggests that there are probably limits to how high carbon payments should increase to compete with agriculture. The scenarios also highlight the spatial variability of agricultural and forest rents. In areas where carbon densities are high and/or which are poorly connected by roads (high transport costs), deforestation might be discouraged with low carbon prices. However, in areas with low carbon density and thus low emissions potential (Fig. 3*B* for annual price of $25/t$CO_2$), and near cities and roads with low transport costs (northeastern regions, Fig. S1), conservation costs would be necessarily higher. However, under the modeled scenarios, payments much above $5/t$CO_2$ per year would offer dramatically diminished returns in terms of area conserved, reducing the cost-effectiveness of emissions mitigation through REDD+.

The model suggests that cost-effective carbon pricing would be spatially variable, potentially fluctuating according to subnational break-even points, although responding to this would be challenging in the context of global carbon markets. A common price per ton of CO_2 across landscapes could lead to directing conservation into high-carbon-density, isolated forests with low break-even prices, while less carbon dense and more accessible areas would be converted. As such, REDD+ benefits might not be evenly distributed—deforestation pressures could shift among sites (leakage), and critical biodiversity areas could be overlooked for conservation (30). This further highlights the importance of robust governance in addition to incentives to mediate REDD+ outcomes, as strong land-use planning would be required to ensure that REDD+ investments match other national development and conservation objectives.

Limitations to the Modeling Approach. The trends we illustrate are most relevant when considered in the context of national policy, landscape-level changes, and longer time scales. They suggest that, over time, policies aiming at agricultural growth through intensification will create net incentives for deforestation. The combination of changing agricultural output prices, yield increases (assuming no effect on labor or capital markets), and market accessibility (45) in the von Thünen land rent model captures the salient dynamics of potential future tradeoffs between privately captured benefits and globally captured climate regulation service values. However, the top-down model cannot predict specific, local spatiotemporal dynamics, such as how incentives will influence different actors, especially during the transition period as new agricultural technologies are widely adopted. Increased agricultural rents may, for example, eventually displace existing communities with the arrival of immigrants, commercial agriculture, or other interests. Complementary farm- and household-level analyses would be necessary to better depict the complex realities of on-the-ground land use changes.

A bottom-up model could also integrate other factors that shape land use change. Demographic changes, for example, are often associated with deforestation as a result of increased consumption and labor availability (46), but can also lead to institutional changes that protect forests (45). Lack of access to land or tenure security can also lead to forest clearing, as a way to claim property rights (47), and although tenure has been observed to lower deforestation in Latin America (48), increased security can also encourage forest clearance by making these investments less risky (45). Bottom-up modeling that reflects subsistence farming behavior would further require understanding risk preferences, capital availability, and motives to account for how income security dynamics shape decisions (49, 50). Moreover, drivers of deforestation are mediated by local institutions and governance conditions that were not modeled, but are of immediate concern including in the DRC (28, 31).

Intensification outcomes are also shaped by changes in agricultural prices and demand. Although our model was based on averages of current prices and did not model future prices or demand endogenously, we considered several macroeconomic contexts. These ranged from increased commodity prices due to projected increases in population growth and oil prices (39) to price decreases as a result of market flooding (51) that would discourage expansion and/or allow agricultural lands to fallow. The three macroeconomic contexts, however, all suggested that increased agricultural rents under intensification would exceed forest rents, unless matched by escalating conservation incentives.

The relative rents between agriculture and forests are further influenced by crop selection and their land requirements. We targeted commodities proposed for intensification in the DRC, all of which are land-intensive (e.g., cereals; 52). Due to data paucity the model did not consider the full diversity of intercropping practices, which crops would be most appropriate at different sites, or the role of nonforest ecosystems. We did not target export crops, as these are currently absent, and our model suggests that coffee production, for example, is not profitable compared with cassava production for domestic markets, largely because of low yields (53), and high transport costs (Fig. S1). Should an export sector emerge, supported by improvements in transport and marketing (28, 31), an annual \$5/tCO_2 incentive is even less likely to match future agricultural rents (cf. 29, 30).

Forest rents and deforestation pressures are also shaped by which natural resources are exploited. Our model did not include nontimber forest products (NTFPs), as their use and commercialization in the DRC vary considerably and remain poorly quantified (54). Where NTFPs are significant to local livelihoods, they could increase forest rents and lower the incentives needed to compensate for agricultural rents, although because many NTPFs are common pool resources, they might not represent an incentive for farmers to halt deforestation. Conversely, reliance on NTFPs and fuel wood could also increase conservation incentives needed to discourage forest degradation (55). Despite a moratorium on new industrial logging, illegal logging remains prevalent and licensed small-scale logging is legal (56), but data are lacking.

Conclusion

The relationship between agricultural intensification and land sparing for conservation in tropical developing countries is dubious. Our conceptual framework, supported by the illustrative model of the DRC, highlights how conservation policies that promote intensification anticipating automatic long-term forest conservation and emissions reductions may face unintended outcomes.

Conservation policies that overlook future agricultural rents may fail to promote long-term conservation. Curiously, conservation policies that promote or impose an intensification agenda on extensive farmers may actually spur future agricultural expansion (20). While our model was illustrative, rather than predictive, and should not be overinterpreted (21), it highlights the possible impacts of agricultural intensification to long-term tenability of conservation incentives such as REDD+, and highlights under-investigated issues such as the importance of recurring conservation incentives and viability of financial versus nonfinancial incentives. Agricultural policy must further account for a range of other interacting factors, including impacts on livelihoods and food security (15), and on- and off-site environmental impacts (8, 22), including carbon stocks (12) and noncarbon greenhouse gasses (17). However, there remain significant gaps between our scientific understandings of the complexity of agricultural technologies and the associated policies (11). As suggested by this analysis, there are equally gaps in our understanding of how conservation incentives will compete with future agricultural rents, with profound implications for long-term conservation finance and policy formulation.

Methods

We used a von Thünen land versus forest rent framework (20) and modeled three scenarios involving stepwise increases in the productivity of key crops in the DRC. All monetary values were expressed in 2010 US dollars.

Agricultural rent. If the agricultural rents exceed forest rents, agricultural expansion into forest is expected. The agricultural land rent (r_a) is

$$r_a = p_a y_a - w l_a - q k_a - \nu_a d,$$

where p_a is the price of agricultural production, y_a is the yield per hectare, l_a and k_a are the labor and capital inputs needed per hectare, w and q are the wages and annual capital costs, v_a is the cost of transport of agricultural products per kilometer, and d is the distance from farm to market. Price of each crop was estimated as the average from 2003 to 2008 (34). Labor requirements were set at 183 man days per hectare for cassava and 90 for maize (57). We assumed the minimum wage in DRC (58) and no capital inputs. Fertilizer use was assumed at three bags of urea per hectare at US \$100 per bag. Because current production at the forest fringe largely corresponds to subsistence production (33), we set transport costs to zero. However, under the intensification scenarios, transport costs were applied to excess production destined to market.

Forest rent. The forest land rent (r_f) is:

$$r_f = (p_t y_t - w l_t - q k_t - \nu_t d) + p_{REDD},$$

where p_t is the timber price, y_t is the maximum sustainable yield of timber per ha, l_t and k_t are the labor and capital needed to cut and process the timber, v_t is the unit cost to transport timber, and p_{REDD} represents the total REDD+ incentive using a price per ton of CO_2 (p_{CO2}) and a spatially explicit estimation of the potential tons emitted. The price of timber was averaged from timber exports values and quantities from 2008 to 2010 (36). The volume of sustainable yield of timber per hectare was taken to be 0.5 m^3/y (59). Conservatively, we assumed that labor and capital costs were zero. Transport costs to the port of export were applied to potential benefits from logging (Fig. S1*D*). Domestic timber sales were not modeled, assuming that these benefits were of a similar magnitude to the costs of land clearing. In general, landholders' agricultural conversion decisions will be governed by the expected net present value of the sum of rents due to agriculture and forest conservation subject (B), *inter alia*, to the trajectories of the price of the agricultural outputs and REDD+ payments:

$$Max\ \ B = \int_{t=0}^{T} F_A(\alpha_a r_a + (1-\alpha_a) r_f) e^{-rt} dt,$$
$$\text{subject to}: \ \ p_{REDD}(t), p_a(t)$$

where F_A is the area owned by the landholder, α_a is the proportion of area allocated to agriculture, r is the discount rate, and T is the time horizon.

Transport costs. Market accessibility maps were developed using GIS, considering time to travel across each map raster cell (resolution of 0.92 km per cell), unit cost of time and distance traveled, capacity of transportation, and fixed costs (60). Transport by truck in tracks, roads, and motorways, by boat in inland waters, and by train were considered (Table S2). The distance to cities with more than 150,000 habitants was estimated for goods traded in the national market (Fig. S1*C*). Distance to ports was estimated for export goods (Fig. S1*D*).

Carbon emissions. REDD+ payments were estimated from potential CO_2 emissions from forest conversion into agriculture. p_{REDD} was the result of multiplying emissions per hectare by the price per ton of CO_2. Primary and secondary forest coverage was obtained from Hansen et al. (61). We estimated potential emissions from carbon aboveground, belowground, and in soil and dead organic matter. GIS maps of aboveground forest biomass were obtained from Ruesch and Gibbs (62). Biomass was expressed as tons of carbon per hectare, using a 0.49 carbon fraction of biomass (63, 64). Belowground carbon was estimated using Intergovernmental Panel on Climate Change (2006) ratios for tropical forests, applied to the aboveground carbon maps. IPCC tables 2.3 and 2.2 (63, 64) were used to estimate carbon stored in soil and dead organic matter. Soil organic carbon for agricultural areas was corrected using management factors from IPCC table 5.5 (63, 64). Factors of reductions in soil carbon content were only used for areas where no fertilizer or manure was applied (65). All carbon estimates were expressed as tons of carbon dioxide per hectare. Emissions due to increased fertilizer use were not accounted for.

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1. Kshatriya M, Sills E (2010) *Global Database of REDD+ and Other Forest Carbon Projects* (Center for International Forestry Research, Bogor, Indonesia).
2. Cerbu GAA, Swall BM, Thompson DY (2011) Locating REDD: A global survey and analysis of REDD readiness and demonstration activities. *Environ Sci Policy* 14(2): 168–180.
3. Miles L, Kapos V (2008) Reducing greenhouse gas emissions from deforestation and forest degradation: Global land-use implications. *Science* 320(5882):1454–1455.
4. Angelsen A, Kaimowitz D, eds (2001) *Agricultural Technologies and Tropical Deforestation* (CABI, Wallingford, UK).
5. Green RE, Cornell SJ, Scharlemann JPW, Balmford A (2005) Farming and the fate of wild nature. *Science* 307(5709):550–555.
6. DeFries R, Rosenzweig C (2010) Toward a whole-landscape approach for sustainable land use in the tropics. *Proc Natl Acad Sci USA* 107(46):19627–19632.
7. Ghazoul J, Koh LP, Butler RA (2010) A REDD light for wildlife-friendly farming. *Conserv Biol* 24(3):644–645.
8. Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. *Proc Natl Acad Sci USA* 108(50):20260–20264.
9. Shively GE, Pagiola S (2004) Agricultural intensification, local labor markets, and deforestation in the Philippines. *Environ Dev Econ* 9(2):241–266.
10. Lambin EF, Meyfroidt P (2011) Global land use change, economic globalization, and the looming land scarcity. *Proc Natl Acad Sci USA* 108(9):3465–3472.
11. Pirard R, Belna K (2012) Agriculture and deforestation: Is REDD+ rooted in evidence? *For Policy Econ* 21:62–70.
12. Ziegler A, et al. (2012) Transitions in SE Asia: Great uncertainty and implications for REDD+. *Glob Change Biol* 18(10):3087–3099.
13. Forest Carbon Partnership Facility (2012) *Participating Countries Readiness Proposals* (World Bank, Washington, DC).
14. Indonesia UN-REDD (2010) *Indonesia National Strategy for the Reduction of Emissions from Deforestation and Forest Degradation Draft 1 Revised* (United Nations REDD Programme, Geneva, Switzerland).
15. Van Vliet N, et al. (2012) Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: A global assessment. *Glob Environ Change* 22(2):418–429.
16. Ewers EM, Scharlemann JPW, Balmford A, Green RS (2009) Do increases in agricultural yield spare land for nature. *Glob Change Biol* 15(7):1716–1726.
17. DeFries RS, Rudel T, Uriarte M, Hansen M (2010) Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nat Geosci* 3: 178–181.
18. Rudel TK, et al. (2009) Agricultural intensification and changes in cultivated areas, 1970-2005. *Proc Natl Acad Sci USA* 106(49):20675–20680.
19. Morton DC, et al. (2006) Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proc Natl Acad Sci USA* 103(39):14637–14641.
20. Angelsen A (2010) Policies for reduced deforestation and their impact on agricultural production. *Proc Natl Acad Sci USA* 107(46):19639–19644.
21. Fischer J, et al. (2011) Conservation: Limits of land sparing. *Science* 334(6056):593.
22. Balmford A, Green R, Phalan B (2012) What conservationists need to know about farming. *Proc Biol Sci* 279(1739):2714–2724.
23. Perfecto I, Vandermeer J (2010) The agroecological matrix as alternative to the land-sparing/agriculture intensification model. *Proc Natl Acad Sci USA* 107(13):5786–5791.
24. Geist HJ, Lambin EF (2002) Proximate causes and underlying driving forces of tropical deforestation. *Bioscience* 52(2):143–150.
25. Boserup E (1965) *The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure* (Allen & Unwin, London).
26. Corbera E, Schroeder H (2010) Governing and implementing REDD. *Environ Sci Policy* 14(2):89–99.
27. Corbera E, Pascual U (2012) Ecosystem services: Heed social goals. *Science* 335(6069): 655–656, author reply 656–657.
28. DRC Ministry of Agriculture, Ministry of Rural Development, Ministry of Environment Nature Conservation and Tourism & REDD Coordination Unit (2010) *Document D'Orientation: Programme REDD+: Reduction de L'Impact de L'Agriculture de Subsistence sur la Foret* (Government of the Democratic Republic of Congo, Kinshasa, Democratic Republic of Congo).
29. Butler RA, Koh LP, Ghazoul J (2009) REDD in the red: Palm oil could undermine carbon payment schemes. *Cons Lett* 2(2):67–73.
30. Venter O, et al. (2009) Harnessing carbon payments to protect biodiversity. *Science* 326(5958):1368.
31. Laporte N, et al. (2007) *Reducing CO2 Emissions from Deforestation and Degradation in the Democratic Republic of Congo* (Woods Hole Research Center, Falmouth, MA).
32. Harris NL, et al. (2012) Baseline map of carbon emissions from deforestation in tropical regions. *Science* 336(6088):1573–1576.
33. United Nations Environment Programme (2010) *Université D'été REDD: Classification des Causes de Déforestation par Province* (United Nations Environment Programme, Kinshasa, Democratic Republic of Congo).
34. DRC Ministry of Environment Nature Conservation and Tourism (2010) *Democratic Republic of Congo Readiness Plan for REDD 2010-2012* (Government of the Democratic Republic of Congo, Kinshasa, Democratic Republic of Congo).
35. Kasulu V (2010) *The Early-Action REDD+ Programmes from the DRC* (Ministry of Environment, Nature Conservation and Tourism, Kinshasa, Democratic Republic of Congo).
36. Food and Agriculture Organization Statistics Division (FAOSTAT) (2010) *Crops* (Food and Agriculture Organization of the United Nations Statistics, Rome).
37. Olasantan F, Lucas E, Ezumah H (1994) Effects of intercropping and fertilizer application on weed control and performance of cassava and maize. *Field Crops Res* 39(2–3):63–69.
38. International Institute for Tropical Agriculture (ITTA) (2009) *Cassava* (International Institute for Tropical Agriculture, Idaban, Nigeria).
39. Organization for Economic Co-operation and Development (OECD), Food and Agriculture Organization (FAO) (2012) *Agricultural Outlook 2012-2021* (OECD Publishing & FAO, Rome).
40. Diaz D, Hamilton K, Johnson E (2011) *State of the Forest Carbon Markets 2011: From Canopy to Currency* (Ecosystem Marketplace & Forest Trends, Washington, DC).
41. Tol R (2008) The social cost of carbon: Trends, outliers and catastrophes. *Ecol Econ* 2: 2008–20025.
42. Naidoo R, Iwamura T (2007) Global-scale mapping of economic benefits from agricultural lands: Implications for conservation priorities. *Biol Conserv* 140(1–2):40–49.
43. Brazil Ministry of Environment (2012) *ProAmbiente* (ProAmbiente, Porto Alegre, Brazil). Available at http://www.proambiente.cnpm.embrapa.br/index.php.
44. Blom B, Sunderland T, Murdiyarso D (2010) Getting REDD to work locally: Lessons learned from integrated conservation and development projects. *Environ Sci Policy* 13(2):164–172.
45. Angelsen A, Kaimowitz D (1999) Rethinking the causes of deforestation: Lessons from economic models. *World Bank Res Obs* 14(1):73–98.
46. Pascual U, Barbier EB (2006) Deprived land-use intensification in shifting cultivation: The population pressure hypothesis revisited. *Agric Econ* 34(2):155–165.
47. Mendelsohn R (1994) Property rights and tropical deforestation. *Oxf Econ Pap* 46(5): 750–756.
48. Pichón FJ (1997) Colonist land-allocation decisions, land use and deforestation in the Ecuadorian Amazon frontier. *Econ Dev Cult Change* 45(4):707–744.
49. Grepperud S (1997) Poverty, land degradation and climatic uncertainty. *Oxf Econ Pap* 49(4):586–608.
50. Rudel TK, Horowitz B (1993) *Tropical Deforestation: Small Farmers and Land Clearing in the Ecuadorian Amazon* (Columbia Univ Press, New York).
51. Hazell P, Wood S (2008) Drivers of change in global agriculture. *Philos Trans R Soc Lond B Biol Sci* 363(1491):495–515.
52. López R Agricultural intensification, common property resources and the farm-household. *Environ Resour Econ* 11(3–4):443–458.
53. Monfreda C, Ramankutty N, Foley JA (2008) Farming the planet: 2. *Global Biogeochem Cy* 22(1):GB1022.
54. Hoare AL (2007) *The Use of Non-Timber Forest Products in the Congo Basin: Constraints and Opportunities* (Rainforest Foundation, New York).
55. Fisher B, et al. (2011) Implementation and opportunity costs of reducing deforestation and forest degradation in Tanzania. *Nature Clim Change* 1(3):161–164.
56. Greenpeace (2012) *'Artisanal Logging' = Industrial Logging in Disguise: Bypassing the Moratorium on the Allocation of New Industrial Logging Concessions in the Democratic Republic of Congo* (Greenpeace, Washington, DC).
57. Nweke FI, Ezumah HC (1988) *Cassava as Livestock Feed in Africa*, eds Hahn SK, Reynolds L, Egbunike GN (International Institute of Tropical Agriculture Ibadan, Nigeria).
58. U.S. Department of State (2008) *DRC Human Rights Report* (US Department of State, Washington, DC).
59. Torras M (2000) The total economic value of Amazonian deforestation 1978-1993. *Ecol Econ* 33(2):283–297.
60. Farrow A, Nelson A (2001) *Accessibility Analyst, a Simple and Flexible GIS Tool for Deriving Accessibility Models* (International Center for Tropical Agriculture, Cali, Colombia).
61. Hansen MC, et al. (2008) Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data. *Proc Natl Acad Sci USA* 105(27):9439–9444.
62. Ruesch A, Gibbs HK (2008) *New IPCC Tier-1 Global Biomass Carbon Map for the Year 2000* (Carbon Dioxide Information Analysis Center, Oak Ridge, TN).
63. Intergovernmental Panel on Climate Change (IPCC) (2006) *Agriculture, Forestry and Other Land Uses, 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, Hamaya, Japan), Vol 4.
64. Feldpausch TR, Rondon MA, Fernandes ECM, Riha SJ, Wandelli E (2004) Carbon and nutrient accumulation in secondary forests regenerating on pastures in central Amazonia. *Ecol Appl* 14(4):164–176.
65. Potter P, Ramankutty N, Bennett EM, Donner SD (2010) Characterizing the spatial patterns of global fertilizer application and manure production. *Earth Interact* 14(2): 1–22.