LETTER

Lowering environmental costs of oil-palm expansion in Colombia

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Abstract

Colombia is the fifth largest producer of palm oil in the world. The country's government and oil-palm farmers association target a sixfold increase of crude palm-oil production by 2020. We model the impacts of expanding oil-palm agriculture in Colombia through a spatially explicit scenario analysis. We demonstrate that the impacts of oil-palm expansion (e.g., deforestation, conversion of natural savannahs) would be minimized by establishing new plantations on pasture lands, given the low environmental value and economic utility, and the high agricultural potential of this land use. Impacts of oil-palm expansion on beef and dairy production could be compensated by improving productivity of pasture lands elsewhere. However, the profitability of oil-palm production in these areas might suffer over the long term due to high land purchase costs.

Introduction

Industrial-scale agriculture is a key contemporary driver of deforestation in the tropics (Rudel *et al.* 2009; Laurance 2010). Rapid oil-palm expansion in Southeast Asia in particular has negatively impacted biodiversity, forests and their carbon stocks (Koh & Ghazoul 2008; Koh & Wilcove 2008; Gaveau *et al.* 2009); but it has also brought significant economic benefits to this region and in many cases improved the livelihoods of rural communities (Rist *et al.* 2010; Lee *et al.* 2011). Due to its high profitability and the rising demand of edible oils and biofuels, oil palm is expected to expand across the neotropics, which could result in high environmental costs in regions such as the Amazon (Butler & Laurance 2009) or the Orinoco Savannah. Land-use decisions in these regions therefore require careful considerations of the trade-offs between environmental (e.g., forest conservation) and agroeconomic priorities (e.g., food security, economic development).

Commercial oil-palm plantations in Southeast Asia have contributed to deforestation, biodiversity loss, and greenhouse gas emissions (Sodhi *et al.* 2010; Koh *et al.* 2011). The conversion of ~880,000 ha of Southeast Asia's peat-swamp forests to oil palm by the early 2000s resulted in the loss of ~140 million metric tons (Mt) of aboveground biomass carbon and annual emissions of ~4.6 Mt of belowground carbon from peat oxidation (Koh *et al.* 2011). Emissions from oil-palm expansion could be reduced if new plantations are established on degraded lands (e.g., abandoned agricultural land; Gibbs *et al.* 2008). However, degraded lands might not be economically viable in areas of poor soil conditions, nor socially acceptable where rural livelihoods depend on them

(Fairhurst & McLaughlin 2009; Fairhurst *et al.* 2010).Expansion of oil-palm agriculture might also intensify land-use conflicts with other food production systems and affect the food security of producing countries, unless these trade-offs are explicitly assessed prior to expansion (Thirtle & Piesse 2009; Godfray *et al.* 2010).

Colombia is the fifth largest producer of oil palm in the world, having a planted area of ~360,500 ha and annual production of ~802,000 tons of crude palm oil (CPO) in 2010 (Fedepalma 2010). The Colombian government has recently identified oil palm as a key economic sector and a priority for national agricultural development and the country's biofuel program (MADR 2006, 2008). The Colombian oil-palm farmers association (FEDEPALMA) plans to maintain Colombia's position as the largest palm-oil producer in South America by increasing annual CPO production sixfold to ~3.5 Mt by 2020 (see http://www.fedepalma.org/vision.htm, accessed 16 March 2012).

In Colombia, concerns about the oil-palm sector has been mainly associated with human rights violations (Mingorance 2006), rather than environmental impacts (Rodríguez-Becerra & Hoof 2005). The environmental and economic costs of oil-palm expansion in the country remain poorly understood. The main objectives of this article are: (1) to model the trade-offs and impacts of the projected expansion of oil-palm agriculture in Colombia with respect to food security, natural ecosystems, biodiversity, and biomass carbon stocks under different scenarios; and (2) to identify an "optimal" (low impact) oil-palm expansion development pathway that reconciles these priorities. We do not include social dimensions of analysis such as human rights, but our approach implicitly recognizes that the issues of human rights and social well-being are inextricably tied to equitable access to food and natural resources.

Methods

Model scenarios of oil-palm expansion

Using a spatially explicit model, we evaluated the potential impacts of oil-palm expansion under five scenarios: (1) production-oriented, which maximizes oil-palm productivity, (2) agroindustrial development, which prioritizes food security, (3) ecosystem protection, which prioritizes the conversion of human-modified and least profitable land use and cover, (4) carbon conservation, which prioritizes the conservation of carbon-rich vegetation, and (5) a hybrid scenario, which simultaneously considers all the aforementioned priorities (Table 1).

Spatial database

We generated a comprehensive environmental and socioeconomic spatial database for Colombia by overlaying geographic information systems (GIS) data layers of:

Land use and land cover

Data derived from a continental, coastal, and marine ecosystems data set for Colombia (IDEAM *et al.* 2007). This data set is based on 30 m-resolution satellite imagery (Landsat TM and ETM+) for 2001, and it is the best available and most widely used land use and land cover data set for Colombia. We reclassified its 19 land cover classes into nine main classes: (1) forests, (2) natural grasslands and shrublands, (3) secondary vegetation, (4) mosaics (heterogeneous mixes of natural vegetation and agriculture), (5) annual crops, (6) perennial crops, (7) pasture lands, (8) forest plantations, and (9) human disturbed areas and other ecosystems (Table S1). Additionally, we included the distribution of oil-palm plantations of year 2008 as a 10th category by digitizing plantation thematic maps (scale 1:1,500,000) published by Fedepalma (2009).

Above- and belowground biomass carbon

Data taken from the IPCC Tier-1 global biomass carbon map for the year 2000 (Ruesch & Gibbs 2008). This 1 km-resolution carbon map includes 17 biomass carbon classes for Colombia.

Crop yield potentials

Calculated for oil palm, sugarcane, rice, and maize based on a spatially explicit database for crop suitability (Fischer *et al.* 2002). This database classifies areas according to a suitability index, which is a standardized measure that reflects the suitability make-up for rain-fed crops, relative to a global maximum yield, on the basis of soil, climate, and terrain conditions. We derived an expected yield factor for each of the nine suitability classes of the index by calculating the midrange attainable yield within each suitability class (Table S2). Crop yield potential was calculated by multiplying the yield factor with the maximum attainable yield reported for the tropics (Table S3) (FAO 2009).

Land profitability

We generated a new land-cover profitability map by assigning estimated per-hectare profitability values to the annual-crop, perennial-crop, pasture lands, and mosaic land-cover classes of the IDEAM *et al.* (2007) map. Land-cover profitability was based on local revenue and cost

Table 1 Scenarios constructed for modeling the expansion of oil-palm agriculture in Colombia

Scenario	Expansion rule[a]
Single-priority scenarios	
Production-oriented scenario	Expansion prioritized to areas with high yield potential for oil palm, and well located (in proximity to road networks and existing oil-palm plantations)
Agroindustrial development	Favoring conversion of areas with low yield potential for rice, maize, and sugarcane, minimizing impacts on food production capacity
Ecosystem protection	Expansion prioritized to areas highly modified and low annual profitability (of current land uses), minimizing conversion of natural areas
Carbon conservation	Expansion prioritized to areas with low levels of above- and belowground carbon stocks
Hybrid approach (Multipriority scenario)	A combined scenario of all issues addressed in the single-priority scenarios, thus favoring expansion on highly modified areas, with high oil-palm yield potential, low suitability for food production, low biomass carbon content, and in proximity to road network and other oil-palm plantations

[a]For each scenario, the model selects and converts first polygons with high a conversion-priority index, and then progressively converts those with lower priority. Conversion-priority indices are based on individual attributes (e.g., distance to roads). See "supplementary methods S2" for a detailed account of the methods used to calculate all conversion-priority indices.

data for 27 agricultural land uses at the municipality level (see supplementary methods S1).

Basic geographical information layers

Elevation map, municipalities boundaries, map of protected areas, and map of special territories of minorities' communities (SIG-OT 2006).

Finally, we also included two geographical determinants that influenced the location of oil-palm expansion in our production-oriented scenario and, by extension, the hybrid scenario. In these scenarios, expansion was more likely in areas close to (2) existing road networks, as defined by SIG-OT (2006), or (2) existing oil-palm plantations, as defined by the FEDEPALMA maps (Fedepalma 2009). To include this distance factor in the spatial database, we created GIS buffer areas every 25 km around roads and plantations, for a total of seven categories: 0–25, 25–50, 50–75, 75–100, 100–125, 125–150, and >150 km. These spatial determinants help ensure a more realistic simulation of oil-palm expansion that takes into account the agroeconomic viability of new plantations (Sloan & Stork 2010).

After intersecting all GIS layers, we obtained a data set comprising 572,473 land-use and land-cover polygons covering a total area of ~111.97 million ha; each polygon has an attribute value for each input GIS layer. Our simulation of oil-palm expansion excludes those polygons with missing spatial data or unsuitable for oil palm due to biophysical or institutional factors. Unsuitable areas include urban areas, barren lands, bedrock outcrops, areas permanently covered with ice, water bodies, coastal ecosystems, national parks and other protected areas, existing oil-palm plantations, areas not suitable or with very marginal suitability limited for oil palm, and areas above 1,000 m elevation as oil palm can only be produced commercially in lowland areas (Corley & Tinker 2003). Of the 572,473 total polygons, 381,503 were excluded, representing ~53.3 million ha or 47.6% of the national land area.

Simulating oil-palm expansion

For every scenario, the model simulates oil-palm expansion by progressively converting the land-cover polygons of our spatial database for Colombia. At each stage of the simulation, polygons are selected according to a conversion-priority index constructed from their GIS attributes and the narratives of the scenario (Table 1 and supplementary methods S2). Thus, each polygon was assigned an individual conversion-priority index for each of the five scenarios.

We iterated the simulations of oil-palm expansion 10,000 times for every scenario and assessed outcomes in terms of (1) the total area converted oil palm, (2) the area of natural ecosystems converted (i.e., forests, natural grasslands and shrublands, secondary vegetation), (3) the area of agricultural land covers converted (i.e., mosaics, annual crops, perennial crops, pasture lands), (4) the amount of biomass carbon lost, (5) the reduction in rice and maize production capacity, and (6) in sugarcane production capacity (Table S4). Additionally, we assessed changes in forest bird diversity, based on projected land-use changes for each scenario, by applying the matrix-calibrated species-area model proposed by Koh & Ghazoul (2010a) (see supplementary methods S3).

Results

Based on our data, a total of 58.6 million ha of land in Colombia have at least a marginal suitability for oil palm.

Table 2 Simulation outcomes of the expansion of oil-palm agriculture in Colombia for a production target of 15 Mt of fresh fruit bunches per year (equivalent to 3.5 Mt/year CPO), as set by the Colombian oil-palm producers association for 2020

Scenario	Oil -palm area expansion (1,000 ha)	Original land use before simulated conversion (1,000 ha)					Biodiversity losses[b]	Biomass carbon loss (Mt)[c]	Production capacity losses (Mt/year)[d]	
		Forests	Shrublands and grasslands	Secondary vegetation	Agricultural land[a]	Pasture lands			Sugarcane	Rice/ Maize
Production-oriented	727.8 (±3.80)	258.69 (±3.53)	15.66 (±0E-12)	129.56 (±1.03)	81.19 (±0.16)	242.74 (±1.17)	0.08% (±0.04)	4.36 (±4.9E-02)	38.56 (±0.3)	1.05 (1.5E-03)
Agroindustrial development	919.57 (±2.92)	794.78 (±2.72)	0.92 (±6.0E-14)	120.64 (±1.28)	1.82 (±2.6E-13)	1.41 (±1.5E-13)	0.25% (±0.13)	15.80 (±4.0E-02)	0.03 (±1.3E-03)	0.03 (±7.2E-04)
Ecosystem protection	1′218.87 (±2.19)	0.00 (±0.00)	0.00 (±0.00)	0.00 (±0.00)	22.02 (±2.4E-12)	1′196.84 (±2.19)	0.00% (±0.00)	2.71 (±8.4E-03)	48.06 (±0.2)	3.00 (±1.1E-13)
Carbon conservation	1,568.08 (±1.87)	379.50 (±0.20)	92.69 (±0.11)	158.25 (±0.35)	260.54 (±0.80)	677.11 (±1.66)	0.12% (±0.06)	0.55 (±7.5E-04)	56.27 (±7.6E-02)	1.93 (±4.5E-03)
Hybrid[e]	1′073.46 (±0.24)	0.00 (±0.00)	0.00 (±0.00)	0.00 (±0.00)	83.06 (±0.24)	990.41 (±9.6E-11)	0.00% (±0.00)	1.63 (±9.6E-05)	40.70 (±1.8E-02)	1.50 (±1.1E-03)

Mean values and standard deviation of each outcome variable are shown for 10,000 modeling runs.

[a] Includes annual- and perennial-crops, as well as mosaic lands.

[b] Proportion of species (forest-dwelling birds) lost due to projected land use. Calculations based on the matrix-calibrated species-area model by Koh & Ghazoul (2010), see supplementary methods for model description and assumptions.

[c] Does not include carbon uptake and fixation by oil-palm plants.

[d] As a guide to the reader, Colombia's average annual production of sugarcane was 38.1 Mt/year, and 4.1 Mt/year for rice and maize between 2000–2009.

[e] Multipriority scenario: a combined approach of all other single-priority scenarios. All priorities are equally weighted.

The vast majority of this area (~80%) is currently under natural vegetation covers: forest (~70%), shrubland (~0.2%), and grasslands (~9%). Most of the remaining area (~8.8 million ha) is agricultural land, of which ~86% is cultivated pasture lands used for ranching and dairying. Thus, it is likely that the planned expansion of oil palm will impact Colombia's natural ecosystems, agropastoral production or both.

In the production-oriented scenario, whereby expansion would be directed at the most productive lands for oil palm, 730,000 ha of land would be required to meet Colombia's 2020 oil-palm production target (Table 2). The conversion of this area would entail the loss of ~4.4 Mt C of biomass carbon, a considerable amount compared to other scenarios (Table 2). On the other hand, the carbon conservation scenario would substantially reduce biomass carbon losses relative to the production-oriented (87% decrease to 0.55 Mt), but it would also require double the land as production-oriented to reach the same production level (Figure 1). Indeed, the carbon conservation scenario entailed the greatest loss to agricultural land of all scenarios with the conversion of 260,000 ha of annual crops, perennial crops, and mosaics (~10% of the country's total pasture and agricultural land) with a production worth ~405 million USD at 2010 prices. In addition, it reduced agricultural production capacity by 2 Mt/year of maize and rice and 56 Mt/year of sugarcane (Table 2, Figure 1).

Expanding oil palm under the agroindustrial development scenario would greatly reduce impacts on rice/maize and sugarcane production capacity to only 0.06 Mt/year in total, or 99.9% less than the Carbon scenario. However, this scenario would also result in significant trade-offs in terms of Colombia's natural ecosystems, biodiversity, and carbon emissions. It entails the conversion of 800,000 ha of forest cover, the local extirpation of 0.23% species equivalent to three species of forest birds, the highest of all scenarios, and the loss of 15.80 Mt of carbon (Table 2)

Contrarily, the ecosystem protection scenario resulted in no conversion of natural ecosystems or biodiversity losses, and reduced biomass carbon losses by ~82% (2.71 Mt) compared to the agroindustrial development scenario (Table 2). Yet, the ecosystem protection scenario also resulted in the conversion of 1.2 million ha of pasture lands as well as a dramatic decrease in Colombia's rice/maize and sugarcane production capacity by up to 3 and 48 Mt/year respectively, or 75 and 126%[1] of average annual production levels over 2000–2009 (FAO 2009).

Every single-priority scenario resulted in significant negative trade-offs. Such trade-offs can be mitigated by explicitly incorporating multiple priorities into planning, that is, the hybrid scenario. Such a scenario, which equally prioritized all issues addressed in this exercise (i.e., oil-palm production, food security, carbon

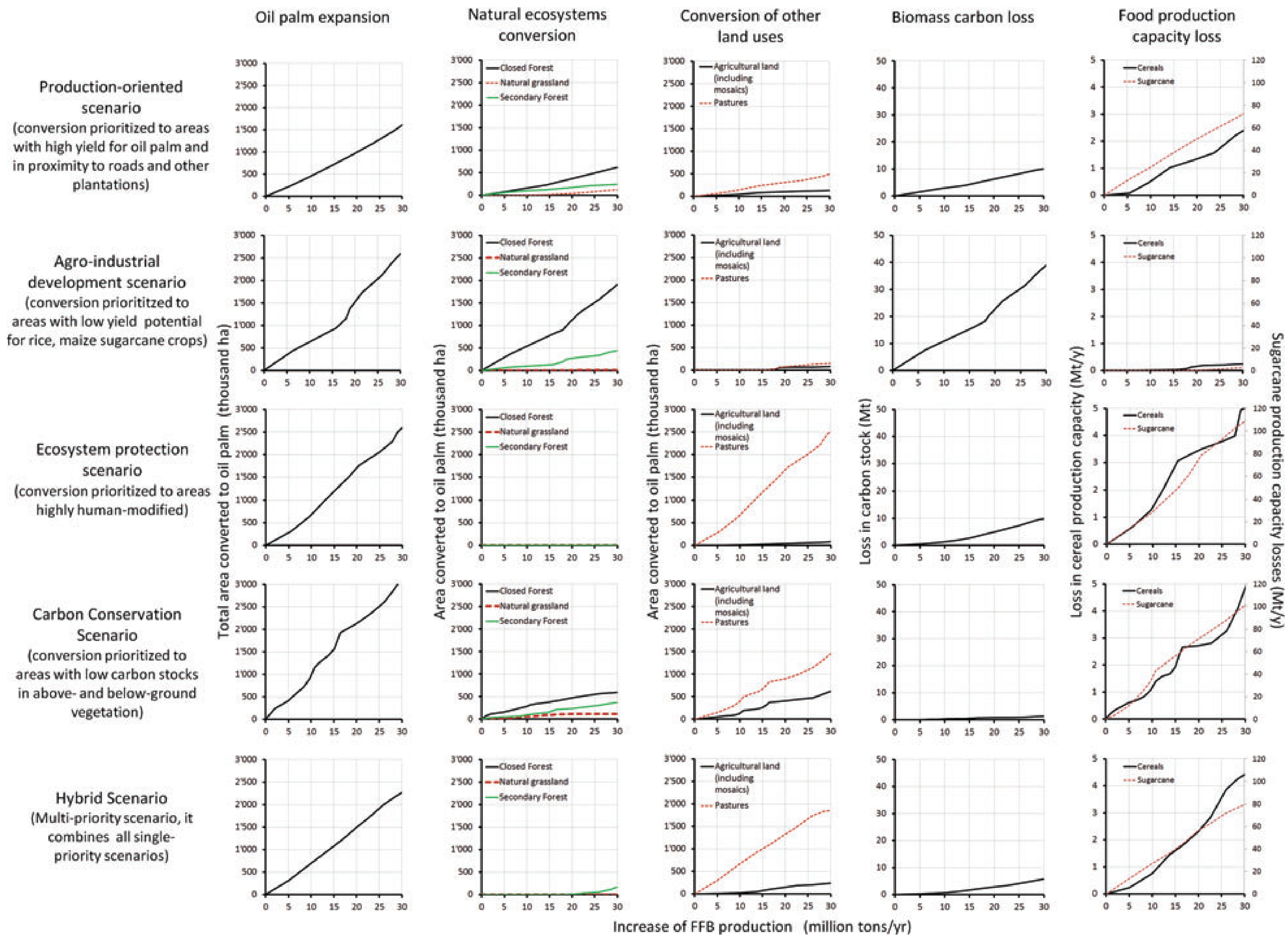

Figure 1 Modeling outcomes of the expansion of oil-palm agriculture in Colombia under five scenarios that prioritized different levels of oil-palm production, food security, natural ecosystem protection, and biomass carbon conservation (see Tables 1 and S4 for a detailed description of scenarios and outcomes). The production target set by the Colombian oil-palm sector is 15 Mt of fresh fruit bunches (FFB) per year by 2020 (equivalent to 3.5 Mt/year CPO).

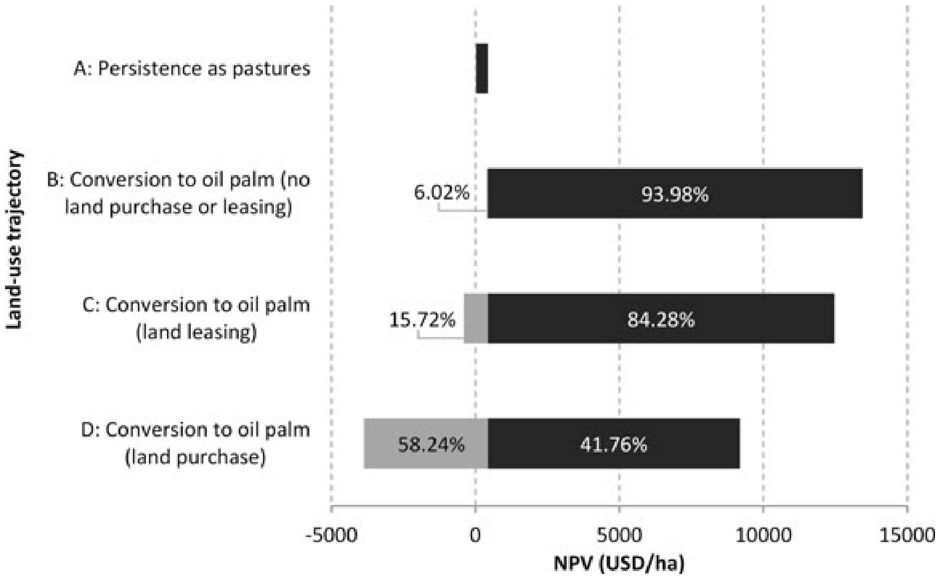

Figure 2 Projected profitability range of maintaining pastures or developing oil-palm agriculture on the pasture lands considered for conversion under the hybrid scenario. We considered three types of oil-palm development with regards to land ownership: (B) conversion led by current land owners (i.e., no land purchase or leasing); (C) companies lease land to develop plantations; and (D) conversion led by companies through the purchase of land. The range of net present values (NPV) where oil-palm development is less profitable than ranching is depicted in grey, whereas the black shading represents the range of NPV where oil-palm is more profitable than ranching. The area of land within each of the grey and black categories is expressed as a percentage of the total land converted in the hybrid scenario. NPV were calculated individually for each polygon over a 25-year period using 2010 prices and costs, and a discount rate of 10%. Profitability of maintaining lands in pasture (A) is based on the annual profitability model (see supplementary methods S2) and assumes a constant annual production and economic return over the period considered. Profitability of converting these pasture lands to oil-palm (B,C, and D) was modeled following Butler *et al.* (2009), under high-yield and constant price conditions (See additional methods S4 for a full description of assumptions).

emissions, and ecosystem conservation), resulted in a mix of moderate environmental and agroeconomic impacts. No conversion of natural ecosystems occurred, and the extent of new oil-palm plantation and their impacts on biomass carbon stock were both relatively low (Figure 1). Impacts on food production capacity were also reduced to some extent, though still appreciable in absolute terms (Table 2). For instance, losses in cereal (maize/rice) production capacity amounted to 1.50 Mt/year (Table 2), equivalent to a third of the average annual production between 2000 and 2009 (∼4.1 Mt/year) (FAO 2009). Pasture lands were by far the main land use converted to oil palm (Figure 1). Interestingly, future sugarcane production capacity was highly affected by oil-palm expansion in all scenarios except for the agroindustrial development scenario (Figure 1).

Discussion

Koh & Ghazoul (2010b) explored the trade-offs between future oil-palm development, forest conservation, biodiversity maintenance, carbon preservation, and food security in Indonesia. They demonstrate that the impacts of oil-palm expansion could be substantially mitigated if future development explicitly accounts for environmental and agricultural trade-offs. Such a "hybrid" approach would involve establishing oil palm on degraded lands or on agricultural areas with moderate to high yield potentials for oil palm, low biomass carbon content, and low suitability for rice cultivation. Our findings corroborate many of the trade-offs observed in the Indonesian case (Koh & Ghazoul 2010), but also feature peculiarities of the neotropical context. As in Indonesia, the trade-offs in Colombia are largely forest conservation versus food production, biomass carbon conservation versus maintenance of agricultural land, and oil-palm production versus ecosystem conservation. However, the Colombian context also featured extensive pasture lands that can accommodate the expanding oil palm in the hybrid scenario. Thus, while quadrupling Colombia's oil-palm production will inevitably have some negative effects, regardless of how many priorities feature in its planning, pasture lands may buffer the conversion of natural and

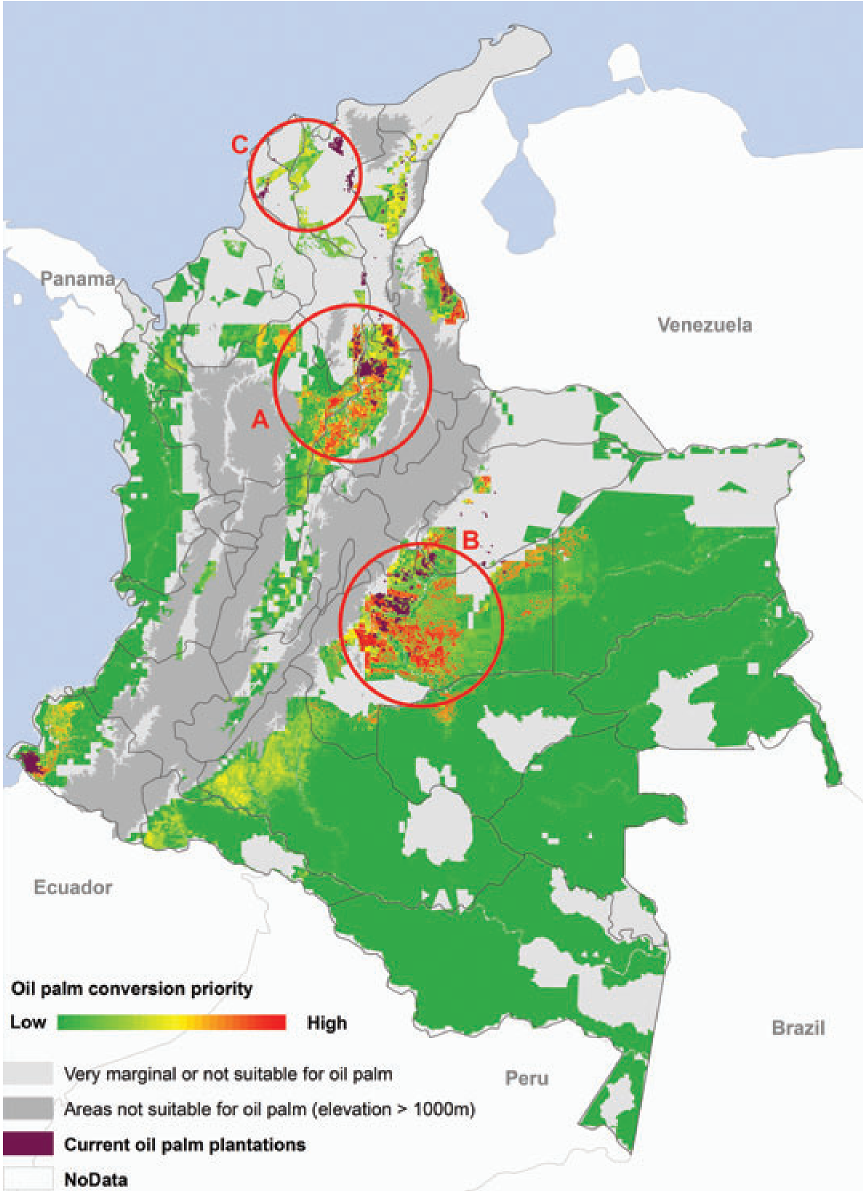

Figure 3 Oil-palm conversion priority map under the hybrid scenario (10,000 runs). Yellow and red clusters represent high intervened areas with low biomass carbon content, high oil-palm yield potential and low yield potential for sugarcane, maize, and rice. Priority regions are circled in red: (A) the upper Magdalena Valley and (B) the western Altillanura. In our analysis, some of the already established plantations are located in areas with very marginal suitability for oil palm (C). This is due to the fact that the yield potential maps used in this study are only for rain-fed crops and do not include irrigation practices, which are common in relatively dry areas as the northern Caribbean coastal plains.

agricultural land and avert major impacts to a degree not possible in the Indonesian case.

Under the hybrid scenario, the majority of pasture lands that would be converted to oil palm is currently used for ranching. Conversion of these pasture lands would represent the loss of ∼1–2% of the country's annual beef and milk production (worth ∼9.48 million USD).[2] This loss in dairy production could potentially be offset by increasing the production efficiency of remaining pasture lands by ∼0.002 t beef/ha,[3] which would avoid the displacement of ranching to natural ecosystems to meet demand. Such efficiency improvements might be achieved by increasing the carrying capacity of the land through the use of better grass varieties and cattle breeds, as well as improving livestock nutrition with complementary fodder. These improvements would admittedly increase production costs. Another potential cost-related barrier for adopting the hybrid scenario concerns land prices and establishment costs. These considerations would be most relevant for farmers who currently do not own land and/or have limited capital for investing in land, high-quality seeds, infrastructure, and irrigation. In ∼60% of pasture lands designated for conversion under our hybrid scenario, high land prices would render development less profitable in the long term than maintaining current ranching systems (Figure 2D). In this case, additional economic incentives would be needed to encourage oil-palm conversion in pasture lands.

Two areas stand out as the most appropriate for expanding oil-palm agriculture under the hybrid scenario: the inter-Andean Magdalena valley and the western Altillanura (Figure 3). Both regions already host clusters of plantations and have good market accessibility, factors which facilitate economies of scale (Sloan & Stork 2010). However, the country's internal conflict and drug producing and dealing activities may hinder the establishment of oil-palm plantations in these areas. Municipalities in these regions had double the national average frequency of armed confrontations between 2001 and 2009 (SIG-OT 2006), and in many of them coca cultivation has been reported over the same period (UNODC 2010).

Directing oil-palm agriculture to ranching areas could undermine the potential benefits for smallholders and poor rural communities, as long-term profits from oil-palm development might concentrate in a smaller number of beneficiaries with larger land holdings. On average, in the municipalities with suitable areas for oil palm according to the hybrid scenario, ∼35% of the farms with cattle are larger than 50 ha[4] and account for ∼70% of all ranching land.

More positive, the territories of ethnic minorities may be spared of conversion to oil palm under the hybrid scenario, as they account for only 0.6% (6,422.9 ha) of the total land required to achieve the sectors' production targets. In practice, this relatively small area doesn't need to be converted as oil palm can enter other less sensitive zones elsewhere. Many would think of this as a positive environmental outcome, as much of these territories is covered by tropical forests or other types of natural vegetation and have been important for conservation purposes (Armenteras *et al.* 2009). Equally important, this finding implies that oil-palm expansion could be achieved without compromising the land, welfare and traditional ways of these vulnerable communities, especially when considering the history of human rights violations associated to the Colombian oil-palm sector.[5] However, this could also represent a missed opportunity for development as oil palm could improve the livelihoods of these communities, of course, under the assumption that business models are explicitly designed for their benefit.

Our hybrid scenario, however efficient in accommodating oil palm while minimizing impacts on agriculture and the environment, is but a theoretical optimum and may fail to materialize without political commitment. Policies and incentives created to direct oil-palm expansion over pasture lands may have to offset the initial costs of land acquisition and/or infrastructure in order to ensure long-term profitability. However, these policies may run afoul of ranching communities, perhaps especially those where policy does not promote oil-palm expansion. Policy may also "artificially" inflate land prices for the oil-palm industry and ranchers alike, and generally prove more troublesome for politicians than simply allowing oil palm to expand on sensitive areas. Nevertheless, we believe that our analysis although not intended for accurate prediction of land-use outcomes, would contribute to a more informed discourse on future land-use options in Colombia. Finally, we emphasize that an expansion oil palm in Colombia, with relatively low environmental impacts, can be achieved due to the extent of unproductive pasture lands. Its realization depends on whether decision makers look beyond the economic dimension and incorporate multiple priorities when planning such expansion.

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Endnotes

[1]Under the ecosystem protection scenario Colombia's sugarcane production capacity is reduced by up to 48 Mt/year, which is a higher volume than the average annual production between 2000 and 2009 (∼38.1 Mt/year)

[2]In total, the production of 19'187 t of beef and 78.9 million liters of milk would be lost to the expansion of oil-palm agriculture in our hybrid scenario. The economic value of this production was calculated through our profitability models (see supplementary methods S1) and is based on 2010 prices at wholesale markets and regional production costs for the same year.

[3]The average pasture productivity in Colombia is 0.043 t beef/ha, whereas the highest productivity reported is 0.109 t beef/ha.

[4]In Colombia, the average farm size is 14.60 ha (DANE 2008)

[5]Impacts on vulnerable communities are also an issue of high concern among national and international human right organizations, due to the history of illegal land grabbing and establishment of oil-palm plantations in territories of indigenous and Afrocolombian minority communities (Mingorance 2006).

Supporting Information

Additional Supporting Information may be found in the online version of this article. The spatial database and model are available upon request.

Supplementary methods S1. Land cover profitability calculations

Supplementary methods S2. Conversion-priority index

Supplementary methods S3. Matrix-calibrated species-area model

Supplementary methods S4. Oil palm and pasture profitability calculations

Table S1. Reclassified land-cover categories

Table S2. Yield factors for oil palm, sugarcane, rice, and maize

Table S3. Maximum yields in 2008 as reported by FAO (2009)

Table S4. Outcomes evaluated when modeling oil-palm conversion for the six scenarios constructed

Table S5. Markets included and geographical scale used when compiling prices of crops' produces

Table S6. Geographical scale and equivalence used to calculate profitability of land covers

Table S7. Data sources for production costs

Table S8. Land-use composition of the land cover class mosaic for all productive regions in Colombia

Figure S1. Yield potential for oil palm, rice, maize, and sugarcane.

Figure S2. Land cover classes

Figure S3. Above- and belowground biomass carbon stocks

Figure S4. Minorities' territories and protected areas

Figure S5. Road network

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