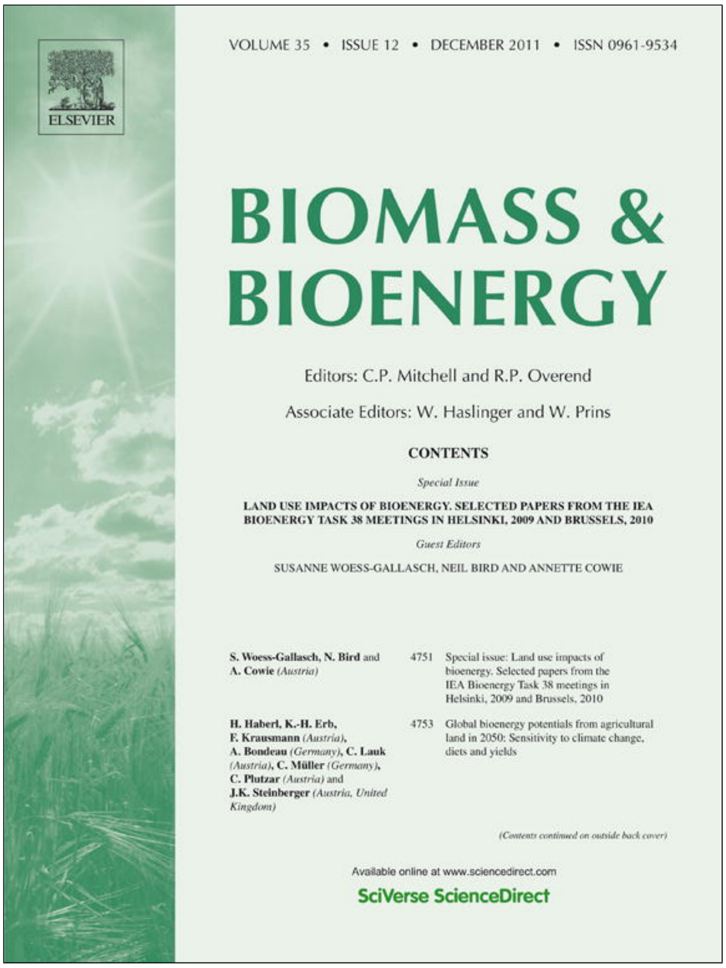
ELSEVIER
VOLUME 35 • ISSUE 12 • DECEMBER 2011 • ISSN 0961-9534
BIOMASS & BIOENERGY
Editors: C.P. Mitchell and R.P. Overend
Associate Editors: W. Haslinger and W. Prins
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Stabilizing the agricultural frontier: Leveraging REDD with biofuels for sustainable development

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ARTICLE INFO

Article history:
Received 2 August 2010
Received in revised form
9 June 2011
Accepted 14 June 2011
Available online 19 July 2011

Keywords:
REDD+
Biofuels
Reforestation
Deforestation
Sustainable development
CDM

ABSTRACT

We evaluate the potential of a proposed policy model that would explicitly link the cultivation of biofuels with forest conservation (*Biofuel + FC*) as part of the United Nations Framework Convention on Climate Change. The model postulates that a ratio of 4:1 forest conservation to biofuel cultivation be linked to proposals for reducing emissions from deforestation and forest degradation (*REDD + Biofuel*), while a ratio of 9:1 biofuel cultivation to reforestation on degraded landscape (*RDL + Biofuel*) be linked to the afforestation/reforestation component of the Clean Development Mechanism. Both biofuel production options would be limited to the cultivation of woody perennial biofuel species on low biomass landscapes in order to maximize the carbon benefits of the proposed policy model. The potential to conserve forest, avoid GHG emissions, improve carbon sequestration, and produce renewable energy are evaluated by an illustrative model for five case studies (Pará – Brazil, East Kalimantan – Indonesia, Madagascar, Colombia and Liberia). The *Biofuel + FC* policy model is then compared with three counterfactual scenarios: *REDD Alone* with no biofuel cultivation; *Biofuel Alone* with expanded biofuel cultivation in the absence of REDD and a *Most Likely* scenario where REDD and biofuel cultivation are implemented without explicit regulatory linkages. The proposed policy model would leverage forest carbon with biofuel markets, which would reduce greenhouse gas emissions and conserve biodiversity, as well as improve human welfare in developing countries, a win–win–win strategy for sustainable development.

1. Introduction

Climate change, tropical deforestation, biodiversity loss and the degradation of ecosystem services are driven by linked economic phenomena, particularly the quest for energy security, increased demand for commodities, poverty in developing countries and inadequately regulated global markets. Multiple policy and market initiatives are being proposed to address different aspects of these economic, environmental and social challenges; however, it is unlikely that any one of these initiatives will be effective – unless they simultaneously address the linkages among the drivers. For example, reducing emissions from deforestation and conversion to biofuels are both being promoted as means to stabilize the global climate; however, the expansion of biofuels may increase deforestation [1], while the economic incentives linked to forest conservation may be overwhelmed by the profitability of biofuel production [2,3]. Consequently, efforts to reduce deforestation would be more effective if they simultaneously address the expansion of biofuel cultivation,

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doi:10.1016/j.biombioe.2011.06.027

especially in regions where the agricultural frontier may expand due to the demand for biofuels.

Deforestation is responsible for ~17% of all global greenhouse gas (GHG) emissions annually [4] and the parties to the United Nations Framework Convention on Climate Change (UNFCCC) have agreed to develop a mechanism to provide incentives to tropical countries for reducing emissions from deforestation and forest degradation (REDD) [5]. Discussions have focused on general principles, carbon accounting systems, opportunity costs, appropriate scale of implementation and the organizational framework of national REDD programs [6]; however, many aspects of REDD implementation remain uncertain. Many counties have implemented programs to reduce deforestation rates by creating protected areas and improving forest management, but these measures have not been successful in reducing overall levels of deforestation [7]. Many analysts propose improving governance, arguing that mandated regulations of land-use are the best option for controlling deforestation [8]. This objective, although laudable, will be difficult to achieve over the medium-term due to the highly fluid social conditions of the agricultural frontier and the complex dynamic of national, regional and local governments [9]. The importance of economic incentives is widely recognized as essential for reducing deforestation; however, there are few convincing proposals for compensating the individuals, communities and corporations that must change their production systems to make REDD effective on the agricultural frontier [10]. Climate funds managed by the state run the risk of being bureaucratically encumbered, while project-based approaches are difficult to implement at large scales. Moreover, the positive commitment to slow deforestation must contend with sovereign decisions to optimize land-use and economic development, which are often amplified by social forces not easily controlled by governmental action [9]. In the end, REDD must compete with economically attractive alternatives to clear forest for the cultivation of biofuels, fiber, food crops and pasture [2,3]. Liquid biofuels have been selected as priority investments by governments seeking energy independence and as a response to climate change [11]. Biofuels have many advantages because they can be produced from existing crops and processing technology, displace fossil fuels in internal combustion engines, and require relatively minor modifications to the fuel distribution infrastructure. Eventually, new technologies may eliminate the dependence on liquid fuels [12,13], but over the medium-term, biofuels could provide an important part of the world's transportation energy infrastructure.

Current policies in Europe and North America favor domestic production based on corn and rapeseed, both of which offer only limited GHG emission reductions when compared to fossil fuels. Second generation technologies will displace these species eventually [14]; however, developed countries will continue to import biofuel feedstocks over the short-term as mandated levels of consumption of biofuels are increased [11], while lower production costs in developing countries favor imports over the medium-term. Emerging nations will promote the cultivation of biofuel feedstocks to benefit national economies and to supply a rapidly expanding transportation sector [15]. As demand increases, biofuel production will gravitate to the humid tropics where available land, climatic conditions, and high yielding species combined with efficient processing systems will maximize production and profitability.

The relative climate benefit of biofuel production systems depends upon the molecular composition of feedstock, yield and technology, as well as GHG emissions from cultivation and processing [2,16]. Biofuel production may cause a net increase in GHG emissions, because the expansion of feedstock cultivation will lead to the conversion of natural habitat [17]. Biofuels cause land-use change directly via the conversion of native habitat and indirectly by displacing food crops and pasture [18]. If feedstock cultivation displaces food production—without a concomitant increase in crop yield or area under cultivation—food price increases will impact impoverished populations throughout the developing world. Unless carefully planned and regulated, the expansion of biofuels could stimulate deforestation, increase GHG emissions and exacerbate global warming, the opposite of the intended purpose of replacing fossil fuels with biofuels [19].

The challenges inherent in the implementation of any REDD mechanism and the parallel threats from poorly regulated biofuel markets motivated us to examine an integrated policy model that would not only resolve these potential conflicts, but align them to create synergies that would reduce greenhouse gas emissions, conserve biodiversity and maintain ecosystem services. Moreover, resolving the conflict between biofuel cultivation and forest conservation, the proposed policy model would create new economic opportunities for developing nations, limit competition between food and biofuels and contribute to global energy security.

2. Proposed policy model: biofuel and forest carbon (Biofuel + FC)

We propose to explicitly link the cultivation of biofuel feedstocks with forest conservation and reforestation. However, an even more important provision – and a condition central to its effectiveness – is the use of carbon credits to subsidize the cultivation of biofuel feedstocks on recently deforested or other degraded landscapes.

2.1. *Forest conservation: REDD + Biofuel*

The first component of the model is an explicit link between biofuel feedstock cultivation and a binding commitment to reduce emissions from deforestation and forest degradation (REDD). Land deforested between 2000 and 2010 would be converted to biofuel cultivation and threatened forest would be designated as a matching conservation commitment. The area conserved as forest would exceed the biofuel plantation by a predetermined ratio; the amount might vary according to individual countries, but we adopt the Brazilian model of a 4 to 1 ratio of forest to cultivated land [20]. The year 2010 is used as a permanent cut-off date for eligibility to avoid creating perverse incentives to deforest landscapes, while the adoption of the year 2000 as the starting point for eligibility ensures that the initiative will be focused on the agricultural frontier where forests are most threatened and food crop production is at a minimum.

2.2. Reforestation: RDL + Biofuel

The second component of the model would promote reforestation on degraded landscapes (RDL) in areas near newly established biofuel plantations. The cultivation of biofuel feedstocks on degraded lands avoids impacts on food production, because these lands are usually not under agricultural cultivation. Habitat restoration brings multiple benefits in the form of carbon storage, the provision of ecosystem services and the conservation of biodiversity. In the case studies, we define a degraded landscape as land deforested prior to 2000 that is covered with low productivity cultivated pasture or secondary forest or anthropogenic grasslands with severely degraded soils. We adopted a 1 to 9 ratio of forest restoration to biofuel plantation, a value that was deemed appropriate in terms of landscape management and feasible considering the high cost of habitat restoration [21]. The *RDL + Biofuel* option is based on a reformed (more flexible) version of the afforestation and reforestation component of the Clean Development Mechanism (CDM/AR).

2.3. Carbon credits for perennial biofuel crops

To increase benefits to biofuel producers that commit resources to forest conservation and reforestation, our model incorporates a component that allows producers to benefit from the carbon sequestered in biofuel plantations. Only woody perennial feedstock species would be eligible to ensure that biofuel plantations are a long-term investment and avoid GHG emissions characteristic of annual biofuel crops. We assume that ligno-cellulose technologies will become economically viable and that demand for vegetable oils will remain strong even after the introduction of second generation biofuels [14]. The quantity of carbon offset generated by biofuel plantations would be the difference between the biomass of the landscape prior to establishment of plantations and the average biomass sequestered by plantations over a 30-year period.

3. Methodology

The policy proposal was evaluated via a model that explores the potential outcomes for five case studies with different land-use histories: Pará – Brazil, East Kalimantan – Indonesia, Madagascar, Colombia, and Liberia (S1). The modeling approach is "illustrative" rather than "predictive" and is based on a spatial analysis that generates land-cover statistics according to the criteria described in Section 2. Output from the spatial analysis was fed into a spread sheet model that calculated the potential reductions in CO_2 emissions from avoided deforestation and the potential carbon offsets in reforested landscapes and biofuel plantations. The potential production from biofuel feedstocks is expressed in terms of biomass and its energy potential after conversion to a liquid fuel (S2).

The spatial analysis was based on a re-interpretation of the best available land-cover datasets for each individual case study (see references in S1 and S2), where the various land-cover strata were re-assigned to one of several standardized classes: forest (humid evergreen), native non forest, anthropogenic, and water. The anthropogenic strata include cropland, pasture and degraded grassland, as well as plantations and secondary forest. In Liberia and Madagascar where it was not possible to distinguish between anthropogenic and natural non forest, a simple non forest category was used. These standardized land-cover maps were used as templates for creating potential biofuel cultivation polygons based on suitability criteria for temperature, precipitation, and elevation for two biofuel feedstock species: oil palm for the production of biodiesel and eucalyptus for the production of cellulosic ethanol (S3). These polygons were constrained to exclude large areas of contiguous natural forest and were either located on: 1) active frontier landscapes characterized by forest fragments and recently deforested areas, or 2) areas with large areas of fallow or degraded land (Fig. 1). The land-cover maps and the existing intensity of land-use were validated by comparison with satellite images from Google Earth®.

Within each of these potential biofuel cultivation polygons, land area was allocated to biofuel cultivation, traditional agriculture, or forest conservation – depending on the circumstances of each case study and the prescriptions outlined in the two biofuel production models (see Results and S1). According to the *REDD + Biofuel* policy model, the biofuel plantations should be located on lands deforested between 2000 and 2010; since we lacked precise temporal data, however, we estimated this amount by multiplying mean annual deforestation by a factor of ten. Deforestation rates were derived from FAO estimates of land cover between 2000 and 2005, or a spatial analysis available from both published and unpublished sources (S2). The forest area set aside as a REDD based conservation offset was then 4 times this value (e.g., 40 times the annual deforestation rate). This area corresponds approximately to the total potential REDD offset that would be available to a country (or sub-national unit) based on a historical baseline.

Following that initial allocation of land for biofuel production explicitly linked to the *REDD + Biofuel* module, the *RDL + Biofuel* module was applied within each polygon and additional anthropogenic non forest area was assigned for biofuel cultivation up to a maximum area. This maximum area varied for each case study, based on the assumption that biofuel feedstock plantations would not completely displace other production systems. For example, in the case of Pará – Brazil this amount was determined to be 50% of the total anthropogenic landscape and the remainder of the previously deforested landscape would continue as pasture, cropland, or secondary forest (see description of individual case studies in S1 for justifications of variable rates of land-use intensity).

The spread sheet model converts land-use allocations into estimates of the potential production of biofuel feedstocks and CO_2 emission reductions and C sequestration based on coefficients that relate the proportion of land dedicated to a specific crop (%), crop yield (Mg of biomass), conversion factors from biomass to biofuel (Mg of liquid fuel) and from biofuel to energy content (GJ), as well as from biomass to carbon (Mg of C) and CO_2 equivalents (Mg of CO_2). Detailed descriptions for each line of the spread sheet model and the source and value of each coefficient are provided as

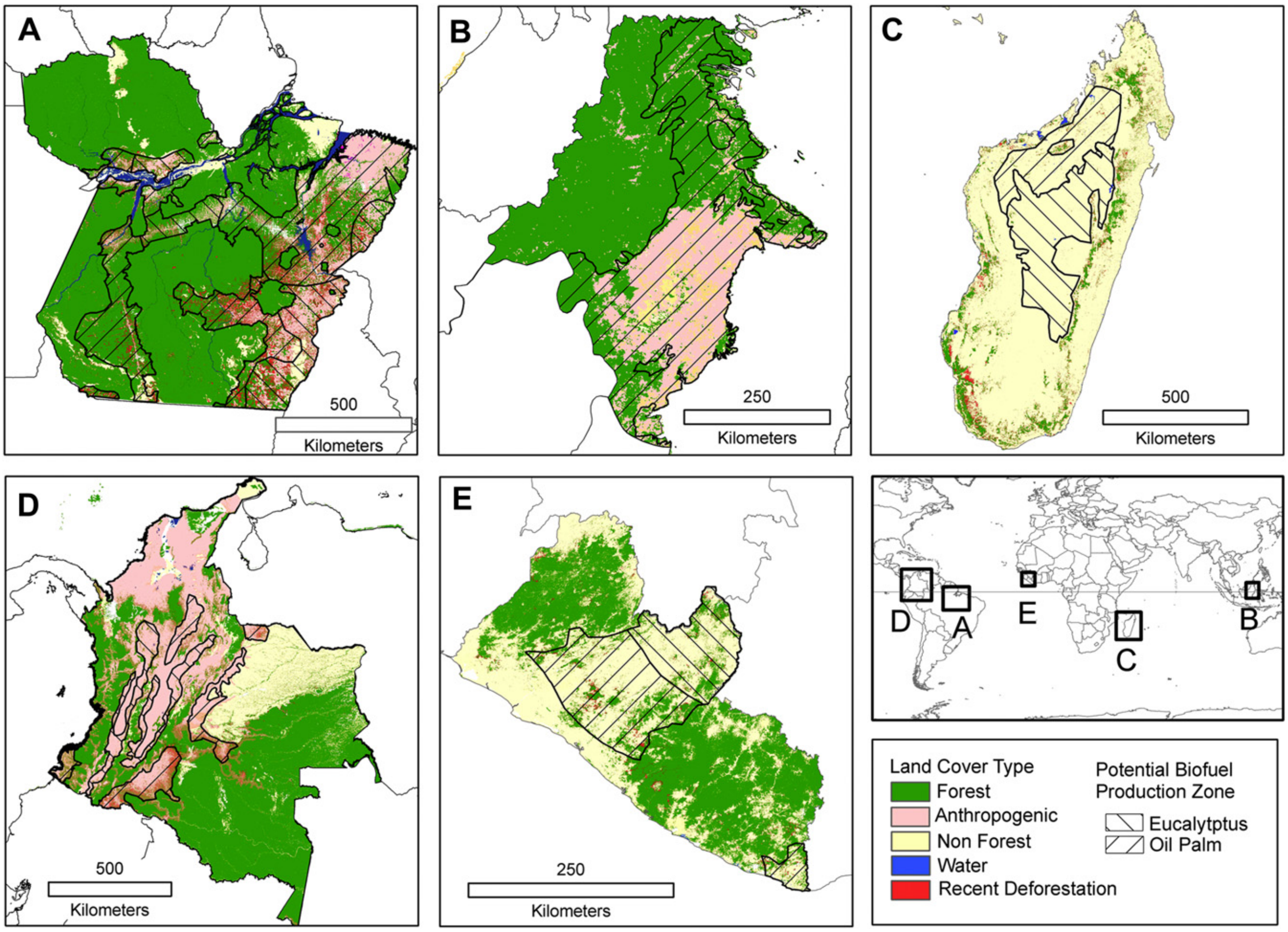

Fig. 1. The results of the spatial analysis for the five case studies showing the biofuel cultivation zones in the context of land-cover (A Pará – Brazil; (B) East Kalimantan – Indonesia; (C) Madagascar; (D) Colombia; and (E) Liberia (S1); the polygons were defined based on optimum precipitation ranges and topography (S3). The stratification scheme of the different land cover maps that were standardized into forest, non forest and anthropogenic classes to facilitate comparisons (S2); in Madagascar and Liberia the available datasets did not distinguish between native and anthropogenic land cover types, while multi-temporal data was not available for East Kalimantan- Indonesia.

Supporting material (S2); carbon stocks, feedstock yield and conversion efficiencies are conservative in all phases of the model. The implementation of the proposed biofuel production systems would span at least three decades and model outputs are based on values after production systems have been fully implemented and represent summary totals (C stocks and CO_2 emission reductions) and annual production (liquid biofuels).

The biofuel crop species used in the case studies are two woody perennial species with known climatic requirements, cultivation practices and existing global markets: eucalyptus and oil palm. The potential cultivation zones for both species were determined for each case study area using mean annual precipitation from the WorldClim dataset [22] and topographic data from NASA's SRTM digital elevation model [23]. Eucalyptus (*Eucalyptus grandis x urophyla*) is adapted to moderately high precipitation regimes (mean annual precipitation 1000–2000 mm), a strong seasonal climate and a broad range of soil conditions; above ground net primary productivity ranges between 10 and 40 Mg ha^{-1} y^{-1} of carbon, depending on precipitation and soil fertility [24]. We use conservative estimates of 10 Mg ha^{-1} y^{-1} of carbon for the severely degraded soils of Madagascar and 20 Mg ha^{-1} y^{-1} of carbon for other localities. Oil palm (*Elaeis guineensis* Jacq.) is adapted to seasonal tropical climates with high precipitation regimes (mean annual precipitation 2000–3000 mm). Documented yields of vegetable oil range between 3 and 6 Mg ha^{-1} y^{-1}; we use a value of 3 Mg ha^{-1} y^{-1} in our estimates of the potential yield of vegetable oil [25].

The potential emission reductions from REDD are based on a value (100 Mg ha^{-1} of C) for above ground biomass, which is on the low end of published values for humid tropical forest [26], while the carbon that would be sequestered via reforestation (82.4 Mg ha^{-1} of C) is based on estimates of above ground biomass in secondary forest [27] 30 years after establishment (S2). For eucalyptus plantations, the annual growth rate used to model biofuel feedstock production (10 and 20 Mg ha^{-1} y^{-1}) was also used to calculate the mean carbon stock in biofuel plantations when averaged over 30 years (26 and 16 Mg ha^{-1}), taking into account they would be harvested on 15 and 7 year cycles, respectively (S2). For oil palm, above ground biomass is based on diameter, height and specific gravity of stems, which was multiplied by a planting density of 140 stems ha^{-1} that take into account that palm plantations are destroyed and replanted on 25 year intervals [25] to yield a mean average carbon stock of 35 Mg ha^{-1} (S2). Net carbon sequestered in both eucalyptus and oil palm plantations was based on the difference between the 30-year mean of above ground biomass of the plantations and the biomass of land-use prior to its conversion, which was assumed to be either pasture or secondary forest. The mean carbon stock in secondary forests (82.4 Mg ha^{-1}) is derived from studies in the Amazon [27] and only considers above ground biomass (S2), while 2 Mg ha^{-1} was used for grasslands/pasture.

Finally, the potential outcome of a *Biofuel + FC* policy model was evaluated by comparing the aggregate output from the different case studies with three contrasting scenarios. One was a "*Stand-Alone REDD*" scenario where an effective REDD mechanism is adopted but is not linked to the cultivation of biofuels, which in turn do not expand into the agricultural frontier. This is contrasted with a "*Business as Usual*" scenario where biofuel cultivation expands in the absence of REDD and deforestation continues at historical levels. Finally, we evaluate a "*Most Likely*" scenario where a REDD mechanism is adopted, but is not explicitly linked to biofuel cultivation; in this scenario, REDD slows deforestation by 50%, while the area dedicated to the cultivation of biofuel feedstocks is limited to 50% of the *Biofuels + FC* scenario.

4. Results

The case studies were selected because they have different rates of deforestation and land-use dynamics, but also because they represent contrasting social conditions and landscapes where biofuel cultivation might compete with food crops. The cultivation of biofuels was limited to anthropogenic landscapes and only a fraction of those areas was converted to biofuel feedstock cultivation with that fractional amount depending on the land-use history of each case study (Table 1). Landscapes converted to biofuel plantations were characterized by low productivity pasture (Pará – Brazil and Colombia), degraded soils (Madagascar) or secondary forest (Liberia and E. Kalimantan – Indonesia). The criteria and results for Pará – Brazil are described here and similar information is provided for the other case studies as supporting material (S1).

Pará – Brazil incorporates within its boundaries large expanses of intact tropical forest, as well as one of the planet's most dynamic agricultural frontiers. Deforestation is linked to the improvement of roads, but is driven by land speculation, cattle ranching, soy farming and global commodity markets [10]. The deforestation rate in Pará – Brazil has fluctuated between 5500 and 8500 km^2 per year over the last two decades [20]; most has occurred along the eastern border on a transportation corridor linking Belem with central Brazil, which spread westward eventually reaching the boundaries of protected areas and indigenous reserves (Fig. 1a). Spatial models predict that deforestation will increase as two additional transportation corridors are improved [28]. Brazil has adopted a variety of policies to slow deforestation, but it has simultaneously promoted the production, consumption and exportation of biofuels [29], which some believe will lead to the expansion of the agricultural frontier and increased deforestation [18]. The *RED-D + Biofuel* mechanism would harness market forces to resolve potential conflicts between these two national policies, while *RDL + Biofuel* would transform landscapes deforested prior to 2000 by converting low productivity cattle pasture to biofuel production, improve watershed management, and contribute to biodiversity conservation.

The potential biofuel cultivation zone in Pará – Brazil includes all previously deforested landscapes that surround major transportation corridors corresponding to ~238,000 km^2 (Fig. 1a), but limit the expansion of biofuel plantations within this area to 50% (~119,000 km^2) and assume the remaining 50% would be dedicated to food crops and cattle ranching. Based on an annual deforestation rate of ~6250 km^2 per year, ~53% was allocated to the *REDD + Biofuel* production model with the remaining 47% assigned to the *RDL + Biofuel* system (Table 1 and S2). Based on the 4 to 1 rule outlined in Section 2.2, the REDD allocation would support the conservation of ~29% of the extant forest in the state, while the 9 to 1 RDL allocation would lead to the reforestation of 2.3% of previously deforested landscape (Table 1). The distribution of the two biofuel feedstock species was based on optimum climate adaptability with more than twice the area planted to oil palm when compared to eucalyptus. The reduction in CO_2 emissions from REDD would surpass 9.7 Gt (9.7 Pg), while the CO_2 sequestered by perennial biofuel plantations represents almost 1.2 Gt (Table 1). The precise physical location of the forest to be protected by a REDD allocation was not determined by this model, which is based on summary values generated by the spatial analysis; theoretically, the forest reserves linked to the *REDD + Biofuel* model should be as close to the agricultural frontier as possible. Moreover, the model makes no assumptions regarding the tenure or management of the forest lands protected by REDD, recognizing that land-use regulation is a sovereign right of individual states.

The Pará – Brazil case study provides an example of how the potential negative impact of biofuel cultivation on national and global food supplies can be avoided. Pastures in the Brazilian Amazon are characterized by relatively low stocking rates of one to two animal units per hectare. A variety of technological options are available for improving productivity, including rotational grazing, fertilizers, feed supplements and improved animal husbandry [30] and the conversion of 50% of the existing pasture land in Pará to biofuels could be accompanied by measures that double the productivity on cattle farms. The shift in Pará's rural land-use from one based almost exclusively on cattle ranching and logging to a more diversified and intensive production system would improve the regional economy, while supplying ~24% of Brazil's current liquid fuel consumption [31].

The remaining case studies provide other examples of land-use, land-use change and social conditions; in each case, however, important forest remnants within globally important biodiversity hotspots would be conserved (Fig. 1b–e). East Kalimantan is a dynamic frontier state

Table 1 Summary outputs from the Biofuel + FC policy model that links forest conservation (REDD) with reforestation on degraded landscapes (RDL) and the cultivation of woody perennial biofuel crops; values used to model carbon stocks in forest and biofuel plantations are conservative, as are annual yields and conversion efficiencies of the selected feedstocks (see S1 in supplementary materials).

	Pará	East Kalimantan	Madagascar	Colombia	Liberia	Aggregate Totals
Native tropical forest (km^2)	852,682	121,595	96,484	526,058	45,289	1,642,107
Anthropogenic landscapes (km^2)	237,869	63,240	484,366	293,407	48,416	1,127,298
Annual deforestation rate ($km^2\,yr^{-1}$)	6249	3900	2840	1434	116	14,540
Forest protected by REDD + biofuels (km^2)	249,960	121,595	96,484	57,374	4652	530,065
as % of total forest	29%	100%	100%	11%	10%	32%
Habitat restored by RDL + biofuels (km^2)	5560	0	10,135	2320	472	18,486
as % of anthropogenic landscape	2.3%	0.0%	2.1%	0.8%	1.0%	1.6%
Biofuel plantation (km^2)	118,088	31,620	129,749	37,542	5879	322,878
as % of anthropogenic landscape	50%	50%	27%	13%	12%	29%
REDD Gt [Pg] of CO_2	9.17	4.46	3.54	2.11	0.17	19.45
RDL Gt [Pg] of CO_2	0.17	0.00	0.16	0.04	0.01	0.37
Biofuel plantations Gt [Pg] of CO_2 of CO_2 [Pg]	1.20	0.09	1.33	0.35	0.00	2.97
Energy potential in PJ (10^{15} J) per year	1109	287	851	348	55	2650
% national petroleum production	24%	10%	2276%	62%	703%	
% USA petroleum consumption	2.6%	0.7%	2.0%	0.8%	0.1%	6.2%
Potential annual sales of biofuel [$US millions]	18,900	4743	14,641	5855	945	
GDP (2006) [$US millions]	17,098	10,024	17,200	337,286	3292	
GDP per capita ($)	2405	3645	884	7654	1031	
Population (millions)	7.11	2.75	19.45	44.07	3.19	

similar to Pará and the model outcome shows the potential of the *REDD + Biofuel* to arrest deforestation, while promoting the development of a sustainable oil palm industry on low biomass landscapes. The other three case studies represent landscapes with longer histories of human occupation and, consequently, more complex land-use mosaics. Madagascar has a high relative rate of deforestation and the *REDD + Biofuel* mechanisms could lead to the conservation of 100% of its extant forest; however, it is also characterized by vast areas of degraded landscape where the *RDL + Biofuel* mechanism would be particularly relevant (Table 1). About one third of Colombia can be defined as anthropogenic landscape and the integrated *Biofuel + FC* policy model could lead to the protection of ~11% of the existing forest cover, while producing ~62% of the country's current liquid fuel consumption on 13% of its anthropogenic landscape. In Liberia subsistence farmers would benefit by converting only 12% of their forest fallow to a perennial cash crop (S1). In all three countries, the potential revenues from emission reductions and CO_2 offsets could constitute an important incentive to develop sustainable biofuel industries, improve social services, and support agricultural extension services while also conserving or restoring forests (Table 1).

When the model outputs are aggregated for the five case studies, a total of 530,000 km^2 of natural forest would be conserved and 322,300 km^2 of biofuel crops could produce the equivalent of ~6.2% of US petroleum consumption in 2005. The conservation and reforestation components would reduce or offset emissions ~19.4 Gt (19.4 Pg) of CO_2, while woody perennial biofuel species could sequester an additional ~3 Gt of CO_2 (Table 1). A comparison of different policy scenarios (Fig. 2) shows that positive outcomes are maximized when biofuel cultivation and forest conservation are explicitly linked (*Biofuel + FC*). Other policy configurations might lead to similar areas set aside for forest conservation (*Stand Alone REDD*) or result in the same quantity of biofuels (*Business as Usual*). Even if REDD is agreed upon and implemented within the framework of the UNFCCC, the demand for biofuels might be so great that REDD is not fully successful in stopping deforestation, while the absence of carbon subsidies and high transportation costs constrain the expansion of biofuels on the agricultural frontier (*Most Likely*).

5. Discussion

In all five case studies, the proposed policies would provide important opportunities for forest conservation and reforestation, while stimulating economic growth and creating globally important energy supplies. In Pará and East Kalimantan, *REDD + Biofuel* would stabilize highly dynamic, agricultural frontiers in two countries responsible for ~60% of global deforestation [7]. In Madagascar, 100% of the standing native forest would be protected, while the conversion of the central highlands to biofuel cultivation would transform an impoverished country. Colombia and Liberia have extensive anthropogenic landscapes and large tracts of standing forest with moderate to low deforestation rates; although the impacts on their development trajectories would be less pronounced, they would still be large in absolute and relative terms.

Biofuels are controversial because of the risk they represent to world food supplies and their potential to stimulate deforestation. The proposed policies address these risks, but do not eliminate them. Unfettered biofuel cultivation would

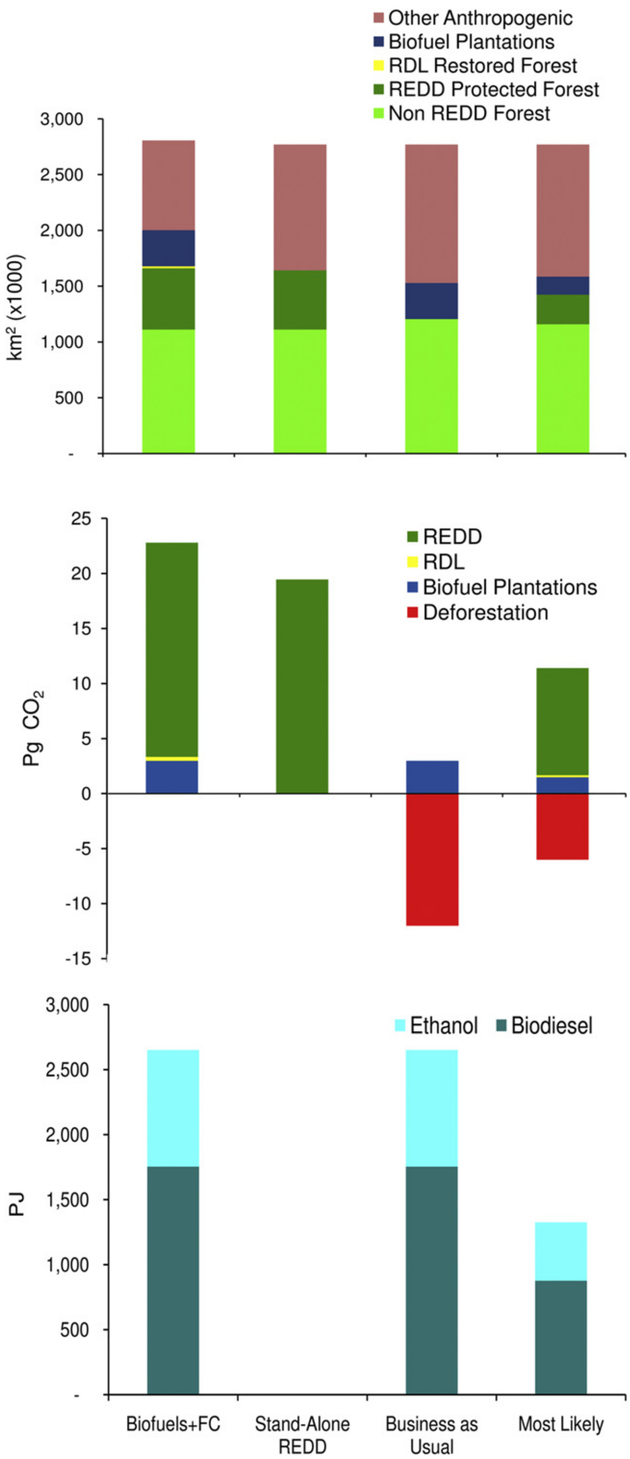

Fig. 2. Alternative development scenarios with model outputs aggregated over all five case studies: (A) Land cover; (B) CO_2 cumulative emissions reductions and sequestration offsets; and (C) energy produced. The four scenarios are: (i) *Biofuel+FC* where an effective REDD policy is implemented and is explicitly linked to biofuel cultivation; deforestation is reduced to zero (ii) *Stand-Alone REDD* where an effective REDD policy is implemented and there is no biofuel expansion on the agricultural frontier; deforestation is reduced to zero; (iii) *Business as Usual* where biofuels expansion occurs in the absence of an effective REDD mechanism; deforestation rates remain at historical levels and (iv) *Most Likely* scenario where an effective REDD policy is implemented and biofuel expansion occurs without an explicit link to forest conservation; historical deforestation rates are reduced by 50% and biofuels expansion is 50% of the business as usual scenario.

lead to further deforestation and effective regulation must accompany the proposed market-based mechanisms. The danger of monoculture is well known and future feedstock production systems should be based on genetically diverse agro forestry systems that include multiple species. These policy mechanisms have the potential to create significant economic growth, but benefits may not be shared equitably in many countries, particularly if small landholders are displaced by corporate farms. Cooperative systems could compete with corporate models in most instances, if the incentive system was structured to benefit small growers, while channeling corporate investments to post-harvest processing and commercialization.

If adopted by the international community, REDD could generate an important revenue stream for developing countries. In many cases, REDD revenues may provide sufficient incentive to conserve forests and there will be no need to link forest conservation with biofuel cultivation. In areas characterized by a dynamic agricultural frontier, however, REDD schemes must contemplate an alternative production system that creates jobs for the rural poor and generate wealth for the private sector – the two major forces driving deforestation. The failure to link forest conservation with sustainable production systems will limit the effectiveness of REDD where it counts most and, quite possibly, lead to its demise as an effective climate change and conservation policy. In contrast, the *REDD + Biofuel* policy model provides a realistic option for making REDD effective by providing an economically attractive alternative production system for landholders and a straightforward means to counteract leakage by establishing long-term land-use on both sides of the agricultural frontier. The distribution of the REDD revenues could be used to subsidize the production of biofuels, defray the costs of forest conservation and management, or to subsidize social services in poor rural communities. Like all national level REDD options, however, these decisions will be made by sovereign nations acting in their own perceived interest.

The proposed *RDL + Biofuel* mechanism provides an avenue for reforming the CDM/AR, which is plagued by complex regulations that makes it unattractive to investors and limits carbon subsidies to projects that are otherwise economically unviable (e.g., the concept of additionality). We suggest a simpler system that relies on direct economic subsidies derived from carbon markets that is neither project-based, nor concerned with a producer's profit margin. By restricting subsidies to woody perennial species, *RDL + Biofuel* plantations would mimic the hydrological services provided by a forested landscape, particularly if restored habitat is targeted at wetlands and water courses.

The production of biofuels in developing countries will provide economic opportunity; in most of these nations, however, those plantations located on the agricultural frontier will be at a competitive disadvantage with long-established producers with better access to transportation infrastructure. Similarly, biofuels produced by developing nations may not be able to compete with subsidized second generation biofuels produced in developed nations. However, these more competitive biofuel production systems may have a larger impact on global food supplies and, indirectly, increase pressure on tropical forests [19]. The denial of carbon-based subsidies to biofuel crops that are not perennial and which are not explicitly linked to forest conservation could provide sustainable biofuel production a competitive advantage in both domestic and international markets. The timing is right because carbon and biofuels are being traded in nascent markets with large growth potential and still immature—and therefore malleable—regulatory frameworks. Finally, the conversion of cropland dedicated to food production is avoided by planting biofuel feedstocks on degraded soils or in areas that have been incorporated only recently into the global food production system and, arguably, never should have been converted to agriculture in the first place.

The intensification of land-use and the creation of an agricultural production system linked to global markets would provide a route out of poverty for many developing nations. Consider the potential economic benefits that biofuels would bring to these five case studies: it would more than double the GDP of Pará – Brazil, East Kalimantan – Indonesia, Madagascar, and Liberia, while contributing to Colombia's already impressively diversified economy (Table 1; S2). Biofuel production would contribute to energy independence via a labor intensive production system that would add value to agricultural commodities. Finally, it is now widely recognized that revenues from REDD should be used to promote sustainable development and, in that context, the *Biofuels + FC* policy model is particularly advantageous because REDD revenues would be invested in a productive activity that generates wealth and creates jobs—rather the being distributed as a rent to impoverished populations in exchange for forest conservation.

Climate change threatens to bring economic dislocation to tropical countries and biofuel production provides these nations with an opportunity to adapt via economic growth, rather than development assistance. Developed countries need biofuels and developing countries can produce them competitively—if given the opportunity—an opportunity that can be linked to carbon markets that would benefit both developed and developing nations. Many argue that technological solutions based on other renewable energies will eventually make biofuels unnecessary [12,13], while others maintain that forest conservation and energy-use efficiencies are more cost effective climate change abatement strategies when compared to biofuels [32]. However, technological solutions and forest conservation do not provide the same level of benefits for developing countries that need economic growth and labor intensive production models to escape from poverty. In contrast, the proposed integrated mechanism that links forest carbon and biofuel markets would reduce GHG emissions, conserve biodiversity, and promote economic growth in developing countries: a scenario that can be described accurately as "win–win–win."

Acknowledgments

We thank an anonymous reviewer who provided a constrictive critique that substantially improved the manuscript. Support for this research was provided by The Department of Energy (GO18044), the Gordon and Betty Moore Foundation via its commitment to Conservation International, and the Oxford Martin School and the Oxford Centre for Tropical Forests at Oxford University.

Appendix. Supplementary material

Supplementary data associated with this article can be found, in the on-line version, at doi:10.1016/j.biombioe.2011.06.027.

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