ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Oil palm for biodiesel in Brazil—risks and opportunities

To cite this article: Oskar Englund *et al* 2015 *Environ. Res. Lett.* **10** 044002

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
12 January 2015

REVISED
26 February 2015

ACCEPTED FOR PUBLICATION
6 March 2015

PUBLISHED
30 March 2015

LETTER

Oil palm for biodiesel in Brazil—risks and opportunities

Oskar Englund[1], **Göran Berndes**[1], **U Martin Persson**[1] **and Gerd Sparovek**[1,2]

[1] Div. of Physical Resource Theory, Dept. of Energy and Environment, Chalmers University of Technology, SE-41296 Gothenburg, Sweden

[2] 'Luiz de Queiroz' College of Agriculture, Department of Soil Science, University of São Paulo. Av de Pádua Dias, 11, Piracicaba (SP), Brazil, 13418-900

E-mail: oskar.englund@chalmers.se

Keywords: oil palm, biodiesel, Brazil, land use, GIS

Supplementary material for this article is available online

Abstract

Although mainly used for other purposes, and historically mainly established at the expense of tropical forests, oil palm can be the most land efficient feedstock for biodiesel. Large parts of Brazil are suitable for oil palm cultivation and a series of policy initiatives have recently been launched to promote oil palm production. These initiatives are however highly debated both in the parliament and in academia. Here we present results of a high resolution modelling study of opportunities and risks associated with oil palm production for biodiesel in Brazil, under different energy, policy, and infrastructure scenarios. Oil palm was found to be profitable on extensive areas, including areas under native vegetation where establishment would cause large land use change (LUC) emissions. However, some 40–60 Mha could support profitable biodiesel production corresponding to approximately 10% of the global diesel demand, without causing direct LUC emissions or impinging on protected areas. Pricing of LUC emissions could make oil palm production unprofitable on most lands where conversion would impact on native ecosystems and carbon stocks, if the carbon price is at the level $125/tC, or higher.

1. Introduction

Among cultivated plants, oil palm has the highest known yield of vegetable oil and can be a profitable feedstock for biodiesel production (Serraõ 2000, Gui *et al* 2008, Butler 2010, Schwaiger *et al* 2011). About 90% of the global oil palm production takes place in Indonesia and Malaysia, with around six and four million hectares (Mha) of oil palm plantations, respectively. Of these plantations, about 40% were established at the expense of tropical forests (Gunarso *et al* 2013) causing negative impacts on, e.g., biodiversity and also greenhouse gas (GHG) emissions associated with the forest conversion and peatland drainage.

Brazil presently only has 0.1 Mha of oil palm plantations (FAO 2013), but roughly half of Brazil's land area (565 Mha) could support some level of oil palm production (IIASA and FAO 2012). Much of the suitable land is forested, but there are also large deforested areas, e.g., cattle pastures, where conversion to oil palm plantations could possibly result in carbon sequestration and partial reversal of hydrological changes caused by earlier land use change (LUC), e.g., effects on subregional precipitation due to deforestation (Loarie *et al* 2011, Lathuillière *et al* 2012, Pires and Costa 2013). Both establishing oil palm plantations and managing them are relatively labour intensive activities (compared with, e.g., beef cattle production), having a positive effect on local incomes. According to government estimates, a family could increase its net income fourfold by shifting from traditional staple crops to oil palm cultivation (Butler 2010). Biodiesel production could also increase energy self-sufficiency in villages that are currently dependent on diesel supply for electric power generation (Villela *et al* 2014).

The Brazilian government acknowledges the risks of negative environmental impacts associated with oil palm expansion, and the aim is for plantations mainly

Table 1. Summary of the main 18 scenarios, including the total area in the scenarios where oil palm plantations would have a positive NPV, and the percentage of forest area and protected land, respectively, where conversion to oil palm plantations has positive NPV.

Establishment year	WEO scenario	LUC carbon price ($/t C)	Area where oil palm establishment has positive NPV (Mha)	Share of total forest area where establishment of oil palm plantations has positive NPV (%)	Share of total area with positive NPV that is protected by law (%)
2013	CP	No	389	86	42
	NP	"	363	84	43
	450 ppm	"	378	86	42
	CP	22 (mid)	333	73	39
	NP	"	294	66	39
	450 ppm	"	318	71	39
	CP	64 (high)	233	46	33
	NP	"	191	38	30
	450 ppm	"	220	44	33
2025	CP	No	414	90	41
	NP	"	385	87	42
	450 ppm	"	411	90	41
	CP	43 (mid)	324	67	36
	NP		269	57	36
	450 ppm	86 (mid)	252	48	32
	CP	125 (high)	147	20	19
	NP	"	98	9	14
	450 ppm	249 (high)	92	4	9

to be established on degraded agricultural land (Villela *et al* 2014). Brazil's 'Agro-Ecological Zoning of Oil Palm in Deforested Areas of the Amazon' (EMBRAPA 2010) identified 29.7 Mha of land where the Brazilian Investment Bank (BNDES) is allowed to provide credit on favourable terms to support oil palm establishment. About 5 Mha of new oil palm plantations have been authorized so far (Villela *et al* 2014). Oil palm can be planted in other areas than those designated by the government, but without support from the BNDES. In addition to policies related to environmental protection, Brazil has launched a number of initiatives that seek to promote and regulate expansion of oil palm, involving, e.g., technical assistance to farmers, agricultural and industrial incentives and credits, sustainability monitoring and evaluation, land titling, traditional people's protection, and social inclusion (Villela *et al* 2014). However, despite the recent policies, large forest areas in Brazil can still legally be converted into cultivated systems (Sparovek *et al* 2010).

Here, a spatially explicit model was developed to: (i) determine the net present value (NPV) of establishing new oil palm plantations for biodiesel production under different climate and energy policy regimes in order to map areas in Brazil where production would be profitable; (ii) estimate the associated biodiesel production and LUC; and (iii) investigate whether pricing of carbon emissions from LUC could make oil palm production unprofitable on lands with high carbon stocks. Finally, we delineate areas where oil palm expansion would minimize LUC emissions and displacement of native ecosystems, and avoid impinging on land protected by law.

2. Methods

The NPV of establishing new oil palm plantations for biodiesel production was calculated using (1) for each hectare in Brazil for a total of 27 scenarios: the 18 main scenarios (table 1) are based on the three energy scenarios from the 2012 World Energy Outlook (WEO) (IEA 2012)—'Current policies' (CP), 'New policies' (NP), and '450 ppm'—providing variations in oil, coal and carbon price developments that affect the willingness to pay for biodiesel and palm oil residues. The WEO scenarios were combined with three different levels of a LUC carbon price to form nine scenarios. Finally, two different establishment years (2013 and 2025) were used for each scenario to analyse how the results differ over time, given the price projections on oil, coal and carbon. In addition to the 18 main scenarios, all scenarios having an establishment year of 2025 were analysed with both present and prospective road infrastructure, to facilitate a complementary analysis of how improvements in road infrastructure would affect the profitability of establishing oil palm plantations. The NPV of establishing oil palm plantations for biodiesel production was estimated for each scenario with a resolution of 100 m

$$\mathrm{NPV} = -\mathrm{P_l} + \mathrm{R_t} - \mathrm{C_p} - \mathrm{C_m} - \mathrm{C_{em}} + \sum_{n=1}^{25} \frac{\mathrm{R}(n) - \mathrm{C_c}(n) - \mathrm{C_t}(n) - \mathrm{C_{N_2O}}(n)}{(1+r)^n} \quad (1)$$

$\mathrm{P_l}$ = Land price
$\mathrm{R_t}$ = Revenue from timber
$\mathrm{C_p}$ = Cost of establishing plantations
$\mathrm{C_m}$ = Cost of establishing mill

C_{em} = Cost of LUC carbon emissions
$R(n)$ = Revenue from palm oil and residues
$C_c(n)$ = Cultivation cost
$C_t(n)$ = Transport cost
$C_{N_2O}(n)$ = Cost of N_2O emissions
r = discount rate

The land price is spatially explicit and based on FNP (2012). Revenue from timber produced when land is cleared to make place for oil palm (in all cells classified as 'forest') (Busch *et al* 2009)and mill establishment cost are spatially explicit. Cost of establishing plantations is set to be constant (data and references given in supplementary information stacks.iop.org/ERL/10/044002/mmedia). Cost of LUC carbon emissions is estimated by multiplying the change in carbon stock in each cell from establishing oil palm plantations by the carbon price in the different scenarios. Here, carbon stocks in natural vegetation are based on Baccini *et al* (2012), but adjusted using spatial data on current land use (see SI for details stacks.iop.org/ERL/10/044002/mmedia). Revenue from palm oil production is spatially and temporally explicit, based on the potential yield in each cell, following a specific yield profile over 25 years (Persson 2012), and the willingness to pay for biodiesel. The latter was assumed to be equal to the willingness to pay for petrodiesel, estimated using projected global oil prices in the different WEO scenarios (IEA 2012), with costs for refining oil into petrodiesel (Li *et al* 2012), and the projected EU carbon tax (IEA 2012), added. The willingness to pay for residues (to use for bioenergy) was assumed to be equal to the willingness to pay for coal, calculated using projected coal prices, with a Brazilian carbon tax added in the WEO scenarios that assume such a tax (IEA 2012). Cultivation cost (SUFRAMA 2003) depend on the plantation year. Milling cost per tonne of palm oil and palm kernel oil yield is estimated for each cell on each plantation year (SUFRAMA 2003). Transport cost is calculated using the estimated cost in each cell of transporting one tonne of goods the cheapest way to an export port, multiplied by the palm oil yield in the same cell, depending on the plantation year (see SI stacks.iop.org/ERL/10/044002/mmedia). Carbon cost from N_2O emissions is only added in the 450 ppm scenarios, where Brazil is assumed to have implemented a carbon tax. It is constant at 0.42 tC/ha/a multiplied by the carbon price (Forster *et al* 2007, IEA 2012, Persson 2012). The discount rate r is set at 10% and the plantation lifetime n is 25 years (Persson 2012). Spatial NPV calculations as well as various spatially explicit algebraic and statistical operations on the NPV results were made using ArcGIS. All costs and prices are expressed in constant (inflation adjusted) USD for the year 2010. See the SI for more methodological details (stacks.iop.org/ERL/10/044002/mmedia).

3. Results

Palm oil production for biodiesel can be profitable (positive NPV) over very large areas in Brazil, including areas where oil palm would displace native vegetation and cause LUC emissions. There are however opportunities to produce substantial amounts of palm oil without compromising objectives for GHG emissions reduction and nature conservation.

For establishment year 2013, without a price on LUC carbon emissions, results show that it would be profitable to establish oil palm plantations on about 360–390 Mha (figure 1, table 1), corresponding to a biodiesel production almost equal to the present global diesel demand (FAO 2013). The situation for 2025 is similar. These results do not account for the dynamic effects an increase in the biodiesel production of this magnitude would have on global oil prices, and hence on the willingness to pay for biodiesel (Rajagopal *et al* 2011). Nevertheless, they give a clear indication of the geographical pattern of exploitation pressure in a situation where biodiesel prices follow the trajectories given in the WEO scenarios (figure 2).

3.1. Risks

In the absence of a LUC carbon price, establishment of oil palm plantations would have a positive NPV in almost all forests in Brazil where climate and soil conditions support oil palm cultivation, including rainforests (figures 1–3, table 1). To illustrate the GHG dimension: if this forest land were converted to oil palm plantations, up to 50 Gt of carbon would be emitted to the atmosphere (figure 4). This corresponds to over 70 times the emissions from forest conversion and peat oxidation due to oil palm expansion in Southeast Asia in 1990–2010 (Agus *et al* 2013) or almost half of the US cumulative emissions from fossil fuels since preindustrial times (Boden *et al* 2013). Such forest conversion would also, obviously, cause a number of other impacts, including adverse impacts on biodiversity.

The effects of pricing LUC carbon emissions on the profitability of converting forests to oil palm plantations, naturally depends on the carbon price (figures 1, 2 and 4, table 1). The LUC carbon levels used for year 2013 correspond to the current average carbon price on voluntary carbon markets ($22/t C: 'mid') (Peters-Stanley *et al* 2013) and the modelled carbon price on the EU ETS market as presented in the WEO ($64/t C: 'high') (IEA 2012). Carbon price levels diverge over time and are assumed to grow faster in the more stringent climate policy (i.e. 450 ppm) scenarios. By 2025, in the 450 ppm scenario, the highest carbon price used ($249/t C) results in oil palm establishment having a positive NPV on 4% of the forest area, compared with 90% in the absence of a LUC carbon price. If this high carbon price is cut in half, oil palm establishment still has a negative NPV on 80–90% of the

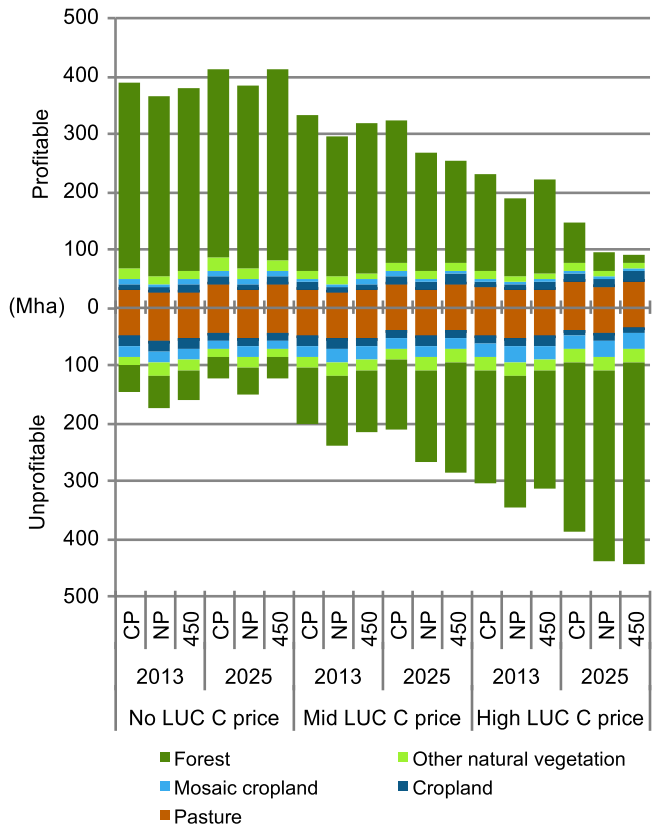

Figure 1. Area of six land use/land cover (LULC) categories where establishment of oil palm plantations for biodiesel production would be profitable (NPV > 0; bars above the *x*-axis) and unprofitable (NPV < 0; bars below the *x*-axis), in each of the main 18 scenarios. Land unsuitable for oil palm production is excluded.

forest area, but if reduced by two thirds, the NPV would only be negative on about half the forest area. Thus, pricing of LUC carbon emissions may strongly discourage forest conversion to oil palm plantations if the carbon price is sufficiently high, i.e., $125/t C or above.

A large share of the area where NPV is positive, in the absence of a high LUC carbon price, is protected by law (figure 5, table 1), either as natural parks, indigenous land, or for military purposes. Today, Brazil has achieved a high level of protection of these lands (Sparovek *et al* 2010), but large scale oil palm plantations established in adjacent areas may increase the pressure on protected lands and the buffer zones surrounding the parks, especially in areas where the prospective profitability is particularly high. Such pressure may not just come from individual farmers aiming to claim land illegally, but also from industrial agents advocating a reclassification of parks due to economic reasons, or permission to produce oil palm in the buffer zones that surround them. This is probably not likely to occur before oil palm production has matured and available land for further conversion starts to become scarce, but policymakers should be aware of the possibility. Currently legislation is being debated in the congress that calls for protected areas to open for mining concessions and general prohibition of new protected land in areas of high mineral or hydropower potential (Ferreira *et al* 2014). A LUC carbon price can steer interests away from protected land, due to, typically, high carbon stocks in natural parks and indigenous areas (figure 5, table 1). However, as previously discussed, the carbon price levels seen today on voluntary carbon markets would only have a marginal effect.

3.2. Opportunities

There are only small variations between the different scenarios concerning the NPV of establishing oil palm plantations on other land types than forests. For year 2013 (on average, across all scenarios), about 30 Mha of pastures, 10 Mha of cropland, 6 Mha of mosaic cropland, and 15 Mha of natural vegetation (excluding forests) had a positive NPV (figure 1). Palm oil plantations on these lands could support production of roughly 6–7 EJ/a of biodiesel. In 2025, a positive NPV is found for similar areas of mosaic cropland and non-forest natural vegetation, on 40 Mha of pastures, and 13 Mha of cropland (figure 1). The corresponding biodiesel production is about 1EJ/a higher than in 2013. However, the calculation of NPV in 2025 has not considered that certain costs, such as for labour and land (especially agricultural land), may increase at a higher rate than inflation, affecting NPV negatively.

Establishing oil palm plantations on currently unprotected land, where carbon stocks would

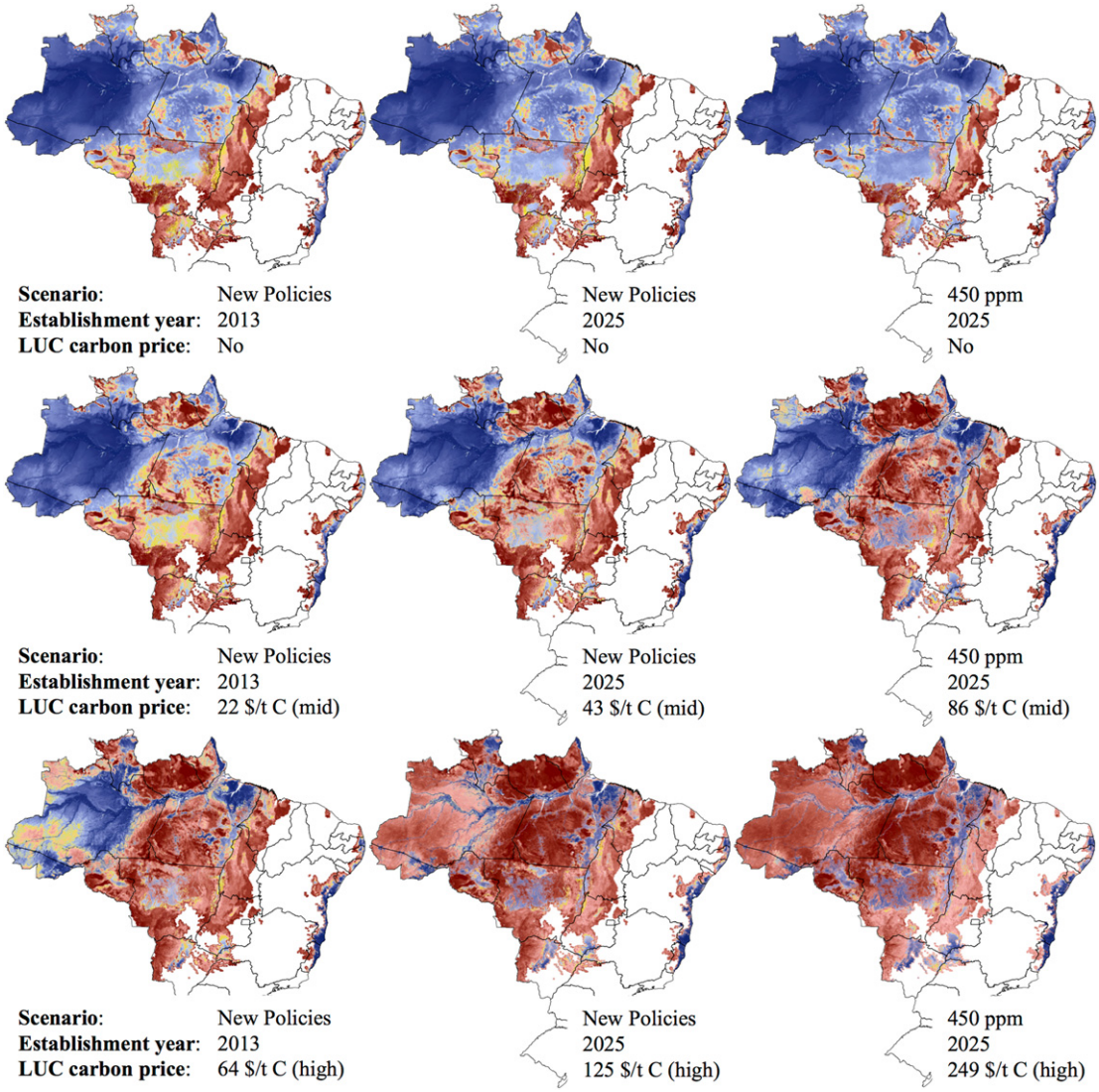

Figure 2. Spatial distribution of NPV values in the 'New Policies' (left, middle) and '450 ppm' (right) scenarios, with different establishment years and LUC carbon price levels. Blue colours: positive NPV, red: negative NPV, yellow: NPV close to zero. Darker colours represent higher absolute values. The NPV value range is −17 678–26 503 $/ha in the top left and −74 076–44 128 $/ha in the bottom right. See figure 3 for example results on smaller scales.

either increase or be roughly unaffected, would have a positive NPV on 40–60 Mha. The corresponding biodiesel production is estimated at 4–6 EJ/a, which is 40–60 times the current demand for biodiesel in Brazil, 2–3 times the Brazilian demand for petrodiesel and biodiesel combined (Barros 2013), or about 10% of the current global petrodiesel demand (figure 6). Almost all of this land is presently in agriculture, with roughly 3/4 pasture (15–25% of all pasture in Brazil) and 1/4 cropland (10–15% of all croplands). Conversion of this land would also increase the carbon stock and generate solid biomass fuel from plantation renewal. Taking the 2013, CP, *no carbon pricing* scenario as an example (use figure 6(b) for comparisons): converting all 46 Mha would increase the carbon stock with an estimated 3 Gt CO_2-eq, corresponding to more than seven times Brazil's current annual emissions of CO_2 from fossil fuel combustion. In addition, it would generate an estimated 2.4 EJ of annual solid biomass fuel from plantation renewal.

3.3. Effects from expanding and upgrading road infrastructure

Contrary to, e.g., soybean production (Vera-Diaz *et al* 2009), the transportation cost has a small influence on the NPV for oil palm (see figure 3(b)). This is due to local processing of palm oil and a generally high NPV of palm oil production, compared with alternative land uses. Also, the cost of river transportation is roughly the same as transportation on paved roads (Barros and Uhl 1995, Lentini *et al* 2005, Vera-Diaz *et al* 2009, Salin 2011), which makes it a competitive alternative in many areas where the road infrastructure is poor. Since palm oil can be exported through, e.g., Manaus and Santarém, the

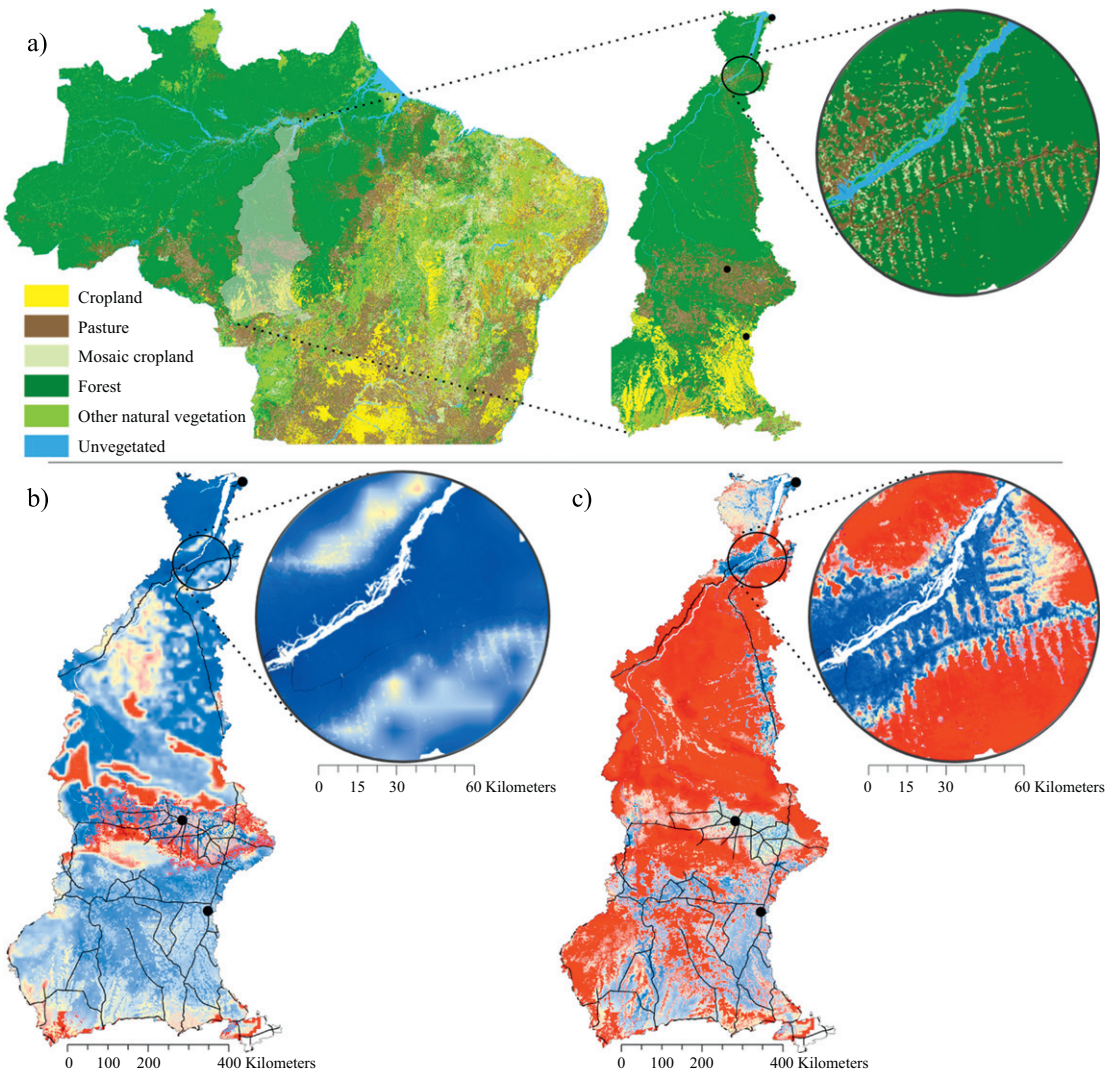

Figure 3. Example of modelling results on a regional and local scale. (a) Shows the location and land use of the Tapajós watershed in Brazil, and the area magnified in the circles. The black dots in the top-middle map indicate the location of, from north to south, Santarem, Alta Floresta, and Sinop. (b) Shows the NPV results for the 2013—CP—no LUC carbon price scenario. (c) Shows the NPV results for the 2013—CP—high LUC carbon price scenario.

transportation cost from areas near navigable rivers in Amazonas is already relatively low. If all existing national and regional infrastructure plans in Brazil were realized by 2025, including the paving of unpaved roads, the total area where establishment of oil palm plantations for biodiesel would have a positive NPV increases by only a few per cent. Most of this area is presently forested (65–95%). See SI for full analysis (stacks.iop.org/ERL/10/044002/mmedia).

3.4. Uncertainties

The main uncertainties in this study are the oil price projections (the basis for revenues from palm oil) and the discount rate. The benchmark interest rate in Brazil has averaged almost 16% from 1999 until 2014, but in the latest decade it has averaged around 10% per year (Segura-Ubiergo 2012). We therefore used a 10% discount rate as a baseline assumption, but stress that results would change significantly with another discount rate. For example, without a LUC carbon-pricing scheme, using a discount rate of 5% increases the total area with positive NPV with an average 16 and 12% for establishment years 2013 and 2025, respectively. Using instead a discount rate of 15%, the profitable area decreases with 29 and 22%, respectively (figure 1 in SI). A more thorough discussion on uncertainties is available in the SI (stacks.iop.org/ERL/10/044002/mmedia).

4. Discussion

Most of the land where oil palm could be planted without impinging on protected areas, and/or decreasing carbon stocks, is already under agriculture. The net GHG savings that can be obtained by planting on agricultural areas obviously depend on whether such planting indirectly leads to LUC with high GHG emissions elsewhere (Berndes *et al* 2012). The

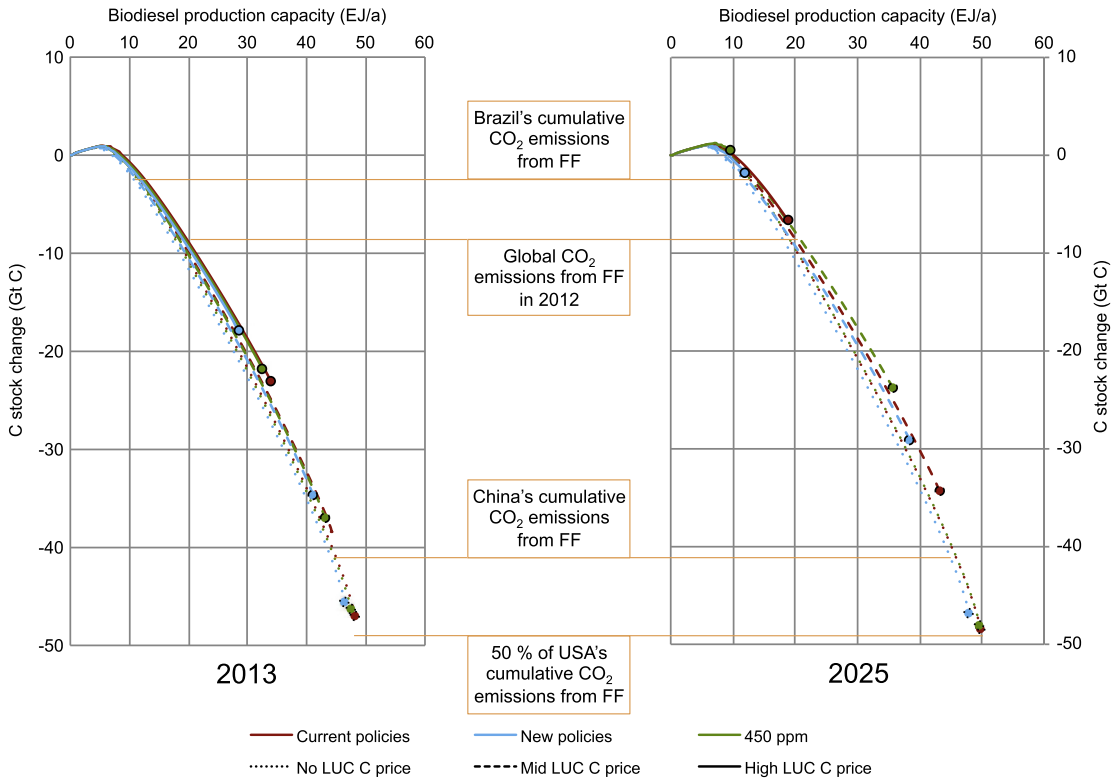

Figure 4. Biodiesel production capacity supported by oil palm (horizontal axis) and the corresponding effect of oil palm establishment on ecosystem C stocks (vertical axis), for each of the scenarios presented in figure 1 and table 1. The lines end at the maximum biodiesel production capacity for that scenario. Textboxes provide selected magnitude comparisons (FF = fossil fuels), based on (Boden *et al* 2013).

outcome depends on many factors, including governance of land use, food demand development, and productivity development in agriculture, especially concerning meat and dairy. For example, Sparovek *et al* (2012) estimate that modest increases in stocking and slaughter rates could free up almost 70 Mha of pasture land for other purposes, i.e., approximately double the pasture area here estimated to be suitable for oil palm (figure 6). Examples of policy measures to stimulate intensification include, e.g., taxing cattle from conventional extensive pasture or subsidizing cattle from semi-intensive pasture (Cohn *et al* 2014). These measures have been estimated to reduce the total pasture area by 2030 with 21 and 16 Mha, respectively, compared with a baseline scenario. However, agricultural land use may not decrease as a consequence of intensification since the intensification measures potentially also make the agricultural activity more profitable and thus more attractive, resulting in an increase in agricultural land rather than a reduction (Balmford *et al* 2005, Ewers *et al* 2009, Rudel *et al* 2009, Lambin and Meyfroidt 2011). Thus, unless appropriate policy measures are taken, there is a risk that large-scale oil palm expansion could displace existing agricultural land onto natural vegetation.

The results also show that a LUC carbon-pricing scheme can make conversion of forests to oil palm plantations unprofitable, provided that the carbon price becomes substantially higher than the present level on voluntary carbon markets. However, establishing an effective LUC carbon pricing scheme with sufficiently high carbon prices, or other mechanisms for forest protection such as REDD+ (Gebara *et al* 2014), is challenging. In the case of a LUC carbon-pricing scheme, it would have to be applied for all agricultural activities, not just oil palm production, to avoid indirect LUC effects within Brazil. To avoid international leakage the carbon pricing scheme would have to be global.

During the past decade, deforestation has increased in the Cerrado biome (Soares-Filho *et al* 2014), but has decreased drastically in the Amazon biome and in Brazil as a whole, mainly due to successful enforcement of new policies (Barretto *et al* 2013, Nepstad *et al* 2014). This indicates that large-scale oil palm plantations established on natural vegetation land, or on protected areas, is less likely to occur now than it was previously, especially involving large companies targeting markets for sustainably certified products. Historically, land conversion by individual small farmers seeking to secure tenure rights has been a major driver of land conversion at agricultural frontiers (Barretto *et al* 2013), but this is unlikely in the oil palm context which requires substantial start-up capital. However, companies may buy farmland as part of land development for oil palm, and

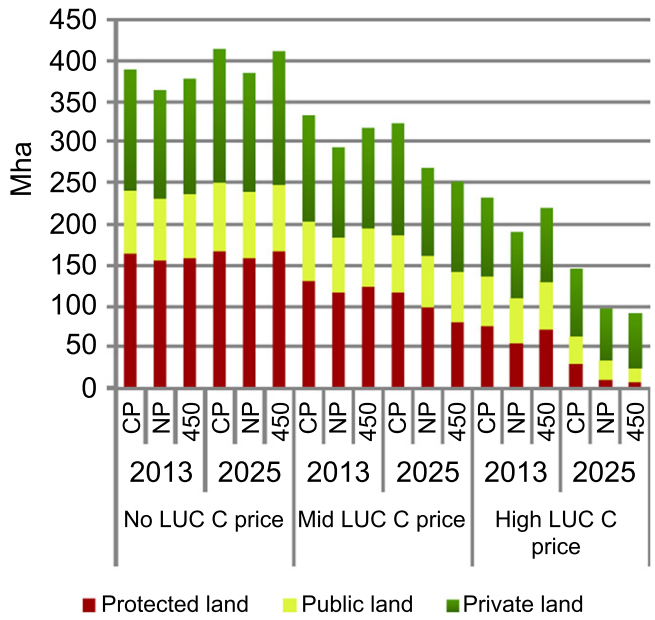

Figure 5. Amount of land in three land tenure classes (protected, public, and private land) where establishment of oil palm plantations for biodiesel production would be profitable (NPV > 0).

since farmlands may contain forests that can be legally felled, such land development may involve deforestation. Another possible, albeit speculative, mechanism through which oil palm expansion could lead to deforestation is through land speculation, where expectations about future growth of the oil palm industry might induce land development projects where there are not yet any announced plans for oil palm planting. This might be avoided with appropriate policies, either discouraging land conversion in general, or promoting oil palm on land that fulfils certain requirements so as to not allow plantations on, e.g., recently deforested land.

Legislation and other measures can prevent forests and other native vegetation from being converted to agricultural use (Sparovek *et al* 2010) but its outcome depends on comprehensiveness and effectiveness of enforcement (Yui and Yeh 2013). Brazil has launched several policy initiatives that can reduce the extent of deforestation associated with oil palm expansion. The 'Terra Legal' program (Ministério do Desenvolvimento Agrário 2013) aims at securing land tenure rights in the Legal Amazon, where most of the land without secure tenure rights is located (Barretto *et al* 2013). If tenure rights can be determined for all land, the incentives for land conversion as described above are likely to decrease. A land title will also give farmers access to loans, which are a necessity for investing in many of the more profitable production systems, such as oil palm. Another initiative, the Brazilian Sustainable Palm Oil Production Program, was launched to promote the development of oil palm only in areas deforested before 2007, excluding all protected land. In the Amazon Region, oil palm must follow other specific social and ecological criteria as presented in the agro-ecological zoning for oil palm in deforested areas of the Amazon (Villela *et al* 2014). Finally, the Forest Act (Federal Law #12.651—25 May 2012) affects land use decisions on 571 Mha of private farmland (out of 850 Mha of continental territory), of which 55% is covered with natural vegetation, and may thus be the most influential legal framework for agricultural land use decisions. The recent revision of the Forest Act favours the expansion of agricultural production, especially in the Amazon region, but the effects cannot yet be fully assessed. However, since the Forest Act now requires that 50% instead of 80% of farmland is set aside as Legal Reserve for those properties in the Amazon Biome that deforested more than allowed before 2008, 26 Mha of additional land is now available for agricultural use in the Amazon Biome. The exemption of small farms to restore Legal Reserve deficits added 7 Mha, and the possibility to use natural vegetation in riparian buffer zones to fulfil deficits of Legal Reserves added 3 Mha, resulting in 36 Mha of additional land available for legal agricultural use compared with the prior Forest Act, most of it in the Amazon. Furthermore, Legal Reserve deficits in one farm can now be compensated by a surplus in other farms, and half of the required area for Legal Reserves can be planted with non-native tree species, including oil palm (Ab'Sáber 2010, de Sousa *et al* 2011, Tollefson 2011, Nazareno 2012, Sparovek *et al* 2012, Schwartzman *et al* 2014, Soares-Filho *et al* 2014).

As previously noted, existing policies can limit deforestation if sufficient resources and political will is available for enforcement and continuous monitoring. However, recent efforts to, e.g., reduce the extent of existing protected areas, weaken environmental laws (e.g. the forest code), and provide amnesty for

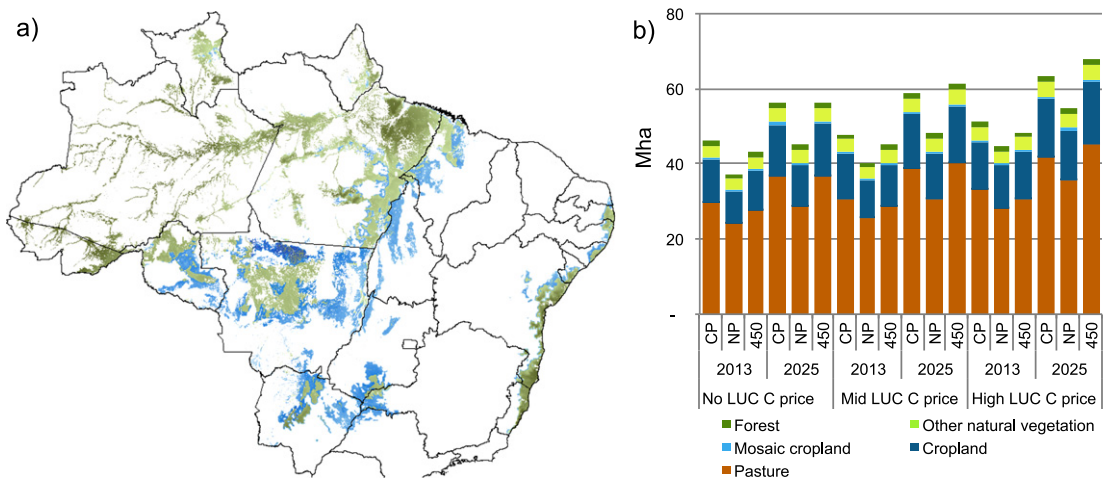

Figure 6. Areas where establishment of new oil palm plantations would (1) be profitable (NPV > 0); (2) increase carbon stock; and (3) not impinge on land protected by law. (a) Shows the spatial distribution of this land in the scenario with the lowest potential (green) and highest potential (green + blue). Darker colours indicate higher yields; (b) shows quantified results for all scenarios divided into six LULC classes.

illegal deforestation prior to 2008, have raised concerns (Arima *et al* 2014). To the extent that palm oil and biodiesel are traded on global markets, sustainability requirements associated with export markets may influence the way oil palm biodiesel is produced in Brazil. For example, the EU Renewable Energy Directive (EU RED) includes a specific set of sustainability requirements on biofuels with which companies producing for the EU RED market need to comply. Compliance with these requirements can be verified through an approved voluntary certification scheme. By becoming certified, producers also get access to the international market for certified products, in addition to the domestic and the EU RED market. There is also in general a strong trend internationally, among corporations that produce and trade agricultural and forestry commodities, to pledge not to source products from cleared forest land. Such zero deforestation policies now cover 60% of global trade in palm oil, following commitments by major global traders such as Golden Agri-Resources, Wilmar International and Cargill that apply to their own operations as well as to those of third party suppliers (United Nations 2014). These companies also recently called on the Indonesian government to codify the elements of zero deforestation pledges in Indonesian law. Given this development and the precedence of the Brazilian Soy Moratorium, it is not implausible that similar accords would accompany a large-scale expansion of oil palm in Brazil.

Acknowledgments

We would like to thank Paulina Essunger and two anonymous reviewers for valuable comments on the manuscript. Financial support from the Swedish Energy Agency, the Swedish Research Council Formas, and the Norden Top-level Research Initiative sub-programme 'Effect Studies and Adaptation to Climate Change' through the Nordic Centre of Excellence for Strategic Adaptation Research (NORDSTAR) is gratefully acknowledged.

References

Ab'Sáber A N 2010 Do Código Florestal para o Código da Biodiversidade *Biota Neotropica* **10** 331–6

Agus F *et al* 2013 Historical CO_2 emissions from land use and land use change from the oil palm industry in Indonesia, Malaysia and Papua New Guinea In: ed T J Killeen and J Goon *Reports from the Technical Panels of the 2nd Greenhouse Gas Working Group of the Roundtable on Sustainable Palm Oil (RSPO) Kuala Lumpur, Malaysia Roundtable on Sustainable Palm Oil (RSPO)*

Arima E Y *et al* 2014 Public policies can reduce tropical deforestation: lessons and challenges from Brazil *Land Use Policy* **41** 465–73

Baccini A *et al* 2012 Estimated carbon dioxide emissions from tropical deforestation improved by carbon- density maps *Nat. Clim. Change* **2** 182–5

Balmford A, Green R E and Scharlemann J 2005 Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production *Glob. Change Biol.* **11** 1594–605

Barretto A G O P *et al* 2013 Agricultural intensification in Brazil and its effects on land-use patterns: an analysis of the 1975–2006 period *Glob. Change Biol.* **19** 1804–15

Barros A C and Uhl C 1995 Logging along the Amazon River and estuary: patterns, problems and potential *Forest Ecology Manage.* **77** 87–105

Barros S 2013 Brazil, biofuels annual *Annual Report 2013* Sao Paolo: Global Agricultural Information Network (GAIN)

Berndes G *et al* 2012 Bioenergy and land use change-state of the art *Wiley Interdiscip. Rev.: Energy Environ.* **2** 282–303

Boden T A, Marland G and Andres R J 2013 *Global, Regional, and National Fossil-Fuel CO_2 Emissions* (Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy)

Busch J *et al* 2009 Comparing climate and cost impacts of reference levels for reducing emissions from deforestation *Environ. Res. Lett.* **4** 044006

Butler R A 2010 Brazil launches major push for sustainable palm oil in the Amazon (http://news.mongabay.com/2010/0507-amazon_palm_oil.html)
Cohn A S *et al* 2014 Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation *Proc. Natl Acad. Sci. USA* **111** 7236–41
de Sousa P T, Fernandez Piedade M T and Candotti E 2011 Ecological oversight: Brazil's forest code puts wetlands at risk *Nature* **478** 458–458
EMBRAPA 2010 Zoneamento Agroecológico do Dendezeiro para as Áreas Desmatadas da Amazônia Legal (Brazilian Agricultural Research Corporation—Embrapa)
Ewers R M *et al* 2009 Do increases in agricultural yield spare land for nature? *Glob. Change Biol.* **15** 1716–26
FAO 2013 *FAOSTAT* (Rome: Food and Agriculture Organization of the United Nations)
Ferreira J *et al* 2014 Environment and development Brazil's environmental leadership at risk *Science* **346** 706–7
FNP 2012 *ANUALPEC 2012* (Sao Paolo: FNP Consultoira & Agroinformativos)
Forster P *et al* 2007 Changes in atmospheric constituents and in radiative forcing In ed M Tignor *et al Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)
Gebara M F *et al* 2014 REDD+ policy networks in Brazil: constraints and opportunities for successful policy making *Ecology Soc.* **19** art53
Gui M M, Lee K T and Bhatia S 2008 Feasibility of edible oil versus non-edible oil versus waste edible oil as biodiesel feedstock *Energy* **33** 1646–53
Gunarso P *et al* 2013 Oil palm and land use change in Indonesia, Malaysia and Papua New Guinea, RSPO (www.rspo.org/file/GHGWG2/4_oil_palm_and_land_use_change_Gunarso_et al.pdf)
IEA 2012 *World Energy Outlook 2012* (Paris: OECD)
IIASAFAO 2012 *Global Agro-Ecological Zones (GAEZ v3.0)* 3rd edn (Laxenburg/Rome: IIASA/FAO) (www.gaez.iiasa.ac.at/)
Lambin E F and Meyfroidt P 2011 Global land use change, economic globalization, and the looming land scarcity *Proc. Natl Acad. Sci. USA* **108** 3465–72
Lathuillière M J, Johnson M S and Donner S D 2012 Water use by terrestrial ecosystems: temporal variability in rainforest and agricultural contributions to evapotranspiration in Mato Grosso, Brazil *Environ. Res. Lett.* **7** 024024
Lentini M *et al* 2005 *Fatos Florestais da Amazônia 2005* (Belém, Brazil: IMAZON)
Li W *et al* 2012 A process-based model for estimating the well-to-tank cost of gasoline and diesel in China *Appl. Energy* **102** 718–25
Loarie S R *et al* 2011 Direct impacts on local climate of sugar-cane expansion in Brazil *Nat. Clim. Change* **1** 105–9
Ministério do Desenvolvimento Agrário 2013 Ministério do Desenvolvimento Agrário (www.mda.gov.br/sitemda/institucional-0)
Nazareno A G 2012 Sustainable development: call to veto Brazil's forest-code revisions *Nature* **481** 29–29
Nepstad D *et al* 2014 Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains *Science* **344** 1118–23
Persson M 2012 Conserve or convert? Pan-tropical modeling of REDD—bioenergy competition *Biol. Conservation* **146** 81–8
Peters-Stanley M *et al* 2013 Maneuvering the mosaic state of the voluntary carbon markets 2013 forest trends' ecosystem marketplace & bloomberg new energy finance available at (www.forest-trends.org/documents/files/doc_3898.pdf)
Pires G F and Costa M H 2013 Deforestation causes different subregional effects on the Amazon bioclimatic equilibrium *Geophys. Res. Lett.* **40** 3618–23
Rajagopal D, Hochman G and Zilberman D 2011 Indirect fuel use change (IFUC) and the lifecycle environmental impact of biofuel policies *Energy Policy* **39** 228–33
Rudel T K *et al* 2009 Agricultural intensification and changes in cultivated areas, 1970–2005 *Proc. Natl Acad. Sci. USA* **106** 20675–80
Salin D 2011 Soybean Transportation Guide USDA (www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5098677)
Schwaiger H *et al* 2011 Technologies to Produce Liquid Biofuels for Transportation: An Overview, CIFOR (www.cifor.org/publications/pdf_files/WPapers/WP72CIFOR.pdf)
Schwartzman S, Moutinho P and Hamburg S 2014 Policy Update: Amazon deforestation and Brazil's forest code: a crossroads for climate change *Carbon Manage.* **3** 341–3
Segura-Ubiergo A 2012 *The Puzzle of Brazil's High Interest Rates* (Washington, DC: International Monetary Fund)
Serraõ E 2000 Introduction *A Cultura do Dendezeiro na Amazônia Brasileira* ed I de J M Viegas and A A Muller (Brazil: Embrapa Amazônia)
Soares-Filho B *et al* 2014 Land use cracking brazil's forest code *Science* **344** 363–4
Sparovek G *et al* 2010 Brazilian agriculture and environmental legislation: status and future challenges *Environ. Sci. Technol.* **44** 6046–53
Sparovek G *et al* 2012 The revision of the Brazilian forest act: increased deforestation or a historic step towards balancing agricultural development and nature conservation? *Environ. Sci. Policy* **16** 65–72
SUFRAMA 2003 Dendê *Superintendência da Zona Franca de Manaus Report*
Tollefson J 2011 Brazil revisits forest code *Nature* **476** 259–60
United Nations 2014 *Press release: UN Secretary-General announces new initiatives and partnerships to mobilize climate finance and promote action in cities, forests, farms and industry* (www.un.org/climatechange/summit/wp-content/uploads/sites/2/2014/05/Climate-Summit-main FINAL-PR.pdf)
Vera-Diaz M D C, Kaufmann R K and Nepstad D C 2009 The environmental impacts of soybean expansion and infrastructure development in Brazil's Amazon Basin *Global Development and Environment Institute Working paper* No. 09-05
Villela A A *et al* 2014 Status and prospects of oil palm in the Brazilian Amazon *Biomass Bioenergy* **67** 270–8
Yui S and Yeh S 2013 Land use change emissions from oil palm expansion in Pará, Brazil depend on proper policy enforcement on deforested lands *Environ. Res. Lett.* **8** 044031