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Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology

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Abstract
Biofuels from land-rich tropical countries may help displace foreign petroleum imports for many industrialized nations, providing a possible solution to the twin challenges of energy security and climate change. But concern is mounting that crop-based biofuels will increase net greenhouse gas emissions if feedstocks are produced by expanding agricultural lands. Here we quantify the 'carbon payback time' for a range of biofuel crop expansion pathways in the tropics. We use a new, geographically detailed database of crop locations and yields, along with updated vegetation and soil biomass estimates, to provide carbon payback estimates that are more regionally specific than those in previous studies. Using this cropland database, we also estimate carbon payback times under different scenarios of future crop yields, biofuel technologies, and petroleum sources. Under current conditions, the expansion of biofuels into productive tropical ecosystems will always lead to net carbon emissions for decades to centuries, while expanding into degraded or already cultivated land will provide almost immediate carbon savings. Future crop yield improvements and technology advances, coupled with unconventional petroleum supplies, will increase biofuel carbon offsets, but clearing carbon-rich land still requires several decades or more for carbon payback. No foreseeable changes in agricultural or energy technology will be able to achieve meaningful carbon benefits if crop-based biofuels are produced at the expense of tropical forests.

S Supplementary data are available from stacks.iop.org/ERL/3/034001

Keywords: tropical forests, deforestation, biofuels, carbon emissions, carbon debt

1. Introduction

The global biofuel industry is growing explosively as rising oil prices and government mandates encourage increased production of ethanol and biodiesel. Indeed, some predict that global biofuel production will quadruple within the next 15–20 years (IEA 2004, Himmel 2007, Fairless 2007). By displacing petroleum fuels, liquid biofuels may be able to provide significant reductions in greenhouse gas emissions. Realizing this potential, however, depends on how and where these fuels are produced (Farrell *et al* 2006, Hill *et al* 2006, Alder *et al* 2007).

Industrialized nations with biofuels targets, such as the United States and members of the European Union, are unlikely to have the land base needed to meet their growing demand for current-generation agricultural biofuels, which are largely produced from food and feed crops (e.g., maize, oil palm, rapeseed, soy) (Brown 2004, Hill *et al* 2006, Nepstad *et al* 2008). As a result, recent biofuel mandates are spurring feedstock production in land-rich tropical countries to help meet these rising demands (IEA 2006, MOU 2007, UN 2007).

Indeed, liquid biofuels are one of the fastest-growing markets for agricultural products globally (Mathews 2007, Fairless 2007). Well-positioned tropical countries—including Brazil, Malaysia and Indonesia—are among the leading producers of prominent biofuel feedstock crops such as oil palm and sugarcane (Johnston and Holloway 2007, FAOSTAT 2007, Dufey 2006). Simultaneously meeting the increased demand for crop-based biofuels along with the rising demand for food and feed from global trends of population growth and increasing dietary affluence, will almost certainly require expanding agricultural production at the expense of tropical ecosystems (Tilman *et al* 2001, Green *et al* 2005, Nepstad *et al* 2006, 2008, Carpenter 2005). In fact, we have already observed tropical forest clearing due to large-scale expansion of soybeans and oil palm in response to food and feed demands over the last two decades (Fearnside 2001, Nepstad *et al* 2001, Morton *et al* 2006, Koh and Wilcove 2008) and evidence is mounting that biofuel production has contributed to recent deforestation (Laurance 2007, Koh and Wilcove 2008).

Tropical ecosystems store an enormous 340 billion tonnes of carbon (Gibbs *et al* 2007), equivalent to more than 40 times the total annual anthropogenic emissions from fossil fuel combustion (Canadell *et al* 2007). This carbon is released to the atmosphere when forests and grasslands are cleared, burned and converted to agricultural systems (Eggleston *et al* 2006). Even before the emerging biofuel revolution, tropical deforestation, driven largely by agricultural expansion, already released ~1.5 billion tonnes of carbon to the atmosphere each year, accounting for ~20% of annual worldwide CO_2 emissions (IPCC 2007).

Indeed, concern is mounting that crop-based biofuels could *increase* net greenhouse gases emissions by converting natural ecosystems to biofuel plantations, potentially negating a major benefit of bioenergy systems (Righelato and Spracklen 2007, Fargione *et al* 2008, Searchinger *et al* 2008). For example, Fargione *et al* (2008) estimated that the direct impacts of biofuel crop expansion into natural landscapes could release 17–420 times more CO_2 than the annual greenhouse gas reductions biofuels provide by displacing fossil fuels. Similarly, the indirect or 'leakage' land use impacts of US corn ethanol—from land potentially converted elsewhere in the world due to the influence of changing US corn consumption patterns on the global market—have been estimated to double the greenhouse gas emissions per fuel mile compared to conventional gasoline over 30 years (Searchinger *et al* 2008).

Fargione *et al* (2008) highlight the importance of natural landscapes in storing carbon, and use the metric of ecosystem 'carbon payback time' (ECPT) of different biofuels—or how many years it takes for the biofuel carbon savings from avoided fossil fuel combustion to offset the losses in ecosystem carbon from clearing land to grow new feedstocks. However, their calculations do not take into account potential crop yield increases, 'upstream' emissions from future, non-conventional petroleum sources, or potentially revolutionary advances in biofuel feedstock and processing technology (Dale 2008, Morris 2008, Porter *et al* 2008). Here we aim to examine trade-offs between industrial and ecological carbon life cycle emissions (Righelato and Spracklen 2007, Fargione *et al* 2008) and the potential of advanced agricultural, biofuel and petroleum technologies (Brandt and Farrell 2007, Dale 2008, Lynd *et al* 2008).

We quantify the ECPT of different biofuel expansion pathways, building on the results of previous studies in two important ways. First, we use new, geographically detailed databases of crop locations and yields, along with updated estimates of global vegetation and soil carbon stocks, to provide refined, regionally specific carbon payback estimates. Furthermore, we estimate the carbon payback time under different scenarios of agricultural productivity, future petroleum sources, and biofuel technology. We attempt to inform the debate surrounding the environmental implications of biofuel expansion by examining a wide range of expansion strategies to find those pathways with the greatest promise to mitigate climate change through real reductions in carbon emissions.

2. Methods

In our analysis of the carbon costs and benefits of biofuel expansion, we define the ECPT as the number of years required for avoided fossil fuel emissions from biofuels to compensate for losses in ecosystem carbon stocks during land conversion.

$$\mathrm{ECPT} = \frac{\mathrm{Carbon}_{\text{land source}} - \mathrm{Carbon}_{\text{biofuel crop}}}{\text{Biofuel carbon savings/ha/yr}}. \qquad (1)$$

ECPT is expressed in years, and is calculated by estimating the change in ecosystem carbon stocks from converting the land source ($\mathrm{Carbon}_{\text{land source}}$) into biofuel cropland ($\mathrm{Carbon}_{\text{biofuel crop}}$) and dividing by the annual carbon savings from using biofuels in place of petroleum fuels (Biofuel carbon savings/ha/yr). Below we describe the two major terms in the equation.

Changing carbon stocks. The above and below-ground biomass carbon stocks of tropical landscapes were estimated using the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance Tier-1 methodology for reporting national greenhouse gas emissions (Eggleston *et al* 2006, Gibbs *et al* 2007). Following this approach, tropical forest carbon stocks ranged from ~200 t C/ha across the humid tropics to ~100 t C/ha in the dry tropics (table S1 available at stacks.iop.org/ERL/3/034001). Other natural ecosystems, such as grasslands and woody savannas, had carbon stock densities of ~6 to ~50, respectively (table S1 available at stacks.iop.org/ERL/3/034001). For biofuel cropping systems, we estimated the time-averaged carbon stocks as

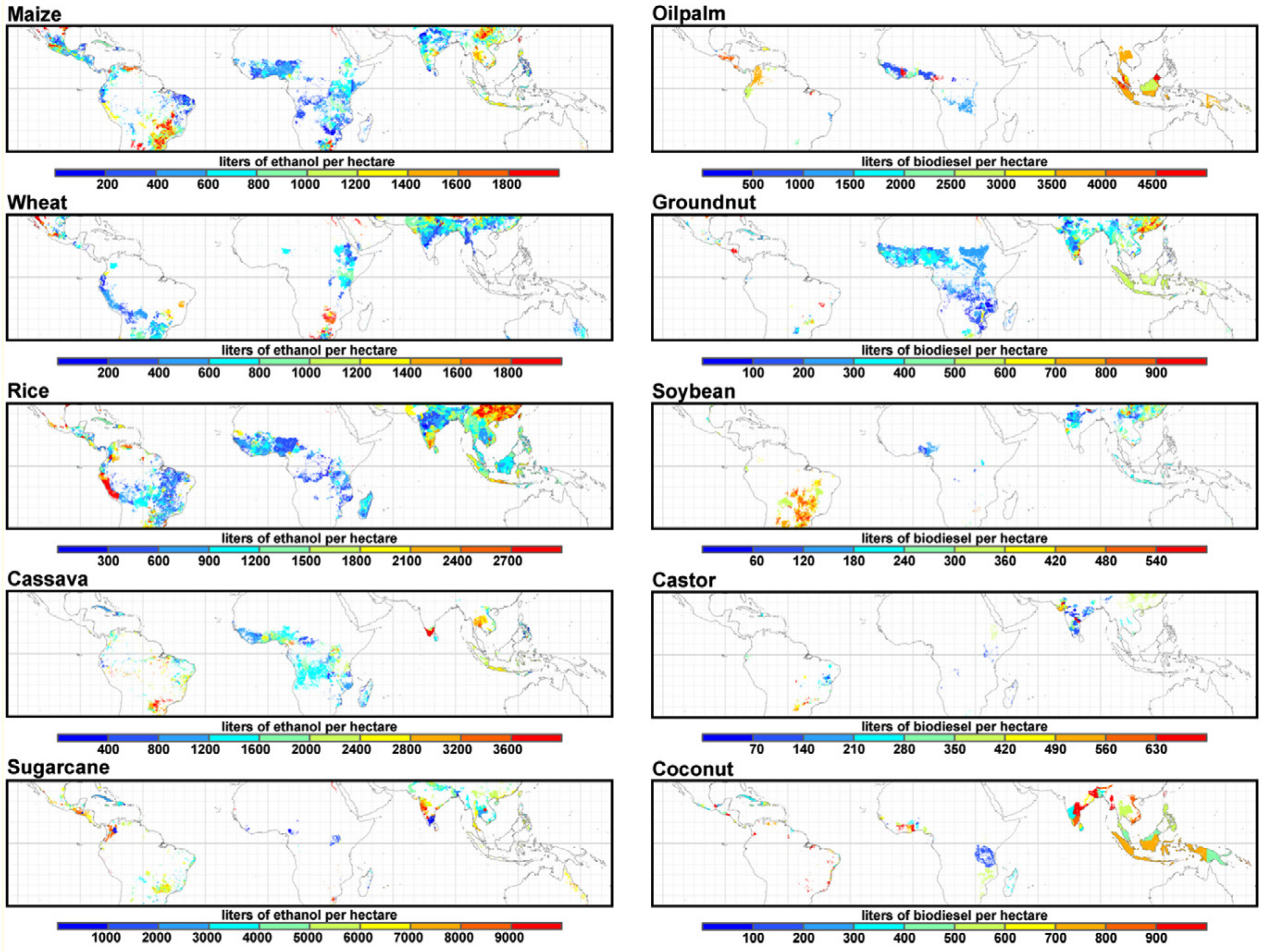

Figure 1. Potential biodiesel and ethanol yields derived from a new global database of crop yields and locations (Monfreda *et al* 2008). Agricultural census data gathered at the county, state, and country levels were combined with recent satellite-derived maps of global croplands (Ramankutty *et al* 2008) to produce the most detailed global maps of crop area and only global maps of crop yield available (5 min × 5 min of longitude and latitude spatial resolution, ~10 km × 10 km at the equator). The maps represent conditions circa 2000 but were averaged across the years 1997–2003, and thus avoid anomalous annual yields or weather fluctuations.

half the peak carbon stock at harvest (vanNoordwijk *et al* 1997). Annual biofuel crops, such as soybeans, maize and sorghum, have minimal carbon storage (~5 t C/ha) but woody plantation crops such as oil palm and coconut can temporarily store up to ~80 t C/ha (table S1 available at stacks.iop.org/ERL/3/034001). Geographically explicit soil carbon stock estimates for each land source type were derived from the Batjes (2006) database and range from ~40 t C/ha in grasslands to ~120 t C/ha in humid forests (table S2 available at stacks.iop.org/ERL/3/034001).

We calculated the change in ecosystem carbon stocks by taking the difference between initial ($\mathrm{Carbon}_{\mathrm{land\ source}}$) and final carbon stocks ($\mathrm{Carbon}_{\mathrm{biofuel\ crop}}$) (Fearnside 1997). We assumed that 25% of the soil carbon would be lost with conversion of natural ecosystems to croplands and 10% with conversion to plantations (Murty *et al* 2002, Guo and Gifford 2002, Houghton and Goodale 2004), except in the case of peat swamp soils in Southeast Asia where we followed Hooijer *et al* (2006).

Annual biofuel carbon savings. The annual carbon savings from using liquid biofuels in place of fossil fuels (Biofuel carbon savings/ha/yr) were calculated for biofuels derived from 10 prominent feedstock crops grown in humid, seasonal and dry ecoregions across Latin America, Africa and Southeast Asia (namely maize, wheat, rice, cassava, sugarcane, oil palm, groundnut, soybean, castor, and coconut). We first derived area-weighted mean crop yield estimates for each tropical region from a newly developed global crop database (Monfreda *et al* 2008). Monfreda *et al* (2008) integrate the best available agricultural statistics gathered at the county, state, and country level with a recent map of global croplands (Ramankutty *et al* 2008) to depict crop areas and yields circa the year 2000 on a 5 min × 5 min (~10 km × 10 km) latitude–longitude grid.

The conversion factors from table S3 (available at stacks.iop.org/ERL/3/034001) were then used to convert the crop yield estimates into potential biofuel yields (figure 1, table S4 available at stacks.iop.org/ERL/3/034001). Biodiesel and ethanol fuel yields were further converted to energy

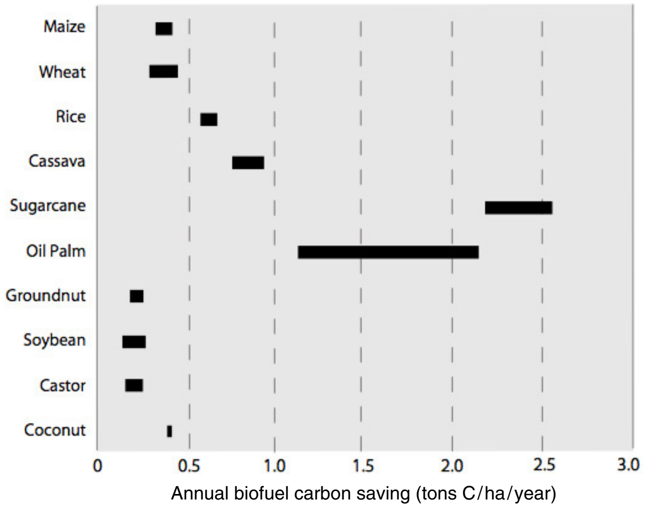

Figure 2. Estimates of potential annual carbon offsets (tons C/ha/year) from biofuels grown in the tropics. Bars indicate the range of mean annual biofuel carbon of savings across the humid, seasonal and dry tropics. Sugarcane and oil palm are the highest yielding tropical biofuel crops and consequently provide the greatest carbon offsets.

equivalents of petroleum-based diesel and gasoline, 1.09 and 1.38 per gallon, respectively, to calculate annual carbon savings from substituting biofuels for contemporary petroleum fuels (figure 2). To consider possible improvements in global agricultural yields, we repeated these calculations using contemporary 90th percentile yields for each crop (i.e. top 10%). We calculated the area-weighted 90th percentile yields for each crop by first sorting all of the global cropland data according to yield and then aggregating the area cultivated until the top 10th per cent was reached—this was done to ensure small agricultural plots with lower than normal yields would not skew the results.

In-depth biofuel energy balances for specific feedstocks production schemes have been examined and debated by others (e.g., Hill *et al* 2006, Alder *et al* 2007) and are beyond the scope of this analysis, which considers a wide range of feedstocks and locales not yet evaluated for life cycle emissions. Instead we focus on carbon emissions from land conversion and exclude emissions from the production, manufacture and distribution of biofuels, assuming that biofuel use offsets potential fossil fuel combustion with perfect efficiency. This gives biofuels the full 'benefit of the doubt' on the industrial life cycle carbon emissions. And, in this way, our carbon results can be viewed as land-conversion 'additions' that could be employed in future life cycle analyses considering specific regions, agricultural crops and production systems.

3. ECPT under current agriculture, current technology

The calculated ecosystem carbon payback times vary greatly across the tropics according to changes in carbon stocks from land conversion, and the biofuel crop yields expected in each region (figures 1 and 2). Accordingly, ECPT is longest when low-yielding biofuel crops replace carbon-rich land sources, and shortest when high-yielding biofuel crops replace carbon-poor sources (figure 3(a)).

Forests are the most carbon-dense tropical land source. As a result, clearing tropical forests to cultivate biofuel crops will lead to *net* carbon emissions (even accounting for the carbon 'savings' of biofuels) for decades to millennia. For example, the production of annual biofuel crops—such as maize, cassava, or soybeans—on deforested land requires approximately 300–1500 years of biofuel carbon savings to compensate for the initial loss of ecosystem carbon stocks. Tree plantation crops, such as oil palm, also lead to net CO_2 emissions long into the future, with biodiesel compensating for forest carbon losses only after 30–120 years for non-peat soils, and after more than 900 years for forests growing on peatlands in Southeast Asia. Carbon emissions from agricultural conversion of even a logged or otherwise diminished forest still require several decades.

On the other hand, the expansion of biofuel crops into non-forest ecosystems requires less payback time. In woody savannas, several decades to centuries of biofuel production can offset ecosystem carbon losses, while grasslands require less than 100 years to offset losses in most cases. There are some tropical land sources where biofuels can provide a short-term carbon payback: the conversion of already degraded lands provides nearly immediate carbon payback because the biofuel crops can *increase* ecosystem carbon storage while simultaneously offsetting fossil carbon emissions. For instance, biofuel expansion into West Africa's degraded scrublands, where cocoa plantations once grew, could provide carbon savings immediately. Replacing highly degraded Amazonian pastures, or degraded regions of Southeast Asia where shortened fallow cycles have greatly reduced land productivity, could also provide both land restoration and carbon benefits. However, growing biofuel crops on these marginal lands may require significantly more land area than other regions due to relatively lower yields, and will likely require more energy-intensive management such as fertilizer application or irrigation to remain productive.

Utilizing existing croplands and pastures for biofuel feedstock production may also be carbon beneficial in the short term. But if the pressure to expand biofuel crops simply 'pushes' existing agricultural lands needed for food or feed further into the agricultural frontier, then biofuels development could indirectly spur increased conversion emissions. For example, soy expansion in southeastern Brazil, largely in response to global demand for animal feed, indirectly expanded the 'arc of deforestation' by pushing smallholder farmers and cattle ranchers deeper into the Amazonian rainforests (Fearnside 2001, 2003, Morton *et al* 2006, Nepstad *et al* 2006, 2008). Similarly, smallholder farmers on agricultural frontiers in parts of Southeast Asia are sometimes replaced by agro-industrial estates, pushing these largely subsistence farms further into the highland forests (Lambin and Geist 2003).

In short, our analysis shows that the carbon benefits of biofuels are strongly influenced by the geographic

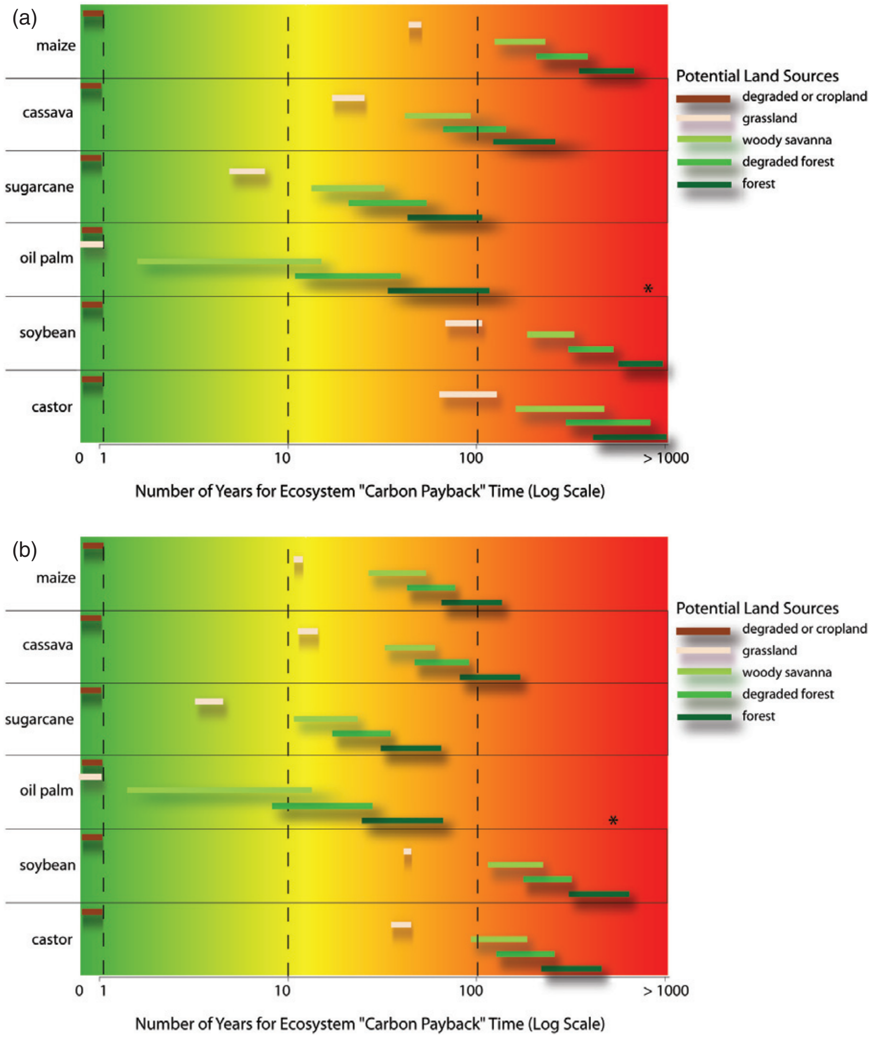

Figure 3. The ecosystem ‘carbon payback’ time (ECPT) for potential biofuel crop expansion pathways across the tropics[4]. The bars represent the range of ECPT across the humid, seasonal and dry tropics for different combinations of land sources and biofuel feedstock crops across the tropics[5]. The green to red background represents a stop light—indicating green for ‘go’ in replacing degraded lands, yellow for ‘caution’ in replacing grasslands, woody savannas and red for ‘stop’ replacing forests for biofuel crop expansion. In (a) we show the payback period for potential biofuel production based on crop yields circa 2000 as reported in Monfreda *et al* (2008). Note that ‘$*$’ indicates the 918 year payback time if oil palm expands into peat forests. In (b) we show the potential payback period if all crops achieved the top 10% global yields through gradual or abrupt improvements in agricultural management or technology. Yield increases for crops such as maize, castor and rice have the largest impact on ECPT because these crops were substantially below global 90th percentile yields, while sugarcane, soybeans and oil palm were already high yielding so the change has a smaller impact. Note that ‘$*$’ indicates the 587 year payback time if oil palm expands into peat forests.

location, land source and crop yields for newly expanding agricultural feedstocks. Expansion may be carbon beneficial in some limited regions, yet not at all in many others, as demonstrated by ECPT variation across continents and ecoregions (tables S5a, S5b and S5c available at stacks.iop.org/ERL/3/034001). Our more detailed, regional analysis shows the shortest ECPTs are generally found in Latin America followed by Southeast Asia and then Africa. All three continents have similar ecosystem carbon contents, but Africa generally has lower yields for most biofuel crops and consequently has much higher carbon payback times in some cases. It is important to note that these results are based on *current* global patterns of crop yields, which could improve with changes in agricultural management and biotechnology.

These results largely confirm the recent analysis by Fargione *et al* (2008), which considered five cases of biofuel expansion and concluded that clearing tropical forests and grasslands to produce biofuels leads to long-term carbon debt while only converting degraded lands will provide carbon

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[4] Numbers presented in this figure were averaged across the pan-tropics. Variations in ECPT according to continent and ecoregions are described in tables S5 a, b, c (available at stacks.iop.org/ERL/3/034001). Only 6 of the 10 biofuels crops are depicted here and the grassland category is excluded to simplify the figure; see supplementary information for full detail.

[5] The annual biofuel carbon offsets shown here were calculated for conventional petroleum sources. Petroleum derived from tar sands, likely to be the only other major source of liquid transportation fuels over the next two decades, would decrease payback time for all land sources and crop types by 25%.

savings. Our study differs from Fargione *et al* (2008) in terms of the exact magnitudes of the carbon payback time, in part because our analysis is more geographically detailed, relying on thousands of different data sources for *reported* crop yields. Thus we provide more comprehensive estimates of ECPT and highlight important regional variations by considering a wider range of potential feedstock crops and land sources. However, a rigorous quantitative comparison is challenging due to the different approaches and assumptions used in each study (e.g., different assumptions about agricultural co-products, carbon stocks and emissions, and biofuel life cycle emissions).

4. ECPT under changing agricultural and energy technology

The ECPT results presented above were estimated using *current* patterns of global crop yields, biofuel technologies and fossil fuel production efficiencies. These results, however, could be affected by expected future changes in cropping and energy systems. To account for these possible changes, we estimate ECPT with different assumptions about future crop yields, biofuel technologies and fossil fuel sources. Increases in crop yields and the continued development of more carbon-intensive petroleum sources, can be viewed as scaling factors that will modify our results, but not our core analysis. Advanced, lignocellulosic biofuels from non-agricultural feedstocks, on the other hand, will likely require new analyses as the crop sources, yields, and production processes are largely unknown and thus highly uncertain at this time (Royal Society 2008).

4.1. Improved crop yields

Crop yield improvements could substantially increase biofuel production per hectare and in turn reduce the carbon payback time. Global yield increases are projected to be gradual, approaching ∼1–2% per year (IEA 2004, Bruinsma 2003, Rosegrant *et al* 2006). However, crop yields across much of the tropics are roughly half the yields achieved under more intensive management practices for many crops (table S3 (available at stacks.iop.org/ERL/3/034001); Monfreda *et al* 2008, Johnston *et al* 2008), and the gap between tropical and more managed agriculture is expected to converge, with tropical yields increasing rapidly if the price of food and biofuel commodity crops continue to rise. Regions characterized by less-intensive, smallholder agriculture—such as Sub-Saharan Africa—likely have the greatest opportunity for dramatic yield increases through 'green revolution' or future advances in agricultural technology including: efficient management and mechanization, optimal applications of fertilizer, irrigation and pesticides, and regionally tailored crop strains from advances in biotechnology and breeding programs. To account for potential yield increases, we re-estimate ECPT using the 90th percentile global crop yields derived from the Monfreda *et al* (2008) crop database. Our assumption that tropical farms could achieve the yield of the top 10% of global farms today is likely optimistic, but this approach offers an upper bound on how future yield advances tailored to these areas could affect ECPT.

We find that carbon payback times would be substantially reduced if median tropical crop yields approached the top yields currently achieved around the world (figure 3(b)). The ECPT would be cut roughly in half for feedstock crops such as soy, castor, and rice, which have large gaps between average tropical yields and maximum yields in comparable growing conditions ('yield gaps'). For highly productive tropical crops, such as sugarcane, oil palm and cassava, ECPT values would be reduced by a third. The carbon payback for maize, which has the largest yield gap, would decrease by a factor of five with dramatic increases in crop yield.

Despite the significant reductions in ECPT from crop yield increases, many biofuel expansion pathways would still require extremely long carbon payback times. For example, several decades to centuries are needed to compensate for the carbon debt generated from clearing forests, even with the highest yielding biofuel crops (figure 3(b)). In fact, biofuel production from crops such as soybeans, castor and cassava will likely never become carbon beneficial based on yield increases alone. Comparing figures 3(a) and (b), showing the effects of increasing yields on the carbon payback time, we find that only degraded or previously cleared lands and some grasslands can achieve carbon benefits within a decade, and even then only for the most efficient feedstock crops achieving top yields.

Thus, increasing yields of tropical crops can improve the carbon payback time of biofuel production, but the potential impact is still extremely limited. Furthermore, our calculations likely present an overly optimistic analysis: these heightened yields will require additional fertilizer, irrigation and mechanization that may increase other greenhouse gas emissions not accounted for in this analysis, particularly in marginal lands (Royal Society 2008).

4.2. 'Upstream' emissions from conventional and future petroleum sources

Conventional oil supplies may be nearing peak production, and future, unconventional petroleum sources will be more energy intensive to produce (Farrell and Brandt 2006, Brandt and Farrell 2007). Some estimate that higher 'upstream' emissions from unconventional fuels could increase the net CO_2 emissions by ∼17–30% for tar sands and heavy oils, ∼75% for coal-to-liquid synthetic fuels, and from 30% to more than 250% for very low grade oil shale resources (Bergerson and Keith 2006, Brandt and Farrell 2007). Among these options, the International Energy Agency (IEA 2006) estimates that only tar sands production will contribute significantly to global oil supplies within the next two decades.

The carbon payback time from biofuel expansion will be shorter if we compare biofuel carbon savings against these unconventional fossil fuel sources instead of today's gasoline and diesel fuels. Here we focus on tar sands and calculate the ECPT assuming a ∼25% increase in upstream emissions from fossil fuel combustion. Our results show that even if biofuels are compared to carbon emissions from oil sands, the story remains much the same—several decades to centuries are still required to replace lost forest carbon stocks while converted grasslands require less than 50 years in many cases, and converting degraded lands will quickly provide carbon savings.

Moreover, roughly 95% of the world's petroleum supply still comes from conventional sources and even the rapidly increasing production of oil sands is only expected to comprise ∼4–8% of global oil production in 2030, in part due to the higher costs of producing these synthetic fuels (EIA 2005, IEA 2006). Consequently, over the near term biofuels will largely be offsetting emissions from conventional petroleum sources.

It is important to note that our ECPT analysis has excluded life cycle or 'upstream' emissions from *both* contemporary petroleum and biofuels to ensure fair comparison, especially considering that detailed upstream emissions estimates for most biofuel feedstocks produced across the tropics are not yet available. Accounting for upstream emissions from contemporary gasoline and diesel sources would increase our current ECPT benchmark by ∼20% (Brandt and Farrell 2007) and scale back the biofuel carbon payback time accordingly. However, including generalized estimates of upstream emissions to grow, produce and transport would decrease biofuel carbon offsets used here by ∼80% for corn-ethanol, ∼20% for cane-ethanol and ∼60% for soy-biodiesel (Hill *et al* 2006), thereby increasing the carbon payback time.

4.3. Advanced biofuel technology

Future biofuel technologies, including advanced fuels, feedstocks and processing plants, are expected to be more efficient, and thus decrease the carbon payback time for biofuels. A new generation of transportation fuels based on lignocellulosic biomass from switch- and prairie-grasses, trees and forestry waste, and non-grain parts of crops could provide major improvements in biofuel carbon offsets (Lynd *et al* 2008). Many of these advanced feedstocks could be efficiently produced on marginal or degraded land (Tilman *et al* 2001, 2006), and consequently would create much less ecological carbon debt (Fargione *et al* 2008). Advanced ethanol or biodiesel plants running on biomass or waste products, rather than fossil fuels, would reduce greenhouse gas emissions even more.

However, even if second-generation cellulosic technologies were to double the ethanol yield per unit crop mass of sugarcane—the most productive feedstock crop today—more than three decades would still be required to replace lost rainforest carbon. Advanced technology biofuels will dramatically improve many processing pathways, but we estimate that no foreseeable technologies can make tropical deforestation for biofuel crop expansion a carbon beneficial enterprise.

Furthermore, second-generation fuels, such as cellulosic-ethanol and algae-biodiesel, and biofuels utilizing non-food feedstock crops, such as jatropha and switchgrass, are not expected to offer a viable, large-scale alternative to contemporary feedstocks until the 2020s or later (IPCC 2007, Himmel 2007, Fairless 2007). Unfortunately, this means that most biofuel expansion over the next decade will rely on less efficient, current-generation feedstocks and technology.

5. Additional considerations

The potential scenarios described in section 4 are critical considerations for evaluating expanding bioenergy systems, but aside from gradual yield increases, none are expected to contribute significantly to global biofuel supplies in the next decade. So while we illustrate how future changes in biofuel, agricultural and petroleum technologies paint a more optimistic picture, it is important to note that these technological advances are not immediately available.

Our analysis focuses on carbon emissions from biofuel expansion, but other drawbacks to implementing biofuels must also be carefully weighed. For instance, crop-based biofuels have been implicated in recent and projected food price hikes, which are likely to affect the most food insecure people (Naylor *et al* 2007). Other important greenhouse gases such as methane and nitrous oxide are not considered here, but are expected to increase with agricultural biofuel expansion due to increased fertilizer and irrigation use particularly in marginal lands (e.g. Crutzen *et al* 2007), which may worsen ocean hypoxic zones (Donner and Kucharik 2008) and otherwise affect the chemical balance of the atmosphere and hydrosphere. Additionally, increasing the role of biotechnology in tropical agriculture is still a highly contested issue due to the uncertainty and scale of the risks it may pose (Herdt 2007). Biodiversity and other ecosystem services including disease regulation and watershed maintenance, all would also likely be degraded by cropland expansion in tropical forests and grasslands (Scharlemann and Laurance 2008).

On the other hand, biofuels have many benefits that cannot be easily dismissed. Depending on how and where they are produced, some biofuels will help reduce petroleum dependence from foreign suppliers, improve air quality, support agricultural economies, improve trade balances, and increase rural income through increased employment (Mathews 2007, Royal Society 2008). The local use of liquid biofuels across the developing world may increase access to reliable energy (especially through electricity generation), thus spurring rural development and improving quality of life (UN 2007, Royal Society 2008).

6. Summary and conclusions

This study presents an analysis of direct carbon impacts of crop-based biofuel expansion in the tropics, and addresses major criticisms levied at recent studies. In addition to presenting a geographically specific analysis of carbon budgets under current biofuel production practices, we evaluated the impact of increased crop yields, advanced biofuel technology, and carbon emissions from unconventional petroleum sources on ECPT. As such, we attempt to clarify aspects of the debate between concerns of industrial and ecological carbon life cycle emissions (e.g., Righelato and Spracklen 2007, Fargione *et al* 2008) and the potential of changing agricultural, biofuel and petroleum technologies (Dale 2008, Morris 2008, Porter *et al* 2008).

This new analysis, based on recently developed, geographically explicit crop and carbon stock databases, largely confirms the conclusions of Fargione *et al* (2008) that biofuel expansion into natural tropical ecosystems will lead to net carbon emissions for decades to centuries in most cases. Expansion of contemporary feedstocks into tropical forests will lead to net carbon emissions for ∼40–120 years with the most productive biofuel crops, and for ∼300–1500 years with lower yielding biofuel crops, such as maize and soybeans. However, we also find that some biofuel expansion pathways may achieve carbon savings within a decade. Substantial carbon benefits are possible from expanding high-yielding crops, such as sugarcane and oil palm, into already degraded lands. Replacing other crops with agrofuels may also yield carbon savings provided these croplands are not displaced into tropical ecosystems elsewhere. In short, we find that the expansion pathways and geographic locations for increasing biofuel crop production exert great influence on their net carbon emissions.

Our results also show that future carbon payback times could be substantially shorter with increases in crop yields, changing petroleum sources and improved biofuel technology. Crop yield increases from gradual improvements or more revolutionary management changes fueled by high market prices, will reduce carbon payback times by ∼30–50%. In addition, the baseline ‘upstream’ CO_2 emissions from gasoline or diesel fuel used to estimate biofuel carbon offsets will likely increase by another ∼25% as petroleum is produced from more energy-intensive tar sands over the next two decades. These processes, combined with increases in advanced or cellulosic feedstock processing, could substantially reduce carbon payback times and make expansion of highly productive biofuel crops into grasslands or disturbed forests more carbon beneficial.

However, converting tropical rainforests requires ∼30–300 years for carbon payback for all feedstock crops, even when accounting for these major changes in energy and agricultural technology. We argue that the carbon payback times for clearing tropical forests are unacceptably large in the context of any reasonable carbon mitigation efforts. It is hard to imagine any plausible scenarios where clearing tropical forests for agricultural biofuels could be carbon beneficial.

Moreover, these changes in technology require further research, development, and investment before they will impact global biofuels supplies (IEA 2006). As a result, only the carbon payback times under *current* conditions should be considered for *immediate* policy decisions. Navigating the waters between current decisions and future technologies is a major challenge: how long will we use current agricultural systems and biofuel technologies until next-generation methods are available, and how can we avoid serious environmental damages in the meantime? How do we move through these technical, policy and market transitions, striking a balance between supporting developing markets and technologies, while minimizing the unintended environmental and social costs? In the meantime, rising biofuel demand may unintentionally increase greenhouse gas emissions to the atmosphere through increased pressure on carbon-rich tropical ecosystems, particularly over the next decade while we rely on current-generation technology. These increased emissions could be particularly problematic if they push our changing climate system closer to dangerous tipping points.

Indeed, as we look to the future—with growing population, increasing dietary affluence, and increasing energy demands—agricultural expansion in the tropics to produce food, feed and fuel appears inevitable. Global demand for feed and food is expected to nearly double in the next half-century, and demand for transport fuels will increase even faster (IEA 2006)—with both factors adding pressure on tropical forests (Searchinger *et al* 2008, Nepstad *et al* 2006, 2008). Thus, it is critical that we move quickly to provide policy and economic incentives to protect tropical forests (Santilli *et al* 2005, Gullison *et al* 2007), while other potentially carbon beneficial pathways for biofuel expansion are explored.

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