# Greenhouse Gas Implications of Land Use and Land Conversion to Biofuel Crops

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## Biofuel Production and Land-use Issues

Globally, there is a large interest in finding renewable fuels to substitute for petroleum-based fuels, with the dual purpose of enhancing energy security and mitigating climate change. Biofuels such as ethanol and biodiesel are potential options for meeting these needs in the transportation sector (IPCC 2007). Volatile oil prices and uncertainty about sustained oil supplies have added a sense of immediacy to the search for fossil fuel substitutes. In response to these pressures, a number of countries have already set targets for substituting biofuels for diesel and gasoline, with proportions ranging from 5% to 20%, to be met at various times within the period 2010-2030.

Production of first -generation biofuels requires cultivation, processing, and transportation of feedstocks, all of which lead to greenhouse gas (GHG) emissions. Presently, biofuels are produced from conventional food and feed crops such as sugarcane, maize, soybean, sweet sorghum, and oil palm. Technologies for the conversion of lignocellulosic feedstocks, such as perennial grasses or short rotation woody crops, have yet to become commercially viable. The emissions from biofuel production and processing have been well studied with a classic life cycle approach (LCA), showing that, except for maize ethanol grown in energy intensive agrosystems in the U.S., most biofuels have net GHG savings between 20% and 90% (Thow and Warhurst 2007) relative to fossil fuels. However, these estimates do not include emissions from land use change, which may be significant, depending on how biofuels are produced.

Increasing biofuel production to meet the political targets set requires crop expansion, leading to direct and, in many instances, indirect land-use change (LUC). Direct LUC occurs when additional cropland is made available through the conversion of native ecosystems such as peat lands, forests, and

grasslands, as well as by returning fallow or abandoned croplands to production. Indirect LUC can occur when land currently cropped for non-energy production is diverted for biofuel feedstock cultivation. The diverted crops must then be made up for by converting other arable land, usually native systems. Studies have shown that the possible GHG emissions from the induced LUC can substantially influence the climate benefit of biofuels production and use (Leemans et al. 1996; Schlamadinger et al. 2001; Fargione et al. 2008; Searchinger et al. 2008; Gibbs et al. 2008). Recent studies by Fargione et al. (2008) and Gibbs et al. (2008) show that land-use conversion from native land-uses to biofuel crops lead consistently to significant GHG emissions and a negative carbon balance, or carbon-debt, for decades to centuries. The only instances where clearing native habitat for food-based biofuel crops has a payback time of less than ten years is for grasslands converted to sugarcane or oil palm, because these are the lowest carbon ecosystems and the highest yielding crops (Gibbs et al. 2008). Palm is best suited to areas currently containing rainforest, so the scenario of grassland conversion to oil palm is unlikely.

Cropland and abandoned cropland are potential sources of land for biofuels. Currently cropped land will have no direct carbon debt, but may have indirect effects, as mentioned above. Abandoned cropland is often suggested as an ideal source of land for biofuel production (Campbell et al. 2008). However, after cropland is abandoned it may accumulate carbon, which typically takes many decades to return to prior carbon levels. This accumulated carbon in abandoned cropland is lost when converted back to cropland. For example, in the U.S. there were 15 Mha of abandoned cropland in the conservation reserve program (CRP) in 2007. CRP land is primarily planted to grasses, which accumulate

about 0.69 tons $CO_2$ ha$^{-1}$ annually and have been abandoned for about 15 years on average (Fargione et al. 2008). Other abandoned cropland reverts to forests (Campbell et al. 2008), which accumulate and store larger amounts of carbon than do grasslands. In some cases, abandoned cropland may have accumulated negligible amounts of carbon either because it was only abandoned recently or because degradation has limited new carbon inputs from plant growth. Overall, abandoned cropland has the advantage that it does not compete with food production, does not cause clearing of native ecosystems, and emits less carbon than natural ecosystems. However, some abandoned cropland, such as CRP in the U.S., serves some of the same functions as do natural ecosystems, including as important wildlife habitat (Haufler 2005).

Studies have also highlighted that land-use conversion and cultivation of food-based biofuel crops could have adverse impacts on food security, biodiversity, and water (IEA 2006; IPCC 2007; Thow and Warhurst 2007; RFA 2008; Royal society 2008). Second-generation biofuels use less or no water for irrigation, will not compete with food if grown on abandoned or marginal cropland, and may maintain or increase habitat if grown in ways that are compatible with wildlife (FAO 2008b). These issues are considered in the subsequent chapters of this report.

Assessment of the GHG implications of land-use and land conversion to biofuel crops is a very complex and contentious issue. A complete assessment of the GHG implications would require an accounting of the following: all GHG emissions associated with growing, processing and transporting the biofuel; the land categories that will be cleared in response to increased biofuel demand (peat land, forest land, crop land, marginal lands, etc.); the carbon stocks present in those land categories

along with the rates of release of carbon associated with land conversion; potential carbon uptake rates in those land categories if the current land-use pattern continues; the quantity of petroleum fuels to be replaced by biofuels to meet the projected demand; the biofuel crops selected (oil palm, jatropha, soybean, sugarcane, maize, etc); biofuel yields and the likely rates of change in future yields; the quantities of byproducts of biofuel crops and their potential uses (such as livestock feed, energy generation from sugarcane bagasse, etc). The present assessment is limited due to the lack of data required to address all of these issues.

In this chapter, we explore one scenario of significantly increased first-generation biofuel production to make a preliminary estimate of the potential GHG emissions associated with land use change at the global level. We first estimate the demand for diesel and gasoline for transportation sector based on the Energy Information Administration (EIA 2008) for 2030. Second, we calculate the land required for production of biofuels assuming a scenario where 10% of the projected diesel and gasoline demand of transportation sector for 2030 will be met by biodiesel and ethanol, respectively. The land requirement is estimated considering different biofuel crops and indicative yields of biodiesel and ethanol crops; no attempt is made to consider the potential changes in the yields of biofuel crops, although we briefly discuss the factors that are likely to affect biofuel crop yields. Finally, we estimate the potential carbon dioxide ($CO_2$) emissions from land use change, considering 1) different scenarios of land conversion with different biodiesel and ethanol crops; 2) the area under the biofuel crops; and 3) the mean annual $CO_2$ emissions per hectare due to land-conversions based on Fargione, et al. (2008). In this paper we focus only on $CO_2$. The $CO_2$ emission

estimates are preliminary and do not include the following:

- Indirect emissions due to land conversion and use for biofuel crops leading to additional land conversion to substitute any loss of production (e.g. food grains, grazing, or fuel wood) from the land used for biofuel production.

- Land and carbon emission offsets due to byproducts (e.g. livestock feed production from oil-seeds or maize and electricity production from sugarcane bagasse).

We do include carbon sequestration in the degraded lands in the absence of biofuel production but assume that other ecosystems are in equilibrium and are thus not storing carbon.

Potential conversion of forest land for biofuel crops is not considered, except for palm oil production, since the land assumed to be converted to biofuel crops largely belongs to permanent pasture category of 'Agricultural area' which includes both cropped land (i.e. 'arable land' + permanent crops) and permanent pastures. The location for biofuel production will vary depending upon the region of the world. De Vries et al. (2007) suggest that grassland will be the primary target for biofuel expansion. Furthermore, many countries such as India and China have policies prohibiting conversion of forest land for crop production including that for biofuels.

**Targets for biofuels in different regions**

Based on the potential of biofuels in mitigating climate change and enhancing energy security, countries have moved quickly to set up targets for fossil fuels substitution by biofuels (FAO 2008b). For example, India has announced a target of 5-10% of ethanol blending and 20% biodiesel blending by 2017,

the European Union 10% by 2020, with UK aiming at 5% blending by 2010, China with 15% transportation energy needs to be met through biofuels by 2020 and different states in the U.S. have announced different targets ranging from 7% to 20% over different periods. IEA (2006) assumes that even under the Advanced Policy Scenario biofuels will constitute only 7% of the demand by 2030. We consider the effects of a 10% biofuels substitution by 2030, which represents a scenario in which aggressive biofuel goals are set and achieved. This is the upper bound of scenarios considered by the IPCC (2007), which suggests that biofuels will grow to 3% of total transportation energy demand by 2030 under the baseline scenario,

Table 6.1 Area (Mha) under agriculture, arable land, permanent pasture, and forest during 2005. (Source: FAOSTATS; FAO Metadata: www.fao.org/metadata)

| Regions | Land Area[a] | Agriculture[b] | Arable[c] | Perm. Pasture[d] | Forest[e] |
|---|---|---|---|---|---|
| Asia | 3096.6 | 1675.0 | 511.5 | 1097.9 | 571.5 |
| Africa | 2963.6 | 1145.9 | 213.1 | 906.6 | 635.4 |
| South Africa | 265.2 | 168.2 | 16.5 | 150.7 | 29.4 |
| India | 297.4 | 180.2 | 159.7 | 10.5 | 67.7 |
| China | 932.7 | 556.3 | 143.3 | 400.0 | 197.3 |
| Latin America | 2005.8 | 708.7 | 139.3 | 551.3 | 918.2 |
| **World** | **13013.5** | **4967.6** | **1421.2** | **3405.9** | **1001.4** |

[a] Total land area excluding areas under inland water bodies. The definition of inland water body generally includes major rivers and lakes

[b] Agricultural area refers to (i) arable land (ii) permanent crops - land cultivated with crops that occupy the land for long periods and need not be replaced after each harvest - and (iii) permanent pastures. Agricultural land does not include forest land as per FAO.

[c] Arable land refers to land under temporary crops (double cropped are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens, and temporarily fallow land (less than 5 years)

[d] Permanent pasture refers to land used permanently (5 years or more) for herbaceous forage crops, either cultivated or growing wild (i.e. Wild prairie or grazing land)

[e] Land under natural or planted stands of trees, whether productive or not. This category includes land from which forests have been cleared but that will be restored in the foreseeable future, but it excludes woodland or forest used only for recreation purposes
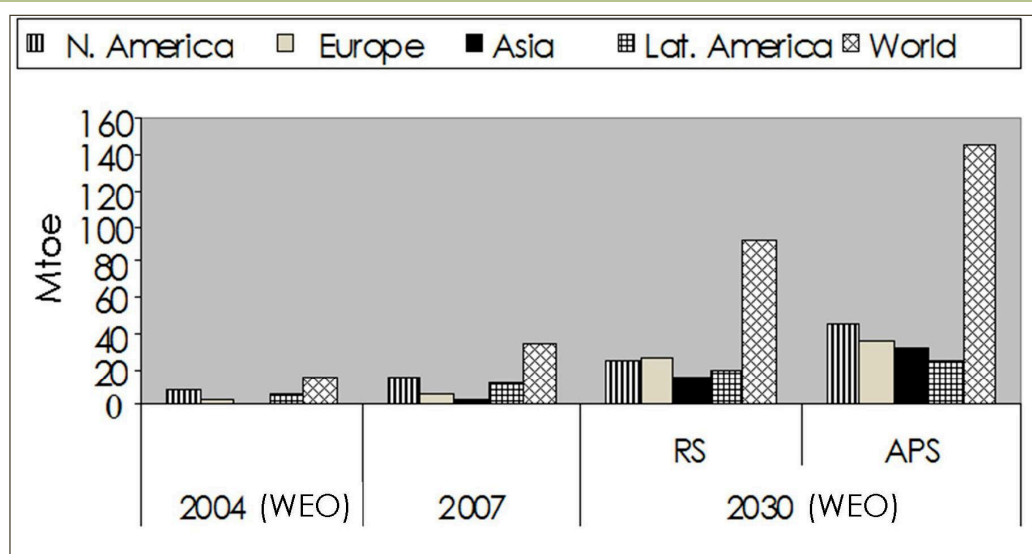
Figure 6.1 Current and projected biofuel consumption (Mtoe). Reference scenario (RS) assumes that no new government policies are introduced during the projection period (to 2030). This scenario provides a baseline vision of how global energy markets are likely to evolve if governments do nothing more to affect underlying trends in energy demand and supply. The Advanced Policy Scenario (APS) analyzes the impact of a package of additional measures aimed at addressing energy security and climate change concerns. This scenario illustrates the implications of policies currently under discussion. (Source: IEA/OECD World Energy Outlook 2006, FAPRI 2008, 2007, RFA 2008)

but could increase to about 5-10% by 2030, depending on future oil and carbon prices and technological developments.

**Past, Current and Future Trends in Land Use**

Total agricultural area consists of "arable land", "permanent crops", and "permanent pasture" according to FAO. Global and continental land areas are presented in Table 6.1. Globally, arable land (i.e. land that is planted to temporary crops or is temporarily fallow) accounts for 28% of the total agricultural area of 4967 Mha. Permanent pasture is the most dominant use of agricultural area, accounting for 68%. This indicates a very low intensity cattle production on a large share of the land claimed. Arable land for food production is projected to increase by 6% by 2015 compared to 1999 (956 Mha), plus an additional 6% by

2030 (FAO 2008a). Biofuel expansion would increase arable land in addition to that required to meet increased demand for food. Such an increase is likely to come from the conversion of permanent pasture or forests (particularly in developing countries). However, the notion that large areas of pastures/grasslands and marginal/degraded lands are available for biofuel crop production must be verified in relation to water availability and use.

**Projected Biofuel Demand for Transportation**

Global biofuel consumption has more than doubled in recent years, from 28 billion liters in 2004 (IEA 2006) to 62 billion liters during 2007 (RFA 2008 and FAPRI 2008). Various projections are available for the future global demand or consumption of biofuels, as well

as in key countries and regions. For example, OECD/FAO (2008) projects an annual growth in consumption by 6.6% for biodiesel and 5.12% for ethanol, during the period 2008-2017 under its Current Trend Scenario. IEA (2006) projects that biofuel consumption will increase from 35 billion liters in 2005 to 160 billion liters in 2030 under its Reference Scenario and to 255 billion liters under the Alternate Policy Scenario (Figure 6.1).

We estimate projected demand for biofuels based on projections for total petroleum oil demand for transportation for 2030 (EIA 2008), and assume a 10% substitution by biofuels. We also assume the diesel and gasoline ratio in 2030 is identical to the ratio in 2005 (45.5% diesel and 54.5% gasoline). To be consistent with IPCC 2007 and IEA 2006, the biofuel demand, corresponding land requirement, and resulting $CO_2$ emissions from land use change projections are made for the year 2030.

Total demand for petroleum fuels for transportation is estimated to be 3390 Mtoe of oil (EIA 2008). The share of OECD and non-OECD is nearly equal (~50% each). Globally, 179 Mtoe of biodiesel and 289 Mtoe of ethanol are required to substitute 10% of the projected diesel and gasoline consumption by 2030 (Table 6.2). The scenario of 10% biofuel use is significantly higher than some other projections of future biofuel use. IEA-WEO projects that biofuels will substitute 4% and 7% of transport fuel demand in 2015 and 2030 respectively (IEA 2006).

## Land Required For Producing Biofuels

Demand for land needed for food, animal feed and biofuels is rising leading to increased pressure on land and other resources, such as water. Estimates of future demand for land for these activities are highly uncertain (RFA 2008). Thus, the calculations of land required

for producing biofuels and potential competition for other uses (particularly for food production) should be considered as indicative only. Land required for producing biofuels to meet the projected demand for 2030 is estimated by taking the total biofuel demand and dividing it by indicative average biofuel yield per hectare. Estimated land used for biofuel production in 2004 is 13.8 Mha, accounting for about 1% of global cropped area (IEA 2006). We estimate that the land used for biofuels was about 26.6 Mha in 2007 (Figure 6.1).

*Biofuel yields.* Estimation of land required for meeting the projected biofuel demand must account for future potential yields. The biofuel crop yields could increase or decease depending on the varieties of biofuel crops used, the land category considered, the soil quality and cultivation practices such as fertilizer and irrigation use, etc. Where improved crop varieties and increased inputs will likely cause crop yields to increase, expansion of crops onto marginal lands will reduce yields. Further, increased biofuel production may cause "price-induced yield increases"; in other words, increased demand of biofuels may increase crop prices, causing farmers to invest in higher yielding seed and increased fertilizer addition and agronomists to increase investment in plant breeding and other technological advances, all of which could lead to yield increases. Trends in crop yield over time are available for some biofuel crops such as sugarcane and maize, but not for biofuel crops such as jatropha and oil palm. Given these uncertainties, and in the absence of quantitative alternative estimates, we assume constant biofuel yields. Yields are roughly based on current average global yields (see footnote to Table 6.3). Although current biofuels are primarily produced by countries with relatively high yield, under our scenario of major expansion of biofuel production,

Table 6.2 Projected petroleum demand (in Mt) for transportation (EIA, 2008) and the associated biofuel demand (in Mt) assuming a 10% substitution for Year 2030
a Diesel and gasoline consumption for 2030 is calculated @ 45.5% share for  diesel and 54.5% share for gasoline demand - based on 2017 projected ratio of diesel and gasoline consumption, FAO/ OECD 2007.
b 1 t Biodiesel = 0.86 toe; 1 t Bioéthanol = 0.64 toe; Source: EIA, 2008 for transportation oil demand.

| Region | Transport Oil Demand for 2030[a] | | | Biofuel Demand in 10% substitution scenario for 2030[b] | |
|--------|-------|--------|----------|-----------|------------|
| | Total | Diesel | Gasoline | Biodiesel | Bioethanol |
| OECD | 1725 | 785 | 940 | 91 | 147 |
| Non-OECD | 1665 | 758 | 907 | 88 | 142 |
| **World** | **3390** | **1542** | **1848** | **179** | **289** |

global average yields are an appropriate indicator of potential global land demand.

*Scenarios for estimating land for biofuels.* Our scenarios are intended to illustrate simple examples of the potential impact of different biofuel crops on land demand. We consider scenarios where a single biofuel crop is projected to meet 100% of the biodiesel or ethanol requirement estimated for 2030, assuming 10% petroleum substitution (Table 6.2). Under each scenario, either jatropha, palm, or soybean will meet the 100% of the projected demand for biodiesel, while either maize, sugarcane, or sweet sorghum will meet the 100% of the projected demand for ethanol.

*Land required.* Total global land required to meet the biodiesel demand is estimated to be 173 Mha for jatropha, 48 Mha for palm oil, and 361 Mha for soybean. Similarly, the land required for meeting the ethanol demand is estimated to be 147 Mha for maize, 70 Mha for sugarcane, and 116 Mha for sweet sorghum. The total land required for substituting 10% of petroleum fuel depends on the biodiesel and ethanol crop selected and their yields. For example, if a combination of jatropha and sugarcane is considered, the total land

required will be 243 Mha, on the basis of current global yields. Among all the crops considered, the combination of palm oil and sugarcane has the smallest land requirement, covering 118 Mha. The largest land requirement was 508 Mha using soybean and maize crops. The Gallagher Report (2008) estimates that 56 to 166 Mha of land area will be required to substitute 10% of petroleum fuel demand by 2020. The lower value takes into account the avoided land-use benefits of co-products, second-generation technologies from wastes and residues and significant improvements in yield. The higher estimate is a gross value, for the low yield scenario, not taking into account the anticipated benefits of co-products and without a positive contribution from second-generation technologies (RFA 2008).

Land required and land available: new biofuel crops could come from abandoned cropland, pasture lands, forests, or other natural areas, though De Vries et al (2007) suggest that the grassland will be the primary target for biofuel expansion. For the scenario of biofuel production using jatropha and sugarcane, the land area required to meet 10% of the petroleum demand in 2030 would account for 17% of

box.6.1

# Area required for biofuel production and land availability: Africa Case Study

Compared to all the world's major regions, Sub-Saharan Africa has the largest bio-energy potential as a result of large areas of suitable cropland, pasture land, and high potential for increased crop yields (Smeets et al. 2004). In 2005, the 'Arable area' (i.e. cropped area) in Africa was 213 Mha. FAO (2007) estimates that the this will increase by 26% (to 288 Mha) by 2030. As per the estimates derived from the current study, 5-20 Mha is required for meeting the biofuel demand in Africa in 2030 under different biofuel crop scenarios. A separate study estimated that only 3 to 11 Mha are required to meet the biofuel demand for 2020 assuming a 10% import substitution scenario (Wetland International 2008). Total projected land area required is equivalent to ~ 2.2% of the region's available permanent pastures, thus there should be no need for going into closed canopy forests and wetlands, though this is no guarantee that biofuel production will not occur on forest and wetlands.

Permanent pasture includes savanna woodlands and scrub and demand is most likely to be met using these land covers (De Vries et al. 2007). These lands are important to rural livelihoods (fuelwood, medicines, etc.) and biodiversity. There are substantial areas where over-utilization of preferred species has decreased the economic value of the lands. Hence, they are degraded in terms of services from vegetation, but they do not necessarily exhibit evidence of soil degradation. Such degraded lands have the potential to meet the biofuel demand without competing for food or converting carbon rich native habitats, but may still risk biodiversity impacts.

Further, in Sub-Saharan Africa, there is a large potential to increase crop productivity, since the average productivity of different crops is low relative to the global average. If biofuel production is associated with increased inputs and improved crop yields, it will be possible to increase overall crop production and produce energy on the existing land base without competing with food, especially if biofuel production is targeted towards marginal croplands.

Expansion of biofuel production associated with displacement of native ecosystems, particularly dry and tropical forests, will result in a carbon debt, which will need to be dealt with (Canadell et al. 2008). Africa has 142.6 Mha of tropical forest that is suitable for production of soybean, sugar cane, or palm oil (Stickler et al. 2007). This extent of forest area contains about 81 Gt of $CO_2$ equivalent in carbon stocks. Displacement of dry and tropical forests in Sub-Saharan Africa continues at an annual rate of 4 Mha leading to a loss of 240 Mt soil carbon annually. Future growth of biofuel production must avoid conversion of these forests if its potential to reduce carbon emissions is to be realized.

Estimated GHG emissions from land conversions for energy cropping in Africa range from 29 Mt $CO_2$ (jatropha and sugar cane) to 71 Mt $CO_2$ (soybean and maize) annually, under different biofuel crop scenarios. The total $CO_2$ emission for Africa in 2030 from 10% of petroleum fuel for transportation consumption, targeted to be substituted by biofuels, is estimated to be 33 Mt $CO_2$. Thus, only a scenario consisting of crops such as jatropha and sugarcane could lead to GHG benefits.

current arable area of 1421 Mha. Permanent pastures, which could potentially be used for biofuel crops, account for 3406 Mha. Thus, the total land area required for producing biofuels using jatropha and sugarcane would account for around 7% of the permanent pastures. It should not be assumed that all pastures are suitable for biofuel crops; some proportion of permanent pastures may have previously avoided conversion to cropland because of their unsuitability for cropping due to lack of precipitation, infertile soils, slope, erodibility, or rockiness.

If forests were converted to biofuels they would require about 24% of current forest area under the jatropha and sugarcane scenario. Oil palm is even more likely to replace forests, as much of its suitable cropping area is currently covered with tropical forest. Current rates of global deforestation are about 13 Mha per year (FAO 2006). If present trends continue, an additional 286 Mha would be deforested by 2030. The biofuel land demand scenarios considered here represent a land demand equivalent to 85% of ongoing de-forestation if sugarcane and jatropha are considered. Thus, biofuels, depending on where they are located and their indirect effects, could have globally significant impacts on rates of land-use change. For example, if biofuels were produced on existing tropical forest: 745 Mha of tropical forests are suitable for soybean, sugarcane, or palm production (Stickler et al. 2007). The forest on these susceptible areas contains the equivalent of about 443 Gt of $CO_2$ (Stickler et al. 2007).

**Greenhouse Gas Emissions**

GHG emissions are expressed in terms of tons of $CO_2$ per hectare ($CO_2$ ha$^{-1}$). Recent studies have shown that conversion of land such as forest, grassland, and abandoned cropland to biofuel crops leads to significant $CO_2$

emissions and 'carbon debts' of up to several hundred years (Fargione et al. 2008; ABI 2008; Gibbs et al. 2008 and Fritsche 2008). The carbon debt is the time necessary to counter balance the $CO_2$ emissions resulting from the conversion of a native ecosystem. The conversion from forest peatland to oil palm releases about 3452 t$CO_2$ ha$^{-1}$ over 50 years and requires 423 years to pay the 'carbon debt' (Fargione et al. 2008).

In this study, $CO_2$ emissions from land conversion are estimated by considering 9 scenarios (Box 6.2) of land conversions and by using the total area required for each biofuel crop (Table 6.3). The mean annual $CO_2$ emission estimate (Table 6.4) ranges from 753 Mt $CO_2$ (conversion of grassland to jatropha and sugarcane) to 1825 Mt $CO_2$ (conversion of grassland to soybean and abandoned land to maize). It is difficult, however, to predict which land categories will be converted to biofuel production in the future. The rationale for using grassland and abandoned land includes; (1) there is no ban on conversion of these lands to crops including biofuel crops, (2) the large extents of permanent pastureland (3406 Mha) are available globally (De Vries et al 2007) and (3) there is a legal ban in some countries for converting forest land for non-forest purposes including biofuel crops.

We estimated the emissions from conversion of abandoned cropland to maize. This estimate is based on U.S. abandoned cropland that is threatened with conversion to maize, which is largely under the Conservation Reserve Program in the United States (Fargione et al. 2008). We estimate 1.6 tons of C ha$^{-1}$ in aboveground biomass and 6.7 tons of C ha$^{-1}$ in root biomass (Mokany et al. 2007). This land accumulates carbon at a rate equivalent to 0.69 tons $CO_2$ ha$^{-1}$ yr$^{-1}$ and has been abandoned for 15 years on average, and would continue to accumulate carbon at this rate for more than

30 additional years, resulting in emissions and forgone sequestration of 145 tons of $CO_2$ ha$^{-1}$ when converted back to cropland (Fargione et al. 2008).

Stickler et al. (2007) estimate the average forest carbon for tropical forest suitable for oil palm plantations to be 182 tons C ha$^{-1}$. Palm oil plantation contains about 36 tons C ha$^{-1}$ averaged over their 25-30 year life-span (Henson 2003). Thus, we estimate emissions of 146 tons of C ha$^{-1}$, or 535 tons of $CO_2$ ha$^{-1}$ from conversion of tropical forest to palm plantations. Conversion of forest to plantations may also lose soil C (Guo and Gifford 2002 and Murty et al. 2002), but we conservatively ignore this loss here.

We have used the same estimates of $CO_2$ emissions from grassland conversion to cropland for sugarcane, jatropha, soybean, and sweet sorghum. Soybean and sweet sorghum are replanted annually, sugarcane is replanted every six years, and it is unclear how frequently jatropha would need to be re-planted. Additional research is needed to determine whether impact on soil carbon varies amongst these crops. We estimate that tropical/subtropical grassland contains 2.8 tons C ha$^{-1}$ in aboveground biomass and litter (de Castro and Kauffman 1998), 4.4 tons C ha$^{-1}$ of roots (Mokany et al. 2006), 43.6 tons of C ha$^{-1}$ in the top 30 cm of soil (Batjes 2005 and Bernoux et al. 2002), 42% of which is lost upon conversion (estimate for dry tropical climates from IPCC 2006). Combined, these numbers yield emissions of 93 Mt $CO_2$ ha$^{-1}$.

The total $CO_2$ emission from 10% of the diesel and gasoline consumption during 2030, proposed to be substituted by biofuels, is estimated to be 0.84 Gt CO2 annually, whereas the annual CO2 emission from land conversion alone is estimated to be in the range of 0.75 to 1.83 Gt $CO_2$ (Table 6.4). This

box 6.2 **Scenarios used for calculating CO2 emissions from land conversion**

Scenario 1:
 Grassland to Jatropha (93 tCO$_2$ ha$^{-1}$) + Abandoned land to Maize (145 tCO$_2$ ha$^{-1}$)
 = 37.4 Gt $CO_2$
Scenario 2:
 Grassland to Jatropha (93 tCO$_2$ ha$^{-1}$) + Grassland to Sugarcane (93 tCO$_2$ ha$^{-1}$)
 = 22.6 Gt $CO_2$
Scenario 3:
 Grassland to Jatropha (93 tCO$_2$ ha$^{-1}$) + Grassland to Sweet Sorghum (93 tCO$_2$ ha$^{-1}$)
 = 26.9 Gt $CO_2$
Scenario 4:
 Grassland to Soybean (93 tCO$_2$ ha$^{-1}$) + Abandoned land to Maize (145 tCO$_2$ ha$^{-1}$)
 = 54.8 Gt $CO_2$
Scenario 5:
 Grassland to Soybean (93 tCO$_2$ ha$^{-1}$) + Grassland to Sugarcane (93 tCO$_2$ ha$^{-1}$)
 = 40 Gt $CO_2$
Scenario 6:
 Grassland to Soybean (93 tCO$_2$ ha$^{-1}$) + Grassland to Sweet Sorghum (93 tCO$_2$ ha$^{-1}$)
 = 44.3 Gt $CO_2$
Scenario7:
 Tropical Forest to Palm Oil (535 tCO$_2$ ha$^{-1}$) + Abandoned land to Maize (145 tCO$_2$ ha$^{-1}$)
 = 46.5 Gt $CO_2$
Scenario 8:
 Tropical Forest to Palm Oil (535 tCO$_2$ ha$^{-1}$) + Grassland to Sugarcane (93 tCO$_2$ ha$^{-1}$)
 = 31.7 Gt $CO_2$.
Scenario 9:
 Tropical Forest to Palm Oil (535 tCO$_2$ ha$^{-1}$) + Grassland to Sweet Sorghum(93 tCO$_2$ ha$^{-1}$)
 = 36 Gt $CO_2$.

does not take into account the emissions released in cultivation, transportation, and processing of the biofuels, which would reduce the amount of $CO_2$ substitution by 20-90%

Table 6.3 Total land area required (Mha) for meeting total projected biofuel demand, where each biofuel crop is assumed to meet 100% of the biodiesel or ethanol demand, and demand is assumed to be 10% of petroleum transportation fuel demand for 2030. Area required for meeting the biofuel demand is calculated by dividing the total biodiesel or ethanol demand (as estimated in Table 6.2), by the mean yield of the respective biofuel crop assuming 100% of the demand of biodiesel or ethanol is met by a single selected biofuel crop, for each of the four scenarios. There are 1.2307 billion liters per Mtoe (IEA 2008).

Biofuel yields (L ha-1yr-1) assumed are:Jatropha (biodiesel) 1250; Oil Palm (biodiesel) 4594; Soybean (biodiesel) 601; Maize (ethanol) 2372; Sugar Cane (ethanol) 5005; Sweet Sorghum (ethanol) 3000 (Source: OECD-FAO 2008b, IEA 2008, Mielkie 2006, Jongschaap et al. 2007, Fresco 2006, Thow and Warhurst 2007).

| Region | Land required to meet 100% of biodiesel demand | | | Land required to meet 100% of bio-ethanol demand | | |
|---|---|---|---|---|---|---|
| | Jatropha | Palm Oil | Soyabean | Maize | Sugar cane | Sweet Sorghum |
| OECD | 88 | 24 | 184 | 75 | 35 | 59 |
| Non-OECD | 85 | 24 | 177 | 72 | 34 | 57 |
| World | 173 | 48 | 361 | 147 | 70 | 116 |

Table 6.4 Mean annual $CO_2$ emission (Mt $CO_2$ yr-1), averaged over a 30 year period, from land conversion to biofuel crop under different scenarios where each biofuel crop is assumed to meet 100% of the biodiesel or ethanol demand in 2030

| Region | Emissions from LUC when 100% 2030 biodiesel demand is met by a single crop | | | Emissions from LUC when 100% 2030 bio-ethanol demand is met by a single crop | | |
|---|---|---|---|---|---|---|
| | Jatropha | Palm Oil | Soyabean | Maize | Sugar cane | Sweet sorghum |
| OECD | 273 | 436 | 569 | 359 | 110 | 183 |
| Non-OECD | 264 | 421 | 550 | 347 | 106 | 177 |
| World | 537 | 857 | 1119 | 706 | 216 | 360 |

Mean annual $CO_2$ emissions = (area of native/original land use converted to the selected biofuel crop under each scenario) X ($CO_2$ emission factor associated with the conversion from native/original land use to the selected biofuel crop). Emission factors considered for the 30 year period as well as on a mean annual basis are as follows;

Grassland to Jatropha (93 t$CO_2$ ha-1 over 30 year period) = 3.1 t$CO_2$ ha-1yr-1
Tropical Forest to Oil Palm (535 t$CO_2$ ha-1 over 30 year period) = 17.4 t$CO_2$ ha-1yr-1
Grassland to Soybean (93 t$CO_2$ ha-1 over 30 year period) = 3.1 t$CO_2$ ha-1yr-1
Abandoned Crop Land to Maize (145 t$CO_2$ ha-1 over 30 year period) = 4.1 t$CO_2$ ha-1yr-1
Grassland to Sugar Cane (93 t$CO_2$ ha-1 over 30 year period) = 3.1 t$CO_2$ ha-1yr-1
Grassland to Sweet Sorghum (93 t$CO_2$ ha-1 over 30 year period) = 3.1 t$CO_2$ha-1yr-1

(Thow and Warhurst 2007), i.e. from 0.84 to between 0.17-0.76. Thus, the potential $CO_2$ emission from land conversion to biofuel crops by growing first-generation biofuel crops is likely greater than the savings expected from the first thirty years of growing biofuel crops.

Several factors may mean that our estimates of emissions are too low. The fact that some maize is grown on converted grasslands in addition to abandoned cropland, and some palm is grown on peatlands in addition to rainforest, may lead to underestimates in emissions per ha. Further, a complete GHG accounting would take into account the GHG impact of GHG emissions other than carbon, specifically nitrous oxide emissions associated with the fertilizer added to most biofuel crops. We assume that only abandoned cropland is accumulating carbon and that other ecosystems are in equilibrium, so that there is lost carbon sequestration only on the abandoned cropland.

Several other factors may mean that our estimates of emissions are too high. Some of the biofuel crops, namely maize and soybean, produce co-products in addition to biofuel. This means that production of these crops is likely to offset the need for some additional cropland. For example, the distillers grains produced as a co-product from maize ethanol production are fed to livestock and may offset about half of the need for about half of the additional maize cropland. In addition, it is unknown what yields will be for these crops in 2030, but it could be expected that they may be higher than today, even if biofuel crops are grown on marginal land.

Finally, there is large uncertainty in the amount of carbon emissions for some of the pools that we estimated. For example, there is a very wide range in published measurements of the amount of carbon emitted from tropical soils converted to sugarcane.

## Conclusions

There are multiple reasons why biofuels are attracting global interest, including potential GHG reductions. If climate change mitigation is to be either a primary objective or a co-benefit from other objectives of increased biofuel production and energy security, a systematic assessment of the GHG mitigation potential of biofuels is required, and LCA is a key first step. The second step is to assess GHG emissions from land use changes. In general, when biofuel cropping is associated with the conversion of native ecosystems, the net GHG balance is negative, implying no net immediate climate benefits from shifting to biofuels. The carbon debt of this conversion would have to be re-paid through the extended use of biofuels, but may require from a few years to several hundred years to balance out the initial carbon losses.

Ultimately, any major land surface transformation resulting from the broad utilization of biofuels will require an assessment of its impact on the full radiative forcing including changes in surface albedo and water cycling.

The present analysis was based on projected transportation fuel consumption for 2030 and a targeted petroleum substitution of 10% by biofuels. Emissions from land use change are likely to be significant (753-1825 Mt $CO_2$ $y^{-1}$). compared to the 840 Mt $CO_2$ emissions resulting from the 10% petroleum fuel combustion. Thus, under certain conditions (e.g. conversion of grassland to jatropha and sugarcane) biofuel production could provide net CO2 benefit. The land required for meeting the targeted biofuel production is in the range of 118 to 508 Mha.

The critical issues for both GHG emissions and food production are; which land types will be converted to biofuel crops; which biofuel crops will be grown and what biofuel crop yields will be. If forest land or wetlands or productive pasture lands are used, the implications are likely to be negative for GHG emissions as well as food production. Alternatively, if biofuel production is targeted towards lands previously converted to agriculture, but not currently being used for crop production, such as degraded pasture or abandoned farmland (Field et al. 2008 and Campbell et al. 2008), the GHG and biodiversity consequences will be much more favorable than if biofuel production causes the direct or indirect conversion of natural ecosystems.

Future biofuel systems could take several approaches for supplying feedstocks including:

- The development and implementation of conventional crops (often food crops) or crops with specialized outputs, including food, fuel, and other high-value bioproducts.

- The development and implementation of lignocellulosic crops offering the potential to focus on indigenous woody and grass species best adapted to local conditions, cover crops used in intra-annual rotation on existing cropland.

- Wastes from agriculture, livestock, municipalities, forestry, pests and storm damaged trees, fire risk reduction, or invasive species removal also offer the potential to be used for lignocellusic ethanol or other bio-energy production.

Which of these strategies dominates for the provision of bio-energy by 2030 will be dictated by the technological development profile of critical technologies versus the potential for yield increase mainly through simple and low cost agronomic management gains in conventional cropping. If advanced lignocellulosic biofuel production technologies prove to be cost-effective then options 2 and 3 will dominate and implications for land use change, particularly carbon emissions, need to be re-assessed.

According to the present assessment, the potential $CO_2$ emission from land conversion to biofuel crops by growing first-generation biofuel crops is likely to be greater than the savings expected from the first thirty years of growing biofuel crops. However, if biofuels are produced in ways that minimize conversion of habitat, e.g. by utilizing waste products or cover crops, significantly increasing yields, and targeting degraded pasture and abandoned cropland, biofuels could play a positive role in mitigating climate change, enhancing environmental quality, and strengthening the global economy. This requires significant research, development of sustainable land-use and biofuel production strategies, science-based policy making and enforcement of sustainable production and management practices and policies (Robertson et al. 2008). It is also important to explore and consider technologies and practices that could lead to minimizing the GHG emissions in land conversion and use for biofuel production.

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