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Land Clearing and the Biofuel Carbon Debt

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Increasing energy use, climate change, and carbon dioxide (CO_2) emissions from fossil fuels make switching to low-carbon fuels a high priority. Biofuels are a potential low-carbon energy source, but whether biofuels offer carbon savings depends on how they are produced. Converting rainforests, peatlands, savannas, or grasslands to produce food-based biofuels in Brazil, Southeast Asia, and the United States creates a 'biofuel carbon debt' by releasing 17 to 420 times more CO_2 than the annual greenhouse gas (GHG) reductions these biofuels provide by displacing fossil fuels. In contrast, biofuels made from waste biomass or from biomass grown on abandoned agricultural lands planted with perennials incur little or no carbon debt and offer immediate and sustained GHG advantages.

Demand for alternatives to petroleum is increasing the production of biofuels from food crops such as corn, sugarcane, soybeans and palms. As a result, land in undisturbed ecosystems, especially in the Americas and Southeast Asia, is being converted to biofuel production and to crop production when agricultural land is diverted to biofuel production. Such land clearing may be further accelerated by lignocellulosic biofuels, which will add to the agricultural land base needed for biofuels unless biofuels are produced from crops grown on abandoned agricultural lands or from waste biomass.

Soils and plant biomass are the two largest biologically active stores of terrestrial carbon, together containing ~2.7 times more carbon than the atmosphere (*1*). Converting native habitats to cropland releases CO_2 due to burning or microbial decomposition of organic carbon stored in plant biomass and soils. After a rapid release from fire used to clear land or from decomposition of leaves and fine roots, there is a prolonged period of GHG release as coarse roots and branches decay and as wood products decay or burn (*2–4*).

We call the amount of CO_2 released during the first 50 years of this process the 'carbon debt' of land conversion. Over time, biofuels from converted land can repay this carbon debt if their production and combustion has net GHG emissions that are less than the life-cycle emissions of the fossil fuels they displace. Until the carbon debt is repaid, biofuels from converted lands have greater GHG impacts than the fossil fuels they displace. For crops with non-biofuel co-products (e.g., palm kernel oil and meal, soybean meal, or distillers' dry grains), we partition the carbon debt into a 'biofuel carbon debt' and a 'co-product carbon debt' based on the market values of the biofuel and its co-products (*5*).

Here we calculate how large biofuel carbon debts are, and how many years are required to repay them, for six different cases of native habitat conversion: Brazilian Amazon to soybean biodiesel, Brazilian Cerrado to soybean biodiesel, Brazilian Cerrado to sugarcane ethanol, Indonesian or Malaysian lowland tropical rainforest to palm biodiesel, Indonesian or Malaysian peatland tropical rainforest to palm biodiesel, and US Central grassland to corn ethanol (*5*) (table S1). These cases illustrate some of the greater current impacts of biofuels on habitat conversion. Indonesia and Malaysia account for 86% of global palm oil production (*6*). Accelerating demand for palm oil is contributing to the 1.5% annual rate of deforestation of tropical rainforests in these nations (*7*). An estimated 27% of concessions for new palm oil plantations are on peatland tropical rainforests, totaling 2.8×10^6 ha in Indonesia (*7*). Brazilian Cerrado is being converted to sugarcane and soybeans, and the Brazilian Amazon is being converted to soybeans (*8–10*). Grassland in the US, primarily rangeland or land currently retired in conservation programs, is being converted to corn production. Rising prices for corn, wheat, and soybeans could cause a substantial portion of the 1.5×10^7 ha of land currently in the US Conservation Reserve Program to be converted to cropland (*11*).

We estimated carbon debts by calculating the amount of CO_2 released from ecosystem biomass and soils. Our analyses account for the amount of plant carbon released as CO_2 through decomposition and combustion, the amount converted to charcoal (charcoal is not part of the carbon debt because it is recalcitrant to decomposition), and the amount incorporated into merchantable timber and other long-lived forestry products, which have a half-life of about 30 years (*3*, *12*). Changes in carbon stores caused by land conversion and biofuel production, mainly from accelerated decomposition, were based on evaluation and synthesis of published studies in the relevant ecosystems (*5*). Our estimate of the carbon debt is conservative because timber products continue to decay after 50 years, but this timeframe captures the large majority of the carbon debt in systems with mineral soils.

Our results show that converting native ecosystems to biofuel production results in large carbon debts (Fig. 1A). We attribute 13, 61, and 17% of this carbon debt to co-products for palm, soybeans, and corn, respectively (Fig. 1B) (*5*). The carbon debts attributed to biofuels (quantities of Fig. 1A multiplied by the proportions of Fig. 1B) would not be repaid by the annual carbon repayments from biofuel production (Fig. 1C and table S2) for decades or centuries (Fig. 1D). Converting lowland tropical rainforest in Indonesia and Malaysia to palm biodiesel would result in a biofuel carbon debt of ~610 Mg ha^{-1} of CO_2 that would take ~86 years to repay (Fig. 1D). Until then, producing and using palm biodiesel from this land would cause greater GHG release than would refining and using an energy-equivalent amount of petroleum diesel. Converting tropical peatland rainforest to palm production incurs a similar biofuel carbon debt from vegetation, but the required drainage of peatland causes an additional sustained emission of ~55 Mg of CO_2 ha^{-1} yr^{-1} from oxidative peat decomposition (*5*) (87% attributed to biofuel; 13% to palm kernel oil and meal). After 50 years, the resulting biofuel carbon debt of ~3000 Mg of CO_2 ha^{-1} would require ~420 years to repay. However, peatland of average depth (3 m) could release peat-derived CO_2 for about 120 years (*7*, *13*). Total net carbon released would be ~6000 Mg ha^{-1} of CO_2 over this longer time horizon, which would take over 840 years to repay. Soybean biodiesel produced on converted Amazonian rainforest with a biofuel carbon debt of over 280 Mg ha^{-1} of CO_2 would require ~320 years to repay compared with GHG emissions from petroleum diesel. The biofuel carbon debt from biofuels produced on converted Cerrado is repaid in the least amount of time of the scenarios we examined. Sugarcane ethanol produced on Cerrado *sensu stricto* (including Cerrado aberto, Cerrado densu, and Cerradão), which is the wetter and more productive end of this woodland-savanna biome, would take ~17 years to repay the biofuel carbon debt. Soybean biodiesel from the drier, less productive grass-dominated end of the Cerrado biome (Campo limpo and Campo sujo) would take ~37 years. Ethanol from corn produced on newly converted US Central grasslands results in a biofuel carbon debt repayment time of ~93 years.

Our analyses suggest that biofuels, if produced on converted land, could, for long periods of time, be much greater net emitters of greenhouse gases than the fossil fuels that they typically displace. All but two, sugarcane ethanol and soybean biodiesel on Cerrado, would generate greater GHG emissions for at least half a century, with several forms of biofuel production from land conversion doing so for centuries. At least for current or developing biofuel technologies, any strategy to reduce GHG emissions that causes land conversion from native ecosystems to cropland is likely to be counterproductive.

We also evaluated the possibility that US farmland that has been retired from annual crop production and planted to perennial grasses may have a short payback time when converted to corn ethanol production because these systems have already lost a significant portion of their carbon stores. However, after abandonment from cropping, perennial systems gradually recover their carbon stores. For US Central grassland on farmland that has been enrolled in the US Conservation Reserve Program for 15 years, we found that converting it to corn ethanol production creates a biofuel carbon debt that would take ~48 years to repay (Fig. 1).

If biofuels are to help mitigate global climate change, our results suggest that they need to be produced with little reduction of the storehouses of organic carbon in the soils and vegetation of natural and managed ecosystems. Degraded and abandoned agricultural lands could be used to grow native perennials for biofuel production (*14*, *15*), which could spare the destruction of native ecosystems and reduce GHG emissions (Fig. 1). Diverse mixtures of native grassland perennials growing on degraded soils, particularly mixtures containing both warm season grasses and legumes, have yield advantages over monocultures (*14*, *16–18*), provide GHG advantages from high rates of carbon storage in degraded soils (*14*, *19*), and offer wildlife benefits (*20*). Monocultures of perennial grass and woody species monocultures also offer GHG advantages over food-based crops, especially if sufficiently productive on degraded soils (*21*), as can slash and thinnings from sustainable forestry, animal and municipal wastes, and corn stover (*22*).

Additional factors may influence biofuel impacts on GHG emissions. First, biofuel production can displace crops or pasture from current agricultural lands, indirectly causing GHG release via conversion of native habitat to cropland elsewhere. Second, improvements in biofuel production could reduce payback times (*23*, *24*). Third, if land cleared for biofuel production had been accruing carbon (we assumed lands were at steady state), the debt would be increased by the loss of this future storage. Fourth, greater biofuel production might decrease overall energy prices, which could increase energy consumption and GHG release (*25*, *26*).

Biofuel production that causes land clearing and GHG release may be favored by landowners who receive payments for biofuels but not for carbon management. To accurately incorporate the costs of carbon emissions in market signals, emerging policy approaches to GHG emissions must be extended to the full life-cycle of biofuels including their net GHG emission or sequestration from land-use change.

Indeed, the recently enacted US Energy Independence and Security Act of 2007 specifies reductions in life-cycle GHG emissions, including land use change, relative to a fossil fuel baseline. Moreover, it is important that international policy negotiations to extend the Kyoto Protocol beyond 2012 address emissions from land use change due to increased demand for biofuels (*27, 28*).

Our results demonstrate that the net effect of biofuel production via clearing of carbon-rich habitats is to increase CO_2 emissions for decades or centuries relative to fossil fuel use. Conversely, biofuels from perennials grown on degraded farmland and from waste streams would minimize habitat destruction, competition with food production, and carbon debts, all of which are associated with direct and indirect land clearing for biofuel production.

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Supporting Online Material

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Materials and Methods
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References

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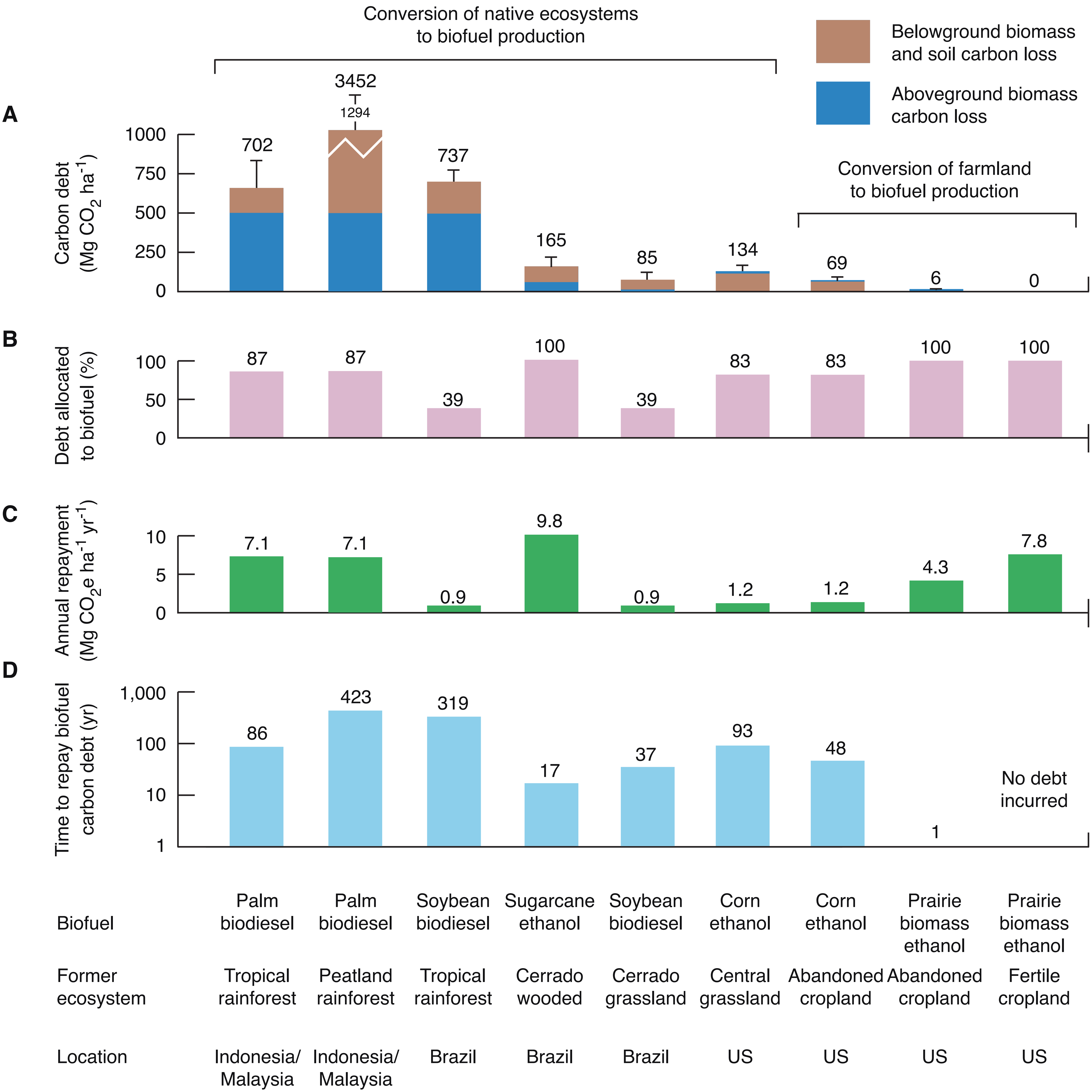
Fig. 1. Carbon debt, biofuel carbon debt allocation, annual carbon repayment rate, and years to repay biofuel carbon debt for nine scenarios of biofuel production. Means and standard deviations are from Monte Carlo analyses of literature-based estimates of carbon pools and fluxes (*5*). (**A**) Carbon debt, including CO_2 emissions from soils and aboveground and belowground biomass due to habitat conversion. (**B**) Proportion of total carbon debt allocated to biofuel production. (**C**) Annual life-cycle GHG reduction from biofuels, including displaced fossil fuels and soil carbon storage. (**D**) Number of years after conversion to biofuel production required for cumulative biofuel GHG reductions, relative to fossil fuels they displace, to repay the biofuel carbon debt.


Conversion of native ecosystems to biofuel production
Belowground biomass and soil carbon loss
Aboveground biomass carbon loss
A
Carbon debt ($Mg\ CO_2\ ha^{-1}$)
1000
750
500
250
0
702
3452
1294
737
165
85
134
69
6
0
Conversion of farmland to biofuel production
B
Debt allocated to biofuel (%)
100
50
0
87
87
39
100
39
83
83
100
100
C
Annual repayment ($Mg\ CO_2e\ ha^{-1}\ yr^{-1}$)
10
5
0
7.1
7.1
0.9
9.8
0.9
1.2
1.2
4.3
7.8
D
Time to repay biofuel carbon debt (yr)
1,000
100
10
1
86
423
319
17
37
93
48
1
No debt incurred
Biofuel
Palm biodiesel
Palm biodiesel
Soybean biodiesel
Sugarcane ethanol
Soybean biodiesel
Corn ethanol
Corn ethanol
Prairie biomass ethanol
Prairie biomass ethanol
Former ecosystem
Tropical rainforest
Peatland rainforest
Tropical rainforest
Cerrado wooded
Cerrado grassland
Central grassland
Abandoned cropland
Abandoned cropland
Fertile cropland
Location
Indonesia/ Malaysia
Indonesia/ Malaysia
Brazil
Brazil
Brazil
US
US
US
US