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Supporting Online Material for

Land Clearing and the Biofuel Carbon Debt

Joseph Fargione, Jason Hill, David Tilman,* Stephen Polasky, Peter Hawthorne

*To whom correspondence should be addressed. E-mail: tilman@umn.edu

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Materials and Methods

General Methods of Carbon Debt Analyses: We reviewed the literature to determine the size of carbon pools in native habitats and the amount of carbon lost from these pools when converted to crop production. All calculations are shown in Table S1. The relevant carbon pools differed depending on the native habitat and the biofuel crop, as described below. When not presented in the literature, dry forest biomass was assumed to be 50% carbon, and US grasslands dry biomass was assumed to be 45% carbon.

Carbon Debt from Converting Amazonian Rainforest: We averaged literature values of carbon pools of live and dead aboveground dry biomass (*S1*, *S2*), root:shoot ratios (*S1*, *S3*, *S4*), and soil carbon (*S5*–*S9*). We similarly estimated the proportions of aboveground biomass stored as charcoal (*S10*, *S11*) and in forest products 50 years after habitat conversion (*S12*), and assumed that all other carbon was emitted as CO_2. For soil carbon loss due to conversion to soybean production, we used reported values of the proportion of soil carbon lost upon farming for this habitat (*S12*–*S14*).

Carbon Debt from Converting Woody Cerrado: Cerrado is the term used to describe the savanna-woodland biome of Brazil. We defined "woody Cerrado" to include Cerrado aberto, Cerrado denso, and Cerradão (*S15*–*S17*). Carbon pools of aboveground biomass (live and litter), roots, and soil carbon were averages of literature values (*S18*–*S20*). Because the root:shoot ratio is thought to be lower in Cerradão than in Cerrado aberto and Cerrado denso, we used published measurements of root biomass where available (*S19*). For studies in Cerrado aberto and Cerrado denso that reported measurements of only aboveground biomass, we estimated root biomass using the average root:shoot ratio from other studies in Cerrado aberto and Cerrado denso (*S19*, *S20*). We calculated the proportions of aboveground biomass stored as charcoal and in forest products 50 years after habitat conversion using literature values (*S12*, *S18*, *S21*), and assumed that all other carbon was emitted as CO_2. We used studies of the proportion of carbon lost from these soils when cultivated to estimate the impact of conversion to sugarcane on soil carbon (*S8*, *S13*, *S14*, *S22*, *S23*).

Carbon Debt from Converting Grassy Cerrado: We defined "grassy Cerrado" to include Campo limpo and Campo sujo. We report carbon pools of aboveground dry biomass (live and litter) (*S18*, *S20*), roots, and soil carbon (*S8*, *S14*, *S22*, *S23*) as averages of published values. We estimated roots as a proportion of live biomass using root:shoot ratios reported for these habitat types (*S18*). We used reported proportions of aboveground biomass stored as charcoal (*S18*, *S21*) and assumed that all other carbon was emitted as CO_2. We estimated soil carbon lost due to conversion to soybeans as a proportion of soil carbon in native habitat (*S8*, *S13*, *S14*, *S22*, *S23*).

Carbon Debt from Converting Southeast Asian Rainforest and Peatland: We used reported values to calculate carbon pools of live aboveground dry biomass (*S24*–*S27*), root:shoot ratios (*S1*, *S3*, *S4*), and proportions of aboveground biomass stored as charcoal (*S10*–*S12*) and in forest products 50 years after habitat conversion (*S12*). We assumed all other carbon was emitted as CO_2. To calculate the difference in carbon in living biomass between rainforest and palm plantations, we compared rainforest biomass to the average above and belowground biomass in palm plantations over the 30 year average life of palm plantations (*S28*). We assumed that no soil carbon is lost from mineral soils planted to forests, including palm plantations. We estimated the CO_2 released from drained peat soils over 50 years and included this in our carbon debt (*S12*, *S29*, *S30*, *S31*). This underestimates the CO_2 that would be released if drainage were to be sustained for longer than 50 years. It is unknown how this annual rate of peatland decomposition compares to the net CO_2 flux in native, undrained peatlands.

Carbon Debt from Converting US Central Grassland to Corn: This carbon debt includes carbon lost from aboveground and belowground plant biomass and from soils in US Central native grassland ecosystems when converted to corn production. For soil carbon losses, we averaged data from studies of paired croplands and grasslands that reported the amounts of soil carbon lost when these grasslands were converted to cropland (*S32–S36*). For biomass carbon, we used measurements of grass biomass on native prairie (*S37*, *S38*) and root:shoot ratios of temperate grassland to estimate belowground biomass (*S4*).

Carbon Debt from Converting US Abandoned Cropland to Corn: When abandoned cropland is planted to perennial grasses in the Central US, soils accumulate carbon (*S35*, *S36*, *S39–S42*). We assume that this accumulated soil carbon would be lost within 50 years if these perennial grasslands were to be converted back into cropland. Most cropland not currently in production in the US is in the Conservation Reserve Program, which was initiated in 1985. We conservatively estimated that these lands have been set aside from crop production an average of 15 years ago (*S43*), and use the average reported annual rate of soil carbon accumulation to determine carbon change for the 15 year period (*S36*). To estimate carbon in aboveground perennial biomass, we used measurements of grass biomass on abandoned cropland in western corn growing states using data from prairies and hay yields from non-alfalfa hay (*S37*, *S38*, *S44*). We used measurements of root:shoot ratios of temperate grasslands (*S4*) to estimate carbon in belowground biomass.

Carbon Debt from Converting US Abandoned Cropland to Restored Prairie: Mixtures of perennial plants that include C_4 grasses and legumes seeded onto abandoned cropland will, if anything, increase the amount of carbon stored in soils and roots rather than cause its loss. Therefore, we included established aboveground biomass as the only component of the carbon debt when harvesting restored prairie biomass for cellulosic ethanol. We estimated grass biomass on abandoned cropland in western corn growing states using data from prairies (*S37*, *S38*, *S44*).

Carbon Debt from Converting US Marginal Cropland to Prairie: There is no carbon debt associated with the conversion of marginal cropland to prairie; rather, there is an increase in the carbon stored in biomass and soils (*S37*, *S38*, *S45–S47*). We accounted for these increases in our estimate of the annual rate of repayment by prairie ethanol on marginal lands, as described below.

Allocation of Carbon Debt to Biofuels and Co-products: A biofuel crop has the potential to generate revenue from both the biofuel and any marketable co-products. We therefore apportion the total carbon debt to biofuels and their co-products by weighting the amount produced of each by its market value. At 2007 average market prices, 39%, 87%, and 85% of the total carbon debt is attributable to the production of soybean biodiesel, palm biodiesel, and corn ethanol, respectively. Soybean crushing yields approximately 18% oil (\$0.88 kg^{-1}) and 82% meal (\$0.31 kg^{-1}) (*S48*, *S49*). Corn ethanol production yields 0.80 kg of DDGS (\$0.13 kg^{-1}) per L of ethanol (\$0.52 L^{-1}) (*S50*, *S51*). Palm biodiesel production yields 82% crude palm oil (\$0.78 kg^{-1}) , 9% palm kernel oil (\$0.89 kg^{-1}), and 9% palm kernel meal (\$0.15 kg^{-1}) (*S49*, *S52*), with palm kernel meal price estimated as 17% of the price of palm kernel oil (*S53*). For sugarcane and diverse prairie biomass ethanol production, the entire carbon debt is attributable to the biofuel.

Whether the carbon debt partitioned to the co-products is repaid, remains unpaid, or grows depends upon the GHG emissions associated with any alternative products displaced by the production of co-products, and is beyond the scope of this paper. Our use of market value partitioning is, obviously and intentionally, sensitive to market prices. This sensitivity provides meaningful information: if demand for biofuels increases biofuel production, the price of co-products is likely to fall as their supply increases, raising the importance of biofuels as a driver of conversion as measured by our market based partitioning method. Thus, this sensitivity to prices is consistent with our intention to partition the carbon debt based on the market forces driving conversion.

Carbon Repayment: We used values from the literature for the annual GHG equivalent offset for production of palm biodiesel (*S52*, *S54–S57*), soybean biodiesel (*S48*, *S54*), sugarcane ethanol (*S58*, *S59*), corn ethanol (*S48*, *S60*, *S61*), and prairie biomass ethanol (*S42*, *S62*). All calculations are shown in Table S2. Our estimates of net GHG emission reductions include full life cycle analyses of crop production, conversion to biofuel, and combustion.

Grass Production for Cellulosic Ethanol: The estimate of carbon repayment for cellulosic ethanol includes both fossil fuel offsets and soil carbon offsets. For conversion of marginal croplands to restored prairie, we also included the amount of carbon stored in prairie root biomass, as determined above, amortized over 50 years. We used two estimates of prairie yields, one for abandoned cropland and one for marginal cropland. Marginal cropland is assumed to be more fertile than abandoned cropland, which may have been abandoned due to low yields. To estimate prairie yields on abandoned cropland, we used measurements of aboveground biomass on prairies in western corn growing states (*S37*, *S38*). This is a conservative estimate because legume-rich plantings of prairie, which we consider, have greater yields. We estimated aboveground biomass on marginal lands from prairie-like perennial grasslands (in Central US corn growing states) that had been burned or cut that year (*S38*). Yields on burned prairie grassland are higher than on unburned because of detritus removal (*S63*). Yields on cut prairie grasslands may be even higher than yields on burned grasslands if all aboveground biomass is removed prior to the growing season (*S45*). We estimated belowground biomass using measurements of root:shoot ratios of temperate grasslands (*S4*). To calculate soil carbon storage rates, we averaged estimates from the literature of soil carbon storage rates under grassland in the US Central grasslands (*S35*, *S36*, *S39–S42*).

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Table S1. Calculated carbon debts from land conversion.

Lowland Tropical Rainforest SE Asia

Parameter	*Unit*	*Average*	*References*	*Estimates*				
Above biomass	Mg C ha^{-1}	222.2	*S24–S27*	236	269.7	160.9		
Forest product after 50 years	Mg C ha^{-1}	42.2	*S12*					
Palm plantation above & below bio	Mg C ha^{-1}	36	*S28*	36				
Dead above bio	Mg C ha^{-1}	no data available						
Below bio	Proportion	24.1%	*S1, S3, S4*	13.0%	21.0%	26.0%	23.5%	37.0%
Charcoal	Proportion	3.3%	*S10–S12*	3.6%	1.9%	4.5%		
Soil C		NA						

	Total	*Above*	*Below*	*Root*	*Soil*
Mg C ha^{-1}	191	145	47	47	0
Mg CO_2 ha^{-1}	702	531	171	171	0
Standard deviation	183				

Peatland Tropical Rainforest SE Asia

Parameter	*Unit*	*Average*	*References*	*Estimates*				
Above biomass	Mg C ha^{-1}	222.2	*S24–S27*	236	269.7	160.9		
Forest product after 50 years	Mg C ha^{-1}	42.2	*S12*					
Palm plantation above & below bio	Mg C ha^{-1}	36	*S28*	36				
Dead above bio	Mg C ha^{-1}	no data available						
Below bio	Proportion	24.1%	*S1, S3, S4*	13.0%	21.0%	26.0%	23.5%	37.0%
Charcoal	Proportion	3.3%	*S10–S12*	3.6%	1.9%	4.5%		
Annual emissions peat	Mg CO_2 ha^{-1} yr^{-1}	55	*S12, S29, S30*	73.3	54.3	36.6	56.5	
Standard deviation peat emissions	Mg CO_2 ha^{-1} yr^{-1}	15.0						

		Total	*Above*	*Below*	*Root*	*Soil*
Carbon debt without peat	Mg C ha^{-1}	191	145	47	47	0
Carbon debt without peat	Mg CO_2 ha^{-1}	702	531	171	171	0
Carbon debt with peat	Mg C ha^{-1}	941	145	797	47	750
Carbon debt with peat	Mg CO_2 ha^{-1}	3,452	531	171	171	2750
	Standard deviation	1,294				

Amazonian Rainforest

Parameter	*Unit*	*Average*	*References*	*Estimates*						
Above bio (live)	Mg C ha^{-1}	154.6	*S1, S2*	163	132	155	155	166	151	160
14% forest product after 50 years	Mg C ha^{-1}	21.6	*S12*							
Above dead (of above alive)	Proportion	9.3%	*S1*	2.0%	9.0%	17.0%				
Above charcoal (live+dead)	Proportion	3.3%	*S10–S12*	3.6%	1.9%	4.5%				
Roots (of above live)	Proportion	24.1%	*S1, S3, S4*	13.0%	21.0%	26.0%	23.5%	37.0%		
Soil C	Mg C ha^{-1}	46.6	*S6–S9*	49.0	45.9	44.5	47.2			
Soil C lost	proportion	45.8%	*S12–S14*	56.0%	21.0%	49.0%	51.0%	52.0%		

		Total	*Above*	*Below*	*Root*	*Soil*
Carbon debt	Mg C ha^{-1}	201	142	59	37.3	21.4
Carbon debt	Mg CO_2 ha^{-1}	737	522	215	137	78
	Standard deviation	75				

Table S1. Calculated carbon debts from land conversion. (Continued...)

Woody Cerrado and Cerradão

Parameter	*Unit*	*Average*	*References*	*Estimates*											
Above biomass	Mg C ha^{-1}	16.3	*S15–S20*	9.65	9.85	15.9	14.5	6.45	11.55	45.85					
Root biomass		23.2	*S18–S20*	23.3	26.5	20.6	30.9	13.8	24.6	22.925					
9% forest product after 50 yrs	Mg C ha^{-1}	1.5													
Root:shoot	ratio	2.1	*S18, S20*	2.4	2.7	1.3									
Litter	Mg C ha^{-1}	2.7	*S18, S20*	2.8	2.6	2.6									
Total biomass	Mg C ha^{-1}	53.6													
Charcoal	Proportion	8.0%	*S18, S21*	8.0%											
Soil C	Mg C ha^{-1}	43.6	*S8, S14, S22, S23*	54.0	35.4	35.8	44.7	39.8	45.3	51.2	43.0	43.0			
% soil C lost	Proportion	13.1%	*S13, S14, S22, S23*	-7.8%	0.2%	6.0%	8.4%	5.1%	15.0%	80.0%	-0.7%	-9.0%	-0.6%	51.0%	9.3%

		Total	*Above*	*Below*	*Root*	*Soil*
Carbon debt	Mg C ha^{-1}	45	16	29	23	6
Carbon debt	Mg CO_2 ha^{-1}	165	59	106	85	21
	Standard deviation	58				

Grassy Cerrado

Parameter	*Unit*	*Average*	*References*	*Estimates*											
Above biomass	Mg C ha^{-1}	3.53	*S18, S20*	2.45	3.7	3.7	3.4	4.4							
Root:shoot	Ratio	3.7	*S18*	3.3	4.1										
Litter	Mg C ha^{-1}	1.4	*S18, S20*	0.3	0.95	0.2	1.32	2.74	2.6						
Total biomass	Mg C ha^{-1}	17.9													
Charcoal	Proportion	8.0%	*S18, S21*	8.0%											
Soil C	Mg C ha^{-1}	43.6	*S8, S14, S22, S23*	54	35.4	35.8	44.7	39.8	45.3	51.2	43	43			
% soil C lost	Proportion	13.1%	*S13, S14, S22, S23*	-7.8%	0.2%	6.0%	8.4%	5.1%	15.0%	80.0%	-0.7%	-9.0%	-0.6%	51.0%	9.3%

		Total	*Above*	*Below*	*Root*	*Soil*
Carbon debt	Mg C ha^{-1}	23	4	19	13	6
Carbon debt	Mg CO_2 ha^{-1}	85	16	69	48	21
	Standard deviation	42				

US Central Grasslands

Parameter	*Unit*	*Average*	*References*	*Estimates*					
Soil C loss on conversion	Mg C ha^{-1}	28.1	*S32–S36*	35.1	28.9	29.6	16.9	17.8	40.3
Aboveground biomass	Mg C ha^{-1}	1.6	*S37, S38*	1.8	1.485				
Root:shoot ratio	Ratio	4.2	*S4*	4.22					
Standard deviation	Ratio	2.1	*S4*	2.07					
Root biomass	Mg C ha^{-1}	6.9							

		Total	*Above*	*Below*	*Root*	*Soil*
Carbon debt	Mg C ha^{-1}	37	1.6	35	7	28
Carbon debt	Mg CO_2 ha^{-1}	134	6	128	25	103
Standard deviation	Mg CO_2 ha^{-1}	33				

Table S1. Calculated carbon debts from land conversion. (Continued...)

US Abandoned Cropland Converted to Corn

Parameter	*Unit*	*Average*	*References*	*Estimates*							
Aboveground biomass	Mg C ha^{-1}	1.6	*S37, S38, S44*	1.5	1.8	1.485					
Root:shoot ratio	Ratio	4.2	*S4*	4.22							
Standard deviation	Ratio	2.1	*S4*	2.07							
Root biomass	Mg C ha^{-1}	6.7									
Rate of C accumulation	Mg C ha^{-1} yr^{-1}	0.69	*S35, S36, S39–S42*	0.49	1.59	0.31	0.62	0.74	0.30	0.78	0.74
Average years abandoned	Years	15.0	*S42*	15							
Soil C loss on conversion	Mg C ha^{-1}	10.4									

		Total	*Above*	*Below*	*Root*	*Soil*
Carbon debt	Mg C ha^{-1}	19	1.6	17	7	10
Carbon debt	Mg CO_2 ha^{-1}	69	6	63	25	38
Standard deviation	Mg CO_2 ha^{-1}	24				

US Abandoned Cropland Converted to Prairie

Parameter	*Unit*	*Average*	*References*	*Estimates*		
Aboveground biomass	Mg C ha^{-1}	1.6	*S37, S38, S44*	1.5	1.8	1.485

		Total	*Above*	*Below*	*Root*	*Soil*
Carbon debt	Mg C ha^{-1}	2	2	0	0	0
Carbon debt	Mg CO_2 ha^{-1}	6	6	0	0	0
Standard deviation	Mg CO_2 ha^{-1}	1				

Table S2. Calculated GHG offsets from biofuel production.

Sugarcane Ethanol

Parameter	*Unit*	*Average*	*References*	*Estimates*		
Cane yield	Tonnes cane ha^{-1}			68.7		
Net avoided per ton	kg CO_2e per metric tons of cane			147		
Net avoided per ha	kg CO_2e ha^{-1}			10,126		
Transportation	kg CO_2e ha^{-1}			195		
New net avoided per ha	kg CO_2e ha^{-1}			9,931		
Net offset	Mg CO_2 ha^{-1} yr^{-1}	9.8	*S58, S59*	9.9	9.7	

Corn Ethanol

Parameter	*Unit*	*Average*	*References*	*Estimates*		
Biofuel production	L ha^{-1}			3,632	3,463	3,998
GHG savings	%			12%	18%	19%
Biofuel production	Gasoline equivalent L ha^{-1}			2,421	2,309	2,665
Petroleum emissions	kg L^{-1}			2.97	2.96	2.97
Adj. biofuel emissions	kg L^{-1}			2.60	2.41	2.41
Biofuel emissions	kg ha^{-1}			6,290	5,570	6,421
Displaced fuel emissions	kg			7,180	6,826	7,928
Net offset	Mg CO_2 ha^{-1} yr^{-1}	1.2	*S48, S60, S61*	0.9	1.3	1.5

Soybean Biodiesel

Parameter	*Unit*	*Average*	*References*	*Estimates*	
Biofuel production	L ha^{-1}			544	541
GHG savings	%			41%	78%
Biofuel production	Diesel equivalent L ha^{-1}			497	504
Petroleum emissions	kg L^{-1}			3.01	3.01
Adj. biofuel emissions	kg L^{-1}			1.79	0.65
Biofuel emissions	kg ha^{-1}			889	327
Displaced fuel emissions	kg			1,495	1,516
Net biofuel offset	Mg CO_2 ha^{-1} yr^{-1}	0.9	*S54, S48*	0.6	1.2

Palm Biodiesel

Parameter	*Unit*	*Average*	*References*	*Estimates*	
Palm oil yield	kg Biodiesel ha-^{1} yr^{-1}	3,294		3,294	3,294
Offset GHG emissions	kg CO_2e ha^{-1} yr^{-1}	10,482		10,482	10,482
Palm oil production costs	kg CO_2e ha^{-1} yr^{-1}	2,800		2,371	3,228
Conversion costs	kg CO_2e ha^{-1} yr^{-1}	562		562	562
Net biofuel offset	kg CO_2e ha^{-1} yr^{-1}	7,121		7,549	6,692
Net biofuel offset	Mg CO_2 ha^{-1} yr^{-1}	7.1	*S52, S54–S57*	7.5	6.7

Table S2. Calculated GHG offsets from biofuel production. (Continued...)

Prairie Biomass Ethanol

Abandoned Cropland

Parameter	*Unit*	*Average*	*References*	*Estimates*							
Yields	Mg biomass ha^{-1} yr^{-1}	3.7	*S37, S38*	4	3.3						
Net biofuel offset	Mg CO_2 ha^{-1} yr^{-1}	1.8	*S42, S62*								
Net soil offset	Mg CO_2 ha-1 yr-1	2.5	*S35, S36, S39–S42*	1.781	5.8143	1.1524	2.2733	2.7133	1.0817	2.86	2.7
Total net offset	Mg CO_2 ha^{-1} yr^{-1}	4.3									

Marginal Cropland

Parameter	*Unit*	*Average*	*References*	*Estimates*										
Yields	Mg biomass ha^{-1} yr^{-1}	7.7	*S37, S38, S45–S47*	6.5	13.2	5.9	9.3	5.2	7.5	14.0	7.6	4.6	6.1	5.3
Root:shoot ratio	Ratio	4.2	*S4*	4.22										
Standard deviation of root:shoot	Ratio	2.1	*S4*	2.07										
Root biomass	Mg biomass ha^{-1}	32.7												
Carbon root storage	Mg C ha^{-1}	14.7												
Carbon root storage	Mg CO_2 ha^{-1}	54												
Annual root storage over 50 yrs.	Mg CO_2 ha^{-1} yr^{-1}	1.1												
Net root offset	Mg CO_2 ha^{-1} yr^{-1}	1.1												
Net biofuel offset	Mg CO_2 ha^{-1} yr^{-1}	4.2	*S42, S62*											
Net soil offset	Mg CO_2 ha^{-1} yr^{-1}	2.5	*S35, S36 S39–S42*	1.781	5.8143	1.1524	2.2733	2.7133	1.0817	2.86	2.7			
Total net offset	Mg CO_2 ha^{-1} yr^{-1}	7.8												