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# Indirect Emissions from Biofuels: How Important?

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**A global biofuels program will lead to intense pressures on land supply and can increase greenhouse gas emissions from land-use changes. Using linked economic and terrestrial biogeochemistry models, we examine direct and indirect effects of possible land-use changes from an expanded global cellulosic bioenergy program on greenhouse gas emissions over the 21st century. Our model predicts indirect land use will be responsible for substantially more carbon loss (up to twice as much) than direct land use; however, because of predicted increases in fertilizer use, nitrous oxide emissions will be more important than carbon losses themselves in terms of warming potential. A global greenhouse gas emissions policy that protects forests and encourages best practices for nitrogen fertilizer use can dramatically reduce emissions associated with biofuels production.**

Expanded use of bioenergy causes land-use changes and increases in terrestrial carbon emissions (*1*, *2*). This recognition has led to efforts to determine the credit toward meeting low carbon fuel standards (LCFS) for different forms of bioenergy with an accounting of direct land-use emissions as well as emissions from land use indirectly related to bioenergy production (*3*, *4*). Indirect emissions occur when biofuels production on agricultural land displaces agricultural production and causes additional land-use change that leads to an increase in net greenhouse gas emissions (*2*, *4*). The control of greenhouse gases (GHG) through a cap and trade or tax policy, if extended to include emissions (or credits for uptake) from land-use change combined with monitoring of carbon stored in vegetation and soils and enforcement of such policies, would eliminate the need for such life cycle accounting (*5*, *6*). There are a variety of concerns (*5*) about the practicality of including land-use change emissions in a system designed to reduce emissions from fossil fuels, and that may explain why there are no concrete proposals in major countries to do so. In this situation, fossil energy control programs (LCFS or carbon taxes) must determine how to treat the direct and indirect GHG emissions associated with the carbon intensity of biofuels.

The methods to estimate indirect emissions remain controversial. Quantitative analyses to date have ignored these emissions (*1*), considered those associated with crop displacement from a limited area (*2*), confounded these emissions with direct or general land-use emissions (*6*–*8*), or developed estimates in a static framework of today's economy (*3*). Missing in these analyses is how to address the full dynamic accounting of biofuel carbon intensity (CI), which is defined for energy as the GHG emissions per megajoule of energy produced (*9*); that is, the simultaneous consideration of the potential of net carbon uptake through enhanced management of poor or degraded lands, nitrous oxide emissions that would accompany increased use of fertilizer, environmental (e.g., climate change, enhanced carbon dioxide concentrations, ozone pollution) effects on terrestrial carbon storage, and consideration of the economics of land conversion. The estimation of emissions related to global land-use change, both those on land devoted to biofuel crops (direct emissions) and those indirect changes driven by increased demand for land for biofuel crops (indirect emissions), requires an approach to attribute effects to separate land uses.

Here, we apply an existing global modeling system that integrates land-use change as driven by multiple demands for land and that includes dynamic greenhouse gas accounting (*10*, *11*). Our modeling system, which consists of a computable general equilibrium (CGE) model of the world economy (*10*, *12*) combined with a process-based terrestrial biogeochemistry model (*13*, *14*), was used to generate global land-use scenarios and explore some of the environmental consequences of an expanded global cellulosic biofuels program over the 21st century. The biofuels scenarios we focus on are linked to a global climate policy to control GHG emissions from industrial and fossil fuel sources that would, absent feedbacks from land-use change, stabilize the atmosphere's carbon dioxide ($CO_2$) concentration at 550 ppmv (*15*). The climate policy makes the use of fossil fuels more expensive and speeds up the introduction of biofuels, and ultimately increases the size of the biofuel industry, with additional effects on land use, land prices, and food and forestry production and prices (*16*).

We consider two cases to explore future land-use scenarios: Case 1 allows conversion of natural areas to meet increased demand for land, as long as the conversion is profitable; Case 2 is driven by more intense use of existing managed land. To identify the total effects of biofuels, each of the above cases is compared to a scenario in which expanded biofuel use does not occur (*16*). In the scenarios with increased biofuels production, the direct effects such as changes in carbon storage and nitrous oxide ($N_2O$) emissions are estimated only in areas devoted to biofuels. Indirect effects are defined as the differences between the total effects and the direct effects.

At the beginning of the 21st century**,** about 31.5% of the total land area (133 million $km^2$) was in agriculture; 12.1% (16.1 million $km^2$) in crops and 19.4% (25.8 million $km^2$) in pasture (*17*). In both cases of increased biofuels use, land devoted to biofuels becomes greater than all area currently devoted to crops by the end of the 21st century, but in Case 2 less forest land is converted (Fig**.** 1). Changes in net land fluxes are also associated with how land is allocated for biofuels production (Fig. 2). In Case 1**,** there is a larger loss of carbon than in Case 2, especially at mid century. Indirect land use is responsible for substantially greater carbon losses than direct land use in both cases during the first half of the century. In both cases, there is carbon accumulation in the latter part of the century. The estimates include $CO_2$ from burning and decay of vegetation and slower release of carbon as $CO_2$ from disturbed soils. The estimates also take into account reduced carbon sequestration capacity of the cleared areas, including that which would have been stimulated by increased ambient $CO_2$ levels. Smaller losses in the early years in Case 2 are due to less deforestation and more use of pasture, shrubland, and savanna, which have lower carbon stocks than forests and, once under more intensive management, accumulate soil carbon. Much of the soil carbon accumulation is projected to occur in sub-Saharan Africa, an attractive area for growing biofuels in our economic analyses because the land is relatively inexpensive (*10*) and because simple management interventions such as fertilizer additions can dramatically increase crop productivity (*18*).

Estimates of land devoted to biofuels in our two scenarios (15-16%) are well below the estimate of about 50% in a recent analysis (*6*) that does not control land-use emissions. The higher number is based on an analysis that has a lower concentration target (450 ppmv $CO_2$), does not account for price-induced intensification of land use, and does not explicitly consider concurrent changes in other environmental factors. In analyses that include land-use emissions as part of the policy (*6*–*8*), less area is estimated to be devoted to biofuels (3-8%).

The carbon losses associated with the combined direct and indirect biofuel emissions estimated for our Case 1 are similar to a previous estimate (*7*), which shows larger losses of carbon per unit area converted to biofuels production. These larger losses per unit area result from a combination of factors including a greater simulated response of plant productivity to changes in climate and atmospheric $CO_2$ (*15*) and the lack of any negative effects on plant productivity of elevated tropospheric ozone (*19*, *20*).

We also simulated the emissions of $N_2O$ from additional fertilizer that would be required to grow biofuel crops. Over the century, the $N_2O$ emissions become larger in $CO_2$-eq than carbon emissions from land use (Fig. 3). The net GHG effect of biofuels also changes over time; for Case 1, the net GHG balance is -90 Pg $CO_2$-eq through 2050 (a negative sign indicates a source; a positive sign indicates a sink), while it is +579 through 2100. For Case 2, the net GHG balance is +57 Pg $CO_2$-eq through 2050, and +679 through 2100. By the year 2100, we estimate that biofuels production accounts for about 60% of the total annual $N_2O$ emissions from fertilizer application in both cases, where the total for Case 1 is 18.6 Tg N $yr^{-1}$ and for Case 2 is 16.1 Tg N $yr^{-1}$. These total annual land-use $N_2O$ emissions are about 2.5 to 3.5 times higher than comparable estimates from an earlier study (*8*). Our larger estimates results from differences in the assumed proportion of nitrogen fertilizer lost as $N_2O$ (*21*) as well as differences in the amount of land devoted to food and biofuel production. Best practices for the use of nitrogen fertilizer, such as synchronizing fertilizer application with plant demand (*22*), can reduce $N_2O$ emissions associated with biofuels production.

The CI of fuel was also calculated across three time periods (Table 1) for comparison with displaced fossil energy in a LCFS and identify the GHG allowances that would be required for biofuels in a cap and trade program. Previous CI estimates for California gasoline (*3*) suggest that values less than ~96 g $CO_2$-eq/MJ indicate that blending cellulosic biofuels will help lower the carbon intensity of California fuel and therefore contribute to achieving the LCFS. Entries that are higher than 96 g $CO_2$-eq/MJ would raise the average California fuel carbon intensity and thus be at odds with the LCFS. Therefore, the CI values for Case 1 are only favorable for biofuels if the integration period extends into the second half of the century. For Case 2, the CI values turn favorable for biofuels for an integration period somewhere between 2030 and 2050. In both cases, the $CO_2$ flux has approached zero by the end of the century when little or no further land conversion is occurring and emissions from decomposition are approximately balancing carbon added to the soil from unharvested components of the vegetation (i.e. roots). While the carbon accounting ends up as a nearly net neutral effect, $N_2O$ emissions continue. Annual estimates start high, are variable from year-to-year because they depend on climate, and generally decline over time.

One of the perplexing issues for policy analysts has been predicting the dynamics of the CI over different integration periods (supporting online text). If one integrates over a long enough period, biofuels show a substantial greenhouse gas advantage, but over a short period they have a higher CI than fossil fuel (*3*). Drawing on previous analyses (*5*, *23*), we argue that a solution need not be complex and can avoid valuing climate damages by using the immediate (annual) emissions (direct and indirect) for the CI calculation. In other words, CI estimates should not integrate over multiple years, but rather simply consider the fuel offset for the policy time period (normally a single year). This becomes evident in Case 1, where despite the promise of eventual long-term economic benefits, a substantial penalty - in fact possibly worse than gasoline – in the first few decades may render the near term cost of the carbon debt difficult to overcome.

In Case 2, where there is less willingness to convert land, the economics of biofuels would be favorable sooner. Greater measures to protect forests could make the economics and CI of biofuels even more favorable because improved management on low quality or degraded land can lead to carbon accumulation in the soil, rather than a carbon loss (fig. S3). Interestingly, our results suggest tropical regions that are currently suffering significant amounts of deforestation may also be the most competitive producers of biofuels. Our suggested strategy of not integrating over future fuel offsets increases the near-term CI of biofuels unless forested lands globally are better protected. Success in avoiding deforestation will be reflected in lower estimates of indirect emissions, and a lower carbon penalty in carbon control areas for their use.

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**Supporting Online Material**

www.sciencemag.org/cgi/content/full/1180251/DC1
Materials and Methods
SOM Text
Figs. S1 to S3
Tables S1 to S6
References

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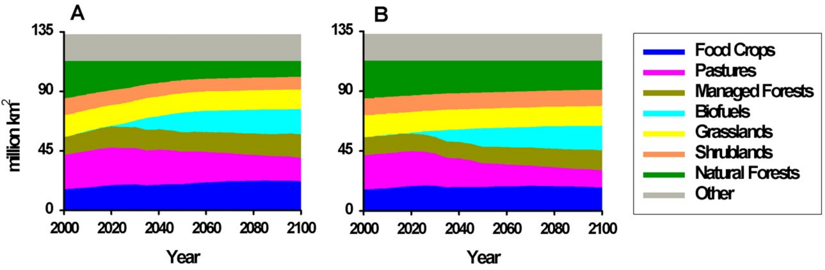
**Fig. 1.** Projected changes in global land cover for land-use Case 1 (**A**) and Case 2 (**B**). In either case, biofuels supply most of the world's liquid fuel needs by 2100. In Case 1, 365 EJ of biofuel is produced in 2100, using 16.2% (21.6 million $km^2$) of the total land area; natural forest area declines from 34.4 to 15.1 million $km^2$ (56%) and pasture area declines from 25.8 to 22.1 million $km^2$ (14%). In Case 2, 323 EJ of biofuels are produced in 2100, using 20.6 million $km^2$ of land; pasture areas decrease by 10.3 million $km^2$ (40%) and forest area declines by 8.4 million $km^2$ (24% of forest area). Simulations show that these major land-use changes will take place in the tropics and sub-tropics, especially in Africa and the Americas (fig. S2).

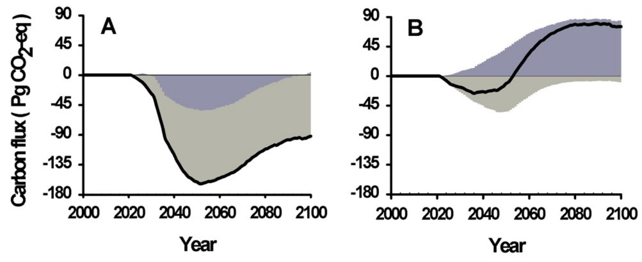
**Fig. 2.** Partitioning of direct (dark grey) and indirect effects (light grey) on projected cumulative land carbon flux since the year 2000 (solid black line) from cellulosic biofuel production for land-use Case 1 (**A**) and Case 2 (**B**). Positive values represent carbon sequestration whereas negative values represent carbon emissions by land ecosystems. In Case 1 the cumulative loss is 92 Pg $CO_2$-eq by 2100, with the maximum loss (164 Pg $CO_2$-eq) occurring in the 2050 to 2055 time frame, with indirect losses of 110 Pg $CO_2$-eq and direct losses of 54 Pg $CO_2$-eq. In the second half of the century there is net accumulation of 72 Pg $CO_2$-eq mostly in the soil in response to the use of nitrogen fertilizers. In Case 2, land areas are projected to have a net accumulation of 75 Pg $CO_2$-eq (see the black line in 1b) as a result of biofuel production, with maximum loss of 26 Pg $CO_2$-eq in the 2035 to 2040 time frame, followed by substantial accumulation.

**Fig. 3.** Partitioning of greenhouse gas balance since the year 2000 (solid black line) as influenced by cellulosic biofuel production for land-use Case 1 (**A**) and Case 2 (**B**) among fossil fuel abatement (yellow), net land carbon flux (cyan), and fertilizer $N_2O$ emissions (red). Positive values are abatement benefits and negative values are emissions. Net land carbon flux is the same as in Fig. 2. For Case 1, $N_2O$ over the century are 286 Pg $CO_2$-eq; for Case 2, $N_2O$ emissions are 238 Pg $CO_2$-eq.

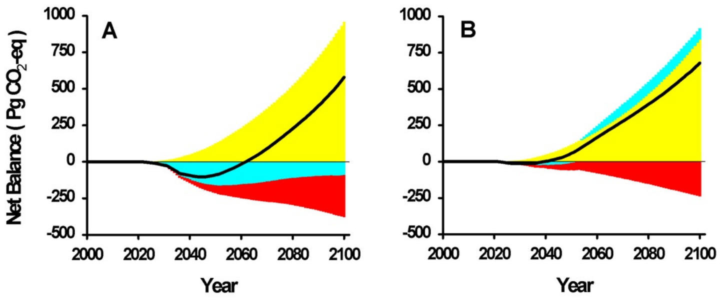
**Table 1.** Carbon intensity index associated with cellulosic biofuel production for two land use scenario cases. Units are g $CO_2$-eq / MJ, with negative values indicating carbon accumulation.

| Variable | | Case 1 | | | Case 2 | |
|---|---|---|---|---|---|---|
| Time Period | 2000–2030 | 2000–2050 | 2000–2100 | 2000–2030 | 2000–2050 | 2000–2100 |
| Direct Land C | 11 | 27 | 0 | –52 | –24 | –7 |
| Indirect Land C | 190 | 57 | 7 | 181 | 31 | 1 |
| Fertilizer $N_2O$ | 29 | 28 | 20 | 30 | 26 | 19 |
| Total | 229 | 112 | 26 | 158 | 32 | 13 |


A
B
135
90
45
0
million km$^2$
2000
2020
2040
2060
2080
2100
Year
Food Crops
Pastures
Managed Forests
Biofuels
Grasslands
Shrublands
Natural Forests
Other



A
B
Carbon flux ( Pg $CO_2$-eq )
90
45
0
-45
-90
-135
-180
2000
2020
2040
2060
2080
2100
Year


A
B
1000
750
500
250
0
-250
-500
Net Balance ( Pg $CO_2$-eq )
2000
2020
2040
2060
2080
2100
Year