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## Climate impacts of a large-scale biofuels expansion

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[1] A global biofuels program will potentially lead to intense pressures on land supply and cause widespread transformations in land use. These transformations can alter the Earth climate system by increasing greenhouse gas (GHG) emissions from land use changes and by changing the reflective and energy exchange characteristics of land ecosystems. Using an integrated assessment model that links an economic model with climate, terrestrial biogeochemistry, and biogeophysics models, we examined the biogeochemical and biogeophysical effects of possible land use changes from an expanded global second-generation bioenergy program on surface temperatures over the first half of the 21st century. Our integrated assessment model shows that land clearing, especially forest clearing, has two concurrent effects—increased GHG emissions, resulting in surface air warming; and large changes in the land's reflective and energy exchange characteristics, resulting in surface air warming in the tropics but cooling in temperate and polar regions. Overall, these biogeochemical and biogeophysical effects will only have a small impact on global mean surface temperature. However, the model projects regional patterns of enhanced surface air warming in the Amazon Basin and the eastern part of the Congo Basin. Therefore, global land use strategies that protect tropical forests could dramatically reduce air warming projected in these regions. **Citation:** Hallgren, W., C. A. Schlosser, E. Monier, D. Kicklighter, A. Sokolov, and J. Melillo (2013), Climate impacts of a large-scale biofuels expansion, *Geophys. Res. Lett.*, 40, 1624–1630, doi:10.1002/grl.50352.

### 1. Introduction

[2] Economic studies estimate that future global energy demands will increase substantially, by up to 250% by 2050 [Melillo *et al.*, 2009; Clarke *et al.*, 2007] depending on the availability of resources, and how greenhouse gas (GHG) mitigation policies affect energy demands in the future [Pacala and Socolow, 2004; Farrell *et al.*, 2006]. Biofuels have been proposed as a potential low-carbon energy source that can assist in meeting these energy demands, as well as reduce greenhouse gas emissions to help mitigate global warming [Pacala and Socolow, 2004; Farrell *et al.*, 2006].

All supporting information may be found in the online version of this article.

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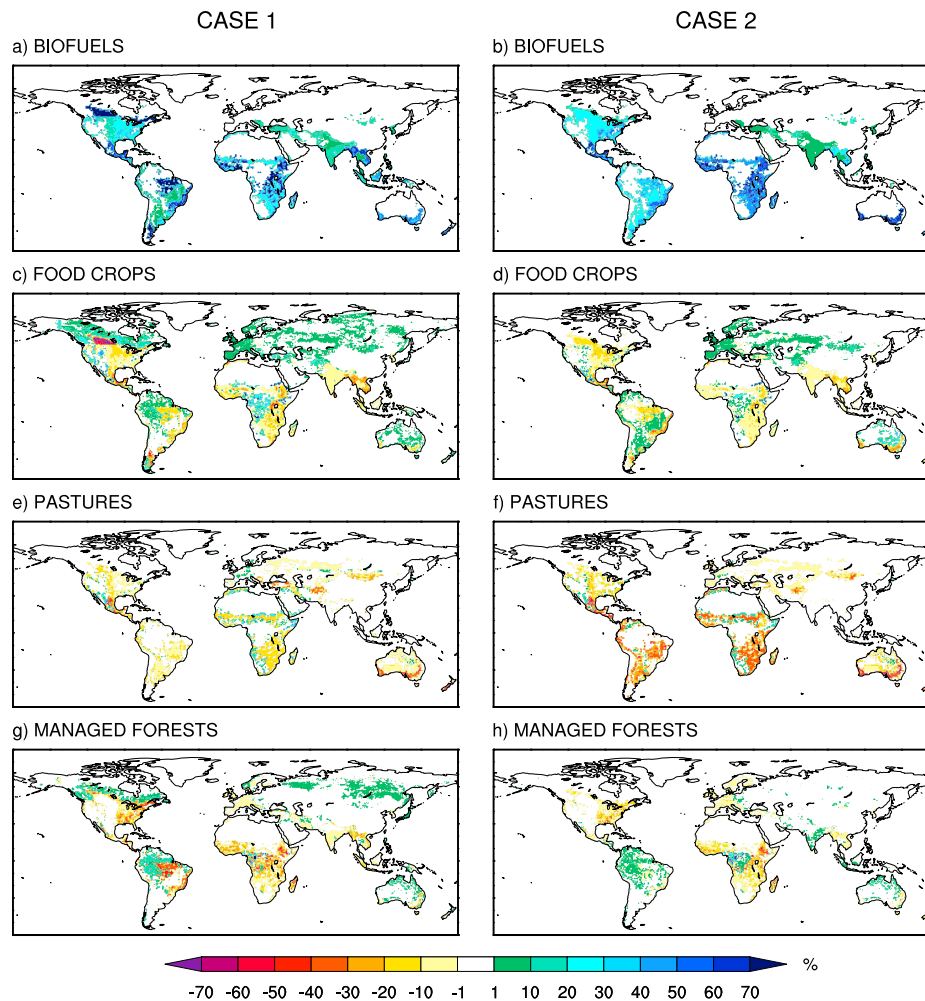
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[3] The large-scale cultivation of biofuel crops for bioenergy will likely have a large impact on the Earth land surface, either directly or by the displacement of other managed lands. The impacts of biofuels on climate can be separated into two major types of processes: biogeochemical and biogeophysical impacts. Biogeochemical impacts are the results of changes in processes such as photosynthesis, plant respiration, decomposition, nitrification, and denitrification that lead to changes in fluxes of carbon dioxide (CO<sub>2</sub>) and nitrous oxide (N<sub>2</sub>O) between the land surface and the atmosphere [Searchinger *et al.*, 2008; Melillo *et al.*, 2009; Wise *et al.*, 2009; Kicklighter *et al.*, 2012; Strengers *et al.*, 2004; Crutzen *et al.*, 2008; Davidson, 2009]. This leads to changes in atmospheric GHG concentrations and radiative forcing. Biogeophysical impacts are caused by changes in albedo [Bonan, 2008; Lee *et al.*, 2011] and evapotranspiration [Pitman *et al.*, 2009] from the varying characteristics of different types of vegetation; albedo is surface reflectivity and evapotranspiration is the combination of evaporation from plant and soil surfaces and the pumping of soil water through plant leaves to the atmosphere. Together, these changes affect the surface energy budget.

[4] Different land use policies have different influences on the impacts of biofuels on climate. Previous work [Melillo *et al.*, 2009] shows how a policy (Case 2) that relies on more intensive use of existing managed lands can reduce GHG emissions from second-generation (i.e., cellulosic) biofuels production over the 21st century more than a policy (Case 1) that allows the profitable conversion of natural areas to meet an increased demand for land. Here, we expand on this study to examine how both biogeophysics and biogeochemistry impact future surface air temperature (SAT). Our analysis takes a novel approach to this issue, by employing an integrated climate impact assessment framework [Sokolov *et al.*, 2009; Monier *et al.*, 2012], which takes into account the complex interactions of energy and land use policies, GHG emissions, and economic factors (such as food prices, land prices, population growth, and environmental regulation) that influence where and how much biofuel crops are planted. Land cover changes projected in the two land use scenarios (as shown in Figure 1) include both direct effects on GHG emissions, albedo, and heat fluxes at the location of biofuel plantations and their indirect effects, caused by the biofuel-induced displacements of other managed lands such as food crops, pastures, and managed forests. Most of these land use changes occur in the tropics (Table 1).

### 2. Methods

[5] To determine the climate impacts of second-generation biofuels, this study makes use of land cover changes and GHG emissions (CO<sub>2</sub> and N<sub>2</sub>O) from biofuels estimated by the coupled Terrestrial Ecosystem Model [Sokolov



**Figure 1.** Biofuel-induced changes in land cover by 2050 (adapted from *Kicklighter et al.* [2012]) for policy Case 1 and Case 2. Changes include the (a, b) distribution of second-generation biofuels and the displacement of (c, d) food crops, (e, f) pastures, and (g, h) managed forests. The values represent the percent of a grid cell undergoing specified land cover changes associated with biofuel production. The green and blue colors indicate increases in a particular land cover within a grid cell, whereas the yellow and red colors indicate decreases.

*et al.*, 2008] and the Massachusetts Institute of Technology (MIT) Emissions Prediction and Policy Analysis model [Paltsev *et al.*, 2005] framework, as previously described [Melillo *et al.*, 2009]. These potential drivers of global and regional climate changes are used as input to an integrated assessment modeling framework that links the MIT Integrated Global System Model [Sokolov *et al.*, 2009] to a global climate model that includes the Community Atmosphere Model (CAM3.1 [Collins *et al.*, 2004]), the Community Land Model [Oleson *et al.*, 2004], and a mixed layer ocean model. The biofuel-induced land cover changes and GHG emissions were integrated into the modeling framework as previously described [Hallgren *et al.*, 2012].

[6] The climate model simulates global and regional climate changes that result from changes in atmospheric GHG concentrations, changes in the surface albedo (due to differences in vegetation reflectivity), and the local hydrological cycle. The integrated assessment model also allows changes in atmospheric circulation, including potential teleconnections, and interactions between local and global climate responses to be simulated. Further information about the modeling framework can be found in the auxiliary material.

[7] The experimental design consisted of 80 year equilibrium climate model simulations for the year 2050, which were conducted at a spatial resolution of  $2^\circ \times 2.5^\circ$ , the last 50 years after spin-up being used to conduct analyses. A set of experimental simulations were run for the two land use scenarios described in Melillo *et al.* [2009]. The set of simulations included the following: (1) a control simulation that did not incorporate a biofuels policy, (2) a simulation with land use (at 2050) that reflected the second-generation biofuel-based energy policy and also incorporated the direct and indirect ( $\text{CO}_2$  and  $\text{N}_2\text{O}$ ) emissions as a result of growing biofuels, and (3) a simulation that only incorporated the land use and not the greenhouse gas impacts.

[8] Using these six simulations, we were able to isolate the respective (a) biogeophysical and (b) biogeochemical impacts of biofuels on climate. We isolate the biofuels biogeophysical impacts by comparing the simulations (i.e., of surface air temperature) in which a biofuel policy is implemented to one in which a biofuel policy is not implemented. The biogeochemical impacts were isolated by comparing the simulations that included a biofuel policy and the GHG emissions due to biofuels to the simulations that do

**Table 1.** Biofuel-Induced Changes in Land Cover<sup>a</sup>

Land Cover	Region	Area (million km <sup>2</sup> ) Change Since 2000	
		Case 1	Case 2
Second-Generation Biofuels	Extratropics	4.08	3.59
	Tropics <sup>b</sup>	11.17	10.48
	Globe	15.25	14.07
Displaced Food Crops	Extratropics	1.31	0.53
	Tropics <sup>b</sup>	1.72	1.10
	Globe	3.03	1.63
Displaced Pastures	Extratropics	0.12	0.08
	Tropics <sup>b</sup>	0.53	0.29
	Globe	0.65	0.37
Displaced Managed Forests	Extratropics	0.41	0.09
	Tropics <sup>b</sup>	0.86	0.72
	Globe	1.27	0.81

<sup>a</sup>Adapted from *Kicklighter et al.* [2012].

<sup>b</sup>Tropical regions represent areas between 30°S and 30°N.

not include the GHG emissions due to biofuels in the climate simulation. The potential impact of land use policy on surface air temperature is explored by comparing simulations of the two case scenarios (Case 1 and Case 2) from *Melillo et al.* [2009], in which the biofuel policy is implemented. Both land use scenarios have been formulated to produce enough energy to meet at least 10% of the projected global energy requirement in 2050, which necessitates a large amount of land use transformation, although there is a considerable difference in the area of biofuel cropland in the two scenarios ( $2.58 \times 10^6$  km<sup>2</sup>). The difference between the two cases is the result of different economic controls on how land use is partitioned: The Case 1 scenario of *Melillo et al.* [2009] makes all land available for biofuels crops or other managed uses as long as the economic return on the land exceeds the cost of conversion and improvement. This scenario involves large-scale deforestation in support of biofuels production, either directly, when forests are cleared to establish biofuels crops, or indirectly, when biofuel production moves on to croplands or pastures, and causes new forest clearing to relocate agriculture [*Fargione et al.*, 2008]. The Case 2 scenario limits access to unmanaged land (e.g., tropical forests), with the limits based on the recent history of regional land conversion rates. Existing managed lands are used more intensively, with increased inputs of capital, labor, and materials such as fertilizers. This approach results in slower rates of deforestation than would be predicted by cost estimates alone [*Gurgel et al.*, 2007]. Further detail of the methodology can be found in the auxiliary material. Interpretation of our results is limited to the extent of these particular model-generated scenarios, acknowledging the fact that other (simulated) pathways to achieve the targeted biofuel penetration are possible. In this vein, multimodel and intercomparison studies would be useful to confirm our results and further our understanding of this issue.

### 3. Results and Discussion

[9] Our results indicate that at the global scale, the deployment of a global biofuel policy and the associated land use changes has a negligible impact on the Earth's energy budget and surface air temperature (Table 2) by 2050. This is mainly due to the fact that the biogeochemical and the biogeophysical impacts of biofuels on the global mean surface air temperature largely compensate each other. The

biogeochemical impact of biofuel leads to a global warming in both land use scenarios, associated with an increase in GHG concentrations in the atmosphere. However, our analysis of the carbon impacts of the biofuel expansion does not account for the reduction in fossil fuel emissions associated with the energy obtained from the biofuels. Therefore, we expect this warming effect on global temperature at 2050 to be even smaller. On the other hand, the biogeophysical impact leads to a cooling at the global scale, caused by an overall increase in the surface albedo as forests are replaced with cropland (Figure 2).

[10] Previous work on deforestation supports our findings. *Claussen et al.* [2001] found that globally, the biogeochemical effects of tropical deforestation and replacement with grassland outweighed the biogeophysical effects, leading to a regional warming, but that at higher latitudes, the biogeophysical impacts which lead to regional cooling are stronger, with the net impact being that deforestation led to global cooling. *Bala et al.* [2007] also found that global scale deforestation and replacement by grasses and shrublands led to a net global cooling ( $-0.3$  K by 2100) as biophysical changes (i.e., albedo and evapotranspiration) overwhelmed the warming from the changes to the carbon cycle. *Gibbard et al.* [2005] looked at the balance of biogeophysical and biogeochemical impacts of extreme land cover change and found that they do not balance each other out globally, with the potential cooling due to carbon sequestration from a global reforestation simulation of  $3.5^\circ\text{C}$  being offset  $\sim 40\%$  by the  $1.3^\circ\text{C}$  warming due to albedo change.

[11] The *Brovkin et al.* [2004] analysis of 150 years of historical data found the same regional impacts; however, like our study, they found that the net effect of the biogeophysical cooling and biogeochemical warming was negligible on a global scale.

[12] However, the biogeophysical and biogeochemical impacts of biofuels on SAT vary greatly across the globe, resulting in substantially larger impacts on the regional climate. For example, SAT can become up to  $1.5^\circ\text{C}$  higher in the Amazon Basin or central Africa (Figure 3) because, in these regions, the biogeophysical and biogeochemical impacts do not cancel each other out. Our results are confirmed by other studies which have also found the effects of deforestation are broadly latitude specific [*Bala et al.*, 2007; *Pongratz et al.*, 2010].

**Table 2.** The Biogeophysical and Biogeochemical Impacts on Surface Air Temperature (°C) up to Year 2050 From Policy Case 1 and Case 2

Type of Impact	Region	Difference in Surface Air Temperature (°C) Between Biofuel and No-Biofuel Scenarios	
		Case 1	Case 2
Biogeophysics <sup>a</sup>	Extratropics	-0.18	-0.12
	Tropics <sup>c</sup>	-0.05	-0.08
	Globe	-0.12	-0.10
Biogeochemistry <sup>b</sup>	Extratropics	+0.16	+0.05
	Tropics <sup>c</sup>	+0.06	+0.03
	Globe	+0.11	+0.04
Combined	Extratropics	-0.02	-0.07
	Tropics <sup>c</sup>	0.002	-0.06
	Globe	-0.01 <sup>d</sup>	-0.06

<sup>a</sup>The “biogeophysical” impact of biofuels represents the difference in SAT between the biofuels and no-biofuels simulations.

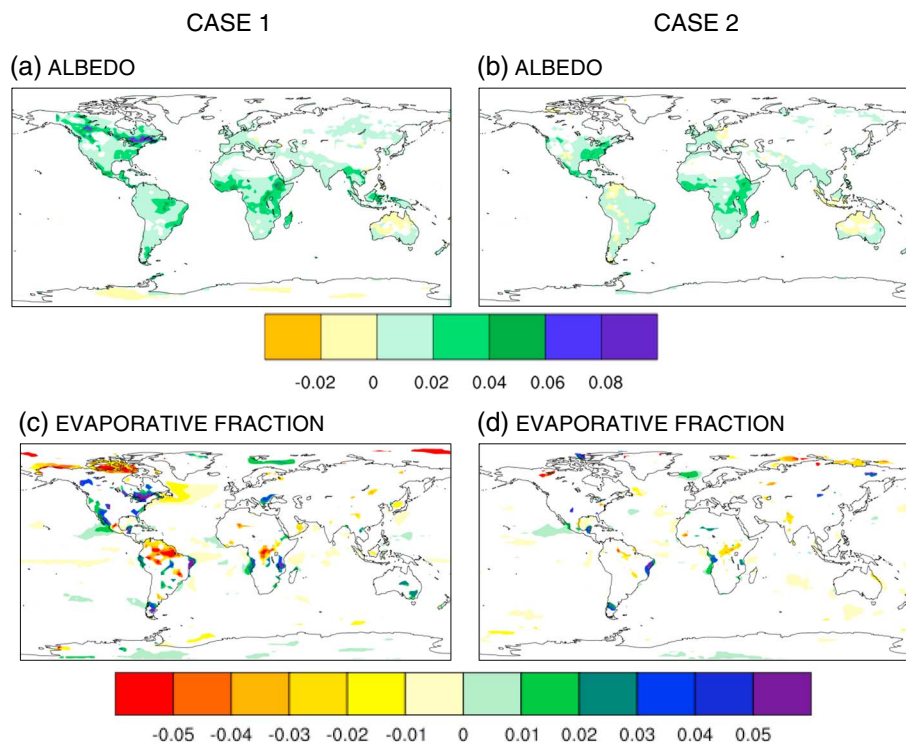
<sup>b</sup>The “biogeochemical” impact represents the change in SAT from just the CO<sub>2</sub> and N<sub>2</sub>O “gain” (positive or negative) to the atmosphere resulting from biofuels in each land use scenario.

<sup>c</sup>Tropical regions represent areas between 30°S and 30°N.

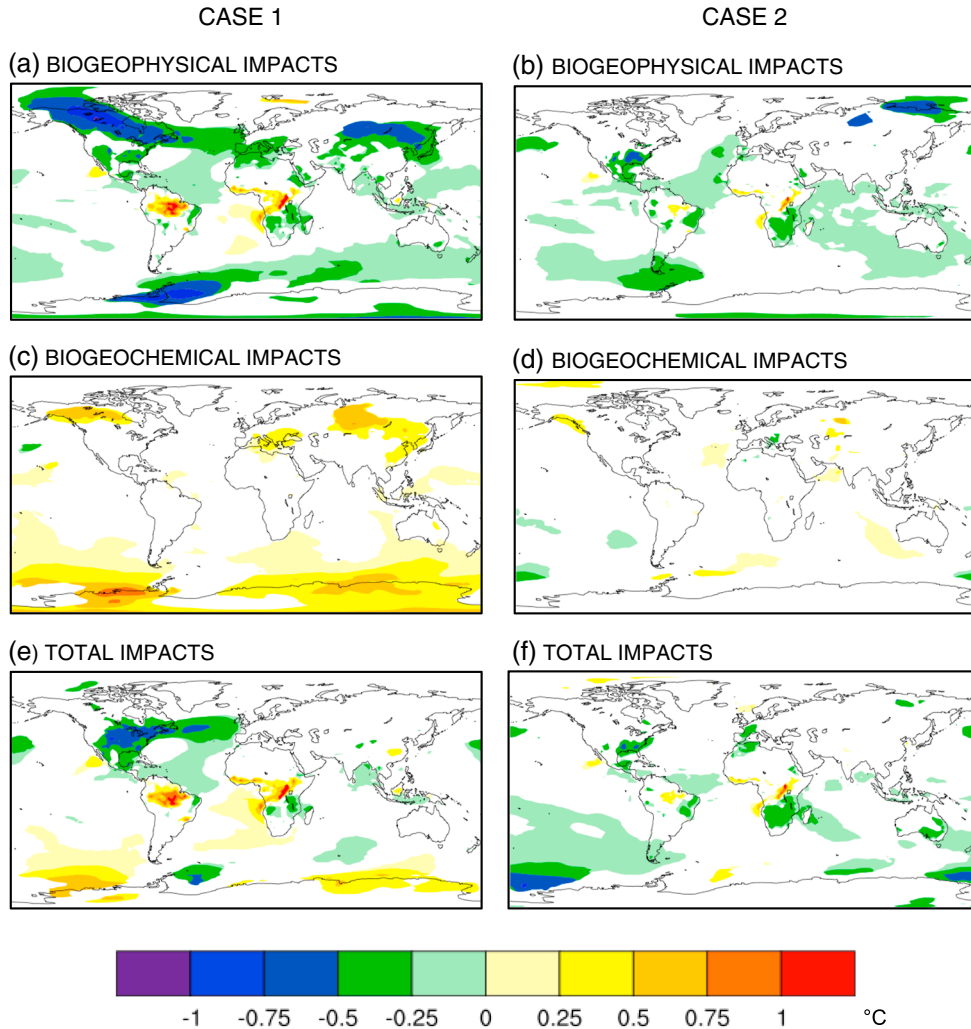
<sup>d</sup>This represents statistically insignificant results.

[13] Tropical forests maintain high rates of evapotranspiration [Bonan, 2008], and their replacement with cropland causes the evaporative fraction to decrease (Figure 2) in response to ecophysiological changes of the new land cover [Pitman et al., 2009]. Less leaf area and shallower root systems lower canopy evaporation and decrease plants’ capacity to transpire moisture from the soil. Changes to

evapotranspiration generate feedbacks that support an overall climatic impact from any tropical deforestation as a result of biofuels plantations. A reduction in evapotranspiration will (in addition to changes in albedo) likely induce a local reduction in convective moisture transport and cloud formation [Bala et al., 2007]. Previous studies have shown that tropical deforestation and the impacts on the surface heat



**Figure 2.** Relative contributions of albedo and evaporative fraction to biogeophysical effects leading to surface cooling or warming in 2050 for policy Case 1 and Case 2. (a, b) Relative changes in albedo (vegetation reflectivity—unitless fraction) associated with biofuel-induced land cover changes. Changes in albedo include both the direct impact of changes to the surface radiation budget due to land cover change and the indirect effects from changes to snow cover, cloud cover, and diffuse radiation. Higher values represent increased reflectivity and lower values represent decreased reflectivity. (c, d) Relative changes in evaporative fraction (unitless) associated with biofuel-induced land use changes. Yellow to red represents relative decreases in evaporative fraction, and green to purple represents relative increases in evaporative fraction. Data are only shown where significant at the 5% level.



**Figure 3.** Surface air temperature (SAT) impacts due to biofuel production in 2050 for policy Case 1 and Case 2. Impacts are shown for (a, b) changes in biogeophysics alone, (c, d) changes in biogeochemistry alone, and (e, f) combined changes in biogeophysics and biogeochemistry. The white areas represent insignificant changes based on statistical testing at the 5% significance level. Yellow and red represent surface warming in a grid cell associated with biofuel-induced land cover change. Green to purple represents surface cooling.

fluxes can result in decreased precipitation and increased surface temperatures [Sud *et al.*, 1996; Lean and Rowntree, 1997; Hahmann and Dickinson, 1997; Henderson-Sellers *et al.*, 1993; Costa and Foley, 2000; Werth and Avissar, 2004]. However, in the extratropics, deforestation leads to regional cooling. Moreover, Georgescu *et al.* [2011] showed that the biogeophysically related climate impacts of second-generation biofuels (replacing natural vegetation) in the U.S. were several times larger than the biogeochemical impacts.

[14] The warming associated with the biogeochemical impacts is stronger over the middle to high latitudes (Figure 3) and is not necessarily located in regions where biofuels crops are grown [Melillo *et al.*, 2009; Kicklighter *et al.*, 2012]. That is because the GHGs released from land clearing ( $\text{CO}_2$ ) and fertilization of biofuel crops ( $\text{N}_2\text{O}$ ) are well mixed in the atmosphere at the global level. In addition, GHG-induced warming reduces the snowpack at middle to high latitudes to change surface albedo, leading to polar amplification [Holland and Bitz, 2003] of the global warming caused by enhanced GHG emissions. Meanwhile, the

biogeophysical impacts lead to cooling in the extratropics and local warming in the tropics. In the extratropics, the cooling can be largely explained by an increase in the vegetation reflectivity (Figure 2) that results from the conversion of forests to cropland and/or pasture [Bonan, 2008; Lee *et al.*, 2011]. However, the climate response is complex and other processes take place that often lead to regional impacts. For example, snow cover on newly created open surfaces increases surface albedo during the winter [Euskirchen *et al.*, 2009]. These changes in surface albedo can also lead to changes in atmospheric circulation and cloud cover, which can feed back to change surface albedo, and subsequently affect the regional response to changes in land cover. In the tropics, the conversion of forests to agriculture also increases the surface albedo, but the cooling effect is counteracted by concurrent warming associated with decreases in evapotranspiration.

[15] Land use policy also influences the strength of different types of impacts of biofuel production on regional SAT—generally, the biofuel impacts on climate are stronger in Case 1 than in Case 2. In particular, the warming effects



from biofuel-induced changes in evaporative fraction in the tropics are more pronounced in Case 1 than in Case 2.

#### 4. Conclusions

[16] These results indicate that a land use policy allowing more deforestation will have a larger impact on regional energy budgets and SAT than a policy that constrains deforestation. The smaller regional changes in SAT occur where there is a less extensive and/or less severe biogeophysical warming from biofuels, indicating that land use policies that promote intensification of land use may result in more tolerable future environmental conditions for local populations in some tropical regions.

[17] Overall, our analyses indicate that at the global scale, the impacts of biofuels on climate are negligible. That is because the warming associated with increases in GHG concentrations is offset by a cooling from changes in albedo. However, at the regional and local levels, biogeophysical and biogeochemical impacts of biofuels are substantial and lead to an overall cooling in the extratropics and warming in the tropics. For these reasons, both types of impacts should be considered in future impact assessments of biofuel and/or land use policies.

[18] Finally, the net effect of biofuels on SAT is not the only consequence of biofuel production. Biofuel production also affects a range of ecosystem services that people depend on including habitat that is the key to biodiversity and the quantity and quality of surface waters.

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