Biogeophysical impacts of cropland management changes on climate

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[1] It is well known that expansion of agriculture into natural ecosystems can have important climatic consequences, but changes occurring within existing croplands also have the potential to effect local and global climate. To better understand the impacts of cropland management practices, we used the NCAR CAM3 general circulation model coupled to a slab-ocean model to simulate climate change under extreme scenarios of irrigation, tillage, and crop productivity. Compared to a control scenario, increases in irrigation and leaf area index and reductions in tillage all have a physical cooling effect by causing increases in planetary albedo. The cooling is most pronounced for irrigation, with simulated local cooling up to ~8°C and global land surface cooling of 1.3°C. Increases in soil albedo through reduced tillage are found to have a global cooling effect (~0.2°C) comparable to the biogeochemical cooling from reported carbon sequestration potentials. By identifying the impacts of extreme scenarios at local and global scales, this study effectively shows the importance of considering different aspects of crop management in the development of climate models, analysis of observed climate trends, and design of policy intended to mitigate climate change. **Citation:** Lobell, D. B., G. Bala, and P. B. Duffy (2006), Biogeophysical impacts of cropland management changes on climate, *Geophys. Res. Lett.*, *33*, L06708, doi:10.1029/2005GL025492.

1. Introduction

[2] Human activities are widely recognized as contributing to climate change [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001], both through combustion of fossil fuels and land use activities. Improved understanding of how these activities influence climate is needed to guide policies aimed at mitigating or adapting to climate change. Many studies have evaluated the climate impacts of land cover changes, which can affect climate through both biogeophysical (e.g., changes in surface albedo, evaporation, roughness length) and biogeochemical (e.g., changes in carbon balance) pathways [*Betts*, 2001; *Bonan*, 1997; *Brovkin et al.*, 1999; *Gibbard et al.*, 2005]. For example, historical clearing of forests for cropland in temperate regions has likely had a cooling biogeophysical effect on climate because of the greater albedo of croplands relative to forests [*Govindasamy et al.*, 2001; *Matthews et al.*, 2003; *Myhre and Myhre*, 2003]. These land cover change impacts can complicate detection and attribution of recent anthropogenic greenhouse warming [*Chase et al.*, 2001], and may play a significant role in driving future climate change [*DeFries et al.*, 2002; *Feddema et al.*, 2005; *Sitch et al.*, 2005].

[3] Despite the focus of past modeling efforts on land cover changes, there are many other land use changes not reflected in land cover that can potentially influence climate. (Land use change includes both conversion and other modifications [*Meyer and Turner*, 1992]). In particular, over the last 50 years, the net increase in global cropland area of ~10% has been relatively minor on a percentage basis compared to land use changes occurring within croplands, such as a doubling of irrigation extent, more than doubling of crop yields, and rapid regional increases in cropping intensity (# crops grown in a field per year) (Food and Agricultural Organization, FAO statistical databases, available at http://faostat.fao.org/, 2004). Similarly, future changes of land use within existing croplands will likely be substantial as society strives to meet growing food demands.

[4] Information on the sensitivity of climate to these management changes is needed to improve understanding of past climate changes, and to identify the climate-related tradeoffs associated with future policy and management decisions [*Gregory et al.*, 2002]. For instance, management practices that demonstrably mitigate regional or global climate change might be encouraged through incentives to farmers. While several studies have quantified the potential of crop management changes to sequester greenhouse gases such as CO_2 [e.g., *Lal*, 2004], the biogeophysical effects of most management changes have been less widely considered [see *Cooley et al.*, 2005].

[5] In this paper, we evaluate the potential biogeophysical effects of various cropland changes using an atmospheric general circulation model (GCM) coupled to a mixed-layer ocean model. We find that current trends in crop management toward more irrigation, higher crop leaf area index (LAI), and reduced tillage all can have substantial cooling effects on local and, in some cases, global climate.

2. Model Description

[6] We used the Community Atmosphere Model version 3.0 (CAM) [*Collins et al.*, 2004] coupled to version 3.0 of the Community Land Model (CLM) [*Oleson et al.*, 2004]. CAM has 26 levels in the vertical dimension and was run using 2.0° latitude × 2.5° longitude resolution. A slab-ocean/sea-ice model, which prescribes horizontal ocean heat transport beneath the oceanic surface mixed layer to ensure realistic sea surface temperatures and ice distributions for the present climate, was linked to CAM to allow interaction between ocean, ice, and atmospheric temperatures. The CLM model, described in detail by *Bonan et al.* [2002], includes up to four different plant function types (PFT's) within each 2.0° × 2.5° grid cell, with a single PFT used to represent croplands. Monthly values of LAI for each PFT in

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Table 1. Model Experiment Descriptions

Name	Description
CONTROL	Default CLM3.0 inputs (does not include irrigation).
IRRIG	Same as CONTROL, except cropland soil moisture at all depths set to soil saturation percentage when LAI > 0.
NOTILL	Same as CONTROL, except cropland soil albedo multiplied by 1.50 if albedo < 0.50. Albedos greater than 0.5 were unchanged, as it was assumed tillage has minimal effect when soils are covered by snow.
2XLAI	Same as CONTROL, except crop leaf area index (LAI) multiplied by 2.0.
2CROP	Same as CONTROL, except croplands in the non-growing season were prescribed to have the same LAI as in the growing season, creating two growing seasons per year. This was only done for grid cells without snow.

CLM are prescribed based on satellite measurements from 1992–1993 [*Bonan et al.*, 2002].

3. Model Experiments

[7] A total of five 50-year simulations were run, as summarized in Table 1, with the first 20 years of each simulation treated as spin-up and the last 30 years used for analysis. The percent of each grid cell with cropland was the same in all simulations, as defined by the default inputs for CLM derived from satellite-based land cover maps [*Loveland et al.*, 2000]. Greenhouse gas concentrations were prescribed at 355 ppm (CAM default) for all runs. The experimental scenarios were simplistic and relatively extreme, and were intended to help understand the sign and bound the potential magnitude of climate effects from cropland management change. We did not attempt in this study to use data on actual land use changes, but assume that the actual effects of past or future changes on existing croplands would be bracketed by the values derived here. (This ignores potential nonlinear effects of landscape heterogeneity [e.g., *Pielke*, 2001]). Indeed, data on actual crop management changes at the global scale are sparse, and sensitivity studies such as these allow one to see whether the effort in developing such data sets is warranted. The increase of soil albedo by 50% in the NOTILL simulation was based on experimental studies [*Andales et al.*, 2000; *Matthias et al.*, 2000] and reflects the higher albedos of crop residue and untilled soil compared with tilled soil.

4. Results

[8] All experiments produced statistically significant changes relative to CONTROL in land surface albedo over most cropland areas (Figure 1). Albedo in IRRIG was reduced since modeled soil albedo decreases linearly with moisture content. Albedo increased very slightly in 2XLAI and 2CROP as higher LAI in crops caused near infrared (NIR) reflectance to rise faster than visible reflectance decreased, but this effect is very small for LAI greater than four [*Tian et al.*, 2004]. The largest changes in albedo were observed for NOTILL, particularly in regions such as India and Europe where croplands occupy a large fraction of grid cells.

[9] Annual average surface temperature changes revealed significant cooling in cropland regions in all four experiments (Figure 2), with IRRIG having an impact several times greater than the other experiments. The primary cause of local cooling in IRRIG was an increase in latent heat flux (Figure 3a) and the associated decrease in sensible heat. Since latent heat fluxes peak during the daytime, the cooling effect was much stronger for daily maximum than minimum temperatures, as reflected by a significant decrease in the diurnal temperature range (Figure 3c). The model also simulated a strong positive feedback associated with increased cloud cover (Figure 3d). Low cloud cover was predicted to increase by as much as 20% over agricultural

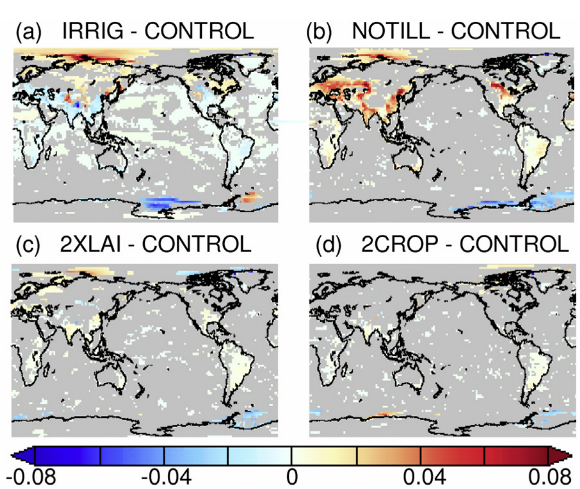

Figure 1. Average annual albedo changes for each experiment. Gray areas are not significant at 5% level.

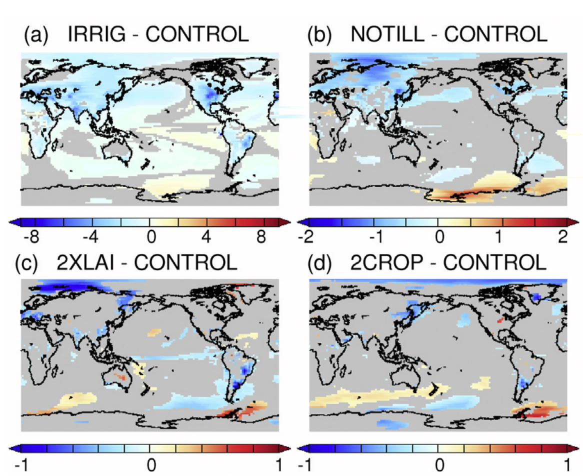

Figure 2. Average annual temperature changes (°C) for each experiment. Gray areas are not significant at 5% level.

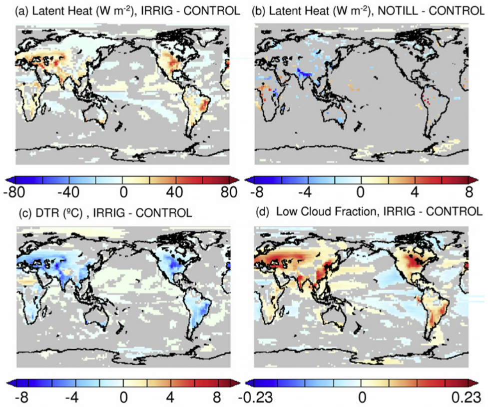

Figure 3. Average latent heat flux changes for (a) IRRIG and (b) NOTILL, and changes in (c) diurnal temperature range and (d) low cloud fraction for IRRIG. Gray areas are not significant at 5% level.

regions, with a resulting decrease in net surface shortwave radiation of up to 20 W m^{-2}.

[10] Significant changes in latent heat fluxes were also apparent over India in NOTILL (Figure 3b), where increased albedo substantially reduced evaporative fluxes. This reduction in evaporation over India also resulted in a 10% reduction in annual precipitation ($p < 0.05$, not shown), suggesting that recent trends toward reduced tillage in India [*Abrol et al.*, 2005] may have important impacts on both temperature and precipitation. Given that a main goal of reduced tillage is to conserve soil moisture, this result is perhaps not surprising. However, India was the only region with a substantial rainfall change in NOTILL, perhaps because of a particularly strong coupling in this region between surface fluxes and precipitation [*Koster et al.*, 2004] and the high proportion of land surface that is cultivated.

[11] While all experiments revealed significant regional temperature changes over croplands, only IRRIG and NOTILL exhibited substantial global climate changes (Table 2), with an average of 1.31°C and 0.23°C cooling over land in IRRIG and NOTILL, respectively. The global temperature changes were highly correlated across the experiments with changes in net surface solar radiation ($r = 0.99$), although not with changes in surface albedo ($r = 0.53$). This emphasizes the importance of cloud feedbacks in driving the global climate effects of irrigation. The evaporative cooling effect that was important locally had a smaller effect globally, because the latent heat in water was eventually released during condensation. Since this heat was released in the atmosphere, there was a significant change in the vertical profile of temperature, with cooling at 350 mb only 56% of surface cooling. This finding agrees qualitatively with the profile changes simulated by *Boucher et al.* [2004], although unlike those authors our simulations do not show a net warming of 350 mb temperature associated with increased irrigation.

5. Discussion and Conclusions

[12] The extreme scenarios investigated here were intended to help understand the sign and bracket the magnitude of possible biogeophysical impacts of past and future crop management changes. We have not considered the biogeochemical changes associated with cropland management, such as sequestration of C in soils or emission of methane and nitrous oxides. The results show that increased irrigation, higher crop LAI, and reduced tillage all tend to cool surface temperatures in cropland regions. Changes associated with crop LAI had negligible global impacts, suggesting that studies focused on global climate changes can reliably ignore these aspects of land use change. However, the regional effect of doubling LAI was as high as 1.0°C in parts of South America and Asia.

[13] The cooling from irrigation and marked decrease in diurnal temperature range is consistent with previous modeling and observational studies of irrigation's impact in specific regions [*Adegoke et al.*, 2003; *de Ridder and Gallee*, 1998]. For example, *Mahmood et al.* [2004] found reductions in diurnal temperature range in irrigated regions of Nebraska relative to adjacent non-irrigated regions. The results presented here demonstrate that irrigation's impact on climate will vary temporally (day vs. night), vertically (surface vs. 350mb), seasonally, and spatially, and therefore that a unique footprint associated with irrigation changes should be discernible in the observational records, as other drivers of climate change will likely have different patterns of temperature impacts.

[14] The substantial increase in cloud cover also indicates that irrigation can indirectly raise the planetary albedo. While this study considered only the CAM model, several climate models (including CAM) as well as available observations show an inverse relationship between soil moisture and cloud base height [*Dirmeyer et al.*, 2005], which presumably reflects a positive correlation between soil moisture and cloud cover. This suggests that a significant feedback between irrigation and incident surface radiation is not an artifact of the particular model we used; however, further study would be needed to confirm this.

[15] The simulated effect of reduced tillage showed that widespread adoption of no-till practices is likely to have a substantial cooling effect because of increased albedo, with a possible negative precipitation response in India. Most work on tillage has considered only the biogeochemical effect on climate, with estimates of global sequestration potential ranging from 25–50 Gt C globally [*Lal*, 2004]. If one

Table 2. Global and Land Surface Averages of Differences Between Experiments and Control Run for Selected Variables

	Irrigation		NOTILL		2XLAI		2CROP	
Variable	Global	Land Only	Global	Land Only	Global	Land Only	Global	Land Only
Surface temperature, °C	−0.55	−1.31	−0.10	−0.23	−0.06	−0.11	−0.04	−0.06
Surface albedo	0.0000	0.0000	0.0017	0.0075	0.0002	0.0011	0.0001	0.0003
Cloud fraction	0.01	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Net shortwave radiation at surface, Wm^{-2}	−1.46	−5.06	−0.12	−0.83	−0.04	−0.04	0.04	0.14

assumes a radiative forcing for doubled CO_2 of 3.5 W m^{-2} [*IPCC*, 2001], a model sensitivity of 2.2°C for doubled CO_2 [*Gibbard et al.*, 2005], and an atmospheric CO_2 reduction of 12–25 ppm corresponding to a sink of this strength, then the potential biogeochemical cooling effect of reduced tillage is 0.11–0.21°C. The biogeophysical cooling effect estimated here (~0.2°C) is therefore comparable in magnitude and in the same direction as the potential biogeochemical effect. Moreover, the biogeochemical effect is likely to diminish with time as the atmosphere equilibrates with the ocean [*Maier-Reimer and Hasselmann*, 1987], while the biogeophysical effect will be permanent.

[16] Overall, this study makes clear that while land cover change is an important aspect of human land use, changes occurring within existing agricultural lands can also have important consequences for climate. Interpretation of climate records in agricultural regions that fail to consider these changes may incur significant errors. For example, the cooling trends simulated here may mask any warming effect of rising carbon dioxide levels, especially at local scales. To better understand the role of crop management in climate, more realistic data sets on irrigation, productivity, and tillage changes should be developed and used to drive additional climate simulations.

[17] Finally, policies that promote management changes such as reduced tillage or increased irrigation may need to consider their climate consequences and possible feedbacks onto crop production. Efforts to incorporate crop management practices such as tillage into international carbon trading programs, which inherently focus on biogeochemical effects, may also wish to consider the potentially significant biogeophysical impacts on climate.

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