Climate Management through Agricultural Albedo Manipulation

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Abstract

Agriculture comprises the largest managed area of the Earth’s surface and could be adversely affected by increased temperatures due to global warming. Deliberately increasing the albedo of cropland might be a method to mitigate the effects of increasing temperatures. Crops that are modified to have greater reflectance, and planted on large scales, could induce an albedo-driven cooling effect. Agricultural scientists have bred soybean varieties with a fourfold increase in pubescence (leaf hairs) that increases shortwave reflectivity by 3-5%. We used NCAR’s Community Atmosphere Model (CAM 3.0) coupled to the Community Land Model (CLM 3.0) to understand the climatic effect of such increases in shortwave albedo. Simulations indicated that agricultural regions planted with the enhanced-albedo crops would have a maximum daily temperature 1.65 °C cooler during summer than if those regions had been planted with unmodified crops. However, this cooling effect was diminished at lower latitudes because lower latent heat fluxes led to reductions in cloudiness, and allowed more solar energy to be absorbed at the surface.

Key words: climate change, albedo, modeling, agriculture, geo-engineering, CAM, CLM
Introduction

Geo-engineering proposals aim to deliberately manage Earth’s climate system by reducing the atmospheric burden of greenhouse gases, or by increasing planetary albedo. Suggested strategies to increase planetary albedo include the injection of reflective aerosols into the stratosphere [Crutzen, 2006; Wigley, 2006], and the deployment of space-borne orbital sunshades [Angel, 2006]. Global albedo manipulation is expensive and risky. An alternative strategy is to modify surface albedo on regional scales to offset, or even reverse, local climate trends. Intensive cropland is an area where local climate trends may limit future productivity, and where surface albedo could potentially be manipulated.

Managing surface albedo as a means to stabilize climate has received less attention than the management of greenhouse gases, yet recent work indicates that the radiative forcing due to albedo can be equally as important as the radiative forcing due to greenhouse gas exchange. In the years following wildfire in boreal forests, the cooling due to the increased albedo of the new vegetation exceeds the warming effects due to greenhouse gas emissions from the fire, and the reduced CO$_2$ uptake of the younger vegetation [Randerson et al., 2006]. The climatic effects of land use changes that affect surface albedo are more localized than those that affect the net exchange of greenhouse gases. However, large-scale changes in albedo could potentially have global effects [Bala et al., 2007].

Incoming solar energy is about evenly divided between visible and near infrared energy. Plants absorb approximately 85% of the visible with photosynthetic pigments and use the energy to fix carbon during photosynthesis. By contrast, only ~10% of NIR is absorbed, the remainder being transmitted (~45%) or reflected (~45%) in typical broadleaf plants. The high reflectance of plants in the NIR is possibly a mechanism to avoid overheating [Gates et al., 1965]. Plants adapted to arid, hot zones have developed distinctive features to reflect excess solar energy. Encelia farinosa has a thick layer of hairs that absorb only 16% to 46% of shortwave radiation depending on pubescence density. Plant water is
largely responsible for NIR absorbance by leaves, but the hollow, air-filled nature of the hairs cause them to scatter strongly in the NIR region [Ehlringer and Bjorkman, 1978a]. Reflective leaf hairs on the underside of leaves can increase reflectivity in the NIR by \(~10\%\) [Eller 1977]. Other plants have thick leaf cuticles or thick wax layers that are able to reflect over 70\% of NIR in the 750-800 nm range [Reicosky and Hanover, 1978].

Agricultural scientists have modified crop morphology to increase yield in crops. For example, leaf pubescence (hair density) in soybeans was increased four-fold over normal varieties to increase water use efficiency in arid areas [Baldocchi et al., 1983a]. Densely pubescent (Harosoy and Clark cultivars) were 3-8 W m\(^{-2}\) more reflective in the short wave than unmodified varieties, an increase of 3-5\% [Nielsen et al., 1984]. The densely pubescent varieties had greater yield, even though most of the increased reflectivity occurred in the visible spectrum [Zhang et al., 1992], possibly due to increased diffuse light penetration within the canopy [Baldocchi et al., 1983a]. The densely pubescent variety also had superior water use efficiency as evapotranspiration decreased per carbon fixed [Baldocchi et al., 1983b] and greater resistance to insect and disease damage, since the hairs provided a mechanical barrier to aphid probing that served as a vector for disease [Pfeiffer et al., 2003].
Globally, if all agricultural areas used crops with a higher albedo, much of the earth’s surface will absorb less energy. Here, we explore the climatic effect of a large-scale agricultural albedo manipulation. We used NCAR’s Community Atmosphere Model (CAM 3.0; http://www.cccm.ucar.edu/models/atm-cam/) [Collins et al., 2006], coupled with the Community Land Model (CLM 3.0) and a slab ocean model. We compared a control simulation to a simulation in which leaf shortwave reflectivity in agricultural regions was increased by 0.1 (0.1 in NIR and 0.1 in visible). The simulations were run at a 20 minute time step at T42 resolution (2.8° by 2.8° at the equator) for 30 years, with no dynamic vegetation response and atmospheric CO₂ held constant at 355 ppm. Final results were calculated as the average of the last 15 years.

The surface albedo was calculated using a two stream radiation model [Dickenson, 1983] and the leaf level crop albedo constant was based on wheat (0.11 visible, 0.58 NIR) [Dorman and Sellers, 1989]. Surface albedo depends on Leaf Area Index (LAI) and ground color, in addition to leaf albedo. LAI for the CLM was prescribed from 1km AVHRR as described in Bonan et al. [2002]. Peak LAI in agricultural grid cells decreased from 30° to the equator, causing a decline in the impact of increased leaf level albedo on surface albedo at lower latitudes (SI figure 1). In regions where peak agricultural LAI’s were >3, surface reflectance increased by ~0.02 (SI figure 2). We also repeated the experiment at a number of higher leaf level albedos and at doubled CO₂ (710ppm) (SI figure 3 and 4).
Results

Significant cooling occurred in 50.8% of agricultural grid cells with an increased agricultural albedo (Figure 1, Student t test, P<0.05). The prescribed 0.1 increase in leaf-level reflectance resulted in an increase of summertime shortwave direct albedo of ~0.02 at LAI’s > 3, and led to cooling in Eurasia, North America, and southern South America. However, agricultural regions at lower latitudes, including areas in India, China and southern Brazil, showed little response to increased albedo.

Globally, maximum daily land temperatures were 0.34 ± 0.55°C cooler with increased agricultural albedo, relative to the control run. In grid cells dominated by agriculture, maximum daily temperatures were 0.77 ± 0.66°C cooler under increased agricultural albedo. Cooling rates were most intense at high latitudes, and during summer. Agricultural regions above 30°N were 1.05 ± 0.62°C cooler over the whole year, and were 1.65 ± 1.3°C cooler during June through August. Albedo-driven changes to maximum daily temperatures were most evident at latitudes above 30° N and S.

The effect of increased agricultural albedo on cloudiness and precipitation was less widespread, and more variable, than the effect on maximum daily temperatures. On average, cloud cover increased by ~0.86 % over agricultural regions at high latitudes (>30° N and S) and decreased by ~0.7 % at low latitudes (<30°) (Figure 2a). Precipitation increased by ~0.7 mm/month over agricultural regions at high latitudes (>30° N and S) and decreased by ~3.0 mm/month at low latitudes (<30°). Rainfall decreased by 10-20 mm/month at several low latitude regions (Figure 2b).

Albedo enhancement caused a smaller cooling effect at doubled CO₂ (710 ppm) than at current CO₂ levels (355 ppm) (SI figure 3). Significant cooling occurred in 36% of agricultural grid cells (compared with 50.9% at 355 ppm CO₂) and globally-averaged agricultural cooling was 0.63°C (compared with 0.77°C at 355 ppm CO₂).

A cooling effect due to increased agricultural albedo was largely dependent on whether
the agricultural region was in a low latitude region (<30°) or in a high latitude region (>30° N and S). This was due to two effects. First, prescribed agricultural LAI values decreased between 30° and the equator, which reduced the potential cooling effect that could be induced by leaf-level changes in albedo (SI figure 1 and 2). Second, as more shortwave energy was reflected, rather than absorbed by the crops, less energy was available for sensible and latent heat. Reductions in these pathways of energy were not partitioned equally. In low latitude regions, increased albedo disproportionately decreased latent heat flux, while in high latitude regions, increased albedo disproportionately decreased sensible heat flux (Table 1). Reductions in latent heat exchange caused a reduction of water vapor flux to the atmosphere, and was correlated with reductions in cloud cover ($r^2 = 0.26$) (figure not shown). The reduced cloud cover at low latitudes allowed more incident solar radiation at the surface ($r^2 = 0.64$), resulting in increases in the net energy absorbed by the surface. The change in energy absorbed by the surface was tightly correlated to the change in daily maximum temperature ($r^2 = 0.63$).
Discussion

Small increases (~0.02) in surface albedo in Northern (>30°N) agricultural systems can result in ~1.65°C cooling of maximum daily temperature during the summer (Figure 1). Increases in albedo also affect rainfall and cloud formation, causing increases (in both) at high latitudes (>30° N and S) and decreases (in both) at low latitudes (<30°) (Figure 2). The latitudinal effect is possibly a consequence of the meridional variation in the Bowen ratio (sensible heat divided by latent heat). At high latitudes, where sensible heat is proportionally abundant, decreases in absorbed radiation lead to decreases in sensible heat (Table 1). At low latitudes, where latent heat is proportionally abundant, decreases in absorbed radiation lead to decreases in latent heat. In the latter case, the reduced latent heat fluxes inhibited cloud formation [Bala et al., 2007].

Field investigations of albedo-driven cooling are scarce, but one study tested the effect of increased pubescence (reflective hairs) in soybean crops [Baldocchi et al., 1983 a and b]. The experiment took place in the US continental interior (Nebraska) where our model results predicted substantial albedo-driven cooling and decreases in sensible heat flux. However, in this field experiment and in contrast to our model predictions, latent heat decreased and sensible heat increased, and this was attributed to increased scattering of solar energy by the more reflective leaves into the sub-canopy where it warmed the soil and stems, causing an increase in sensible heat flux. No change in canopy radiative temperature occurred, possibly because the increased sensible heat flux was offset by the decreased absorption of solar radiation by leaves. A more thorough treatment of canopy radiative balance should be considered before we can fully test whether increased agricultural albedo would cause significant cooling at high latitudes.

We have considered here the effect of changes to surface albedo caused by morphological changes at the leaf level of crops. However, other possibilities exist for deliberately modifying the surface albedo of agricultural regions. Agricultural surface albedo is potentially affected by manipulating crop parameters, such as crop phenology (especially the time of ripening), tillage practices, residue management, and choice of
crop species or cultivar. However, we feel modifying leaf morphology is superior because the substitution would not involve major changes to agricultural practices, may increase yields [Zhang et al. 1992], and probably will not decrease CO₂ uptake despite lower PAR absorption [Baldocchi et al., 1983a].

In the future, if large agricultural regions are converted to biofuels, albedo, in addition to economics and energetics [Pimental and Patzek, 2005], should be considered. For example, switching from corn or soybeans to higher albedo crops, such as sunflowers, could increase reflectance by 0.04 - 0.08 (Table 2), enhancing albedo-driven cooling. Such changes in albedo may have implications for radiative forcing that are of similar magnitude to those associated with the exchange of greenhouse gases.

Most agriculture occurs within middle to high latitude continental interiors where temperature increases due to global warming are expected to be large. Agricultural albedo manipulation is best viewed as a method of reducing heat stress on crops in these regions, rather than as a solution to global climate change. It may have the added benefit of reducing maximum daily temperatures in urban areas located close to large agricultural regions. Agricultural albedo manipulation is inherently reversible as crops are replanted on an annual basis, and its costs are likely to be much lower than other geo-engineering proposals such as sulfate loading (~25 - 50 billion $ US [Crutzen, 2006]) or orbital sunshades (~5 trillion $ US [Angel, 2006]). However, at lower latitudes, agricultural albedo manipulation may interfere with cloud formation and precipitation, and may therefore be an inappropriate strategy in these regions.

We believe that agricultural albedo manipulation deserves consideration as a strategy to avoid adverse impacts of climate change on cropland in mid to high latitude regions. Further field studies and more detailed modeling efforts will improve our understanding of the sensitivity of the local climate of cropland area to changes in the surface albedo.

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**FIGURE LIST**

**Figure 1** – Maximum daily temperature differences between a control run (no albedo manipulation) and a treatment run where agricultural albedo was increased by 10% at the leaf level and ~2% at the surface level. The color level represents the average difference between the simulations during the final 15 years of a 30-year simulation for each grid cell. Agricultural grid cells where statistically significant differences occurred were identified using the paired Student t-test and are indicated by white dot. Agricultural grid cells where no significant temperature change occurred are indicated by black dots. Only land regions with at least partial plant cover are displayed. Agricultural grid cells are those in which agriculture is the primary of four land use types given for each grid cell.

**Figure 2** – (a) Precipitation and (b) percent cloud cover differences between a control run (no albedo manipulation) and a treatment run where agricultural albedo was increased by 10% at the leaf level and ~2% at the surface level. The color level represents the average difference between the simulations during the final 15 years of a 30-year simulation for each grid cell. Agricultural grid cells where statistically significant differences occurred were identified using the paired Student t-test (P<.05) and are indicated by white dot. Agricultural grid cells where no significant temperature change occurred are indicated by black dots. Only land regions with at least partial plant cover are displayed. Agricultural grid cells are those in which agriculture is the primary of four land use types given for each grid cell.

**Table 1** – Average values of maximum daily temperature, shortwave direct albedo, vapor pressure deficit (VPD), cloud cover, rainfall, latent heat flux and sensible heat flux; changes (Δ) in sensible and latent heat between a control run and a run with increased agricultural albedo of 10% at the leaf level and ~2% at the surface level. and treatment-control differences for climate variables for a control run for all majority agricultural grid cells, high latitude agricultural areas (>30°), and low latitude agricultural areas (<30°). Agricultural grid cells are those in which agriculture is the primary of four land use types given for each grid cell.

**Table 2** – Average surface albedos for several crop types compiled from several independent studies. Data compiled from Breuer et al., [2003]. N is the number of independent studies compiled for each crop type in the Breuer study.
Fig. 1
Fig. 2
<table>
<thead>
<tr>
<th>Surface</th>
<th>Average daily max temperature (°C)</th>
<th>surface shortwave direct albedo (%)</th>
<th>VPD (Pa)</th>
<th>cloud cover (%)</th>
<th>rain (mm/m)</th>
<th>Latent heat (W m⁻²)</th>
<th>Sensible heat (W m⁻²)</th>
<th>Δ Latent heat (W m⁻²)</th>
<th>Δ Sensible heat (W m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Agriculture regions</td>
<td>27 ± 8</td>
<td>42 ± 18</td>
<td>582 ± 486</td>
<td>56 ± 12</td>
<td>73 ± 51</td>
<td>68 ± 38</td>
<td>27 ± 16</td>
<td>0.35 ± 1.8</td>
<td>2.1 ± 2.4</td>
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<tr>
<td>Agriculture &gt; 30 °</td>
<td>24 ± 7</td>
<td>46 ± 16</td>
<td>430 ± 347</td>
<td>54 ± 12</td>
<td>52 ± 23</td>
<td>51 ± 27</td>
<td>25 ± 15</td>
<td>0.2 ± 1.5</td>
<td>2.7 ± 2.4</td>
</tr>
<tr>
<td>Agriculture &lt; 30 °</td>
<td>34 ± 0.5</td>
<td>35 ± 19</td>
<td>876 ± 346</td>
<td>62 ± 11</td>
<td>129 ± 52</td>
<td>100 ± 34</td>
<td>30 ± 17</td>
<td>1.3 ± 2.2</td>
<td>0.4 ± 1.5</td>
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<tr>
<td>Crop</td>
<td>Minimum Albedo</td>
<td>Maximum Albedo</td>
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<tr>
<td>Corn (<em>Zea mays</em>)</td>
<td>0.20 ± 0.03</td>
<td>0.23 ± 0.02</td>
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<tr>
<td>Wheat (<em>Triticum aestivum</em>)</td>
<td>0.17 ± 0.05</td>
<td>0.24 ± 0.02</td>
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<tr>
<td>Sunflowers (<em>Helianthus annuus</em>)</td>
<td>0.24 ± 0.04</td>
<td>0.30 ± 0.02</td>
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<tr>
<td>Soybeans (<em>Glycine max</em>)</td>
<td>0.21 ± 0.01</td>
<td>0.21 ± 0.01</td>
<td>2</td>
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Table 2.