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Report

Tackling Regional Climate Change By Leaf Albedo Bio-geoengineering

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Summary

The likelihood that continuing greenhouse-gas emissions will lead to an unmanageable degree of climate change [1] has stimulated the search for planetary-scale technological solutions for reducing global warming [2] ("geoengineering"), typically characterized by the necessity for costly new infrastructures and industries [3]. We suggest that the existing global infrastructure associated with arable agriculture can help, given that crop plants exert an important influence over the climatic energy budget [4, 5] because of differences in their albedo (solar reflectivity) compared to soils and to natural vegetation [6]. Specifically, we propose a "bio-geoengineering" approach to mitigate surface warming, in which crop varieties having specific leaf glossiness and/or canopy morphological traits are specifically chosen to maximize solar reflectivity. We quantify this by modifying the canopy albedo of vegetation in prescribed cropland areas in a global-climate model, and thereby estimate the near-term potential for bio-geoengineering to be a summertime cooling of more than 1°C throughout much of central North America and midlatitude Eurasia, equivalent to seasonally offsetting approximately one-fifth of regional warming due to doubling of atmospheric CO_2 [7]. Ultimately, genetic modification of plant leaf waxes or canopy structure could achieve greater temperature reductions, although better characterization of existing intraspecies variability is needed first.

Results

We have assessed the potential of albedo bio-geoengineering in helping mitigate future global warming using a fully coupled climate model [8], which accounts for ocean and atmosphere circulation, sea-ice, and terrestrial vegetation. In the terrestrial vegetation component, we prescribe an increase in the canopy albedo of C_3 and C_4 vegetation in areas designated as "cropland" [4] (Figure 1), as detailed in Experimental Procedures. In separate experiments, we test changes in the maximum canopy albedo in vegetated cropland areas of: +0.02, +0.04, and +0.08 (Table 1), spanning reported albedo variability existing between different commercial lines and varieties of the same species as well as the impact of artificial (external) treatments. For instance, whereas only small differences in canopy albedo (<0.02 and dependent on wavelength) occur between glaucous (covered with waxy layer or bloom) and nonglaucous varieties of barley [9], differences in the reflectivity of individual leaves of up to 0.16 (with respect to photosynthetically active radiation [PAR] wavelengths) and 0.19 (UV-A + UV-B) have been observed between mutants of *Sorghum bicolor* (L.) Moench with varying wax structure [10]. Canopy morphology is also important, with varieties of maize differing by up to 0.08 in canopy albedo [11]. Artificial enhancements of surface reflectivity involving the application of kaolinite suspension to the upper foliage typically increases canopy albedo by ca. 0.07 [12] and provides a first-order guide as to the possible upper limit of albedo modification. We hence focus our analysis and discussion in this paper on the climatic impacts of a +0.04 canopy albedo change—greater than observed variability due to glaucousness in barley but rather less than that due to morphological differences in maize or as a result of externally applied treatments.

In response to a +0.04 change in maximum canopy albedo across prescribed cropland areas, we predict global annual average surface air temperatures (SATs) to be 0.11°C (±0.091°C) lower than in a control experiment in which no cropland albedo adjustment was made (Table 1). This sensitivity of climate to albedo changes in cropland areas (as measured by global annual average SATs) is similar to estimates made of the historical impacts of agriculture on climate [4, 5]. For instance, Matthews et al. [5], using a more idealized climate model than we have employed here, obtained a 0.17°C cooling in response to a ~0.03–0.09 increase in albedo applied directly to the land surface across modern arable regions. The relevant experiments here, involving 0.04 and 0.08 increases in albedo, produce coolings of 0.11°C and 0.21°C, respectively (Table 1), and thus bracket their reported results.

The relatively small reductions in global SATs belie the occurrence of rather greater regional cooling. Temperatures are depressed by over 1°C during summer months (June-July-August, "JJA") throughout central North America and across Eurasia in a ~30° wide band of latitude centered on approximately 45°N (Figure 2)—a pattern broadly corresponding to the densest cropland coverage in the model (Figure 1). Wintertime (December-January-February, "DJF") temperatures are virtually unaffected in these regions, a consequence of reduced winter canopy cover, the albedo of snow-covered vegetation being independent of the underlying canopy albedo, and low incident solar insolation. In contrast, temperatures in the Indian subcontinent and southeast Asia are depressed more during winter (DJF) months compared to the summer. Strong coolings in the North Atlantic and Barents Sea occur associated with increased wintertime sea-ice extent, with a residual cooling persisting into the summer months. An unexpected benefit of cropland albedo change could thus be a small delay in Arctic sea-ice retreat.

Global precipitation patterns (not shown) are also affected by bio-geoengineering, which together with temperature-driven changes in evapotranspiration results in a pronounced increase in soil moisture in the southern and central United

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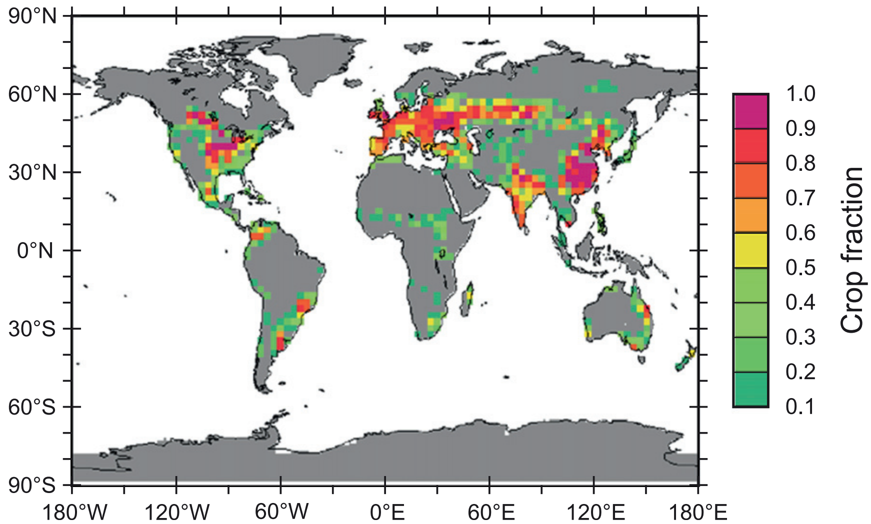

Figure 1. World Cropland Area

Global distribution of croplands, transformed onto the HadCM3 global climate model land surface grid [4]. Only C_3 (taken to represent crops such as rice, wheat, and soybeans) and C_4 (e.g., maize, sorghum, sugarcane, and millet) grasses are allowed to grow in the model within areas designated as cropland (if vegetation is predicted to be present at all).

States (Figure 3). We find adverse impacts occurring remotely from major croplands, with decreased water availability in parts of the subtropics as well as in Australia. Soil moisture predictions need to be treated with some caution, however, first because precipitation fields are difficult to simulate accurately in global-climate models, with substantial disagreement existing between predicted future regional precipitation patterns [7]. Second, the model we use does not take account of cropping cycles, meaning that annual periods of bare soil are not accounted for.

Discussion

Selecting and Modifying Plants for "Climatic" Traits

Historical land-use change, involving a change from natural vegetation with a relatively low albedo to crop vegetation with generally higher albedo [6], has suppressed surface temperatures [4, 5], partially offsetting the warming due to present-day elevated atmospheric CO_2 concentrations. We propose that the climatic cooling that is already afforded by the widespread practice of arable agriculture could be augmented by replacing currently grown crops with types with specific traits, in an approach to climate mitigation we term "bio-geoengineering."

Albedo can vary significantly between varieties of the same crop species, for instance because of differences in canopy morphology [11] and leaf-surface properties [9, 10]. Careful selection of the plant variety grown can, by itself, thus provide a degree of mitigation of future warming. Furthermore, because solar elevation is important in determining the net albedo of the canopy, the specific crop variety could be deliberately selected according to the latitude in which it is grown (although in this respect it must be noted that the model does not distinguish between different crop varieties nor latitude in determining canopy albedo—see Experimental Procedures). Choosing species with variegated leaves, as has been suggested previously in the context of albedo modification of grasslands [13], may also hold some potential. Because significant variability already exists, both among different varieties of the same crop plant [9–11] and between species [6], bio-geoengineering offers the potential for a degree of climatic mitigation in the near term, and at little cost. Future selective breeding and/or genetic modification could provide additional gains. Consideration of climatic impacts in developing new varieties is a natural progression from proposals for epicuticular-wax trait selection for increased UV-B-radiation tolerance [14].

In considering possible strategies for optimizing plant albedo, selection for specific canopy properties is one possible avenue. The presence and properties of leaf hairs are important in determining leaf reflectivity [14, 15], thus presenting a potential second line of research. Here, we propose that the waxy cuticle that covers the aerial parts of the plant, and which is known to be an important site of spectral reflectance [16], also has considerable potential for modification. For instance, Holmes and Keiller [14] demonstrated, in a range of species, that glaucous leaves reflected more UV and visible radiation than leaves in which the waxes had been removed, supporting earlier findings of increased reflectiveness in glaucous leaves of wheat [17] and barley [18]. Subsequently, leaf wax crystal structure [10] and thickness [19] have been identified with significant differences in reflectivity. Recent years have also seen substantial advances in our understanding of plant cuticular-wax biosynthesis and identification of many of the genes involved in this process [20, 21]. This, in conjunction with natural variation existing in crop species, will facilitate both GM and conventional breeding approaches to manipulating the topology, load, and wax composition of the cuticle to achieve a desired change in spectral characteristics.

Table 1. Summary of Climate-Model Experiments and Predicted Global Climate Impacts

Atmospheric CO_2 Concentration	Maximum Canopy Albedo ($\alpha_{0\infty}$)	Global Mean SAT Anomaly[a]	Experiment Description
350 ppm	0.2	−2.84°C	Present-day CO_2, default cropland albedo
700 ppm	0.2	n/a	Elevated CO_2, default cropland albedo—control experiment
700 ppm	0.22	−0.057°C ± 0.097°C	Elevated CO_2, +0.02 canopy albedo (10% increase)
700 ppm	0.24	−0.111°C ± 0.091°C	Elevated CO_2, +0.04 canopy albedo (20% increase)
700 ppm	0.28	−0.213°C ± 0.083°C	Elevated CO_2, +0.08 canopy albedo (40% increase)

[a] Global mean (150 year average) surface air temperature (SAT) anomaly compared to the elevated (700 ppm) CO_2 control experiment. Uncertainty limits represent one standard deviation of interannual variability around the mean.