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Report

Tackling Regional Climate Change By Leaf Albedo Bio-geoengineering

Andy Ridgwell,[1,*] Joy S. Singarayer,[1] Alistair M. Hetherington,[2] and Paul J. Valdes[1]
[1]Bristol Research Initiative for the Dynamic Global Environment
School of Geographical Sciences
University of Bristol
Bristol BS81SS
UK
[2]School of Biological Sciences
University of Bristol
Bristol BS81UG
UK

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

*Correspondence: andy@seao2.org

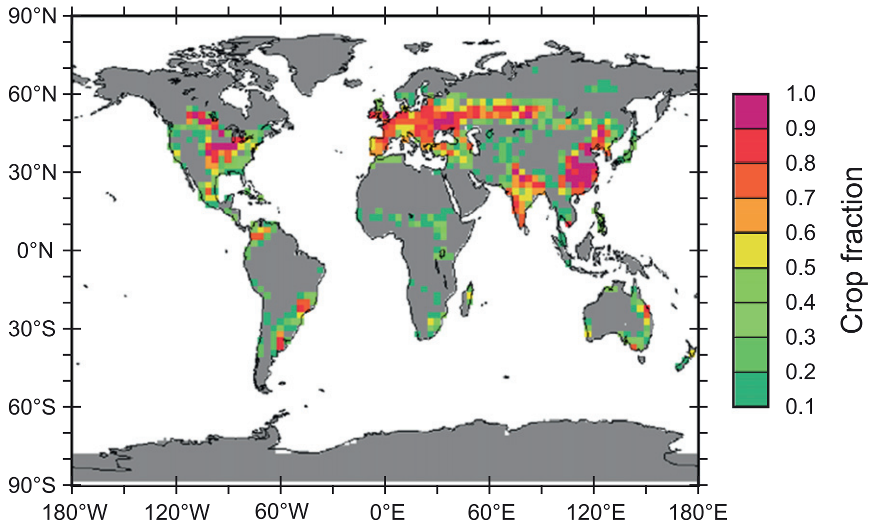

Figure 1. World Cropland Area

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	$-0.057°C \pm 0.097°C$	Elevated CO_2, +0.02 canopy albedo (10% increase)
700 ppm	0.24	$-0.111°C \pm 0.091°C$	Elevated CO_2, +0.04 canopy albedo (20% increase)
700 ppm	0.28	$-0.213°C \pm 0.083°C$	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.

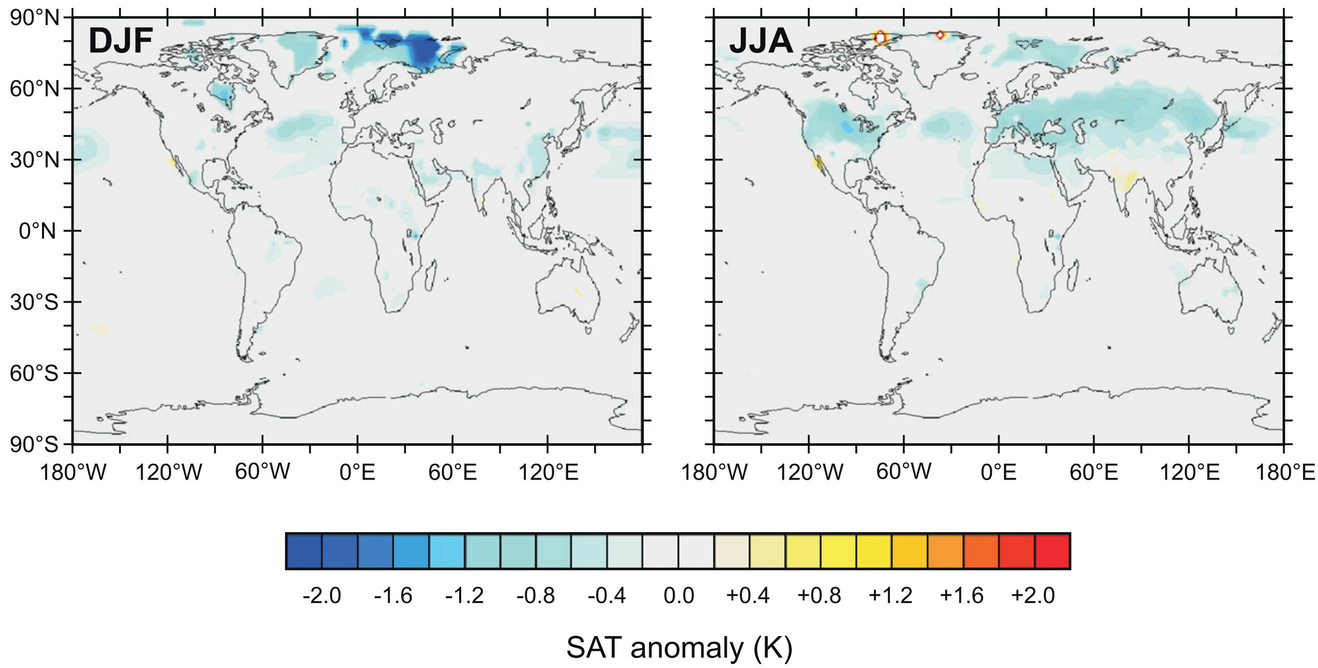

Figure 2. Climatic Impacts of Bio-geoengineering

Global anomalies of summer (JJA) and winter (DJF) surface air temperature resulting from a +0.04 increase in maximum crop canopy albedo and an elevated atmospheric CO_2 concentration of 700 ppm, calculated relative to the (700 ppm CO_2) control experiment. Only differences that are statistically significant at a 99% confidence level, as given by a Student's t test, are plotted. The small "hotspots" of cooling or warming are mostly associated with localized changes in seasonal sea-ice extent or snow cover relative to the control, induced by the cropland albedo changes elsewhere.

It is important that higher canopy albedo is not achieved at the expense of reduced crop yield as a result of excessive reduction in PAR absorption. In this respect, it is interesting to note that glaucous varieties of wheat and barley when grown under water-limited conditions exhibit increased grain yields when compared to their nonglaucous counterparts [9, 22], suggesting the benefits of increased water-use efficiency (mainly from reduced leaf heating) outweigh any reduction in photosynthesis. Furthermore, no significant reduction in plant dry weight is observed when reflectant sprays are applied to foliage [23]. This surprising observation has been explained in terms of increased water-use efficiency [23, 24] and a more even distribution of radiation intensity within the canopy [25] despite a net increase in reflected radiation. Thus, at least in situations in which water availability is (co-) limiting or in which photosynthesis is unevenly distributed within the canopy, primary production is not necessarily adversely impacted by a net increase in reflected PAR at the top of the canopy. In considering the optimal enhancement to leaf-wax reflectivity, genetic modifications could be designed to be wavelength specific and weighted toward wavelengths lying outside of the photosynthetically active radiation region (i.e., <400 nm and >700 nm).

Advantages and Disadvantages of Bio-geoengineering

A variety of "geoengineering" schemes—defined as the "intentional large-scale manipulation of the environment" [26]—have previously been devised for the mitigation of climate change. For instance, solar insolation reaching the Earth's surface might be reduced by the injection of sulfate aerosols into the atmosphere [2, 27] or by the construction of a space-based "sunshade" [3, 28]. Other schemes envisage CO_2 being removed from the atmosphere by the fertilization of ocean biological productivity by added iron [29]. The construction of millions of artificial "trees"—free-standing structures on land that extract CO_2 from the ambient air by chemical scrubbing—have also been proposed [30, 31].

Ethical considerations aside, these schemes all tend to suffer substantial barriers to their implementation because often novel infrastructure and industries must first be created. In additional to the initial investment, which in the case of a solar sunshade has been estimated at trillions of U.S. dollars [3], there would be a multidecade delay before climate change could be substantially mitigated. For sulfate aerosols injected into the stratosphere or iron added to the ocean surface, continual reapplication would be a challenging and costly undertaking, yet essential in order to maintain the mitigation benefits [2, 27, 29]. Bio-geoengineering has the important advantage in that the infrastructure required to create and propagate specific physiological leaf and canopy traits to large-scale cultivation is already in place. In addition, because arable crops are primarily grown for food, the annual replanting of modified varieties that is needed in order to retain continued climatic benefits is automatically achieved. There is thus little danger of "catastrophic failure" as exists for a solar sunshield [32].

We estimate that regionally, up to $\sim 1^\circ C$ of surface warming could potentially be mitigated in the near term by careful selection among existing crop varieties, although better characterization of existing variability will first be needed. In the long term, existing laboratory methodologies and infrastructures used for introducing traits into crops such as herbicide resistance could be employed to augment what is possible from selective breeding. However, climate mitigation with crops is mostly localized to a band stretching from central North America through midlatitude Eurasia (Figure 2), corresponding

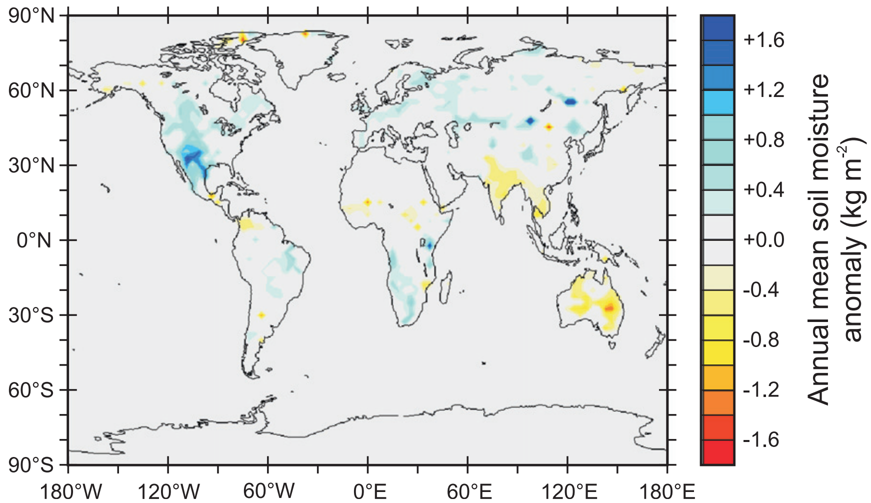

Figure 3. Impacts of Bio-geoengineering on Soil Moisture

Global anomalies of mean annual soil moisture for the +0.04 canopy-albedo experiment, calculated relative to the control and statistically significant at a 99% confidence level.

to a zonal concentration of arable farming (Figure 1). Much of Africa and South America, with less intense arable cultivation and relatively zonally narrow continents, have little potential for achieving significant mitigation of warming. Thus, unlike true geoengineering schemes that have much more of a global-scale effect, modification of crop properties produces an inherently regional (and seasonal) modification of climate. Bio-geoengineering of croplands might therefore need to be considered in conjunction with the deployment of other spatially heterogeneous geoengineering schemes, such as the whitening of built structures [13, 33] or changes to pasture plants [13]. Furthermore, parts of the subtropics and Australia could potentially experience an exacerbation of drought (Figure 3). Thus, particularly for soil moisture, there may be losers as well as winners.

The potential inequity of climate impacts has important implications for social justice and geopolitics, greatly complicating decisions regarding the implementation of bio-geoengineering. The relatively small impact on global annual mean temperatures resulting from regional bio-geoengineering in comparison to the inherent interannual variability of the climate system also poses challenges for observational-based quantification and verification of the degree of mitigation achieved. For instance, even after 150 model years, the 1 SD uncertainty in the global mean (0.091°C) is comparable to the signal (−0.111°C), although the signal-to-noise ratio improves for larger albedo changes (Table 1) as it probably would for detection of a regional (and seasonal) signal.

Conclusions

Increasing canopy albedo of vegetation in designated cropland areas in a global climate model by 20% (0.04) drives a >1°C reduction in summertime surface air temperatures in a wide latitudinal band spanning North America and Eurasia. Genetic modification or selective breeding of crop plants for specific leaf-surface properties and canopy structure could provide further mitigation of surface warming. Because the main investment is in research and field trials, the relatively low cost of implementation of crop albedo bio-geoengineering makes it potentially very attractive when compared to the equivalent costs of geoengineering or carbon sequestration. However, there is a clear need for more research into characterizing the variability in albedo that exists between the different variants and strains of common crop plants to underpin any such undertaking. Changes in crop reflectivity must also not significantly negatively impact on crop yield through excessive reduction in the absorption of photosynthetically active radiation by chloroplasts under nonsaturating light conditions. Overall, bio-geoengineering could fulfill a role as a temporary measure for reducing the severity of agricultural and health impacts of heat waves in the industrialized North, but on a global scale, it has limited effectiveness for the mitigation of future climate change and cannot substitute for CO_2 emissions reductions. Furthermore, although a prominent increase in summertime soil moisture in the southern states of the U.S. also occurs, soil-moisture changes show no simple spatial relationship to the prescribed albedo changes, illustrating the difficulties in predicting the response of the global climate system to deliberate modification, particularly with respect to rainfall patterns. The potential for significant regional inequity in soil-moisture changes poses important geopolitical questions.

Experimental Procedures

To quantify the potential for bio-geoengineering to mitigate climate change, we conducted a suite of climate-model-sensitivity experiments as summarized in Table 1. The climate model we used is the Hadley Centre coupled atmosphere-ocean model, HadCM3 [8], which we chose primarily on the basis that it is widely used and well characterized (e.g., [7], [34], and [35]). The climate component of HadCM3 consists of: (1) a 3D atmosphere circulation model with a spatial resolution of 2.5° × 3.75° and 19 vertical levels, (2) a 3D ocean circulation model with resolution of 1.25° × 1.25° and 20 vertical levels, and (3) a 1.25° × 1.25° resolution model of sea-ice formation and dynamics. For the land surface, the MOSESII land-surface scheme [36] is used, and this scheme predicts soil moisture and primary productivity and calculates the energy exchange with the atmosphere. The TRIFFID dynamic global-vegetation model [37] partitions primary productivity among five possible plant functional types (PFTs) according to the local climate. Two of these PFTs, C_3 and C_4 grasses, we use as a "proxy" for crop plants within areas designated as croplands.

We simulate the effects of crop albedo bio-geoengineering by modifying the snow-free albedo (α_0) of cropland vegetation (C_3 and C_4 grasses) by increasing the value of the prescribed maximum canopy albedo ($\alpha_{0\infty}$) in the model:

$$\alpha_0 = \alpha_{00} \cdot e^{-0.5 \cdot L} + \alpha_{0\infty} \cdot \left(1 - e^{-0.5 \cdot L}\right)$$

where α_{00} is the soil albedo and L the leaf-area index [37]. It should be noted that the level of process detail that is explicitly represented in current global models is limited, and there is no treatment of the radiation balance within the canopy in our version of HadCM3. Nor are different crop species differentiated or latitude effects taken into account, with the result that for the same leaf-area index, the snow-free canopy albedo is the same everywhere. Compared to a cropland canopy albedo in the model of a little less than 0.2 for a typical summertime leaf-area index of 4.0, crops grown at mid latitudes (43°) such as wheat and maize have a slightly higher albedo (~0.22) at maximum ground cover [6], whereas crops grown at lower latitudes (7°) such as ground nuts and sorghum, with albedos of 0.20 and 0.17, respectively, tend to be equal to or slightly lower than vegetation in the model [6].

All control and altered albedo simulations are initiated from the same present-day climate state. In the altered bio-geoengineering simulations, modification of crop-leaf canopy albedo is implemented as an instantaneous change in the value of $\alpha_{0\infty}$ with atmospheric CO_2 concentrations set to 700 ppm. The model then simulates 200 years of bio-geoengineered atmospheric and ocean circulation in parallel with a control experiment, also run with 700 ppm. The first 50 years are discounted because the climate system is still adjusting to a new surface equilibrium during this interval. The following 150 years are then averaged to give mean altered climatic conditions—a length of simulation chosen simply to increase the signal-to-noise ratio between modified and control (700 ppm CO_2) climate and thus distinguish differences that are statistically significant at the 99% level.

It should be noted that we have not used an explicit crop model but instead assumed that crops can be approximated by natural C_3 and C_4 vegetation growing in cropland areas. As a result, although leaf canopy varies seasonally, significant (grassland) canopy cover is present year round, whereas cropping regimes often have little or no canopy between harvesting and the start of the next growing season. However, the minimal wintertime SAT difference we find between control and albedo-modification experiments (Figure 2) suggests that residual wintertime leaf canopy in croplands does not significantly affect our results; i.e., our predictions would be little changed if we had instead prescribed bare ground during the winter part of the crop cycle.

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