

Cooling the Earth with Crops

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ABSTRACT

Food security and climate change are two of the biggest challenges which face humanity in the 21st Century and agricultural land is the physical interface for these interlinked issues. This chapter addresses how cropland interacts with climate; the ways in which crops have affected climate in the past; and how crops could help mitigate climate change in the future. Of the ways that climate issues and crops are related, one of the most relevant to the future is through geoengineering. The concept of deliberately using crops to reduce the surface air temperature is still in development, but has gathered considerable interest in recent years. Models suggest that in North America and Europe, a moderate increase in crop albedo could decrease summertime temperatures by up to 1 °C. Although this amounts to a small change compared with many other geoengineering proposals, it could be made with relatively little cost and would make a significant difference to crops which are particularly sensitive to high temperatures, such as wheat. Along with other climate mitigation strategies, cooling with crops could be one aspect of a deliberate policy to limit the dangerous impacts of climate change.

1 Introduction

Agricultural land currently covers 37% of the world's land surface,¹ and most projections indicate that there will be future increases.² Since crops represent a significant proportion of this anthropogenically altered land cover, they have substantial potential as a platform for land surface based climate

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solutions. Cropland has multiple ways in which it could be used to help mitigate climate warming, including conventional mitigation (reducing carbon emissions from the agricultural sector),³ as a source for carbon capture and storage (CCS) geoengineering⁴ (for instance using bio-char)⁵ and as a way of managing surface net solar radiation (surface SRM geoengineering)⁶ by altering the albedo of cropland. Any of these crop based ideas could be considered as 'cooling with crops'. However, the most commonly discussed idea as a geoengineering method using crops is bio-geoengineering, which proposes higher leaf albedo crops as a way of creating localized cooling.⁷

Bio-geoengineering leaf albedo increase would be a small part of much larger anthropogenic changes to surface albedo, and other surface properties, which have occurred over more than 1000 years.⁸ Forest clearance for agriculture and the subsequent intensification of agriculture mean that crops have affected the regional and global climate substantially, *via* their alteration of the land surface. Similarly, future changes to land use and their consequent changes to land cover will have significant effects on the climate. These changes affect climate inadvertently but may be equal or larger in magnitude to the projections of deliberate interventions such as bio-geoengineering.

In this chapter the mechanisms by which crops can cool the Earth are reviewed, focusing on past and projected future changes to climate from crops and then looking at how future cooling with crops could be achieved and what the implications might be.

2 Mechanisms

The ways which surface properties affect climate can be categorised as biogeophysical or biogeochemical. Biogeochemical properties of the land surface are typified by changes to atmospheric composition from the emissions of greenhouse gases (*e.g.* carbon dioxide, methane, nitrous oxide) from the land surface. Biogeochemical land surface changes impact the climate by changing the atmospheric greenhouse gas composition, which affects the amount of outgoing longwave radiation, changing the energy balance. The land surface is currently a net carbon sink, absorbing around 2.4 gigatonnes of carbon per year.⁹ Changes in land cover, especially deforestation, could alter the size of this sink. Similarly, warming could open up carbon stores such as methane from thawing of permafrost.¹⁰ Russian permafrost regions alone contain 50 gigatonnes of carbon and mid century could account for a 0.012 °C global temperature rise. Changes in emissions of aerosols can also be considered biogeochemical land surface changes.

The biogeophysical properties can be understood as the physical changes to the land surface which affect the energy and momentum balance directly, rather than through changes in the atmospheric composition. The net radiative fluxes are made up of the net short wave and longwave radiation (see

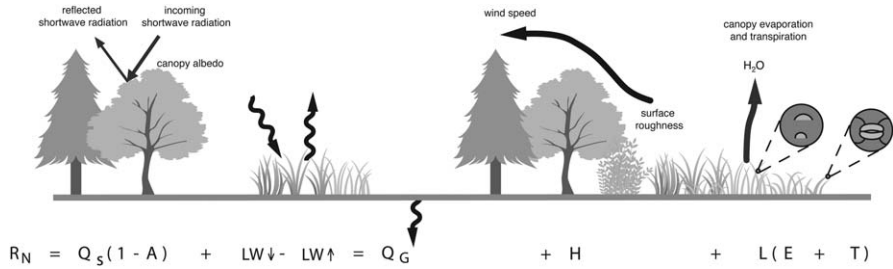


Figure 1 Representation of the biogeophysical parameters in the surface energy balance which are affected by changes in land surface cover. The net radiative fluxes (R_N) are determined by the net short and longwave radiation fluxes. The albedo affects the amount of incoming shortwave solar radiation which is reflected back out of the atmosphere ($1-A$). The surface emissivity is the amount of longwave radiation which is emitted back from the surface ($LW \uparrow$). These two make up the direct removals from the energy budget from the total incoming solar radiation. On the right hand side of the equation, the surface roughness affects the energy balance through the sensible heat flux (H), some energy goes into heating the soil (Q_G) and the latent heat flux (L) is made up of evaporation (E) from the canopy and soil, and transpiration (T) from plant photosynthesis.

Figure 1). These net radiative fluxes are partitioned at the surface into: heat flux into the soil; latent heat (as either evaporation or transpiration); or sensible heat (heat exchange due to the effect of differing temperatures) which may remain or be moved into other areas as convective heat (see Figure 1.) The balance of which of these factors is most important to the resultant temperature varies with latitude and season, as well as the individual surface properties themselves.¹¹

2.1 Biogeophysical Mechanisms

2.1.1 Albedo. Albedo is a measure of the ratio of radiation reflected from a surface to the total amount of radiation incident upon it. The exact albedo is dependent on the amount of incoming solar radiation, making it very difficult to calculate. A range of other measurements and terms are used to represent albedo. For most practical applications, albedo is calculated as the bidirectional reflectance distribution function over a particular range of wavelengths, as opposed to field albedo, which is the value for the entire spectrum of the solar radiation.

Changes to surface albedo are some of the largest in the surface energy budget. This is because albedo is the key parameter in the energy balance which determines the net radiative flux. It also has a large range of values, with land surface albedos varying significantly. For example, snow covered surfaces have very high albedos of about 0.9 and reflect most of the incoming shortwave radiation, whereas water covered surfaces (such as inland

lakes) scatter or absorb most of the radiation and so generally have low albedos of less than 0.1. Vegetated surfaces have relatively low albedos, with grasses around 0.19–0.27 and coniferous forest lower at 0.11–0.14.¹² Therefore an increase in the surface albedo *via* a change from trees to grasses gives an albedo cooling effect. The size of the albedo feedback can be large, especially for changes between snow covered and non-snow covered surfaces.

2.1.2 Evapotranspiration. The amount of evapotranspiration from the surface affects the latent heat flux (see Figure 1). Evapotranspiration is an amalgamation of two water processes, which work at very different scales temporally and have different sources.¹³ Transpiration is a delayed feedback of precipitation to the atmosphere, as the water must infiltrate into the soil, be absorbed by the plant roots and transported up the plant to be transpired. Evaporation from the vegetation canopy provides a much quicker feedback because a large quantity of water can be caught in the canopy and is readily available for evaporation. Soil moisture can also evaporate quickly compared to transpiration, though because of infiltration and lower wind speeds at the surface, is closer in timescale to transpiration. Since trees have more biomass to support than grasses or crops and have deeper roots, theoretically they transpire more water. The larger leaf area of trees can often hold more water in the canopy than grasses. Therefore replacing trees with crops is usually associated with a decrease in evapotranspiration, giving a warming effect because less energy transfers to latent heat are made, and thus the energy goes into sensible heat.

2.1.3 Emissivity. The emissivity of a surface determines how much long-wave radiation it will emit (see Figure 1), from the shortwave radiation the ground absorbs during the day. The importance of emissivity is most obvious at night when longwave radiation dominates the radiative budget. The higher the emissivity of a surface, the more absorbed energy it emits. A perfect black body (emissivity of one) emits energy at the theoretical rate given by the Stefan–Boltzmann equation. The range of emissivity values is small. For instance, desert soils have a relatively low emissivity, of approximately 0.9 whereas vegetated surfaces have higher emissivities of between 0.96–0.98.¹⁴ Emissivity of a vegetated surface is related to the vegetation density and structure. The emissivity generally increases with leaf area index, giving higher emissivity for trees, on average, than grasses or crops.¹⁵ This implies a slight warming effect when crops replace trees. The emissivity effect is relatively small and other atmospheric factors, such as cloud cover, are often much more important for the total outgoing long-wave radiation.

2.1.4 The Aerodynamic Roughness. The aerodynamic roughness length describes the height at which the wind speed theoretically becomes zero. For vegetation, it is essentially related to the canopy height, but is not

simply the height of the vegetation.¹⁶ Typical values of roughness length may be 0.0002 m for open water, 0.03 m for grass, 0.1–0.25 m for crops, and 1.0 m for a forest. Lower values of roughness length allow increased wind speed across a surface, affecting the turbulent flow in the boundary layer atmosphere. This results in more convective heat transfer, and thus a cooler surface temperature as the sensible heat or evaporative cooling is enhanced.

3 Geographical Differences

Changes in land surface and vegetation can have spatially varying effects; high and low latitudes have different responses. Both temperature and precipitation can be strongly affected in different ways in different regions from changes to land cover. Crucial to the geographical variation in changes from land use is that whereas land carbon emissions from a particular location are quickly well mixed into the global atmosphere, biogeophysical effects are predominantly local. Therefore, even when the carbon emissions in a region may give a larger global change in temperature, the regional signal can still be dominated by albedo or other biogeophysical effects. The differences in impact of biogeophysical land use change are here categorized as low latitude (tropical) and high latitude (temperate and boreal), which provide contrasting responses to biogeophysical forcing.

3.1 Tropics

In the low latitudes, changes in the land surface from trees to crops generally give a warming signal.¹¹ A key component in this is the effect of changes in evapotranspiration. The water's change of state requires energy, which then reduces the amount of energy available for sensible heat at the surface. Therefore climate models simulating deforestation in the tropics, particularly in the Amazon, give significant warming in that region.¹⁷ Evapotranspiration is an especially strong feedback in the tropics and has far reaching consequences for regional and global climate.^{18,17} The consequence of loss of evapotranspirative cooling because of tropical deforestation is consistently found to be larger than any potential gains from increased albedo or reduced surface roughness.

Changes in tropical forest cover can have positive feedbacks at both the regional and global scale. Deforestation could potentially tip the region into a different bioclimatic regime. For instance, the increased water deficit created by Amazon tropical forest deforestation, especially when combined with deforestation of Cerrado (tropical savanna), can create a positive feedback of forest dieback.¹⁹ The deforestation changes the local climate, which may then be combined with large scale changes which affect global climate change, making the climate of the whole region drier and leading to further forest dieback where forest remains. This in turn creates further changes to the

regional climate, altering the whole bioclimatic regime in the region. This is important because the changes in water and energy fluxes in the Amazon have teleconnections worldwide which amplify the warming feedbacks.²⁰ For instance, changes in the deep tropical atmospheric convection in the Amazon lead to changes in storm-tracks and a northward shift in the Ferrel cell (a large scale atmospheric circulation feature) which causes warming in Europe.²⁰ This makes local biogeophysical changes to tropical forests very important not just for the regional climate and biosphere, but also for the world climate.

This evapotranspirative cooling acts both directly on the surface energy balance as well as affecting cloud formation in the tropics and seasonal convective rainfall in the mid latitudes.²¹ Trees in the tropics have a large role in maintaining continental precipitation. For instance, in the Amazon, up to 50% of precipitation is sustained by water recycling through vegetation.²² Water drawn from the soil water, sometimes as much as 8 meters deep, is transpired by the vegetation and returns into the atmosphere.²³ Therefore, forests, with high leaf area indexes, deeper rooting depths and greater water requirements than grasses or crops have greater transpiration and potential for water recycling. As well as transpiration, the larger canopy water capacity of trees results in more water intercepted and evaporated from the canopy. This can lead to increased cloud formation because of increased levels of water vapour in the atmosphere, consequently leading to increased rainfall. This process provides quick recycling of precipitation back to the atmosphere, which helps maintain continental rainfall.¹³

These biogeophysical warming and precipitation effects are in addition to the strong carbon feedbacks from deforestation in the tropics. It is estimated that 55% of the worlds terrestrial carbon is stored in tropical forests and are therefore an important store and sink of carbon.⁹ Deforestation and forest fires can release this stored carbon,²⁴ both of which are projected to increase under future climate change.^{25,24} The combined biogeochemical and biogeophysical effects of tropical deforestation make crop growing in the Amazon and other tropical forest areas a 'no-win' scenario.²⁶

The strong impact of changes in evapotranspiration in the tropics, combined with the potential for albedo increase to feedback into lower evapotranspiration because of reduced energy at the surface,²⁷ mean that increased crop albedo may not be a good policy for the tropics. Deforestation for cropland would be particularly damaging. Conversely, policies which avoided warming by preventing Amazon deforestation would be a deliberate and significant contribution to cooling the planet.

3.2 *Temperate and Boreal*

At higher latitudes, deforestation tends to give a net cooling, because of the strong impact of the albedo changes. For boreal forest especially, a change between forest and grass or cropland has a cooling effect because of the different ways that snow lies on trees and crops.²⁸ Snow has a very high albedo (around 0.9) and when it completely covers a surface (*i.e.* grass or

bare soil as opposed to trees), it increases the albedo considerably. For surfaces which are rougher, and therefore snow can fall through the canopy, the albedo is increased only slightly. Therefore the 'snow covered' albedo of trees as opposed to crops is very different.²⁹ Extensive deforestation increases summertime albedo by just 2% and wintertime in the presence of snow by more than 10%.³⁰ This means that the change between high latitude albedo of trees and crops is larger than the physiological albedo differences between the two plant types. The effect of this albedo change may potentially be big enough to offset the reduced carbon sink from boreal deforestation or the increased carbon sink from Boreal afforestation.²⁸

Even where the albedo effect isn't enhanced by the presence of snow, it is still a crucial feedback in the mid to high latitudes. Whereas in the tropics the evapotranspirative effect and carbon emissions from deforestation are particularly strong, the lower temperatures in the mid and high latitudes mean that the cooling effect of evapotranspiration is less important. Since the mid latitudes have a relatively strong response to albedo changes, this makes increased crop albedo a viable proposition. Temperature changes from trees to crops are likely to be larger for areas of substantial snow cover (*i.e.* in areas further north). Regions regularly covered with snow may not be areas where reduced temperatures would aid crop yields but might help create a critical amount of cooling in major crop growing areas or even seasonal sea ice.

4 Historical Land Cover Change

Around 10 000 years ago the Neolithic revolution began the move from predominantly forested land to the cropland we have today as shown in Figure 5(a).¹ The earliest estimates of anthropogenic climate changes from crops are put forward by Ruddiman's early anthropocene theory. Changes in climate from around 7000 years ago may be attributed to methane, emitted from growing rice, and carbon emissions from forest clearance.³¹ These changes in both climate and in greenhouse gas emissions are extrapolated from proxies, so there are considerable uncertainties associated with them. Over the last 1000 years, the estimates are more reliable and an estimated deforestation of 18 million km² (about 12% of the land surface) has occurred. Climate model simulations suggest that this has decreased the global mean annual temperature by between -0.25 to -0.13 °C.³² This cooling mainly originates from the last 200 years, when there was extensive deforestation. Models show that the effect on temperature of this land use change scales approximately linearly with removal of tree cover.³³ However, the mechanisms which give this result are from a range of conflicting climate signals of similar magnitude.

The historical change in land use over the last 150 years is estimated to result in a radiative forcing from albedo change of -0.2 Watts m⁻², (± 0.2 Watts m⁻²), whereas changes in carbon emissions from land use change in the same period gave a radiative forcing of $+0.55$ Watts m⁻²

($\pm 0.17 \text{ Watts m}^{-2}$).³⁴ Generally speaking, the historical change from trees to crops has a cooling effect *via* the biogeophysical mechanisms and a warming effect from the biogeochemical. This is because the majority of historical deforestation has been in the northern hemisphere mid-latitudes and therefore the cooling effect of the increased albedo when trees are converted to grass or cropland, predominates. However, it is still unclear whether the biogeophysical or biogeochemical effect dominates and determines the net impact to the climate. Two studies using coupled climate models find a net increase of around $+0.15 \text{ }^\circ\text{C}$ from land use change over the last 150 years,^{35,36} but a study using lower resolution earth system models of intermediate complexity found a small net decrease in temperature of $-0.05 \text{ }^\circ\text{C}$.³⁷ The estimations of biogeophysical cooling which give these results vary considerably, ranging from just $-0.03 \text{ }^\circ\text{C}$,³⁵ to $-0.26 \text{ }^\circ\text{C}$.³⁷ Although the coupled climate models agree closely on the net signal, the individual signals are more uncertain. This suggests that the biogeophysical changes to land cover can have a significant impact on climate but the size of that impact historically, and whether it is partly or wholly mitigated by the carbon emissions in the same period, is still debatable.

As well as the spatial differences in the impacts of land use change, there are also temporal differences, which make extrapolating the longer term trend more challenging. The latter part of the 20th Century saw a slight reversal of the cooling trend from biogeophysical land use change because of mid latitude afforestation.³² The afforestation gave the opposite effect to deforestation, with a cooling signal from the biogeochemical reduction of carbon emissions and a warming from decreased albedo from trees rather than grasses. This period also saw an acceleration of tropical land use changes with large amounts of deforestation and substantial carbon emissions. Although the pace of Amazon deforestation slowed for five years in the 2000s,³⁸ deforestation rates are again rising and remain a serious issue.^{39,40} The Amazon deforestation alone has given a detectable warming signal.⁴¹ More recent land cover change does not necessarily follow the same pattern as previous historical changes, but can be easier to attribute due to satellite and other global data sources.

Some part of the uncertainty about the effect of past land use change is from differences in estimates of the land cover itself, both past and present. Different sources of data can result in a considerable range of possible land cover changes since 1765.⁴² Even recent past (2001–2005) crop and pasture land cover estimates can differ by over 100% regionally and these differences can result in up to $0.21 \text{ }^\circ\text{C}$ differences in the mean annual global temperature and as much as $5 \text{ }^\circ\text{C}$ locally.^{42,43} This means that the estimates of land use change driven temperature change are uncertain. There are many idealized simulations of natural vegetation which can be used to estimate anthropogenic impact, but this approach comes with its own assumptions and uncertainties.

Future changes to the land surface, whether deliberate or as a side effect of other changes, must be seen in the context of these past changes. Although there is uncertainty about the exact scale of the biogeophysical changes from

land use change in the past, the range of estimates suggests that this has been an important factor in determining present climate, especially regionally in the mid latitudes. Since most historical land use changes occurred in Europe and North America, they gave a stronger albedo feedback relative to an equivalent low latitude change but have less carbon changes associated. Future deforestation is likely to be more in tropical areas, which has very different regional and global impacts. This gives new challenges, but can still be usefully informed by historical analysis which gives insight into the spatial, temporal and data uncertainties.

5 Future Land Cover Change

Future land use change is likely to be determined by factors which influenced the temporal and spatial patterning of historical land cover change, as well as new factors relating to climate change and climate change mitigation. Agricultural productivity, population growth and trade will continue to be important. New factors such as carbon emissions targets through land carbon valuation, biofuels and carbon sequestration will also likely affect the land cover. All of the factors affecting land use change are essential to economic projections and thus future land use change scenarios are often associated with economic projections. In turn, these projections are associated not just with future land use change scenarios but are used to create climate change scenarios. The two sets of scenarios used by the IPCC (Intergovernmental Panel on Climate Change) in the *IPCC 4th and 5th Assessment Reports* give a range of possible land use futures which show some of the issues surrounding changes to the land surface and their affect on climate.

The scenarios presented in the *Special Report on Emissions Scenarios (SRES)* are story-line projections which envisage worlds with different futures,⁴⁴ which were used for the third Climate Model Intercomparison Project (CMIP) and the *4th IPCC Assessment Report*.³⁴ These projections are based on 146 different scenarios of technological and social changes, rather than achieving a particular climate outcome. The land cover changes in these scenarios significantly alter the regional climate.⁴⁵ The high carbon dioxide A2 scenario has substantial agricultural expansion which cools the mean global climate by two degrees but gives a net warming in the Amazon, as suggested by other studies referred to in section 3.1. In contrast, land abandonment in the B1 low carbon dioxide scenario gives a 1 °C warming from the land use change.⁴⁵

The Representative Concentration Pathways (RCPs) used for *CMIP5* and the *IPCC 5th Assessment Report* also have vastly different land surface changes.⁴⁶ The RCPs use integrated assessment models to model the socio-economic paths which achieve certain climate outcomes. Unlike the scenario driven *SRES* storylines, the RCPs have explicit inclusion of climate mitigation policies where they are required to achieve the particular climate forcing aim. There are four RCP scenarios: RCP2.6, RCP4.5, RCP6.0 and

RCP8.5.⁴⁷ The numbers refer to the radiative forcing in Watts m^{-2} at the end of the century. The RCPs projections vary from small decreases in cropland to substantial increases.⁴⁸ Statistically significant differences in the climate with and without the assumed land use changes in RCP2.6 and RCP8.5 exist at a regional, though not the global, scale. Results from earth system models differ, but the net regional mean annual effect of land use change is as much as -0.2 °C in RCP8.5 from 2070–2100.⁴⁹ However, the change in land cover is not consistent with the change in total radiative forcing. The highest and lowest levels of radiative forcing (RCP2.6 and RCP8.5) are associated with high levels of deforestation in order to grow crops. By comparison, RCP4.5 and RCP6.0 both have much lower levels of deforestation and even some afforestation. This non-linearity is caused by three key aspects of the assumptions in the scenarios created by the integrated assessment models: yield increases; biofuel use; and land carbon valuation and population.

The integrated assessment models assume year on year increases in crop yield (also known as agricultural productivity growth). Most of the scenarios take their yield increases from the Food and Agricultural Organization of the United Nations estimates until 2035, which projects around a quarter of a percent increase globally in crop yield per year.^{48,50} However, estimates of future yields under climate change are highly uncertain, with little clarity on even whether they are likely to be negative or positive.⁵¹ The level of crop yield determines to a great extent how much cropland is needed. With populations peaking at between 9–12 billion in the RCPs,^{52–54} without substantial increases in agricultural productivity, considerably more cropland is needed to meet demand. Conversely, lower population projections with higher crop yield increases require less land to be converted to cropland. The biogeophysical aspect of different levels of yield increases can make a significant impact on climate. For instance, the RCP4.5 scenario with no yield increases gives a mean annual climate -0.37 °C cooler than no land use change in North America. In a no mitigation strategy scenario, similar to RCP8.5, the mean annual cooling is up to -1.62 °C regionally.⁵⁵ The changes in land carbon emissions cancel out these effects globally, but residual regional effects would be likely to remain. Due to the regional differences in land use change, the effect of low yield increases or yield decreases will depend on where the cropland expansion takes place.

Biofuel use also results in increased competition for land and therefore pressure to deforest, as it increases the total amount of cropland needed. Biofuel use varies in the RCPs, but is an important element of the mitigation.⁵⁴ There are some synergies between carbon emissions targets and the biogeophysical impacts of land use change because of the avoided fossil fuel emissions and increased albedo in the mid latitudes. However, at low latitudes the carbon savings from biofuels may be less than the impact of the deforestation, giving a net warming.⁵⁶ Further, there are differences in the way that biofuels are specified in the models (as trees or grass crops). In RCP8.5, biofuels are categorized as wood, whereas the other three scenarios categorize them as crops.⁴⁸ These categorizations will be important for the

biogeophysical effects of land use change and therefore are terms that need to be clarified.

As well as being affected by demand for cropland itself, cropland extent is also affected by demand for competing land covers, notably forest. RCP4.5 includes the carbon emissions from the land in the total accountable carbon emissions, making afforestation a feasible mitigation strategy. This creates a counter-incentive to cropland increases required by population increases. Though the amount of afforestation in this universal carbon tax scenario is modest, the avoided deforestation is large when compared to a fossil fuel only carbon tax.^{53,57} By comparison, the other RCPs do not account for the carbon emitted from land cover changes, and therefore are liable to overestimate the carbon benefits of deforestation for growing biofuels, but probably underestimate the other impacts. Therefore the scenarios with afforestation probably underestimate the total radiative forcing and scenarios with deforestation probably overestimate the total radiative forcing.

The RCP and SRES scenarios demonstrate how different cropland policies and changes can affect climate. They represent an unclear future for the land surface's effect on climate, with multiple effects which are subject to many influences. The deliberate action of choosing a pathway that offered biogeophysical cooling from deforestation for crops could be considered geoengineering and certainly, the effect could be bigger regionally than that of deliberately increasing crop albedo or other crop based geoengineering technology.

6 Increased Crop Albedo

The concept of bio-geoengineering is to produce a cooling effect from increased albedo in crops, without other changes which would accompany land cover changes. It is this, along with the deliberateness of the action, which distinguishes it from other, inadvertent, land cover changes. However, since the change is not between primary plant functional types, the achievable albedo change is likely to be smaller for increased crop albedo than land cover change.

6.1 Albedo Values of Crops

Values of albedo of viable crops are likely to be limited by the natural variability of albedo within a particular crop. Crops have an albedo of around 0.2, similar to grasses. However, records of individual variety leaf and plant albedos are limited, with much of the research having been done many years ago and subject to considerable environmental variability. Therefore more research is needed to establish the range of full spectrum albedos of different crops. It has been suggested from measurements given in the literature that an overall albedo increase in crops of 0.02–0.08 is achievable for crops. The higher end of albedos could prove challenging, but a 0.04 increase is likely to be feasible from conventional breeding using the natural variation in leaf

albedo, without the need for genetic modification.^{7,6,58} There are bigger differences between different types of crops (*e.g.* between wheat and corn) than within crop types. However, if intra crop substitutions were possible (*i.e.* a lower albedo wheat variety substituted by high albedo wheat) this could increase crop albedo without disrupting food production systems.

6.2 Determinants of Albedo

The overall albedo of a vegetated surface is determined by several aspects. At the leaf level, the albedo is determined by the amounts of reflectance, transmission and absorption at the leaf surface, at different wavelengths (see Figure 2). Reflectance is the fraction of incident radiation reflected by a surface. Transmittance is the fraction of incident light at a specified wavelength that passes through a sample. Because of differences in cell structure affecting light propagation the transmittance is highly variable.⁵⁹ Both are expressed as the amount of light as a fraction of the light striking the object.⁶⁰

The albedo of a leaf is affected by not only its colour, caused by chlorophyll levels, but also the leaf wax composition and thickness, trichomes (leaf hairs), the leaf thickness and leaf variegation. Reflective sprays could also be used to increase the albedo at the leaf level.⁵⁸ However, at canopy level, leaf albedo is combined with other effects from the canopy morphology; leaf area index; leaf angle distribution; the canopy coverage; the background surface albedo; and the sun zenith angle (see Figure 3).

6.3 Leaf Level Albedo

In general, the spectral characteristics of vegetation are well known due to the use of remote sensing and they have a very high reflection in the near infrared which makes them easily recognisable, see Figure 4(a). Within the leaf,

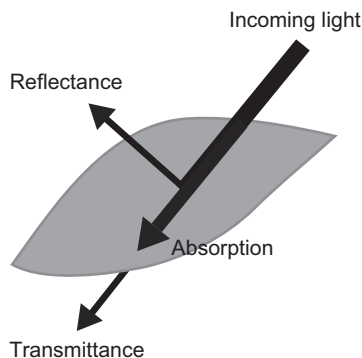


Figure 2 Representation of the potential routes of incoming shortwave radiation at a leaf surface. The light is either reflected away, absorbed by the leaf, or transmitted through the leaf.

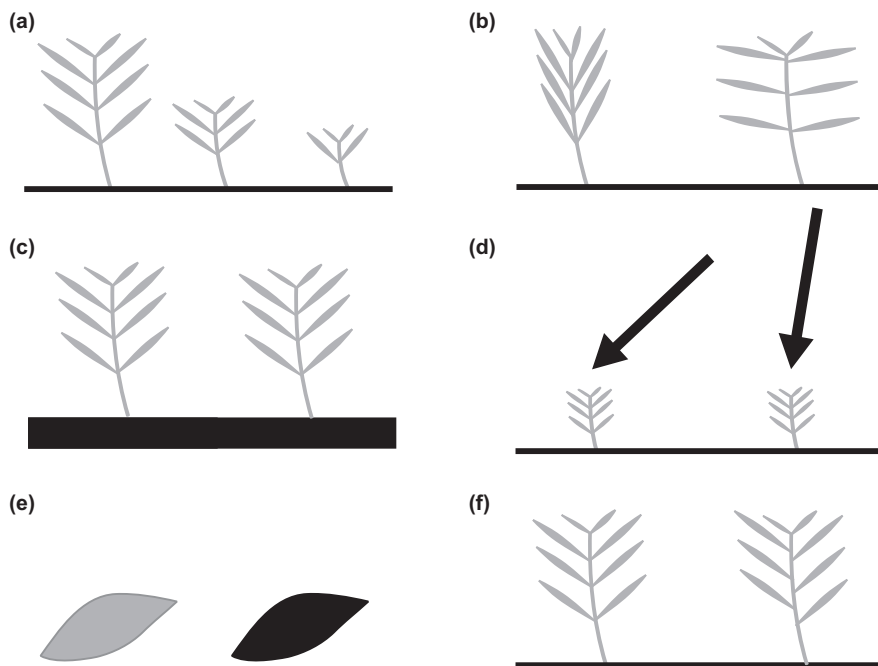


Figure 3 Representation of some the factors influencing crop albedo: (a) leaf area index; (b) leaf angle distribution; (c) background reflectance; (d) solar zenith angle; (e) leaf reflectance; and (f) canopy morphology.

there is low reflectance in the visible blue and red because of high absorption in the photosynthetically active region between 400 and 700 nm.⁶¹ The visible part of the spectrum is also the portion of the incoming solar spectrum with the highest irradiance.⁶² A peak in reflectance in the green part of the spectrum gives vegetation its visible colour, see Figure 4(a).

At the leaf level, research has mainly been concentrated on strong identifiable relationships between reflectance at specific wavelengths and plant stress. This allows the use of remote sensing and spectrometers to see areas of sub-optimal crops, and correct issues before they affect yield.⁶³ The effects of crop health on reflectance are particularly pertinent for bio-engineering because a spectral conflict between optimizing yield and optimizing reflectance would be counter-productive.

Although at specific wavelengths there are positive relationships between plant stress and high reflectance, this is not the case across the whole solar spectrum. Nitrogen deficiency increases reflectance at the leaf level because of the negative relationship between low chlorophyll content and reflectance at narrow spectral bands,⁶³ (at 550 and 700 nm).⁶⁴ This relationship is weaker in annual plants, where the leaf structure creates a higher surface reflectance and quickly reaches saturation.^{64,65} However, looking across a wider spectrum (from 400 to 750 nm, inclusive) and at larger total chlorophyll

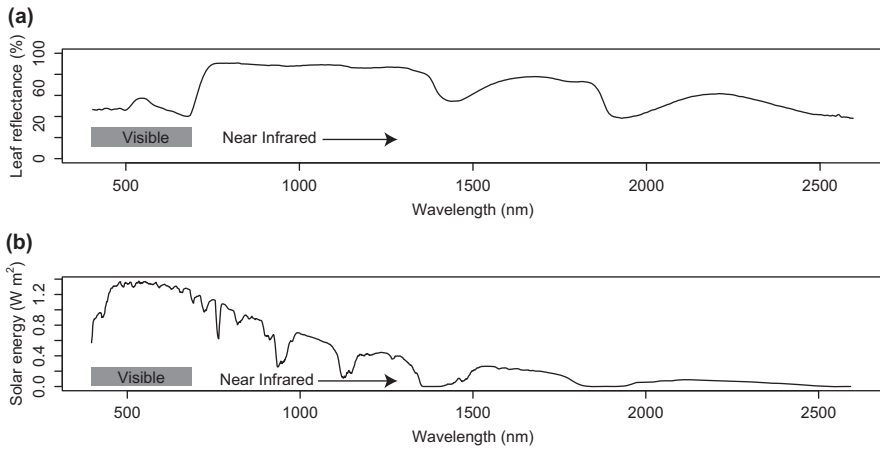


Figure 4 (a) Typical leaf reflectance values (in percent) for wavelengths of 400–2600 nm. (b) Sea level solar spectrum values for wavelengths of 400–2600 nm at sea level, in Watts m^{-2} .

contents, there is a strong statistically significant positive relationship between chlorophyll content and reflection.⁶⁶ Since high chlorophyll levels are a direct determinant of potential primary production, increased chlorophyll content to increase albedo could potentially increase yields.

However, the visible part of the spectrum isn't the only factor in determining albedo. The near infrared makes up around 50% of the energy in the solar spectrum at sea level as shown in Figure 4(b), making this a very important range.⁶⁷ For instance, red ceramics have a higher albedo than light grey stainless steel, despite being a darker visible colour, because they reflect more strongly in the near infrared.⁶⁷ Generally speaking, plant dehydration increases reflectivity at the leaf level in the near infrared.^{68–70} At the canopy albedo level this effect is less important due to weaker spectral irradiance in the near infrared.^{61,71} Since water absorbs strongly in the near infrared and transmits in the visible, any reduction in water increases the potential for reflection at most wavelengths. This makes the near infrared a useful part of the spectrum for diagnosing plant water content and health but as an albedo increase mechanism, reduced water is likely to have undesirable side effects.

6.4 Canopy Level Albedo

At the canopy level, the leaf level albedo is only a small part of the net resultant albedo. Other factors' influence (see Figure 3) becomes dominant. A key factor in this is how much of the background is covered by the plant. The background soil albedo is especially important when the canopy coverage is low (*e.g.* when the leaf area index is low). Soil albedo is mainly determined by the soil type, water content and soil surface roughness. The largest component of this is the soil colour, which varies with the type of soil, as well as

the soil moisture. Dry soil has an albedo up to 0.16 higher than wet soil.⁷² This is especially important for crops, as many fields are left uncovered and fallow over winter and ground coverage can be lower than natural land cover because of weed suppression.

The amount of plant coverage of the background soil is mainly determined by the leaf area index, though the net effect on the albedo is not direct. If the background albedo is high, then an increase in leaf area index may reduce the overall albedo. Conversely though, if the background albedo is low, an increase in leaf area index may increase the overall albedo. The leaf area index is dependent on the plant growth stage, but also on the health of the plant. For instance, across the whole canopy in the visible to near infrared, an increase in nitrogen fertilisation (in winter wheat) has the net effect of increasing reflectance at all stages of growth due to increased leaf area index.^{65,73} It has even been shown that increased albedo from increased leaf area index and health is currently a small scale summertime impact in areas of North America.⁷⁴ Therefore the overall leaf area index and plant health is a significant factor in the overall plant albedo, but is highly dependent on the background albedo.

Similarly, the plant morphology, or architecture, can also affect the albedo, partly through altering the amount of background soil visible. The plant morphology usually refers to the angle and placement of leaves and can vary considerably.⁷⁵ Different distributions of leaves and leaf angles lead to different reflectance at the canopy level. Leaf angle distribution (LAD) is a common measure of the orientation of the leaves, which strongly affects the canopy reflectance. The leaf angle distribution is measured from the zenith and thus a high mean leaf angle distribution indicates that the leaves are mainly upright. Different leaf angle distribution values affect what is the most important factor for the total reflectance. An erectophile canopy (mainly vertical leaves) is considerably affected by the background reflectance. For a planophile canopy (mainly horizontal leaves) the background reflectance exerts a much smaller influence and the leaf properties affect the reflectance more.⁷⁶ Depending on the background reflectance, canopy reflectance can increase with leaf angle distribution at the red and near infrared parts of the spectrum, *i.e.* more erectophile canopies may have higher canopy reflectance.⁷⁷

Like leaf area index, the leaf angle distribution varies with plant health, development stage and variety. An associated affect of increased nitrogen is a more planophile appearance of the canopy.^{78–80} As well as being affected by nitrogen levels, the leaf angle distribution varies naturally between varieties^{79,80} and along with the leaf area index is the dominant control on canopy reflectance.⁸¹ Leaf angle distribution values are also seasonally varying. Young plants tend to have more erectophile canopies and varieties tend to be more homogenous in their leaf angle distributions. Differences in both leaf angle distribution and in reflectance appear as the plants develop, resulting in statistically significant differences.^{77,76} Therefore differences in reflectance from plant architecture are reliant on not just the variety, but

also the growth stage and other factors influencing reflectance. Canopy architecture can also affect the plant health and potentially the crop yield, as planophile leaf angle distributions are also associated with drought resistance.⁸²

The albedo is also affected by the angle of the light which falls on the canopy surface. The angle between the horizon and the sun is known as the sun zenith angle. The sun zenith angle changes both diurnally and seasonally, as well as with latitude. It strongly affects the surface albedo because of the changes in scattering angle at the surface from vertical components, especially those with low transmission, such as soil.⁸³ As the solar zenith angle increases, so does the albedo.^{84–86} However, the solar zenith angle effect on albedo is not uniform; cloud cover significantly reduces the effect and am and pm responses differ.⁸⁶ Although the solar zenith angle is not a factor which can be deliberately changed to affect crop albedo, it is still an important aspect which needs to be acknowledged. Overall, the key components which can be deliberately manipulated are the background soil and various aspects of the plant health, which can help increase the canopy level albedo, and may even have synergies with maximising yields.

7 Simulations with Climate Models

7.1 Crops in Climate Models

Key questions for the bio-geoengineering concept are how big the cooling effect and what other climatic consequences there might be. These are addressed using climate models. Climate models at their core simulate fundamental physical laws (motion, conservation of mass, *etc.*) across the Earth in a three dimensional grid. Early climate models had a simple representation of the land surface, which used averaged approximations or parameterisations which affect the surface energy balance (shown in Figure 1) such as uniform soil water holding capacity, albedo and roughness length.⁸⁷ Later models update the land surface more dynamically (for instance by calculating the restraints on transpiration) and separate out different sections of the land surface (for instance by differentiating between soil and vegetation at the surface, as well as different plant functional types). The newest climate models include new land surface relevant sections such as interactive carbon cycles, dynamic representations of vegetation distribution, higher resolutions and agricultural models. These parts of the model are usually separate to the core physics of the climate model and the model can be run in many different combinations.

Whereas older models either didn't represent different vegetation types or averaged values across a grid box overall, many current models represent vegetation through a tile system. Values for each plant functional type (such as broadleaf or needleleaf trees) are calculated separately and the overall grid box value is calculated according to the proportion of a grid square which is covered by that plant functional type. This has the advantage of providing

much better diagnostics about how changes in species composition are affecting the climate. Different plant functional types vary considerably in many parameters, including their temperature ranges, leaf area index ranges and critical humidity deficit. However, by necessity these are wide ranges and many models have only around four to sixteen plant functional types. As a consequence, some land surface models do not explicitly represent agricultural lands or crops. Most crops are physiologically closest to grasses and thus cropland is frequently represented as grass in models without crops specified as a plant functional type.

Thus far, two climate models have been used to perform simulations of increased crop albedo: the Hadley Centre model and the Community Climate System Model. Simulations of an increase in crop albedo of 0.02, 0.04 and 0.08 have been performed with the UK Hadley Centre model, HadCM3, combined with the land surface scheme MOSES2.1^{6,7,58} and MOSES1.0.⁸⁸ MOSES has only five plant functional types and therefore crops are not explicitly represented. These increased crop albedo simulations use a mask to exclude competition over cropland areas as shown in Figure 5(b). The mask does not allow trees or shrubs to grow in cropland areas, therefore cropland is represented as grass and if the climate is not suitable for the growth of grasses, then the surface is bare soil. The crop albedo was increased by increasing the maximum albedo attainable (calculated with leaf area index) for all the 'crops' within the masked areas.⁵⁸ These simulations were run at a range of different carbon dioxide levels, including 280, 350, 560, 700, and 1400 ppm with other initial conditions held at present day levels.^{88,58}

Simulations of crop albedo increases of 0.05, 0.10 and 0.15 have also been run with the Community Climate System Model, CCM3.0, using the Community Land Model (CLM3.0).⁸⁹ CLM has a more detailed representation of plant functional types and has a separate class for crops, so a crop mask is not needed.⁹⁰ These simulations were run at 370 ppm carbon dioxide.⁸⁹

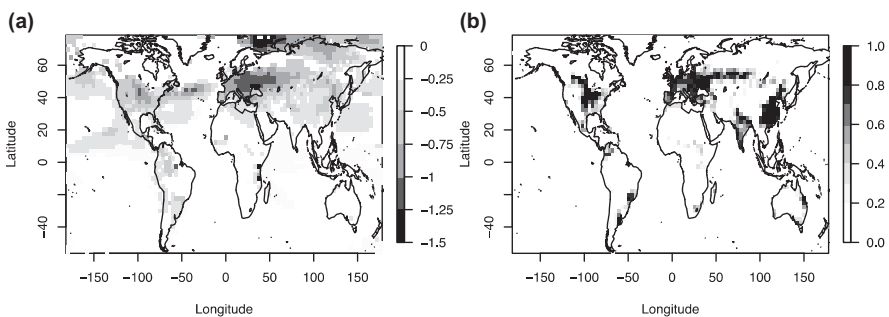


Figure 5 (a) Summertime (June/July/August) statistically significant mean temperature decreases from a 0.04 increase in crop albedo. The simulations shown here have been run to equilibrium at 700 ppm CO₂ using HadCM3. Results were tested using a Wilcoxon rank sum test, at 99%. (b) Present day cropland extent, as used for the crop albedo increase in the model.

7.2 Climate Impacts

All the models simulations run so far show that a 0.04 increase in albedo over current cropland areas gives a mean summertime (June, July, August) cooling of around -1 °C, see Figure 5(a). A 0.02 and 0.08 increase in albedo gives a proportional cooling (-0.5 °C and 2 °C, respectively) equating to around 0.25 °C summertime cooling for each 0.01 crop albedo increase. The cooling is concentrated in the temperate regions of albedo increase, with western Europe and North America most affected. The cooling is greatest in the northern hemisphere summertime because of the plants' higher summertime leaf area index which gives greater ground coverage, reducing the influence of the bare soil albedo. In northern hemisphere wintertime the tropical and Asian surface air temperature is strongly affected by the increases in carbon dioxide and thus changes related to the monsoon circulation, which counteract the cooling effect of the increased albedo.⁵⁸ Globally, the annual mean cooling is much smaller than the regional seasonal effect: only around -0.11 °C,^{7,88,58,6,89} for an increase of 0.04 crop albedo.

Regional patterns of precipitation changes are difficult to predict with climate models, with considerable variability between models,³⁴ and thus the model results for bio-geoengineering need to be considered with some caution. Precipitation shows a pattern of increase over Europe, with soil moisture showing up a more consistent pattern. The changes in evapotranspiration give increases in precipitation and also soil moisture over Europe. These changes to temperature and precipitation appear to be robust, as they appear in both HadCM3 and CCSM. Some displaced low latitudes effects give decreased soil moisture in the sub tropics and Australia, which may be caused by changes in cloud formation and precipitation.⁸⁹ The results from these models is in contrast to simulations using the climate model NCAR CAM3.1 in which large scale increases in albedo over all land surfaces results in decreased rainfall.¹⁴ How these precipitation changes are affected by the extent and location of increased albedo rather than which model is used is an important issue which has not yet been determined.

In addition to the uncertainties associated with climate model simulations, all of these results are averaged over long periods (30 or 50 years) for climates which are in equilibrium. This enables accurate analysis of the causal links in the simulations, but doesn't reflect the reality of conditions under which bio-geoengineering might be implemented. As bio-geoengineering is a relatively subtle effect it may be difficult to identify at a sub-decadal scale due to high inter-annual variability.

8 Yields

If bio-geoengineering could improve the likelihood of higher crop yields in future, this would be an important outcome. Food security in the form of food production is an essential issue for the 21st Century. Reservations about the potential of crops to provide climate solutions have been voiced on the

basis of concerns about reduced yield on the basis that reduced light would reduce photosynthesis.⁹¹ Though this seems intuitively correct, since there is a significant positive correlation of chlorophyll content with increased reflectance, increased reflectance could be beneficial to plant growth. There may also be further advantages in higher albedo crops from the physiological traits used to introduce higher albedo. Trichomes (hairs) and glaucous wax (leaf wax) are both associated with higher yielding varieties in some cases.^{92,93}

Further, the cooler summertime climate produced by bio-geoengineering could be advantageous to crop yields and may overcome any negative direct effect, especially in current crop growing regions of Europe and North America, which may become too warm for important crops currently grown. For instance wheat, whose yield is significantly affected by high temperatures and which requires a vernalisation period of cold temperatures in winter (cooling of the seed during germination in order to accelerate flowering when it is planted), is commonly grown in Europe and could be negatively affected by increased temperatures.

There are also potential feedbacks between crop yields, total cropland cover and bio-geoengineering (see Figure 6). The efficacy of bio-geoengineering would be dependent on the extent of crop cover. With more cropland, the cooling effect would be larger. However, if yields were to increase due to bio-geoengineering, fewer crops would be needed for the same demand, potentially implying less bio-geoengineering would be required.

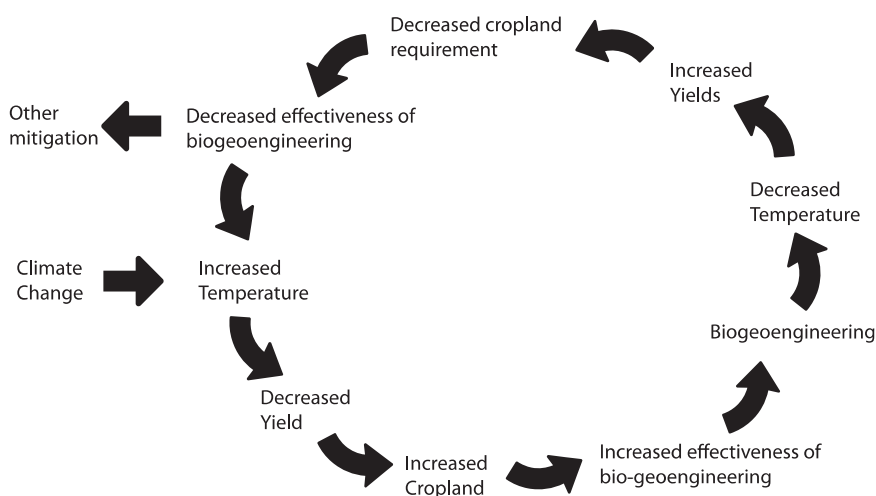


Figure 6 Flow chart of potential interactions between crop yield and biogeoeengineering. The cycle begins with climate change and potentially could continue around unless other mitigation solutions could begin to replace biogeoeengineering when it began to reduce in efficacy.

This could result in a negative feedback loop. The most feasible way out of this feedback loop would be through other climate change mitigation solutions (see Figure 6). This emphasizes that increased crop albedo is inherently a geoengineering solution which must be used in conjunction with conventional mitigation.

9 Other Crop Cooling Potential

Crops not only have potential for bio-geoengineering but also as a carbon capture and storage geoengineering method and a more conventional carbon reduction and mitigation technique. Many of these methods could be synergistic with increased crop albedo and together achieve significant cooling.

9.1 Soil Carbon Sequestration

Soil carbon currently makes up around 80% of the terrestrial carbon store.⁹⁴ However, soil degradation through land use change can release 25–30% of this soil carbon into the atmosphere.⁹⁵ If soil carbon sequestration in degraded cropland could be increased, enhancing the removal of carbon dioxide from the atmosphere, it could additionally take up 0.4–1.2 gigatonnes of carbon each year,⁹⁶ although this is regionally variable.⁹⁷ This is equivalent to up to 15% of fossil fuel emissions and could be a substantial contribution to reducing carbon emissions.⁹⁶ Enhancing carbon removal into soil carbon stores could also have some synergies with increasing crop yield, because of the increased soil organic carbon which is a store of nutrients. Agricultural management policies which deliberately increase soil carbon sequestration could be considered a type of carbon capture and storage geoengineering.

9.2 Biofuels

Most crops are utilized for direct or indirect food purposes, but crops can also be used for textiles, fuel and other uses. Crops which are processed into fuel, especially fuel for vehicles, are known as biofuel crops. Being a renewable source of energy, biofuels have been considered an important way of reducing fossil fuel use and are included explicitly in the RCP scenarios. By replacing fossil-fuels, biofuels avoid the emissions which would be emitted and provide a sustainable power source. However, biofuels have gathered criticism for driving up food prices and causing indirect land use change.^{98–101} Moreover, care must be taken to consider the whole production process since increased use of fertilizers (which currently require considerable carbon emissions in their production as well as emitting the greenhouse gas nitrous oxide) on biofuels could negate the positive carbon impact.¹⁰²

10 Priorities for Future Work

There are currently important gaps in our knowledge about how bio-geoengineering could work. Questions remain in the plant physiological, climatic and practical implementation areas.

One of the most important feasibility issues is what range of higher albedo crops could be bred. Finding out what the existing variability within crops is and seeing if it is sufficient to increase crop albedo using conventional breeding methods is a crucial part of this. If there is not a large, controllable natural variability which could be selectively bred for, would genetic modification be a viable and acceptable way to create high albedo crops? However, if the physiological traits which provide the greatest increase in albedo could be identified and conventionally bred for, then no genetic engineering would be necessary. Further, there may be win-wins between increased albedo, plant health and increased drought resistance or other desirable traits, which would be worth exploring.

From a climatic perspective, it is important that simulations of increased crop albedo are run with more climate models, as two models are unlikely to capture the whole of the potential consequences. Multiple models could also be used to understand how varying levels of implementation (across spatial and temporal scales) would affect the mean climate and the climate variability. Using transient simulations which include bio-geoengineering could aid seeing how bio-geoengineering could work in synergy with other mitigation policies. The extent to which seasonal variability is affected by cropping cycles would also need to be addressed, as the climate models used so far have no parameterization of this, which may affect the wintertime climate, when few crops are being grown. Similarly, the question of what could be the impact on yield from the changes in climate and from the physiological changes to crop varieties is a complicated issue which must be addressed before bio-geoengineering can be considered to be feasible. The answers to these questions are not necessarily straightforward and in some cases there are no strong precedents on how to do this research.

11 Conclusions

Cooling with crops could provide local help towards managing and mitigating against the most harmful aspects of climate change, but is a regional help, rather than a global solution. Future climate and agriculture are inextricably linked; yields determine how much land will need to be converted to cropland, whilst the climate change which is partially determined by the land surface effects will affect crop yields.

Food security is one of the most crucial challenges for the 21st Century and making crops part of the solution can be perceived as a risk. However, the opinion that some things are 'too important' to make concessions to climate change is based on a false assessment of risk and the interconnectedness of these systems. Excluding crops and other important factors as potential

options for reducing the impact of climate change will leave the necessity of a single, large solution. If that one solution fails, then there is the potential for a larger problem. The least risk strategy is actually to draw together many small changes to help combat climate change, spreading the risk. Similarly, criticisms of bio-geoengineering on the basis that it doesn't contribute enough cooling miss the essential point: as a multifaceted problem, climate change needs a multifaceted solution. Doing nothing about climate change is likely to result in substantial and damaging changes to the earth's climate; cooling with crops could be one of many building blocks which creates a whole solution.

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