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Land radiative management as contributor to regional-scale climate adaptation and mitigation

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Greenhouse gas emissions urgently need to be reduced. Even with a step up in mitigation, the goal of limiting global temperature rise to well below 2 °C remains challenging. Consequences of missing these goals are substantial, especially on regional scales. Because progress in the reduction of carbon dioxide emissions has been slow, climate engineering schemes are increasingly being discussed. But global schemes remain controversial and have important shortcomings. A reduction of global mean temperature through global-scale management of solar radiation could lead to strong regional disparities and affect rainfall patterns. On the other hand, active management of land radiative effects on a regional scale represents an alternative option of climate engineering that has been little discussed. Regional land radiative management could help to counteract warming, in particular hot extremes in densely populated and important agricultural regions. Regional land radiative management also raises some ethical issues, and its efficacy would be limited in time and space, depending on crop growing periods and constraints on agricultural management. But through its more regional focus and reliance on tested techniques, regional land radiative management avoids some of the main shortcomings associated with global radiation management. We argue that albedo-related climate benefits of land management should be considered more prominently when assessing regional-scale climate adaptation and mitigation as well as ecosystem services.

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report highlighted the inevitability that additional emissions of greenhouse gases would lead to further warming of the Earth's climate[1]. The projected temperature changes display high regional variability, but generally greater warming over continental surfaces[1], in particular for hot temperature extremes[2]. Given the slow progress in reductions of greenhouse gas emissions (despite their now-recognized urgency at the international level[3]), climate engineering — also known as geoengineering —has been proposed as a potential means to counteract part of global warming or at least slow the rates of warming while other mitigation strategies are implemented[4–6].

Climate engineering is a highly contentious issue[7–11]. Among the various relevant technologies, global solar radiation management (SRMglob) — for instance, through sulfate aerosol injection (SAI) into the stratosphere — has been one of the suggested options[4,7,12]. However, SAI raises important scientific, ethical and societal concerns[4,8,11,13] (Box 1) — as does SRMglob more generally. A main issue in the proposed implementation of global-scale climate engineering is the disparate regional effect of commonly proposed options. At present, however, none of the commonly suggested climate engineering schemes would allow much regional flexibility[14] (Box 1), especially in terms of climate extremes and impacts on continents (for example on human health or agricultural production).

Regional land radiative management

We examine here the intentional modification of radiative properties of the land surface, hereafter referred to as regional land radiative management (LRMreg), as an approach to climate engineering and adaptation. LRMreg may avoid several of the issues associated with SRMglob (Box 1) and could offer opportunities, especially for counteracting the warming of regional temperature extremes. Among its main benefits, LRMreg is regional by design and can build upon tested urban and land management approaches[15–19]. As highlighted in Table 1, several approaches can target increases in surface albedo, or may result in such increases as a by-product of other land modifications.

Albedo modifications in agricultural regions could potentially be performed over larger areas. These regions are thus of particular interest for LRMreg approaches. Albedo increases in agricultural regions could result from varied implementations (Table 1). First, no-till farming may lead to surface albedo increases after harvest, owing to the retention of crop residues, which have a higher albedo than bare ground. The net effects may reach an albedo increase of about 0.05 up to 0.2 in the case of crops with high reflectivity residues, such as wheat[15,20,21], but would be smaller for other crops. It should be noted that the albedo effect would mostly occur after harvest; it would thus be limited in time[21] and would occur at different dates in different locations[22]. Interestingly, the most substantial impact on albedo could be coincident with frequent heatwaves, for instance in August for winter wheat in Europe[15]. In the case of summer crops, no-till management could substantially modify surface albedo in fall, and potentially through spring[22], but less so in the hot summer months when they would be actively growing. Nonetheless, some less densely planted crops such as maize could still have a notable albedo change during the growing season due to the higher fraction of bare soil exposed.

Second, modifications of crop phenology — the timing of the plants' life cycles — could be relevant, although the literature is more limited on this topic (Table 1). The phenology could

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Box 1 | SRMglob and associated concerns

SRMglob, based for instance on sulfate aerosol injection (SAI), is a highly debated issue. Here we list the main concerns raised in the literature with respect to SRMglob and SAI. First, although modelling studies suggest that large-scale SRMglob deployment could offset global mean temperature change, it would not restore earlier, regional climate conditions[1] and would instead lead to heterogeneous regional changes. These include new climate conditions, for example the cooling and warming of extremes[84], as well as substantial changes in hydrology[10,77] (such as weakening of monsoons[79]), compared with the reference conditions. Hence, although a full deployment of SRMglob might reduce global mean temperature, it would redistribute the risks and thus create 'winners' and 'losers'[81], which has prompted the discussion of partial (or moderate) SRMglob in the recent literature[46]. Other concerns that have been voiced include the unabated (or possibly increased[83]) ocean acidification[1,55], potential termination effects (see Table 2)[52–54], negative (non-climate) side impacts[13,80], and a lack of testing of the proposed schemes[9,82]. Finally, there is the 'moral hazard' that the discussion of SRMglob (but also other proposed climate engineering schemes) might reduce the political and public support for mitigation and adaptation, despite the associated risks and uncertainties[7].

The voiced concerns are genuine. But in the face of continued warming[1], the short window of opportunity for effective greenhouse gas reductions[85] and the considerable associated consequences[2,86] (particularly in inhabited regions[87]), it is sensible to assess whether alternative approaches to commonly considered climate-engineering schemes might address some of these concerns. This is particularly relevant in the context of climate adaptation; that is, when considering climate engineering as an option to limit impacts while reductions in greenhouse gases are being implemented, for instance in the context of a (short) temperature overshooting phase[88] prior to stabilization at 1.5 °C global warming.

As highlighted, a main issue in the proposed implementation of global-scale climate engineering is the disparate regional effect of commonly proposed options. Furthermore, many vulnerable human and natural systems respond differently to changes in regional extremes than to changes in the mean climate[89,90]. Some authors have highlighted the need for a reduction of the regional trade-offs of climate engineering, suggesting this issue as an 'optimization' problem[14,78]. It has been argued that a few approaches could provide some degree of regional targeting, for instance through SAI being released preferentially in one hemisphere or at higher latitudes in one hemisphere[77,91], or through regionally variable application of marine cloud brightening[78]. At present, however, none of the commonly suggested climate engineering schemes would allow much regional flexibility[14], particularly in terms of climate extremes and impacts on continents (for example on human health or agricultural production). This is important to emphasize, as support for climate engineering schemes often stems from concern over potential future emergencies associated with extreme climate impacts[11,92]. As we describe in this article, LRMreg addresses some of the highlighted concerns associated with SRMglob and SAI, in particular with respect to regional targeting and the reduced impact of some climate extremes.

potentially be timed to have a maximal albedo in time periods with higher temperatures, or the overall time period with higher albedo could be expanded, for example, with the implementation of double cropping[23].

Third, modification of crop albedo with natural[24], selected or genetically modified reflective varieties (biogeoengineering) has been proposed to provide moderate regional climate cooling[17,18] (Table 1). Albedo variations through crop selection and modifications could reach +0.02 to +0.15 (crop-dependent variations in glaucousness, trichomes or canopy morphology[17,18,25]). Finally, the use of greenhouses may also increase surface albedo by about +0.05 in winter to +0.15 in summer[26] (Table 1).

Beside changes in agricultural regions, surface albedo may also be substantially modified in urban areas[18,19,27,28] (for instance through the use of white roofs, or more reflective pavements, with albedo changes ranging up to +0.1 or +0.15; see Table 1). Although the overall surface area covered by cities is less than for agricultural areas, most of the world population lives in urban areas (54% in 2014)[29], and thus the reduction of heat extremes in cities is particularly relevant for human health[30]. The additional warming through the urban heat island effect is a further reason why temperature cooling in heat-exposed cities should be an adaptation priority under global warming[30,31]. When combined with changes in albedo in rural areas close to cities, the overall albedo anomaly relevant to a city — local effects and close surroundings — could substantially be increased (and thus decrease the temperature).

Whereas some studies consider global-scale surface albedo management as an overall scheme aimed at increasing albedo over both land and oceans (or at least over a wide range of land surface areas, including deserts[18]), we consider LRMreg to encompass more specifically approaches that can modify regional-scale surface albedo over land and that can target the counteracting of climate change impacts in densely populated and agricultural regions. We therefore focus on geographically collocated changes in albedo and the resulting climate amelioration. LRMreg can be considered as a subcategory of SRM, but with a distinctive regional dimension. Other non-radiative biophysical impacts associated with land use such as irrigation could have large effects on regional climate[25,32,33], but we do not consider these aspects here.

There is substantial literature on how land surface reflectivity affects global and regional climate, especially as a consequence of changes in land cover and land use[15,34–39]. Although the climate engineering literature generally focuses on SRMglob (either through SAI or hypothetical 'sunshade albedo geoengineering'[40,41]), modifications of land surface albedo are also occasionally discussed in the context of climate change adaptation or climate engineering[7,18,31,42–45]. Nonetheless, LRMreg approaches targeted at inhabited or agricultural areas are generally not treated in much detail in authoritative climate engineering reports[7,12]. The main reasons are the inherent limits in achievable changes in crop albedo[15,17,42] and the small fraction of urban area[31], which would offer only limited effects on global mean temperature compared with those considered achievable with SRMglob[45]. However, the recent emphasis on moderate SRMglob[46] rather than schemes aiming at a full offsetting of global mean temperature changes reduces the relevance of this consideration.

Balance of concerns for LRMreg versus SRMglob

LRMreg schemes present several advantages over SRMglob in the context of climate engineering and climate adaptation (Table 2). First, land surface properties can be controlled and managed at a country (or even sub-country) level, and previous investigations have suggested that their impacts on climate have a strong local component[15,17,47]. It follows, therefore, that LRMreg could be implemented to better target a counteracting of regional-scale climate

Table 1 | Approaches relevant to LRMreg in agricultural and urban areas

	No-till farming (albedo changes from retaining crop residues)	Crop phenology and timing of practices (for example, double cropping	Biogeoengineering (cropping with natural, selected, or genetically modified reflective varieties)	Greenhouses	Urban albedo (white roofs, higher reflectivity of paving)
Impact on land albedo	Approx. +0.05 to +0.20 in the case of crops with high reflectivity residues (for example, wheat)[15,20,21]; less efficient for other crops.	Not quantified, probably similar to no-till farming in regions with tillage; depends on crop albedo, and background bare soil albedo, may also vary during crop growth[24].	Approx. +0.02 to + 0.15 (including crop dependent variations in glaucousness, trichomes, canopy morphology)[17,18,42,66].	Approx. +0.05 (winter) to +0.15 (summer)[26].	Approx. +0.1 to +0.15 as average increase over the urban areas[16,18,19] (locally: approx. +0.15 over roofs and +0.25 over pavement[19]).
Potential areas of implementation	Agricultural areas, mostly in Europe and Asia (already largely implemented in North and South America)[15,67,68].	Agricultural areas.	Agricultural areas.	Agricultural areas.	Urban areas/densely populated areas.
Temporal extent	Mostly after harvest (late summer for winter crops)[15,20]. Occasional tillage in some locations (for example in the United States) but permanent no-till conditions in others (for example in South America)[67].	Extension of growing season (early and late season), double cropping[23,73].	Mostly during growing season.	Year-round; potentially permanent.	Year-round; multi-year to permanent.
Further climate impacts	Less bare-soil evaporation and more surface soil moisture retention[15,21,69], owing to enhanced surface resistance of residue cover[15] and decreased radiation and temperature[21]. Fuel saved through elimination of tillage operations[70]. Reported increase in carbon storage, mostly in surface layer, but magnitude unclear and possibly small net effect on carbon balance[70–72]. Possible effect on N_2O and CH_4 emissions but sign unclear[72].	Possible enhanced drying and resulting warming in the intercropping period in the case of double cropping[73].	Possible increase in water use efficiency for dry-land crops; less transpiration.	Largely unknown; other impacts include: suppression of evaporation; longwave radiation changes; changes in carbon storage.	Cooler interior temperatures in summer, implying reduced need for air conditioning, and thus reduced energy use (potentially associated with less fossil fuel consumption).
Non-climatic shortcomings	May require more herbicides or extra labour for weed control[70]. Delayed planting may occur in wet climates owing to slower soil drying[70]. Risk of waterlogging in wet climates[69]. Effects on yield unclear, can be negative[74].	Higher vulnerability of second crop to freezing owing to later planting in the case of double cropping[75].	Increased reflectivity in the range of the photosynthetically active radiation may reduce crop productivity[48].	Requires important infrastructures with environ-mental impacts.	No major shortcomings.
Non-climatic advantages	Better rainfall infiltration and water retention[70]. Decreased risk of erosion[69,70]. Generally beneficial for soil quality but net effect dependent on location[69]. Time saved through elimination of tillage operations[70]. Effects on yield unclear, can be positive[74].	Increased yield in the case of double cropping[73,75].	Crop type change not necessary; minimal disruption of food production. May reduce leaf heating and increase yields for dry-land crops.	Provide more controlled environment for crop growth.	Higher-reflectivity roofs cheaper to implement and easier to install than green roofs[76]. Reflective measures superior to enhanced vegetation cover for cooling[28].
Tested (0, no; + , in part; ++, to large extent; +++, fully evaluated)	++ Already widespread in North and South America[67,68]; not specifically investigated with respect to LRMreg effects on larger scale, with exception of regional-scale study for Europe[15].	+ Existing agricultural practices, but not specifically assessed for their impacts on albedo.	+ Field-scale experiments with focus on crop yield and transpiration.	+ Continuous 26,000 ha in Almeria, Spain[26].	++ White roofs common in Mediterranean area. Higher-reflectivity roofs implemented for cooling purposes in some cities[19,27,28,76]. Higher-reflectivity paving less widespread but there is on-going research and application at small scale[19].

Table 2 | Comparison of LRMreg and SRMglob with respect to common concerns over climate engineering

Concern	SRMglob	LRMreg
Regional climate trade-offs	Substantial regional climate trade-offs[8,77,78]. Reduction of monsoon precipitation[79] and major regional overshooting in temperature extremes and precipitation (Supplementary Fig. 3) if aiming at cancelling global temperature response.	Signal mostly regional in scope as long as LRMreg is applied over single regions (Figs. 1 and 2). Application not as effective in all regions, and possible negative effects (weakening of monsoon) if applied in Southeast Asia (Fig. 1).
Environmental side effects	Possible ozone depletion from sulfate aerosol injections[13,80].	In the case of agriculture-based LRMreg, implementation needs to be weighed against other demands for land use[56] No reported side environmental effects of increased reflectivity of buildings or pavement[19].
Risk for cross-boundary conflicts	Large, because of creation of 'winners' and 'losers'[81] and possibility for single country to affect climate in other countries.	Limited because of mostly regional impact, provided deployment is kept regional in scope (Fig. 1).
Testing	Not tested[9,82]; prior volcanic eruptions proposed as analogies[4,81].	Approaches (see Table 1) are generally related to existing agricultural or urban implementations. Testing of relevant techniques available at local to subregional scale (in particular for modified urban albedo[19,76]), but no large-scale testing and assessment with specific focus on LRMreg questions. Monitoring on larger scale in the case of partial deployment would be possible without major investments (existing measurement networks and satellite retrievals).
Reversal	Deployment could be stopped quickly, but environmental effects could be long-lived (ozone depletion). Rapid increase in surface temperature if stratospheric sulfate injections were stopped abruptly, possibly leading to even larger impacts ('termination effect')[52–54].	Over agricultural areas, crops are renewed every year. Reversal possible. No expectation of an abrupt response because of required timescales of implementation on the ground.
Continued detrimental effects of CO_2 concentrations on environment (for example ocean acidification[1,55])	Not addressed (unabated, or possibly increased[83]).	Not addressed.
Moral hazard[7]	Exists for arguments in favour of strong deployment to reduce global mean temperature.	Less critical because of smaller/negligible global impact.

responses (despite the presence of smaller non-local effects as well; see below). Second, unlike conventionally proposed SRMglob schemes, measures leading to modifications of land surface albedo are for the most part already tested, and their local side effects on the environment can generally be assessed. For instance, substantial changes in land radiative properties can be yielded from simple modifications in agricultural practices (such as no-till management[15,43] or the choice of planted crop varieties[17,44,48]), and these practices can be adapted from year to year[42]. Similarly, as previously discussed, the surface albedo of cities can be modified through various measures[18,19,27], some of which are already being tested at small scales[28] (Table 1). By combining these various approaches, regional albedo changes ranging between 0.05 and 0.1 would be achievable — with even higher increases at the local scale — both over cropland and urban areas (see Table 1 and Methods for a summary). Third, investment in LRMreg could be focused on areas associated with the strongest impacts of greenhouse gas forcing on human society, that is with collocated implementation and effects[42]. Densely populated and crop-producing regions would presumably be of most relevance, and — as highlighted above — are also the specific regions where land albedo can most easily be modified. Finally, recent model evidence suggests that land albedo changes could be more efficient at mitigating extreme hot temperatures than at mitigating mean temperatures, owing to interactions with background climate and feedbacks with soil moisture dynamics[15,21,25]. These results highlight the potential ability of LRMreg to target the mitigation of extreme hot (and dry[21]) events rather than mean temperature. Indeed, changes in extremes, and not changes in the mean climate, generally have the largest impacts on human health and crop production[49–51].

These various points suggest that, overall, LRMreg would address several of the concerns voiced on SRMglob (Table 2). Another point to be mentioned is that termination effects (the impacts of sudden suspension of geoengineering)[52–54] would be less likely with LRMreg than SRMglob because the implementation would not be centralized, and the effects on global albedo would be limited (similar to an extremely moderate[46] SRMglob scheme, or with lower impact). In addition, the 'moral hazard'[7] that the consideration of (hypothetical) climate engineering schemes might lead to a hazardous delay in mitigation action is less critical for LRMreg than SRMglob, again because of its more regional characteristics and more limited global impacts. On the other hand, it should be mentioned that in the cases of both LRMreg and SRMglob, non-radiative effects of enhanced CO_2 concentrations, in particular ocean acidification[1,55], would not be addressed. Hence, although LRMreg would not be a panacea and would have concerns of its own, in particular with respect to competition with other demands for land use[56], it might alleviate several of the concerns commonly expressed about SRMglob.

LRMreg model experiments

To illustrate and investigate the impacts of modified global-scale and continental/regional-scale land surface albedo in the context of climate engineering and climate adaptation, we use a climate

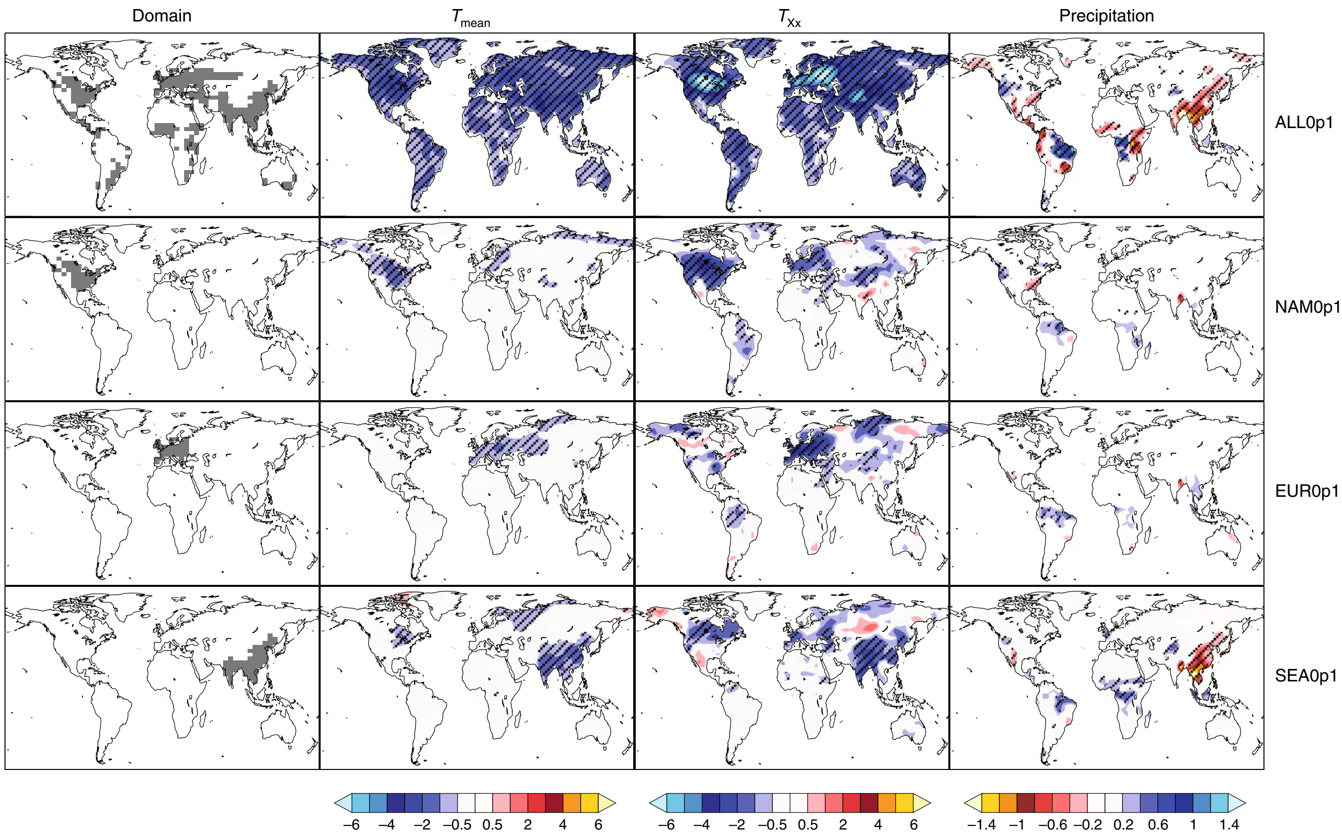

Fig. 1 | Impacts of regionally variable modifications of land surface albedo in agricultural and densely populated areas. Left column: Masks used to modify land albedo in the experiments ALL0p1, NAM0p1, EUR0p1 and SEA0p1. The considered grid points include densely populated regions and agricultural areas (HAA grid points). Second to fourth columns: Simulated effects of LRM on mean temperature T_{mean} (K), annual maximum temperature T_{Xx} (K) and annual mean precipitation (mm day^{-1}) with respect to the abrupt 4×CO_2 experiment (difference), within experiments ALL0p1, NAM0p1, EUR0p1 and SEA0p1 (computed for the last 10 years of each simulation). See Methods for details. Shaded areas indicate significant changes.

model[57,58] to investigate the extent to which the climate response to enhanced CO_2 forcing is offset through increases in land surface albedo. We modified albedo over agricultural and densely populated regions, either globally or over single large regions (see Methods, and Fig. 1, top left panel). We refer to the respective grid points as HAA ('human-affected and -affecting') regions. We note that previous studies also investigated global-scale changes in albedo over agricultural areas[21,25,45], but to our knowledge, no global experiments modifying albedo over isolated large regions have previously been performed. This experimental design allows us to distinguish the effects of regional- versus global-scale modifications of albedo in HAA regions.

We conduct four experiments, in which the albedo is increased by 0.1 over the following: all of the HAA grid points (experiment ALL0p1), or only the HAA grid points that lie within the continental United States/Canada (NAM0p1), Europe (EUR0p1) or India–China–Southeast Asia (SEA0p1). In addition, responses of sensitivity experiments conducted with albedo changes of 0.02, 0.04, 0.08 and 0.16 over all HAA grid points are documented in the Supplementary Information (Supplementary Fig. 2). This provides a scaling over various land albedo perturbations, although modifications of land albedo of 0.1 represent a likely upper bound that can be achieved over larger land regions (see Methods and Table 1). The masks corresponding to the regional-scale experiments are displayed in Fig. 1 (left column). A summary of the design of our experiments is provided in the Methods.

We focus hereafter on the regional impacts of the imposed changes on mean temperature (T_{mean}), annual maximum daytime temperature (T_{Xx}) and precipitation (Figs. 1 and 2). We note that the global-scale temperature response is moderate for the application over the whole HAA regions (about 0.7 °C in the context of a 3.7 °C warming for the 4 × CO_2 scenario) and negligible when only applied over single regions (Fig. 2). This latter result is to be expected given that the surface albedo modification is performed over a limited area and that the overall albedo change is small at the planetary scale. However, as previously highlighted, the main interest of LRMreg is in the possible implied regional effects.

Our experiments reveal contrasting regional responses in the simulations and, in particular, a strong variation of the geographical footprint for the imposed modifications. Although the ALL0p1 experiment confirms that the response to imposed albedo modifications leads to a stronger local than non-local response[15,17,47], the latter is non-negligible, with significant changes in several regions without modifications of land albedo (Fig. 1). Overall, the impacts are substantial in the ALL0p1 experiment, regionally up to 2 °C for T_{mean} and up to 4 °C for T_{Xx} (Fig. 2). The presence of non-local effects implies, however, that this scenario would have similar caveats to SRMglob approaches (see also impacts on precipitation). In addition, it would be difficult to modify land surface albedo over such a large area.

Regionally confined LRMreg experiments

We now consider the results of the regional-scale experiments (NAM0p1, EUR0p1 and SEA0p1). These reveal that limiting the land surface albedo forcing to specific regions allows a better

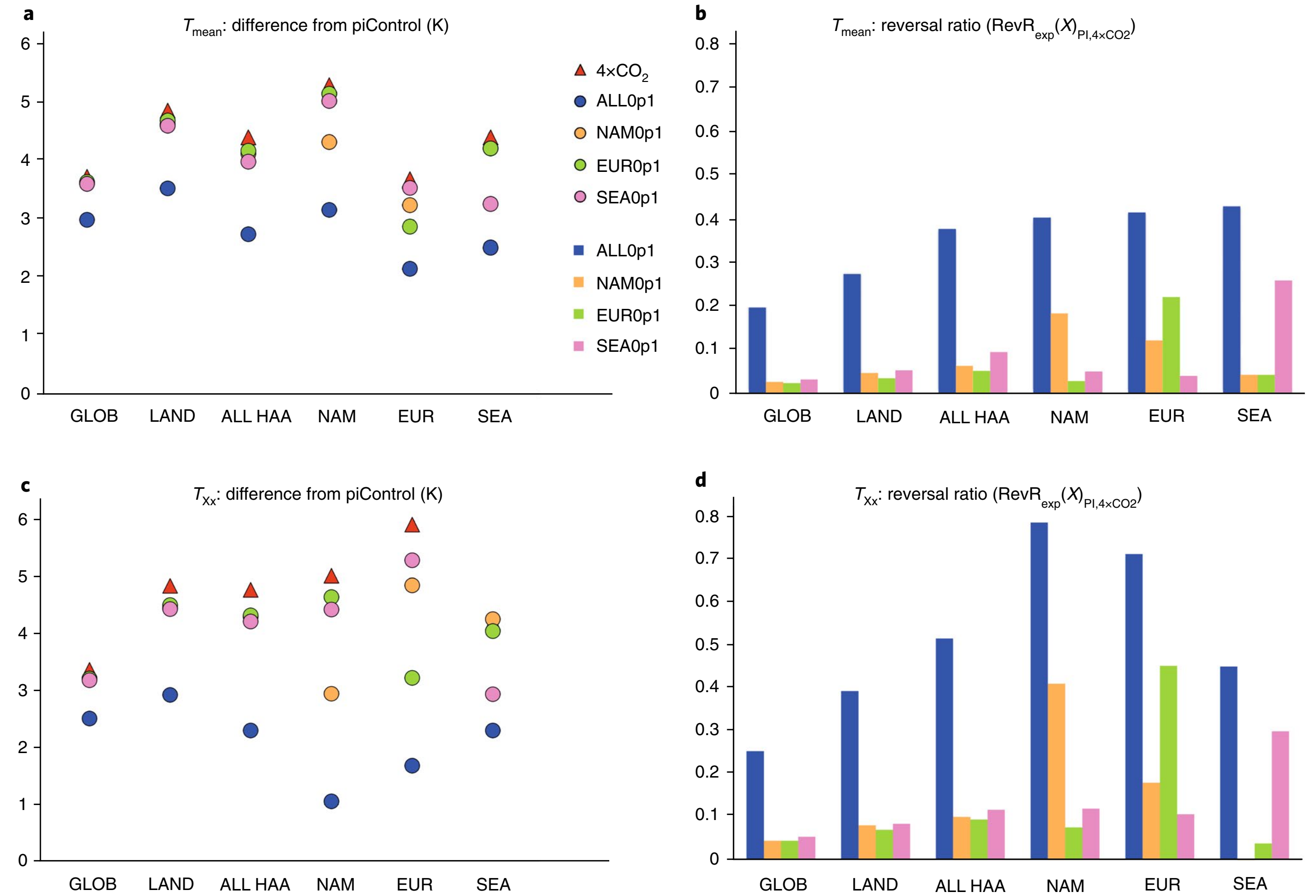

Fig. 2 | Analysed effects by regions for T_{mean} and T_{Xx}. a,c, Changes in temperature mean (**a**) and annual maximum temperature (T_{Xx}) (**c**) in the experiments abrupt 4×CO_2 (4 × CO_2), ALL0p1, NAM0p1, EUR0p1 and SEA0p1 compared with the pre-industrial control (piControl experiment), averaged over the whole globe (GLOB), over the global land (LAND), all HAA grid points (ALL HAA), and the NAM, EUR and SEA regions (see Fig. 1 for definitions of the ALL HAA, NAM, EUR and SEA domains). **b**,**d**, Reversal ratio (RevR$_{exp}$(X)$_{PI,4×CO2}$, see Methods) for experiments ALL0p1, NAM0p1, EUR0p1 and SEA0p1 experiments expressed as the ratio of the change between the experiments and the abrupt 4×CO_2 experiment and the difference between the abrupt 4×CO_2 and PiControl experiments for T_{mean} (**b**) and T_{Xx} (**d**); note that this ratio would be much higher for lower emissions scenarios, for example, RCP2.6 versus PiC.

regional restriction of the resulting temperature signal to the regions where the respective measures are applied (Fig. 1), although some non-local effects are seen, particularly in the SEA0p1 experiment. The total temperature impact is smaller than in the ALL0p1 experiment, but is still of the order of 1 °C for T_{mean}, and 2–3 °C for T_{Xx} in the regions with modified land surface albedo (Fig. 2). This would correspond to a large fraction of the additional warming projected for extremes in many land regions compared with changes in global mean temperature[2]. In the case of the abrupt 4 × CO_2 scenario, we note that the imposed albedo modification is counteracting about 20–40% of the climate response in temperature extremes (Fig. 2), an effect that would be larger for lower CO_2 concentrations (for example as projected for lower levels of global temperature warming such as 1.5 or 2 °C). For precipitation, the effects are negligible for NAM0p1 and EUR0p1, but there is a substantial reduction in Southeast Asia in the SEA simulation (leading to slight overshoot: see Supplementary Fig. 3). The identified overshoot for precipitation in the SEA region is likely to be due to effects on monsoon dynamics, which suggests that LRMreg measures would be more suitable in Europe and North America than in monsoon-prone tropical regions. Nonetheless, the overall effects on precipitation and respective overshoot in the SEA experiment are still of much smaller magnitude than those of a typical SRMglob experiment (Supplementary Fig. 3).

The robustness of the results is supported by the fact that previous experiments with other (regional and global) climate models did indeed show a stronger response of temperature extremes than temperature means to imposed albedo changes[15,21,25]. This can be physically explained through two mechanisms: first, the albedo modifications are more efficient at cooling in hot and clear days, in which the incoming shortwave radiation is higher[15], and second, in some regions the cooler temperatures and reduced radiation lead to less evapotranspiration and thus less soil moisture decrease[21], which is known to mitigate heatwaves in transitional climate regimes[59,60]. As further supporting evidence, the qualitative response of the applied model to large-scale and regional-scale albedo changes is broadly consistent with that of another well-established global climate model (see Supplementary Fig. 1). A new feature of our experiments is the investigation of imposed surface albedo changes in single regions. As highlighted in the Methods, the experiments remain highly idealized, but they illustrate the potential relevance of changes in regional land albedo for climate adaptation and mitigation. Comprehensive follow-up experiments using a multi-model set-up would be useful to fully evaluate the impacts of approaches that could be targeted to increase land surface albedo. A first step towards such experiments has been proposed[61], and the final set-up of that experiment will build upon the results of the current study.

LRMreg as part of the solution

At best, any climate-engineering scheme can only be one part of a possible climate solution, given the implementation challenges. In this context, if solar radiation management is indeed to be considered in mitigation and adaptation scenarios, priority should probably be given to pragmatic low-regrets measures that: (1) have limited negative side effects; (2) are tested and founded in observations; (3) are reversible; (4) have some degree of regional optimization; and (5) have the lowest risks of generating cross-boundary conflicts. Within the range of possible climate-engineering schemes, LRMreg, via land albedo modification, has received little attention so far, although it has the potential to fulfil several of these criteria (see comparison with SRMglob in Table 2). These considerations imply that LRMreg may have a higher public acceptability than SRMglob, which could make implementation more feasible. But this question has not been evaluated, and an assessment of the public acceptability of implementations of LRMreg versus SRMglob and classical mitigation measures would be desirable. Although LRMreg would not be suitable for modifications of global temperature, our review and results suggest that regional increases in surface albedo of ~0.05–0.1 are worth examining in order to counteract the impacts of global mean warming on key vulnerable regions, including major cities and agricultural areas. We emphasize that this examination needs to be conducted with specific consideration of the associated attenuation of hot extremes, for which LRMreg seems to be particularly effective. We also note that LRMreg should be assessed in the wider context of the optimization of ecosystem services, considering the existing competing demands for land use[56].

From this angle, cooling resulting from brighter surfaces could be one ecosystem service to weigh along with, for example, food production, biodiversity, CO_2 uptake and recreational uses. Because of the need to balance these various demands, in particular that of food security, increased albedo in crop areas may not be the sole priority, but instead could be integrated as a co-benefit of other agricultural practices (such as conservation agriculture[15]). We also note that there could be co-benefits of LRMreg with CO_2 mitigation measures, for instance from enhanced carbon storage and reduced fuel use associated with no-till farming, or the reduced need for air conditioning in cities (Table 1). Taking into account these various aspects, the vulnerability of cities and crops to extreme temperatures implies that even if LRMreg only partially counteracts changes in these extremes, its effects could be valuable given the thresholds on human health[62,63], labour productivity[64], infrastructure[65] and crop yields[51] associated with extreme temperatures and heat waves. In the case of cities, we note that the benefits could be particularly high given the increasing urbanization trends.

In summary, we have shown that various approaches to increase the surface albedo over agricultural and densely populated regions could reduce temperature on local to regional scales. Simulations indicate that LRMreg could potentially counteract the warming of hot extremes by up to 2–3 °C over densely populated and crop-producing regions. These values are an upper bound, as in reality the changes in albedo are unlikely to be applied over the whole cultivated or inhabited area, even at the regional scale; in addition, albedo modifications in cropland would be limited in time (with, for example, strongest effects after harvest for no-till farming). But these results show that the net effect, even for lower-level albedo modifications, is non-negligible and worth considering. With the exception of changes in India–China–Southeast Asia where the simulations show a decrease in precipitation compared with pre-industrial conditions, our results suggest that the impacts of LRMreg would generally not lead to detrimental climate effects or overshooting (although some non-local effect could remain for higher levels of albedo forcing). This stands in contrast to the impacts of more commonly examined SRMglob schemes.

As for other climate engineering schemes, several issues would need to be weighed before considering LRMreg in decision-making (Table 2), most importantly the competition with other ecosystem services and, in particular, food security in the case of albedo changes in agricultural regions (but not in urban areas). Despite these limitations, it may be suitable for some level of regional optimization, and directly offset some climate change impacts in the applied areas (such as potentially increasing crop resistance during heatwaves). This approach should thus be more thoroughly considered in future adaptation and mitigation scenarios, particularly in the context of the reduction of changes in hot temperature extremes. Potentially, the resulting differences could help to keep some regional impacts closer to those associated with a global warming of 1.5 °C even under a global warming nearer to 2 °C, or partly counteract the impacts of CO_2 concentrations overshooting on the way towards temperature stabilization.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the https://doi.org/10.1038/s41561-017-0057-5.

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Author contributions

S.I.S. designed the study together with S.J.P. and A.J.P. S.J.P. performed the climate model experiments with inputs from S.I.S. A.L.H. conducted complementary simulations. S.J.P., M.G.D., S.I.S. and M.H. performed the analyses. S.I.S., E.D. and M.W. compiled Table 1. S.I.S and A.J.P. wrote the first version of the manuscript. All authors commented on the manuscript.

Competing interests

The authors declare no competing financial interests.

Additional information

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Methods

Model simulations and analyses. The model simulations analysed in Figs. 1 and 2 are performed with the CSIRO Mk3L model[57,58]. CSIRO Mk3L is a fully coupled general circulation model, incorporating components which describe the atmosphere, land surface, sea ice and ocean. The horizontal resolution is 5.6° × 3.2° in the atmosphere and 2.8° × 1.6° in the ocean, with 18 and 21 vertical levels, respectively. We note that although CSIRO Mk3L has a coarse resolution, it was not found to be an outlier among the models participating in the Geoengineering Model Intercomparison Project (GeoMIP) experiments. In addition, its sensitivity to large-scale perturbations in crop albedo (ALL0p1 experiment) is qualitatively consistent with that identified with more complex and/or higher-resolution global climate models[18,21,25]. Furthermore, experiments with the Community Earth System Model using a comparable (but not identical) set-up to that presented here (that is, including regional changes in land albedo but for transient climate projections) do indeed reveal an overall consistent response compared to that of the Mk3L model, both in terms of the response of temperature extremes versus means, and the more regional response of the NAM0p1 and EUR0p1 experiments (but not SEA0p1, as for Mk3L) compared with the ALL0p1 experiment (see Supplementary Fig. 1).

The Mk3L simulations use as reference the CMIP5 abrupt 4×CO_2 experiment[93], which consists of an instantaneous quadrupling of the atmospheric CO_2 concentration relative to the piControl experiment. The conducted LRMreg simulations resemble the GeoMIP experiment G1 (ref. [40]), except that climate engineering is applied regionally through changes in land surface properties, rather than being applied globally through a reduction in solar irradiance, and that the total forcing is not chosen to restore the pre-industrial value but is limited to achievable changes in albedo in the considered regions (see also hereafter).

With the exception of the piControl simulations, all of the experiments are run as three-member ensembles. Each ensemble member is initialized from a different year of the piControl experiment but is otherwise identical. The analyses of mean differences use average values for the last 10 years of the three members of each respective ensemble experiments in case of the LRMreg, abrupt 4×CO_2 and G1 experiments, and for a representative 1,000-year time slice in the case of the piControl experiment. In Fig. 1, significant differences at the grid scale are based on a *t*-test. Using a Wilcoxon rank sum test or adjustment of the *p*-values due to multiple testing was not found to lead to substantially different results (not shown). Differences are declared significant at the grid-cell scale if the *p*-value is below the critical value ($p < 0.05$).

We note some limitations of the experiments. First, large-scale and long-term land surface albedo modifications of 0.1, as applied in the conducted climate simulations, represent an upper bound (Table 1). In particular, the albedo changes are applied in the simulations over the whole year and in the whole grid cells, whereas changes in albedo in agricultural regions would — if implemented — probably be limited in time[21] and in a fraction of the crop area and surrounding land. Another limitation is that we consider here only effects of changes in surface albedo, whereas most of the approaches leading to changes in albedo would also affect other surface properties and resulting climate (for example soil evaporation for no-till farming, plant transpiration and CO_2 uptake when changing crop varieties; see Table 1 for an overview). The albedo effects on temperature are due to the decreased net radiation at the surface, but can also include interactions with other variables, for example cooler temperatures leading to less evapotranspiration and affecting soil moisture–temperature feedbacks[21]; hence these further modifications could also affect the response to the albedo changes.

Finally, we note that large changes in albedo in desert areas, which have received more attention in the literature, could lead to much stronger global cooling than the achievable albedo changes in agricultural and inhabited areas (Table 1). However, they would have substantial detrimental effects on the hydrological cycle[18,45] and are thus not considered here.

Maps of population density and agricultural areas. We combine maps of population density and agricultural areas to determine the mask for the HAA regions. The population density map is based on 1° data for 2000 (adjusted to match UN totals) provided by the Socioeconomic Data and Application Center[94]. Here we consider highly populated regions to be regions in which the population density is larger than 30 km^{-2} for the HAA mask. The cropland map is derived from a standard dataset[95] for present-day conditions (using data for the year 1992). Grid cells where the cropland area is equal to 10% or larger are considered within the HAA mask. Both datasets (population density, cropland areas) were remapped onto the horizontal grid of the CSIRO Mk3L atmosphere model, prior to deriving the masks.

Quantifying signal reversal and overshooting from climate engineering. Figure 2 and Supplementary Fig. 3 analyse the reversal ratio ($\mathrm{RevR}_{\mathrm{exp}}(X)_{\mathrm{PI},4\times\mathrm{CO2}}$) of the LRMreg experiments ALL0p1, NAM0p1, EUR0p1, SEA0p1 (Fig. 2 and Supplementary Fig. 3), and of the SRMglob GEOMIP G1 simulation[40] (Supplementary Fig. 3), as the ratio of the difference between the respective experiments and the abrupt 4×CO_2 experiment divided by the difference between piControl and abrupt 4×CO_2 (using average statistics for the last 10 years of each experiment), where 'exp' and '*X*' stand for the considered experiment and variable:

$$\mathrm{RevR}_{\mathrm{exp}}(X)_{\mathrm{PI},4\times\mathrm{CO2}} = \frac{X_{\mathrm{exp}} - X_{\mathrm{abrupt}\,4\times\mathrm{CO2}}}{X_{\mathrm{piControl}} - X_{\mathrm{abrupt}\,4\times\mathrm{CO2}}} \quad (1)$$

As can be seen from equation (1), the value of $\mathrm{RevR}_{\mathrm{exp}}(X)_{\mathrm{PI},4\times\mathrm{CO2}}$ at each location indicates the ratio of the abrupt 4×CO_2 response that can be counteracted with a given climate engineering scheme. Negative values indicate changes that lead to a further departure from the piControl climate. Values of $\mathrm{RevR}_{\mathrm{exp}}(X)_{\mathrm{PI},4\times\mathrm{CO2}}$ that are larger than 1 indicate regional overshoot, that is, an excessive response leading to a change beyond the reference piControl climate (for example excessive cooling, in the case of temperature). The reversal ratio is expected to change depending on the level of forcing[25]. The net effect would be much larger in percentage terms for low-emissions scenarios compared with responses under 4 × CO_2 concentrations.

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