Preferential cooling of hot extremes from cropland albedo management

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Changes in agricultural practices are considered a possible option to mitigate climate change. In particular, reducing or suppressing tillage (no-till) may have the potential to sequester carbon in soils, which could help slow global warming. On the other hand, such practices also have a direct effect on regional climate by altering the physical properties of the land surface. These biogeophysical effects, however, are still poorly known. Here we show that no-till management increases the surface albedo of croplands in summer and that the resulting cooling effect is amplified during hot extremes, thus attenuating peak temperatures reached during heat waves. Using a regional climate model accounting for the observed effects of no-till farming on surface albedo, as well as possible reductions in soil evaporation, we investigate the potential consequences of a full conversion to no-till agriculture in Europe. We find that the summer cooling from cropland albedo increase is strongly amplified during hot summer days, when surface albedo has more impact on the Earth's radiative balance due to clear-sky conditions. The reduced evaporation associated with the crop residue cover tends to counteract the albedo-induced cooling, but during hot days the albedo effect is the dominating factor. For heatwave summer days the local cooling effect gained from no-till practice is of the order of 2 °C. The identified asymmetric impact of surface albedo change on summer temperature opens new avenues for climate-engineering measures targeting high-impact events rather than mean climate properties.

As the atmospheric concentrations of CO_2 and other greenhouse gases (GHG) are continuing to rise (1), part of the projected global warming within the next decades is unavoidable, even if measures are taken to curb anthropogenic GHG emissions (2). In this context, climate-engineering techniques aiming at alleviating climate change impacts by intentionally manipulating the climate system are being increasingly debated (3). Among these techniques, changes to agricultural systems represent one set of options that could provide climate benefits through either biogeochemical (4) or biogeophysical (5) effects.

Modifying surface albedo through crop residue management may provide a cooling influence on climate. Indeed, systems retaining crop residues at the surface such as in no-till agriculture tend to increase surface albedo compared with conventional tilled systems (6), thus reducing the solar energy absorbed by the surface. Previous studies, however, have focused exclusively on the potential impact on the mean climate (7), whereas the influence of this practice on temperature extremes has never to our knowledge been explored. Moreover, crop residue management may also influence climate conditions through changes in evapotranspiration (6), and this effect to our knowledge has so far never been considered.

The adoption of no-till management is highly variable around the world. Although no-till systems are widespread in North and South America, they represent only a small portion of the overall cropland area in Europe (*SI Text*). However, with almost 30% of cropland relative to total land area, Europe is one of the most densely cultivated regions in the world (8), implying that no-till practices could be extensively deployed in the future. We use a Regional Climate Model (RCM), supported by observational evidence on the effect of no-till management on surface albedo, to quantify the possible impact of a conversion from conventional to no-till agriculture on the European climate. In the analyses, we focus on climate extremes beyond changes in mean climate conditions. Indeed, changes in climate extremes are more relevant for impacts at the regional scales (9).

Results and Discussion

Albedo Observations. Surface albedo measurements at an experimental site in southern France (*Materials and Methods*) indicate an albedo increase of about 0.1 when comparing no-till management to conventional tillage (Fig. 1). This increase is observed in summer directly after the harvest of the winter wheat and is due to the higher reflectivity of the retained crop residues compared with that of the tilled soil. Fig. 1 also shows rapid drops in albedo on several occasions which are due to rainfall events. One rainfall event caused the decay in albedo in 2004 around day 40, which may indicate a possible reduction of the no-till albedo effect with time under wet conditions. That said, during hot extremes, which is the focus of this study, conditions are expected to remain mainly dry (10). It is also important to note that the 0.1 difference we observed is likely not the upper bound of the no-till effect. The bare soil albedo in Fig. 1 is around 0.2, which is a relatively high albedo for an agricultural soil (due to the relatively high loam/low organic matter content in this soil). Previously reported in situ (11–13) and satellite (14, 15) measurements suggest that the albedo of brown agricultural soils can be lower than 0.1, whereas soils covered with stubble can have albedos largely above 0.3, implying albedo differences

Significance

The projected increase in warm extremes associated with climate change is a major concern for society and represents a threat to humans and ecosystems. This study shows that heat wave impacts could be attenuated locally by increasing surface albedo through crop residue management (no-till farming). This is due to an identified asymmetric impact of surface albedo change on summer temperature distribution resulting in a much stronger influence on hot extremes than on mean temperatures. This finding has important implications for the development of sustainable land management strategies and for the design of climate-engineering measures acting upon high-impact climate extremes.

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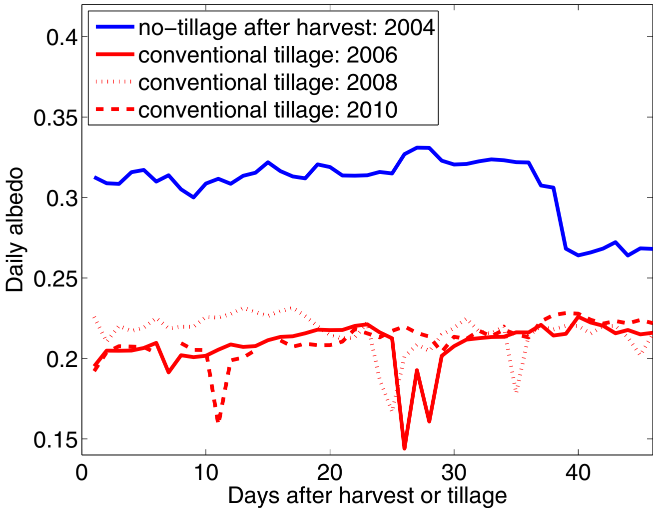

Fig. 1. Time series of albedo measurements contrasting no-till and conventional management. The measurements are taken in summer shortly after harvest of a winter wheat field in Avignon (France). Conventional management was applied in 2006, 2008, and 2010. For these years the soil was tilled shortly after harvest, and the *x* axis represents the number of days since tillage (occurring around July 20). In 2004, wheat residues were retained at the ground after harvest, and no tillage was applied (no-till management). For this year, the *x* axis indicates the number of days after harvest (on June 26).

over 0.2. To summarize, the actual albedo difference depends on various factors including soil darkness, the amount/reflectivity of stubble, and the soil/stubble wetness. A 0.1 albedo difference can be seen as a representative order of magnitude for the no-till effect, whereas the actual difference at a given location may be lower (e.g., effect of rain) or larger (e.g., in the case of dark soils). Importantly, an overall effect of the order of 0.1 implies that the influence of no-till management on surface albedo is substantially larger than the effect that may be obtained through leaf albedo biogeoengineering techniques (5).

Model Experiments. We use the Consortium for Small-scale Modeling–Climate Limited-area Modeling (COSMO-CLM^2) RCM (*Materials and Methods*) to assess the potential impact of no-till farming over Europe. The control experiment (CTL) has a horizontal resolution of ∼50 km and is run over the period 1979–2009 using reanalysis data as boundary conditions. The same setup is used in experiment NOTILL, except that both surface albedo and soil resistance are modified to account for the effect of no-till management. More specifically, surface albedo is increased by 0.1 over croplands based on the observational evidence discussed above. The effect on evaporation is included by increasing soil resistance to empirically represent the additional resistance to soil evaporation associated with the crop residue mulch. A fourfold increase was chosen to obtain an increase in soil water content of the order of 20% (between 0 and 60 cm), which is the effect that has been observed when comparing no-till with conventional management (16).

Both these modifications are applied only from July to October. This assumes that harvest occurs at the beginning of the summer as is the case for winter crops, leaving the soil covered by a residue mulch during summer. This situation is representative of Europe where the two major crops are wheat and barley (17), and where winter varieties are usually preferred because they tend to have higher yields under European climate conditions. The modifications are applied to all cropland areas (Fig. 2*A*), simulation NOTILL thus representing an idealized scenario of a full conversion to no-till management in Europe. We note, however, that the local temperature changes investigated here are largely driven by local land management changes rather than large-scale climate feedbacks (*SI Text*).

Two additional simulations are also performed to isolate the respective role of surface albedo versus evaporation. In these simulations, the modifications to surface albedo (ALB) and soil resistance (EVA) are applied separately.

Asymmetry in the Temperature Response and the Role of Albedo and Evaporation Changes. The conversion to no-till management leads to a pronounced cooling of the hottest summer days, locally of the order of 2 °C or more (Fig. 2*B*). In contrast, the effect on mean summer temperature remains largely below 1 °C of cooling or warming over most regions (Fig. S1). The relatively modest effect on mean temperatures thus hides a much stronger impact on extreme temperatures, which relates to a highly asymmetric response of temperature distributions to the applied modifications in albedo and soil resistance (Fig. 3). Because of the contrasted mean temperature response between northern and southern Europe (Fig. S1), these two regions are considered separately for the analysis.

The temperature response to albedo change alone (Fig. 3 *A* and *B*) is strongly asymmetric, although the change in albedo itself does not vary across the temperature distribution. This asymmetry is due to the amplification of the albedo-induced forcing under clear-sky conditions. Clear-sky conditions, and thus higher incoming solar radiation, prevail during hot summer days, implying that a larger amount of solar radiation is reflected back compared with normal days for a given increase in surface albedo (Fig. S2). In other words, an increase in surface albedo is more efficient at removing the heat away from the surface under

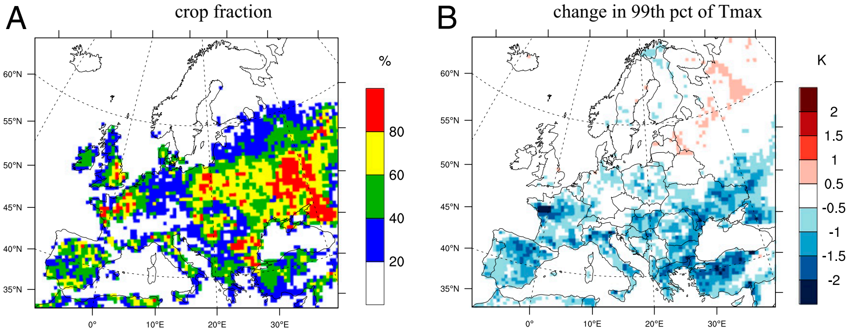

Fig. 2. Cropland distribution prescribed in the model experiments (*A*). Change (NOTILL − CTL) in the 99th percentile of daily maximum temperature for summer (July–August) (*B*).

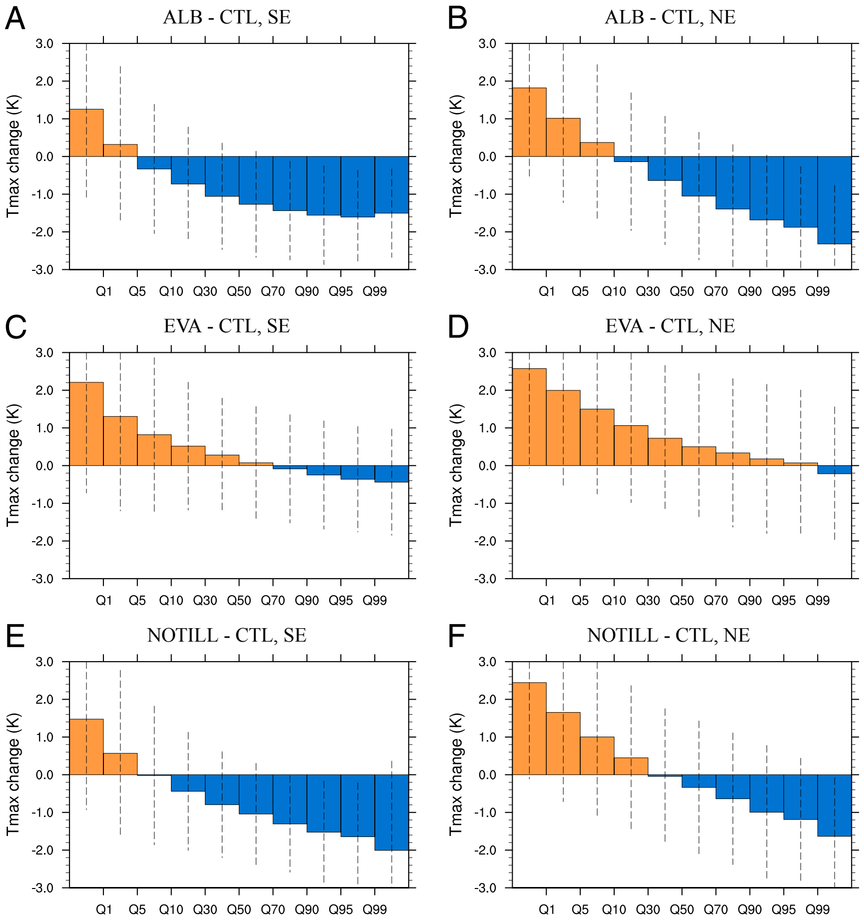

Fig. 3. Change in daily maximum temperature for experiments ALB (*A* and *B*), EVA (*C* and *D*), and NOTILL (*E* and *F*) (in reference to experiment CTL) for different quantiles of the daily maximum temperature distribution. Differences are calculated at each grid point with more than 60% of cropland and for each summer day (within July–August) over the period 1986–2009. Differences are then averaged for each quantile of daily maximum temperature defined based on experiment CTL. The dashed bars represent the SD calculated across all days and grid points. SE, southern Europe (below 45°N); NE, northern Europe (Above 45°N).

extreme warm conditions. A negative cloud feedback mechanism causes a warming effect for the cold tail of the distribution. The albedo increase induces a decrease in turbulent fluxes, thus limiting convection and cloud formation in the model. The reduction in cloud cover then increases net shortwave radiation at the surface (Fig. S2), which counteracts the surface albedo increase. This mechanism, however, is ineffective during warm days, because cloud cover is already low during these days.

The effect of evaporation is also asymmetric (Fig. 3 *C* and *D*). Overall, the increased soil resistance owing to the crop residue cover reduces evapotranspiration rates (Fig. S3) and tends to warm the surface. This effect is amplified for the cold tail of the distribution because of a decrease in cloud cover and associated increase in the amount of absorbed solar radiation at the surface (Fig. S2). For the warmest days, however, there is no substantial change in temperature. Indeed, during these days the larger soil water content under no-till conditions combined with the high vapor pressure deficit counterbalances the increased soil resistance. This mechanism tends to dampen, or even reverse, the initial decrease in evapotranspiration (Fig. S3). This is particularly the case for southern Europe where evapotranspiration is strongly constrained by soil moisture availability (18).

Overall, it appears that the albedo-induced cooling effect is the dominant factor during heatwave conditions. This explains the pronounced cooling found during heat waves when combining the two effects in simulation NOTILL (Fig. 3 *E* and *F*). For the hottest summer days (above the 99th percentile), the cooling effect is of the order of 2 °C for southern Europe and 1.6 °C for northern Europe.

Implication for the 2003 Heat Wave in France. To illustrate the potential impact of no-till management in the context of a specific heat wave, we analyze the temperature evolution over France during the summer 2003 heat wave (Fig. 4), one of the most severe recent heat waves in Europe (19). Simulation NOTILL suggests that the peak temperature over cropland areas would have been substantially mitigated under no-till management. During the peak of the heat wave in August, the daily maximum temperature was 9.9 °C above the 1986–2009 climatology according to a gridded observational dataset for temperature (20) (taking an average over 10 d between the fifth and 14th of August). This figure is well reproduced by the model, with an anomaly of 10.2 °C in the CTL simulation. In simulation NOTILL, the anomaly is only of 8.4 °C owing to the effect of no-till management, which represents a 2 °C reduction of the heatwave anomaly over this 10-d period. Fig. 4 also shows that the albedo increase is the dominant factor, the evaporation effect having a relatively minor role during this specific event.

Conclusion

Through the asymmetric impact of albedo change on summer temperature distribution, crop residue management may provide

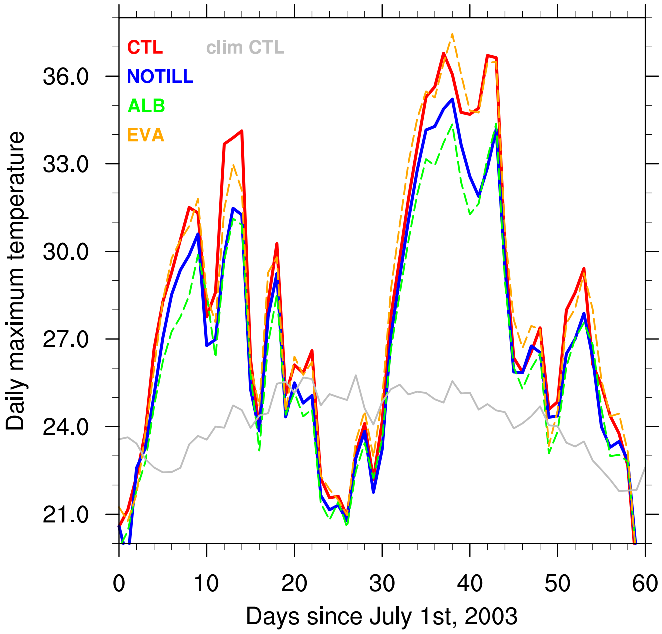

Fig. 4. Effect of no-till management for the 2003 heat wave. Time series of daily maximum temperature during the summer 2003 heat wave averaged over France (44–50°N; −5–5°E), considering only grid cells with more than 60% of cropland.

a promising way to mitigate the local impact of heat waves. This method is expected to be mostly effective for midlatitude crops harvested around July and leaving the soil bare during the months of the year subject to heat waves. This has important implications because warm extremes have a disproportionately large impact on humans and ecosystems and are expected to become more frequent and severe in the future (9). Alleviating the effect of heat waves by 1 or 2 °C can potentially translate into large differences in terms of impacts on humans and ecosystems, because these impacts may evolve nonlinearly with temperature and present threshold effects (9, 21, 22). More generally, all measures aiming at increasing the albedo of the surface (23, 24) may provide a way to act upon warm extremes locally. Whereas current geoengineering proposals usually target a global climate stabilization, we propose to also consider measures modifying the distribution of temperatures, due to its importance for society and ecosystems.

While our study illustrates the potential benefits of no-till farming at the regional scale, in particular in the context of heat waves, a wider adoption of this practice can be justified only if all possible environmental consequences are carefully considered. In particular, possible impacts on the global climate arising from changes in GHG concentrations need to be considered. Although this question has been studied for many years (4, 25), more research is still needed to better understand the biogeochemical effect of no-till management under various soil types, climates, and agricultural conditions (*SI Text*). Future research should also consider possible impacts on large-scale atmospheric circulation and associated changes in precipitation patterns that may occur if no-till farming were to be deployed over large areas.

Materials and Methods

Albedo Observations. The cropland site Avignon (FRAvi) is situated in a periurban area in Provence, southeast France (43.92°N, 4.88°E, 32 m asl). The mean temperature and annual precipitation are about 14 °C and 687 mm, respectively. The land has been cultivated for several decades. During the period from 2001 to 2010, five different types of crops were cultivated: winter wheat (durum wheat), corn, sunflower, peas, and sorghum. Here, we only considered winter wheat and its related tillage management activities. Durum wheat was sown on 7 December 2003, 27 October 2005, 13 November 2007, and 19 November 2009 with different cultivars (Artimon, Acalou, Dakter and Dakter, respectively). These cultivars were harvested on 26 June 2004, 26 June 2006, 1 July 2008, and 13 July 2010, respectively. A first tillage was done shortly after harvest in 2006 (20 July), 2008 (18 July), and 2010 (21 July). In 2004, the first tillage was done more than 2 mo after harvest (2 September). In all cases, tillage depth was 10–15 cm with 0.7–1.2 kg/m^2 residuals buried. The influence of no-till management on summer surface albedo can be assessed by comparing the albedo after harvest in 2004 (no tillage until September) and after tillage in 2006, 2008, and 2010 (conventional tillage). It should be noted that various factors (e.g., type of soil, surface soil moisture, amount of stubble or straw remaining on the ground) may affect the magnitude of the no-till albedo effect estimated from this comparison.

Albedo was calculated as the ratio of reflected to incoming solar radiation measured by two pyranometers. A CM3 pyranometer was used for measuring reflected radiation as part of a CNR1 four-component net radiometer (from Kipp & Zonen) set at a height of 2 m over the crop. It measured radiation over the spectral range 305–2,800 nm. In 2004 and 2006, incident radiation was measured with a PSP pyranometer (The Eppley Laboratory, Inc.) and in 2008 and 2010 with a CMP21 pyranometer (Kipp & Zonen), both measuring in the 285–2,800-nm spectral range. All pyranometers were calibrated by comparison with reference radiation sensors linked to the radiation reference at the World Radiation Center at Davos (Switzerland) through Meteo France calibration facilities in Carpentras (France). Description of the instruments can be found in ref. 26 and at the manufacturer websites. The measurements were made every second and averaged on a half-hourly basis before deriving the daily averages used in this study.

Model Description. The simulations are performed with COSMO-CLM^2 (27, 28), which couples the COSMO-CLM Regional Climate Model version 4.8 and the Community Land Model version 3.5 (CLM3.5). A more detailed description of COSMO-CLM^2 and its evaluation for Europe is provided in earlier studies (27, 28).

COSMO-CLM is a nonhydrostatic limited-area atmospheric model jointly used by the Consortium for Small-scale Modeling (COSMO) and the Climate Limited-area Modeling Community (CLM-Community). The model includes a second-order leapfrog scheme for the time integration. Vertical turbulent mixing is parameterized according to a level 2.5 closure using Turbulent Kinetic Energy as a prognostic variable (29). For moist convection, the mass flux scheme of ref. 30 is used. Large-scale precipitation is parameterized with a four-category one-moment cloud-ice scheme including cloud and rain water, snow, and ice. Radiative fluxes within the atmosphere are calculated based on a δ-two-stream radiative transfer scheme, using three spectral intervals in the solar part and five spectral intervals in the thermal part of the spectrum (31).

CLM3.5 is a state of the art land surface model representing the hydrological, biogeophysical, and biogeochemical processes determining the exchanges of radiation, heat, water, and carbon between the land and the atmosphere (32). CLM3.5 represents vegetation diversity based on 15 different Plant Functional Types (PFTs). Several PFTs can coexist in a given grid cell, and the energy balance and surface fluxes are calculated at the PFT level before being aggregated at the grid-scale level based on the proportion of PFTs in the grid cell. In this study, CLM3.5 is used without carbon/nitrogen dynamics and ecosystem dynamics. There is no distinction in the model between different crop types which are all encompassed within one generic crop PFT. The current distribution of cropland is derived from ref. 33, and the phenological cycle of Leaf Area Index (LAI) for crops (and other PFTs) is prescribed based on satellite data (34). A limitation of this satellite data set is that it does not represent well the crop phenology (e.g., harvest events are not captured, and there is no clear LAI minimum after harvest in summer). This leads to potential inconsistencies in our experiments assuming summer harvest. However, in our approach we prescribe the no-till forcing (change in albedo or soil resistance) based on observational evidence and independently of the initial soil and vegetation state. We cannot exclude that using a more realistic crop phenology would affect the results, but the effect is likely to be minimal because our approach is conservative in terms of the applied no-till forcing.

All performed simulations use a horizontal resolution of ~50 km with 32 atmospheric levels in the vertical and a time step of 240 s. The simulations cover the period from 1979 to 2009. The European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis (ERA-Interim) (35) is used as lateral boundary conditions. The first 6 y are used as spin-up time, and only the following 25 y (1985–2009) are analyzed in this study.

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