

Land management and land-cover change have impacts of similar magnitude on surface temperature

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Anthropogenic changes to land cover (LCC) remain common, but continuing land scarcity promotes the widespread intensification of land management changes (LMC) to better satisfy societal demand for food, fibre, fuel and shelter¹. The biophysical effects of LCC on surface climate are largely understood^{2–5}, particularly for the boreal⁶ and tropical zones⁷, but fewer studies have investigated the biophysical consequences of LMC; that is, anthropogenic modification without a change in land cover type. Harmonized analysis of ground measurements and remote sensing observations of both LCC and LMC revealed that, in the temperate zone, potential surface cooling from increased albedo is typically offset by warming from decreased sensible heat fluxes, with the net effect being a warming of the surface. Temperature changes from LMC and LCC were of the same magnitude, and averaged 2 K at the vegetation surface and were estimated at 1.7 K in the planetary boundary layer. Given the spatial extent of land management (42–58% of the land surface) this calls for increasing the efforts to integrate land management in Earth System Science to better take into account the human impact on the climate⁸.

Human activities have directly affected around 100 M km² of the ice-free land surface leaving, as of today, less than 30% of the land surface largely untouched (Supplementary Table 1). Of this, between 23 and 38 M km² (18–29% of the land surface) has been deliberately converted, mainly by deforestation, for agriculture, infrastructure and urban use. These land cover changes (LCCs) have driven changes in regional and global climate through changes in biogeochemical processes (for example, C and N cycling) and biophysical processes (for example, surface albedo, surface roughness, and evapotranspiration)^{1,9}. A more complete assessment of human contributions to climate change will require the climatic influence of land-surface conditions to be factored into climate-change mitigation strategies⁵.

To date, many studies have investigated the climate effects of changes in land cover; but, with the exception of irrigation effects^{10,11}, have rarely looked into the climate impacts of land management changes (LMC) that occur within the same land cover type and do not result in a LCC (for precise definitions see Supplementary Section 1). However, 55–75 M km² (42–58% of the land surface) have not experienced LCC but are managed to satisfy human demands (Supplementary Table 1). Within land cover types, LMC varies in fertilization and pesticide use, harvest rate, and cropping practices, to mention only a few. For example, 19 M km² of forest, representing 15% of global ice-free land, is subjected to diverse management strategies for wood production and other services that result in changes in albedo, surface roughness, C sequestration, other trace gas fluxes, and sensible and latent heat flux, without changing land cover type^{12,13}.

Owing to the predicted increases in global population and affluence as well as the increasing importance of bioenergy¹⁴, demand for land-based food and fibre will surge during the coming decades. Expansion of active management into relatively untouched regions may satisfy part of the growing demand. However, owing to the prohibitively high carbon costs of converting pristine forests to cultivated land¹⁵, and the looming scarcity of unused but productive land¹⁶, intensification will play a decisive role in forging strategies for global sustainability^{17,18} and enhance the role that LMC plays in human economies and, importantly, in the climate system.

We tested the hypothesis that LCC and LMC have biophysical effects of similar magnitude to surface and atmospheric climate per unit land area. To address the hypothesis, we selected from the FLUXNET database 22 temperate and two boreal Eurasian and American multi-year eddy covariance research sites with high-quality data (Supplementary Fig. 1 and Tables 2 and 3). All sites were paired and 33 out of 351 possible pairs that represented either LCC or LMC were selected for study based on similarity in incoming radiation and energy budget closure (Supplementary Section 2.2.4). Nine of these pairs resulted from a formal paired ecosystem experimental set-up.

We found that LCC and LMC had similar impacts on site-level mean annual radiometric surface temperature (Fig. 1a,b). Mean and upper limit temperature responses to LCC and LMC were similar (Fig. 1b) and around 2 K at the site-level, with a maximum of 6 K. Because LCC was used as a benchmark for LMC and our findings for LCC are in agreement with previous observations regarding LCC in the tropics^{3,7}, Mediterranean¹⁹ and the boreal zone⁶ our study lends support to the hypothesis that LMC other than irrigation^{10,11} also has substantial biophysical impacts on the land surface.

No single accepted approach exists to quantify intensities of LCC and LMC. Although intensity is often thought of in terms of input—for example, fertilizer, irrigation or fossil fuels—it may also be expressed in terms of its output—for example, change in yield or, as applied in this study, biophysical metrics such as the change in surface albedo. Following this definition, more intense LCC or LMC are those land uses that result in larger albedo changes, which were observed to be significantly and positively correlated with larger changes in radiometric surface temperature (Fig. 2a; Pearson correlation, $p < 0.05$).

The site-level analysis was extended by eight time series of MODIS satellite observations (MOD11A2 from 2009 to 2011) of 2,500 km² areas intersected by administrative borders with similar climate but different land cover and land management types (Supplementary Table 4). Remote sensing products do not distinguish managed from unmanaged vegetation. Test-case selection thus requires ground information; therefore, only a limited number of areas were selected for study. The use of remote sensing data confirmed

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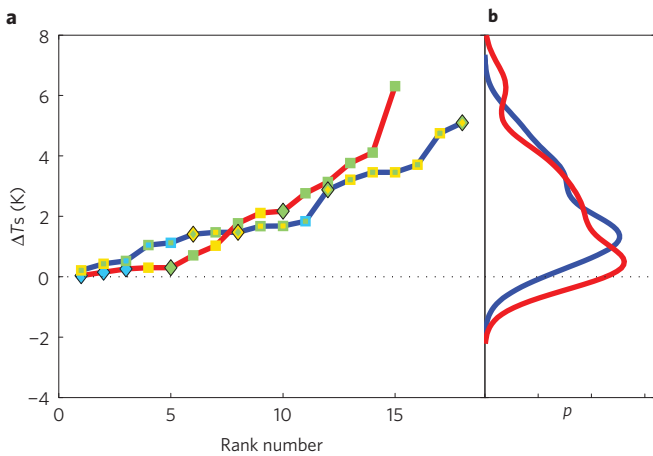


Figure 1 | Effects of land cover change and land management on surface temperature. **a**, Change in radiometric surface temperature (T_s in K) for paired eddy covariance measurement sites (Supplementary Table 3) due to biophysical effects of land cover change (blue) or land management (red), ranked by magnitude. The edge of the marker shows the initial land cover, whereas the interior shows the final land cover, with green for forest, yellow for grassland and blue for cropland. Formal experimental site pairs are marked with a diamond and all other pairs are marked with a square. **b**, Probability density estimates for the surface temperature effects of land cover change (blue) and land management change (red). Radiometric temperature was assumed to have a 0.75 K uncertainty, which explains the negative values for T_s .

the relationship between albedo and temperature and established its validity at larger spatial scales (Fig. 2b; Pearson correlation, $p < 0.01$). Despite its robustness across spatial scales and ecosystems, the observation that an increase in albedo is related to an increase in surface temperature may seem paradoxical if less energy is available for surface heating following an increase in albedo.

A literature search (Supplementary Table 5) showed that from more than 30 studies reporting biophysical effects of LMC all, except one²⁰, did not consider all of the major components of the energy budget. We, therefore, extended an energy balance decomposition approach^{12,21} and analysed the change in surface temperature due to changes in albedo, ground heat, and sensible and latent heat while

accounting for the differences in incoming radiation and imbalances in the energy budget. Despite the sites being well-watered, their Bowen ratio indicates that the sensible heat flux is the dominant mechanism for terrestrial surface cooling (for site-level data on the Budyko index and Bowen ratio see Supplementary Table 2). Across all paired observations, the potential for cooling the surface due to an increase in albedo (Fig. 2a) was outweighed by the potential for warming due to decreased fluxes of sensible heat (Fig. 3a; Pearson correlation, $p < 0.01$) but not latent heat (Fig. 3b; $p = 0.88$). Lack of correlation between the imbalance term and the major components of the energy budget (Supplementary Fig. 3 and Section 2.2.1) strengthens our confidence that the observed relationships are not artefacts. For the sites under study, sensible heat and changes in sensible heat thus seem to be key drivers of the surface temperature and its changes following LCC or LMC.

Surface roughness information for the area encompassing the flux footprint was missing for half of the sites. Alternatively, a proxy for canopy structure, defined as the logarithm of vegetation height divided by leaf area index (LAI; ref. 22), was used. A previously reported relationship between canopy structure and albedo⁶ was present at the study sites (Supplementary Fig. 4a). Furthermore, larger and more structured canopies transfer more momentum from the planetary boundary layer (PBL) to the leaf surface than smaller canopies³. A negative correlation, but no causation, between albedo and momentum flux is thus expected because of shared common drivers—namely, height, LAI, and crown dimensions. The observed decoupling between sensible (Supplementary Fig. 4b, $p < 0.01$) and latent heat flux (Supplementary Fig. 4c, $p = 0.16$) emphasizes the important role of stomatal conductance to surface–atmosphere transport⁶. Although the sites studied here are dominated by forest and grasslands, croplands did not seem to be outliers in any of our analyses.

Whereas the surface temperature response to LCC has long since been understood for boreal (that is, decreases in surface albedo and increases in surface temperature following afforestation, due to snow-masking^{23,24}) and tropical ecosystems (that is, decreases in evapotranspiration following deforestation tend to outweigh increases in albedo on surface temperature²⁵), our study reveals that changes in sensible heat flux outweigh changes in albedo and underlie surface temperature changes in the temperate zone following both LCC and LMC. To the best of our knowledge, our study is the first data analysis showing that the same mechanism

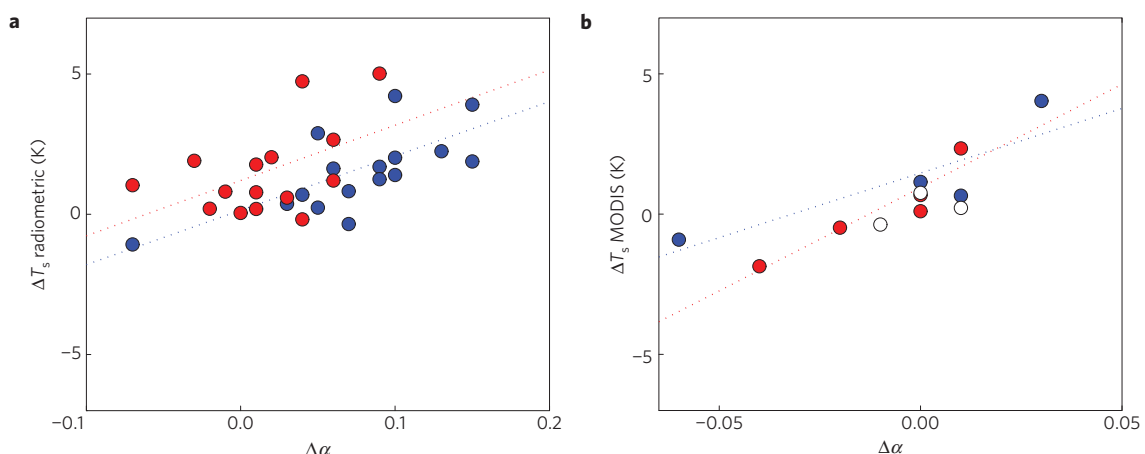


Figure 2 | The relationship between changes in albedo ($\Delta\alpha$) and changes in surface temperature (ΔT_s) following land cover conversions (blue) and land management change (red). **a**, The relationship between changes in albedo and radiometric surface temperature from paired ecosystems in the databases of eddy covariance research sites ($p < 0.05$). **b**, MODIS-derived surface temperature (T_s) and albedo (mean of visible 300–700 nm and near infrared 700–1100 nm) between both sides of an administrative border ($p < 0.01$). White dots show changes observed at homogeneous landscapes (Supplementary Table 4).

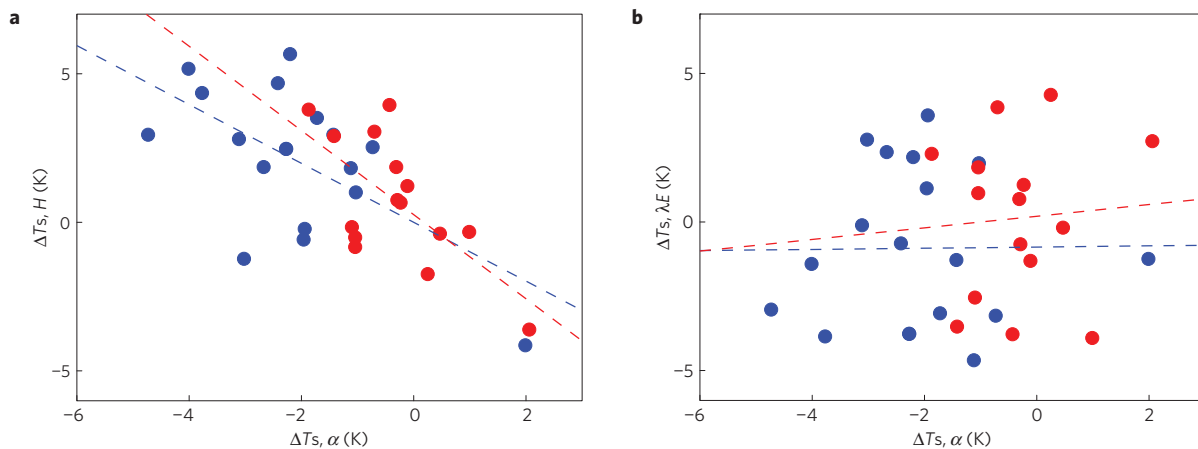


Figure 3 | Biophysical effects of land cover change (blue) or land management (red). **a**, Relationship between the change in radiometric surface temperature due to a change in albedo and the contribution of sensible heat flux (H) to the change in T_s ($p < 0.01$). **b**, Relationship between the change in radiometric surface temperature due to a change in albedo and the contribution of latent heat flux (λE) to the change in T_s ($p = 0.88$).

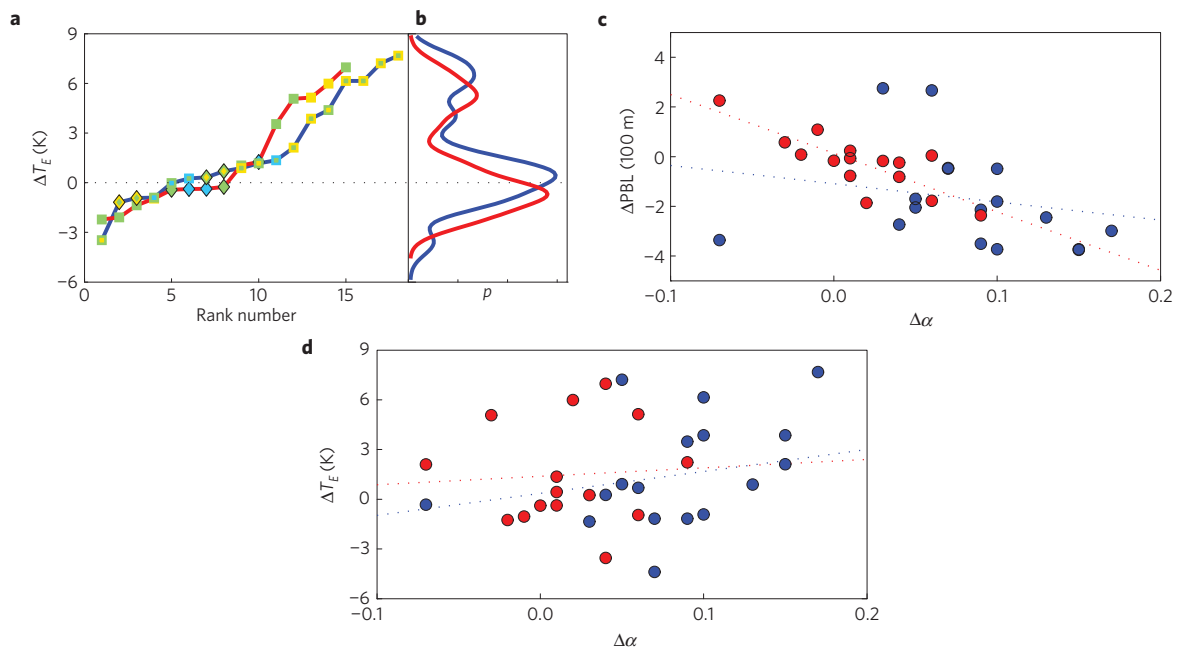


Figure 4 | Effects of land cover change and land management on the height and equivalent temperature of the planetary boundary layer. **a**, Change in equivalent temperature (T_E) for paired eddy covariance measurement sites (Supplementary Table 3) due to the biophysical effects of changes in land cover (blue) or land management (red), ranked by magnitude. The edge of the marker shows the initial land cover whereas the interior shows the final land cover, with green for forest, yellow for grassland and blue for cropland. Formal experimental site pairs are marked with a diamond and all other pairs are marked with a square. **b**, Probability density estimates for the equivalent temperature (T_E) effects of land cover change (blue) and land management (red). Equivalent temperature was assumed to have a 0.75 K uncertainty, which explains its negative values. **c**, Relationship between the change in albedo and the estimated change in the height of the planetary boundary layer by applying a 1D boundary layer model ($p < 0.01$). **d**, Relationship between the change in albedo and the estimated change in equivalent temperature of the planetary boundary layer by applying a 1D boundary layer model ($p = 0.33$).

controlling surface temperature changes following LCC may control surface temperature changes following LMC in the temperate zone, but improved observations of surface roughness at the site-level and additional controlled experiments are required to confirm our field observations.

Despite surface temperature being a meaningful measure for the temperature experienced by the vegetation cover and all living organisms within²⁶, it fails to capture the effects of LCC and LMC on the climate system. Quantifying the full climate effects of LMC and LCC is out of reach for site-level and remote sensing observations and requires coupled surface-atmosphere models to account for boundary layer dynamics, planetary albedo from clouds

and aerosols, precipitation, and radiative forcing from changes in atmospheric composition through C and N cycling.

However, as a first-order estimate of the climate effect, a 1D-PBL model can be used to calculate the equivalent temperature of the PBL (refs 19,27,28). This approach accounts for the growth of the boundary layer, the differential effect of sensible and latent heat fluxes and the entrainment of colder air from above the PBL, but assumes convective clear sky conditions. Both LCC and LMC were found to increase the equivalent temperature of the PBL by on average 1.7 K (Fig. 4a,b). Although the mean temperature changes suggests a smaller effect on the PBL (Fig. 4a,b) compared to the vegetation surface (Fig. 1a,b), the feedback of the PBL

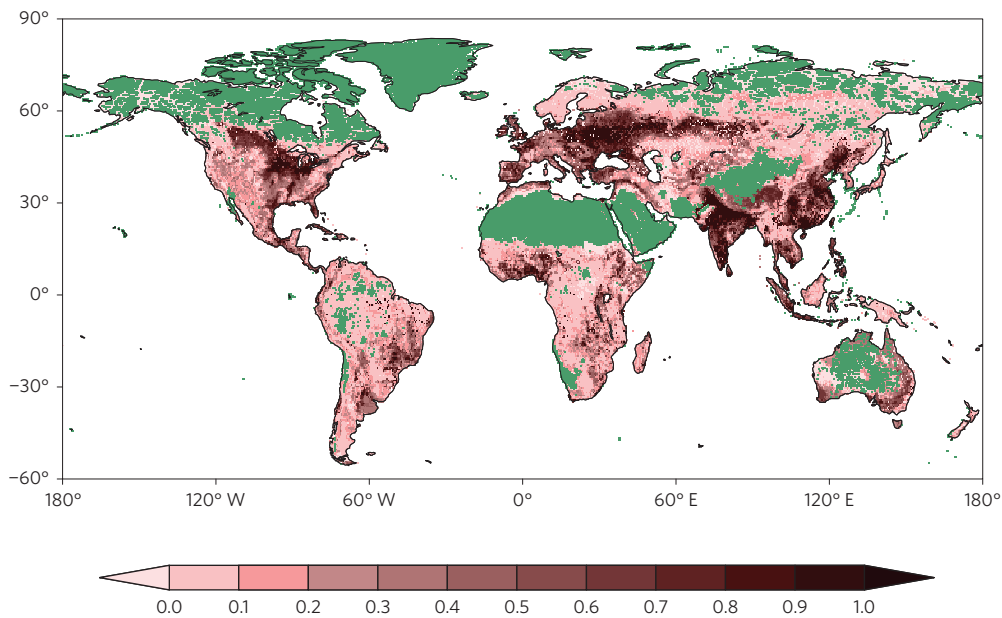


Figure 5 | Spatial extent of land cover change, land management, wilderness and non-productive areas (Supplementary Section 2.3). Wilderness and non-productive areas are shown in green and represent land largely unaltered by humans. The remaining land is used for producing food, fibre and fuels, and for hosting infrastructure. The colour scale represents the fraction of each grid cell for which the original plant cover was converted. Dark colours indicate regions where most of the original plant cover was converted; these regions are the subject of typical land cover change studies. The light colours show areas for which land cover change is low, but which are nevertheless under anthropogenic land management.

model increases the temperature range, both positive and negative. Across site pairs, increases in albedo were found to correlate with decreases in sensible heat flux (Fig. 3a) and thus a decrease in PBL height (Fig. 4b; Pearson correlation, $p < 0.01$). However, the relationship between land use intensity (based on the change in albedo) and change in equivalent temperature in the PBL did not hold (Fig. 4c, $p = 0.33$). Larger ranges and loss of correlation illustrate the complexity of the effects of land use change on atmospheric temperature¹⁹, or the plausibility of the current PBL model, which does not capture any cloud or advective processes²⁸.

Our results demonstrate, however, that the human influence on climate will not be represented adequately over vast areas of the land surface when LMC remains unaccounted for in models (Fig. 5). Similar to recent reconstructions of LCC that enabled historical and contemporary climate effects of LCC to be modelled²⁹, accounting for LMC requires the development of spatially explicit global reconstructions describing the type and intensity of LMC. In conjunction with global reconstructions, the structure of global land surface models needs to be adjusted to incorporate key species and cultivars rather than relying on plant functional types; 3D or effective canopy structure rather than big leaf approximations; and possibly using within-canopy momentum models rather than applying coarse assumptions on the zero plane displacement height. Furthermore, the effects of fertilization, irrigation and grazing on canopy structure, and vegetation and background reflective properties should be accounted for.

The similarity between LCC and LMC sheds new light on the attribution of responsibilities in climate change. Historical LCCs such as in Europe and the USA are penalized less in political negotiations than recent cover changes in Latin America and Southeast Asia. The rationale is given by physical laws, which result in earlier emissions being largely transferred from the atmosphere to the ocean and land carbon pools³⁰. Our results suggest that for a comprehensive assessment of human influences on climate, the effects of LMC have to be taken into account—that is, the climatic effects of recent intensification of LMC without cover change, such as the Green Revolution in Europe, US, China and India. The

large biophysical effects of both LCC and LMC found in this study call for further extending the attribution of climate change from the prevailing greenhouse gas perspective to include biophysical effects⁸. Better understanding the balance between biogeochemical and biophysical effects of LMC on radiative and non-radiative forcing would avoid promoting land management strategies with no guarantee of mitigating climate change.

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Author contributions

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Additional information

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Competing financial interests

The authors declare no competing financial interests.

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