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Importance of background climate in determining impact of land-cover change on regional climate

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Humans have modified the Earth's climate through emissions of greenhouse gases and through land-use and land-cover change (LULCC)[1]. Increasing concentrations of greenhouse gases in the atmosphere warm the mid-latitudes more than the tropics, in part owing to a reduced snow–albedo feedback as snow cover decreases[2]. Higher concentration of carbon dioxide also increases precipitation in many regions[1], as a result of an intensification of the hydrological cycle[2]. The biophysical effects of LULCC since pre-industrial times have probably cooled temperate and boreal regions and warmed some tropical regions[3]. Here we use a climate model to show that how snow and rainfall change under increased greenhouse gases dominates how LULCC affects regional temperature. Increased greenhouse-gas-driven changes in snow and rainfall affect the snow–albedo feedback and the supply of water, which in turn limits evaporation. These changes largely control the net impact of LULCC on regional climate. Our results show that capturing whether future biophysical changes due to LULCC warm or cool a specific region therefore requires an accurate simulation of changes in snow cover and rainfall geographically coincident with regions of LULCC. This is a challenge to current climate models, but also provides potential for further improving detection and attribution methods.

Although many studies of the global and regional biophysical impacts of LULCC have been conducted[4–8], the impact of LULCC on regional-scale climate remains quite uncertain[6,7]. Most probably, LULCC in the form of deforestation acts to cool mid- and high latitudes[3], particularly in the winter and spring, and to warm the tropics and sub-tropics. The biophysical impact of LULCC is realized through three mechanisms: (1) an increased albedo and hence a reduction in net radiation[9] (crops are commonly more reflective than forests); (2) an amplification of the positive snow–albedo feedback (forests mask snow on the ground more effectively than crops and pasture)[10]; and (3) a change in how net radiation is partitioned between latent heat and sensible heat fluxes (crops and pasture have less capacity to sustain high latent heat fluxes, compared with forests, when evaporative demand is high). LULCC in mid- and high latitudes tends to cool because mechanisms (1) and (2) dominate in winter and spring owing to snow. In summer, in the absence of snow, mechanism (3) can be significant if moisture limits evaporation. In the tropics, LULCC tends to be associated with warming and drying[3] because mechanism (3) dominates and sensible heat fluxes increase, warming the atmosphere. The relative dominance of these mechanisms depends on the amount of snow and the amount and seasonality of precipitation. Less snow in a warmer world would weaken the positive snow–albedo feedback, reduce the influence of mechanism (2) and partially negate cooling from LULCC at high latitudes. In all regions, mechanism (3) can be masked by higher precipitation because this would reduce the likelihood of moisture stress limiting the latent heat flux, tending to minimize increases in sensible heat fluxes.

There is a conflicting signal in these two drivers of climate. LULCC tends to cool mid- and high latitudes and potentially offsets CO_2-induced warming whereas LULCC adds to CO_2-induced warming in the tropics. Our focus here is whether these tendencies are sustained as the seasonal extent of snow decreases and the hydrological cycle intensifies[2] in the future under increased CO_2. Does the regional role of LULCC change significantly under future climate conditions? We use a climate model to examine how the changing climate associated with increased CO_2 affects the biophysical impact of LULCC. The LULCC perturbation represents the expansion of crops and pasture until 2000 (Supplementary Fig. S1). We do not increase the scale of LULCC into the future. We use a state-of-the-art land-surface scheme[11], which has been extensively evaluated[11–13], coupled to an atmospheric model that can be integrated for multiple centuries[14]. We use fixed sea surface temperatures (SSTs) representative of an equilibrated climate at pre-industrial CO_2 concentrations (280 ppmv) and doubled CO_2 concentrations (560 ppmv). Each simulation is conducted from an initial stable state for 300 years, providing a stable climatology for two CO_2 concentrations, each with land cover representative of both a natural and a current state.

We focus on the eastern United States, Eurasia and Asia. Because the impact of LULCC in isolation from other forcings on large-scale climate is becoming better known, we describe the impact of LULCC on climate at $1 \times CO_2$ and $2 \times CO_2$ (see Supplementary Information). We focus on the reasons for a change in the impact of LULCC due to the change in CO_2 in March–April–May (MAM) and June–July–August (JJA). Results for other seasons are in the Supplementary Information.

Figure 1 shows the ratio of the impact of LULCC at $1 \times CO_2$ to the impact at $2 \times CO_2$ (minus one so that no change is represented by zero) on surface air temperature. The seasonal version of this figure is shown in Supplementary Fig. S2, and for precipitation in Supplementary Fig. S3. There is a substantial reduction in the impact of LULCC on surface air temperature over Eurasia, eastern United States and northern Asia in MAM under $2 \times CO_2$ relative to $1 \times CO_2$. This is due to a much smaller change in net radiation under $2 \times CO_2$ due to LULCC (Supplementary Fig. S4), because the warmer temperatures decrease the snow depth (Supplementary

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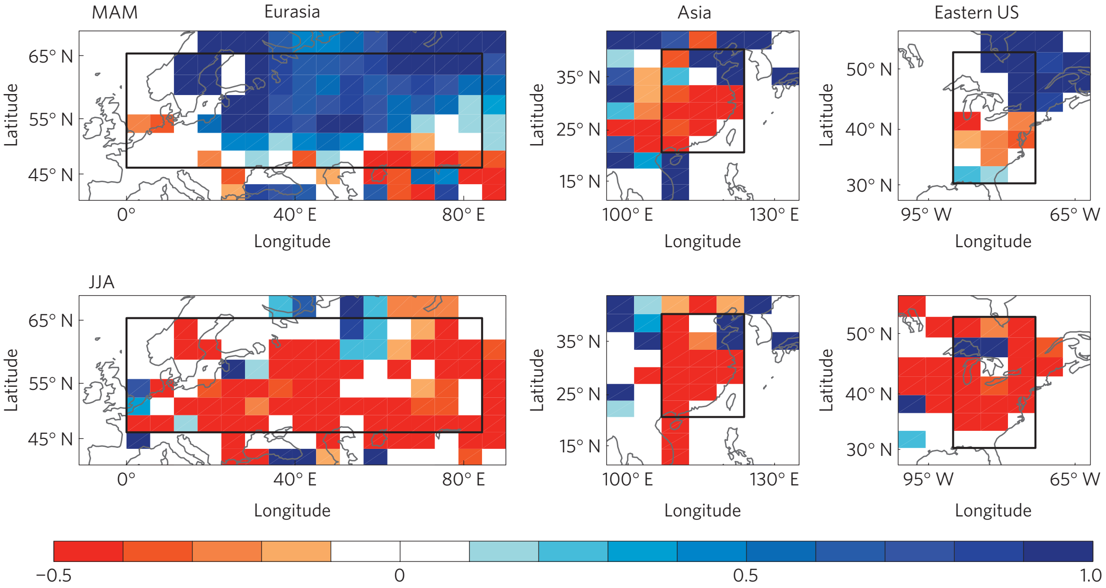

Figure 1 | The change in the impact of LULCC on surface air temperature due to increased CO_2. The ratio of the absolute change in surface air temperature due to LULCC at 1 × CO_2 to the absolute change at 2 × CO_2 for MAM (upper panels) and JJA (lower panels) is shown. Three regions are shown: Eurasia, Asia and the eastern United States. The inlay boxes show the regions used for averaging in Fig. 2. A zero value is where the changes are identical and −0.5 is where the change at 2 × CO_2 is double the impact at 1 × CO_2 (negative values occur owing to the subtraction of one from the ratio to centre 'no change' on zero). Only points that are statistically significant at a 99% confidence level are shown.

Fig. S5) and weaken the positive snow–albedo feedback. LULCC causes cooling across Eurasia of −1.0 °C to −2.0 °C at 1 × CO_2; this is reduced to −0.6 °C to −1.5 °C under 2 × CO_2 (Supplementary Fig. S6). Over the eastern United States, cooling of −0.4 °C to −1.0 °C at 1 × CO_2 is reduced to −0.2 °C to −0.6 °C under 2 × CO_2.

Over Eurasia, in JJA, the impact of LULCC is considerably larger at 2 × CO_2, cooling the region by −0.4 °C to −2.0 °C, compared with very small changes under 1 × CO_2 (Supplementary Fig. S6). Localized cooling over the US East Coast (−0.2 °C to −0.6 °C) increases in geographic scale and intensity at 2 × CO_2 to −0.4 °C to −2.0 °C. These changes are highlighted in Fig. 1. Although the impact of LULCC is larger at 1 × CO_2 over Eurasia and the eastern United States in MAM, it is much larger at 2 × CO_2 in JJA. In contrast, over Asia, warming due to LULCC of up to 2 °C at 1 × CO_2 is replaced by cooling at 2 × CO_2 of −0.6 °C to −1.5 °C. The mechanisms that explain these changes are more varied than for MAM and are explained below.

The relative roles of mechanisms (1), (2) and (3) are regionally and seasonally dependent and change owing to CO_2-induced impacts on climate. Our results therefore show that the impact of LULCC depends on the background regional climate, which is strongly affected by the level of CO_2. Our results show that either the magnitude of the impact of LULCC on temperature (for example in MAM over Eurasia and the eastern United States) or the sign of the impact of LULCC on temperature (for example MAM and JJA over Asia) change as a function of how the background climate changes.

In spring, LULCC has a larger impact on temperature over Eurasia and the eastern United States at 1 × CO_2 due to snow–albedo feedback amplification (Fig. 2). Net radiation is reduced by LULCC by 6.1 W m^{-2} at 1 × CO_2, compared with 4.5 W m^{-2} at 2 × CO_2, over Eurasia, and by 4.5 W m^{-2} at 1 × CO_2, compared with 4.2 W m^{-2} at 2 × CO_2, over the eastern United States. This reduction is due to a CO_2-warming-induced decline in snow depth (Supplementary Fig. S5). Over Eurasia, snow declines from 622 mm to 441 mm linked to warming of 3.5 °C, whereas over the eastern United States snow declines from 391 mm to 218 mm linked to a warming of 2.9 °C (Fig. 2). The lack of significant snow over Asia (Supplementary Fig. S5) explains why LULCC affects net radiation similarly at both levels of CO_2 in this region in MAM. Overall, the change in the net radiation should reduce surface temperature, but the amount of cooling is linked closely to the magnitude of snow depth. Thus, LULCC cools Eurasia by 1.0 °C at 1 × CO_2 but by only 0.6 °C under 2 × CO_2. Similarly, over the eastern United States, cooling of 0.4 °C at 1 × CO_2 is reduced to 0.3 °C under 2 × CO_2.

The mechanisms that explain the summer impact of LULCC are fundamentally different and are dominated by changes in precipitation (Supplementary Fig. S7) caused by the increase in CO_2. Over Eurasia, LULCC has a larger cooling effect at 2 × CO_2 (Fig. 2), which attenuates the warming due to the increased CO_2. This larger cooling is due to a higher latent (Fig. 2) and lower sensible heat flux under 2 × CO_2 despite the change in the nature of the vegetation and the decrease in net radiation (Fig. 2). This is caused by an increase in summer precipitation from 1.3 mm d^{-1} (1 × CO_2) to 2.2 mm d^{-1} (2 × CO_2), and consequently LULCC is imposed in a less moisture-limited environment. Although LULCC in isolation tends to decrease the latent heat flux[3,7], this is counteracted by the CO_2-induced increase in rainfall, which enables a higher latent heat flux and therefore stronger cooling (Fig. 2, Supplementary Figs S7, S8). Over Asia, LULCC causes warming (0.3 °C) at 1 × CO_2. Doubling CO_2 increases precipitation from 4.7 to 4.9 mm d^{-1} (Fig. 2), and again increases moisture availability so that at 2 × CO_2 LULCC is associated with cooling of 0.5 °C. In the eastern United States, LULCC at 1 × CO_2 has little impact on temperature, but at 2 × CO_2 temperatures fall by 0.6 °C. This is again linked to a higher latent heat flux associated with higher precipitation in spring and summer (Supplementary Figs S7 and S8), to higher winter and spring soil moisture levels under 2 × CO_2 and to a longer growing season associated with warmer temperatures.

Overall therefore, for these regions, it is not the land-cover change that dominates the impact of LULCC; it is the hydrometeorological state existing when land cover is changed that is the dominant factor. Our results lead to three key conclusions. First, capturing the impact of LULCC in past and future simulations requires models to simulate, in the correct geographic positions, regional climate changes due to increased CO_2. We conclude

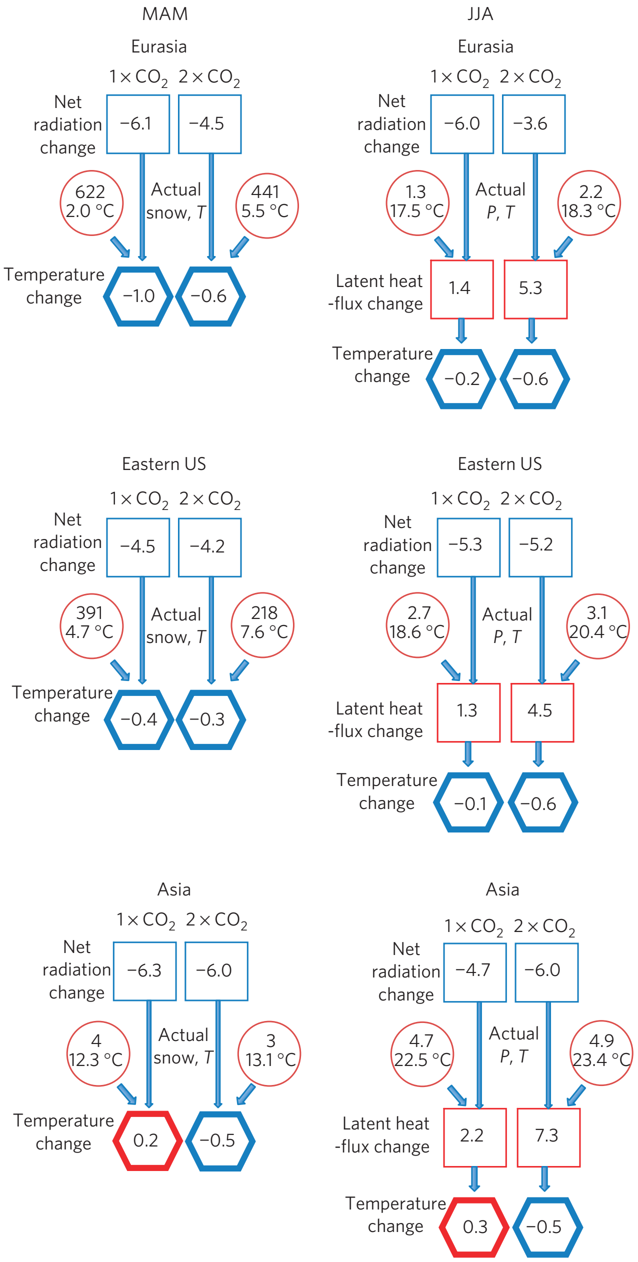

Figure 2 | How LULCC affects key near-surface and surface variables at 1 × CO_2 and 2 × CO_2. LULCC-induced MAM and JJA changes in Eurasia, eastern United States and Asia are shown. Net radiation ($W\,m^{-2}$) and temperature change (°C) are in boxes and the depth of snow (mm of snow) and the actual mean temperatures (°C) at both 1 × CO_2 and 2 × CO_2 for LULCC simulations are in circles. Blue boxes indicate decreases and red boxes indicate increases in each quantity. JJA includes the latent heat-flux change ($W\,m^{-2}$)and the mean climatological precipitation ($mm\,d^{-1}$) for LULCC simulations at both 1 × CO_2 and 2 × CO_2 (circles).

this because our results were strongly affected by how snow and rainfall changed under increased CO_2. Second, the role of LULCC in all regions is intimately linked with the regional-scale hydrometeorology[15]. Soil moisture–evaporation feedbacks are a complex reflection of moisture and energy limitations[15,16] and these must be represented well in climate models to capture the impact of LULCC. Finally, the impact of LULCC on mid-latitudes is intimately linked with snow. Climate models need to capture the amount, seasonality and climate-change-driven changes in snow to capture the changing role of LULCC correctly under increased CO_2.

Many earlier studies have demonstrated significant impacts of LULCC in regions of intensive change and our results demonstrate changes induced by LULCC at both 1 × and 2 × CO_2 of up to 2 °C. Clearly, LULCC needs to be represented in future projections to accurately assess regional changes[5,7]. However, our results highlight a reducing impact of mid-latitude LULCC in the future associated with a reduction in the snow–albedo feedback in a warmer world. This is very unlikely to be affected by any plausible future reforestation strategies, because the warming impact of reforestation seems small when compared with the impact of future increases in CO_2 (ref. 17). This reintroduces the anticipated merits of reforestation in mid-latitudes as a terrestrial CO_2 sink, which was suspected to trigger further warming[10]. If snow is reduced over future pastures and crops, reforesting these regions may warm owing to a reduced albedo, but amplification of this warming due to snow–albedo feedbacks is less likely because this feedback will be less important in a warmer climate. Our results also demonstrate that significant regional rainfall changes due to increasing CO_2 would largely control the impact of LULCC on regional climate, particularly in summer in areas where the latent heat flux is strongly moisture limited.

The significance of the background climate for controlling how a perturbation to the climate is realized has been previously shown in palaeoclimate studies[18] but our results demonstrate that this is true, at regional scales, in future projections in the context of LULCC. This implies that detection and attribution studies[19] must incorporate LULCC, otherwise any amplifying (if moisture is limited) or suppressing (if moisture is not limited) feedbacks associated with LULCC on CO_2-induced warming will be omitted, risking incorrect attribution of observed trends to other climate forcing factors. Further, because forests respond very differently to heatwaves when compared with grasslands[16], and because this response is substantially moderated by moisture availability, LULCC needs to be captured in studies exploring the impacts of CO_2-induced extremes on regional climate. However, the role of LULCC in moderating or amplifying CO_2-induced changes requires that any changes in moisture availability, whether through changes in evaporation or precipitation, are correctly co-located with regions of LULCC. Critically, assessments of the impacts of future LULCC (refs 5,17) require climate models with the capacity to simulate the right CO_2-induced changes in climate over regions of changing land cover. Although global-scale future LULCC is probably small when compared with past changes[5], in regions of strong population growth LULCC is likely to significantly perturb how the surface climate responds to changes in CO_2.

The need to correctly locate changes in rainfall, temperature and snow over regions of intense LULCC presents a significant challenge for climate models. The capacity of climate models to capture the background regional climate depends in part on the horizontal resolution of the model. A rigorous assessment of the relationship between climate model resolution and region simulation skill is lacking. Although finer spatial resolutions may improve global-scale simulations[20], how fine a model needs to be to enable reliable co-location of changes in rainfall and temperature with LULCC is unknown. Most climate models also lack many processes that might affect how LULCC affects precipitation and associated processes (see Supplementary Information). Further, there is emerging evidence that coupled ocean models are required in LULCC experiments, because these amplify the perturbation and enable effects to be captured distant from the perturbation[21]. This suggests that, although the large-scale signal from LULCC on future climates is probably known[5,17], much higher-resolution fully coupled model simulations need to be conducted to build confidence in how LULCC interacts with a changing climate at regional scales. Our use of a coarse resolution model and fixed SSTs probably affects many aspects of our results and we are not suggesting that we have necessarily co-located changes due to

CO_2 with LULCC correctly. However, our main conclusion that changes in rainfall and snow caused by increases in CO_2 dominate how LULCC affects climate, thereby necessitating climate models to correctly locate changes in rainfall and temperature relative to LULCC, is very probably robust.

Methods

The climate model. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) Mk3L climate system model is a relatively low-resolution model developed for studies of climate on centennial to millennial timescales[14]. The atmospheric component has a horizontal resolution of 5.6° by 3.2° and 18 vertical levels. This relatively coarse horizontal resolution enables long simulations, and therefore rigorous statistical testing of our results, but is otherwise a limitation to our methodology (see Supplementary Information for a discussion). To represent terrestrial processes, we use the Community Atmosphere Biosphere Land Exchange model (CABLE)[11]. CABLE is a two-leaf canopy model that calculates the radiation absorbed by sunlit and shaded leaves and enables calculation of air temperature and humidity within the canopy. It also includes a coupled model of stomatal conductance, photosynthesis and partitioning of net radiation into latent and sensible heat fluxes and calculates carbon assimilation through respiratory loss. Physiological effects of increased CO_2 on stomatal conductance and biophysical effects of vegetation height and surface albedo on surface energy balance and partitioning are accounted for[11]. However, we do not account for the biogeochemical effects of LULCC (ref. 22). These would affect the atmospheric CO_2 concentration[17] and therefore the detailed patterns of the changes simulated, but it is very unlikely that they would affect our conclusions. The key impact of biogeochemical cycles is the extra CO_2 released through LULCC; this would probably increase the relative impact of future climate changes and increase the significance of regional climate changes in the future. The CSIRO Mk3L has a competitive climatology[14] and a climate sensitivity to a doubling of atmospheric CO_2 consistent with the range of other models used for climate projections[2] (see Supplementary Information). A detailed analysis of the climate simulated with CABLE, and of how coupling the CABLE model improves the simulation of near-surface and surface variables, is also available[13].

Experiments. To simulate the effect of LULCC and changes in CO_2, we ran the following experiments. The first set of experiments with natural and perturbed vegetation cover was run at the $1 \times CO_2$ concentration (280 ppmv). The natural vegetation-cover map[23] represents the potential vegetation cover without anthropogenic influence. The perturbed vegetation-cover map modified the natural vegetation cover on the basis of the crop and pasture cover in year 2000 of the Land Use Harmonization dataset[24]. Where crop and pasture covered more than 10% of a region naturally covered by forest, the forest was converted to cropland vegetation. These half-degree vegetation cover maps were then interpolated to the Mk3L grid, retaining the mosaic of vegetation types within each CABLE grid cell. The cropland fraction map shown in Supplementary Fig. S1 represents the total fraction of vegetation converted from forest type to cropland type for each grid point. A second set of experiments, with the same natural and perturbed vegetation covers, were run at $2 \times CO_2$ concentration level (560 ppmv). All simulations were run for 300 years and the monthly outputs for the last 200 years of simulations were used in the analysis. For both the $1 \times CO_2$ and $2 \times CO_2$ experiments, we used SSTs from the Mk3L model taken from the model at equilibrium. This is a potential weakness in our methodology, because there is evidence that fixed SSTs lead to an underestimation of the large-scale impacts of LULCC (ref. 21). The statistical significance tests used the modified t-test[25], which accounts for time dependence within the data.

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Author contributions

A.J.P. designed the study. F.B.A. conducted the experiments and managed the data. S.J.P. contributed the Mk3L model. A.J.P., F.B.A., G.A., Y.P.W. S.J.P. and N. de N-D. assisted with the analysis and wrote the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.J.P.