# LETTER

Observed increase in local cooling effect of deforestation at higher latitudes

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Deforestation in mid- to high latitudes is hypothesized to have the potential to cool the Earth's surface by altering biophysical processes[1–3]. In climate models of continental-scale land clearing, the cooling is triggered by increases in surface albedo and is reinforced by a land albedo–sea ice feedback[4,5]. This feedback is crucial in the model predictions; without it other biophysical processes may overwhelm the albedo effect to generate warming instead[5]. Ongoing land-use activities, such as land management for climate mitigation, are occurring at local scales (hectares) presumably too small to generate the feedback, and it is not known whether the intrinsic biophysical mechanism on its own can change the surface temperature in a consistent manner[6,7]. Nor has the effect of deforestation on climate been demonstrated over large areas from direct observations. Here we show that surface air temperature is lower in open land than in nearby forested land. The effect is $0.85 \pm 0.44\,\mathrm{K}$ (mean ± one standard deviation) northwards of $45^\circ\,\mathrm{N}$ and $0.21 \pm 0.53\,\mathrm{K}$ southwards. Below $35^\circ\,\mathrm{N}$ there is weak evidence that deforestation leads to warming. Results are based on comparisons of temperature at forested eddy covariance towers in the USA and Canada and, as a proxy for small areas of cleared land, nearby surface weather stations. Night-time temperature changes unrelated to changes in surface albedo are an important contributor to the overall cooling effect. The observed latitudinal dependence is consistent with theoretical expectation of changes in energy loss from convection and radiation across latitudes in both the daytime and night-time phase of the diurnal cycle, the latter of which remains uncertain in climate models[8].

The latitudinal gradient of land-use impact is evident in the comparison of the surface air temperature recorded at FLUXNET (www.fluxnet.ornl.gov) forest towers[9] (Supplementary Table 1 and Supplementary Fig. 1) and surface weather stations in North America (Fig. 1a). Here we use the surface stations as proxies for cleared land. In accordance with the requirement of the World Meteorological Organization, these stations are located in open grassy fields that have biophysical characteristics similar to those of open land, such as being covered by snow in northern latitudes in the winter[10]. Latitude accounts for 31% of the variations in the temperature difference ΔT between the forest sites and the adjacent open lands (number of site pairs $n = 37$). The rate of change in ΔT with latitude is $-0.070 \pm 0.010\,\mathrm{K}$ per degree (mean ± one standard error, s.e., $P < 0.005$). At these sites, the annual net all-wave radiation R_n
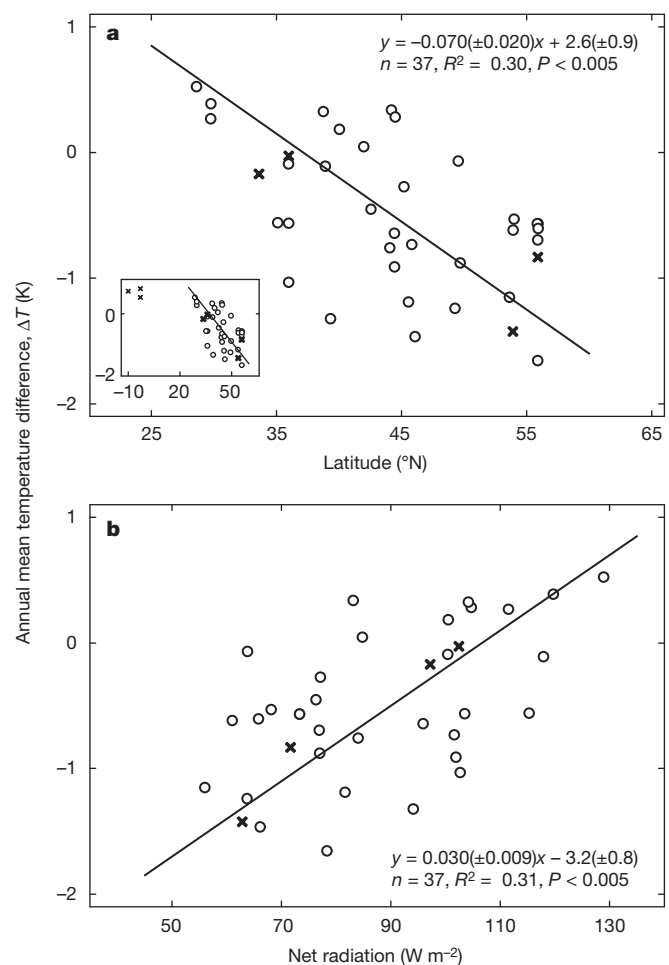
Figure 1 | Annual mean difference (open land minus forest) in surface air temperature. a, Correlation with latitude. b, Correlation with surface net radiation. The inset to a has the same axes as the main panel but also shows tropical FLUXNET site data. Parameter bounds in the linear regression are for the 95% confidence interval. Circles indicate weather station/forest site pairs and crosses indicate FLUXNET site clusters.

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decreases linearly with latitude. If R_n is used as the independent variable, the correlation becomes positive (Fig. 1b, linear correlation 0.55, $P < 0.005$). Combining the site-pair observations with the limited tropical FLUXNET data suggests that the latitudinal dependence may level off in zones south of the paired analysis (inset to Fig. 1a).

For the site pairs north of $45°$ N (Fig. 2a), the mean annual ΔT is -0.85 ± 0.44 K (mean ± 1 standard deviation, s.d.), a result in agreement with, but weaker than, those of climate model simulations of large-scale land-use changes in the boreal zone[11,12]. If we approximate the net shortwave radiation change at these site pairs by the boreal FLUXNET site cluster data (Supplementary Table 2), we arrive at an apparent local climate sensitivity of about 0.027 K W^{-1} m^2. The mean monthly ΔT does not seem to depend on season (Fig. 2a); the modelled maximum temperature change from March to May[12,13] is not discernible in our data, suggesting some strong compensating signals in the real atmosphere.

For the site pairs south of $45°$ N (Fig. 2b), the mean annual ΔT is -0.21 ± 0.53 K, giving an apparent sensitivity of about 0.012 K W^{-1} m^2. There appears to exist a weak seasonality, with the open sites cooler than the forests (-0.52 K) in January and slightly warmer (0.08 K) in June. For comparison, the cooling signal associated with historical land clearing since the 1700s, which has occurred primarily in mid-latitudes[13], is 0.5–1.0 K.

The latitudinal dependence can be understood by examining the intrinsic biophysical mechanism. Forests have lower surface albedo than shrubs, grasses and pastures[6,7,14]. Deforestation decreases the net shortwave absorption by an amount ΔS that depends in part on climate regimes. Local surface temperature would fall in response to the decreased surface radiation loading associated with deforestation if radiation were the only energy transfer process involved. Similar to the global analysis[15,16], the surface temperature change would be

$\Delta T_s = \lambda_0 \Delta S$, where $\Delta S < 0$ and the temperature sensitivity resulting from the longwave radiation feedback $\lambda_0 = 1/(4\sigma T_s^3) \approx 0.2$ K W^{-1} m^2. (T_s is surface temperature and σ is the Stephan–Boltzmann constant.) The actual temperature change also depends on energy redistribution through convection and evapotranspiration. Owing to their larger aerodynamic roughness, forests dissipate sensible heat more efficiently to the atmospheric boundary layer than do open landscapes[6]. In humid climates, they also remove from the surface more latent heat[14], which is released above the atmospheric boundary layer by cloud condensation.

The intrinsic biophysical mechanism can be expressed as a temperature change in response to changes in these energy exchange processes:

$$\Delta T_s \approx \lambda_0 \Delta S/(1+f) + (-\lambda_0)R_n \Delta f/(1+f)^2 \qquad (1)$$

where f (> 0) is an energy redistribution factor. Equation (1) reveals a number of useful properties of the biophysical effect. The first term on the right (radiative forcing term) results from albedo changes but is always damped by energy redistribution. The second term (energy redistribution) has two additive components contributed by changes in Bowen ratio and in surface roughness and over the diurnal cycle is usually positive when forests are converted to open land. Because these terms have opposite signs, the local climate sensitivity with respect to ΔS cannot exceed the upper limit of λ_0 and can even be negative[6]. Equation (1) calls attention to a previously unrecognized role of R_n, which is to amplify the effects of roughness and Bowen ratio changes in low latitudes and reduce these effects in high latitudes. Because with increasing latitude ΔS becomes more negative[2] and R_n decreases, equation (1) suggests that ΔT_s should be negatively correlated with latitude (Fig. 1a).

A conceptual analysis using equation (1) suggests that the relative contribution of the different biophysical forcings of deforestation to ΔT_s should depend on the climate zone (Fig. 3 and Supplementary Table 2). In the boreal zone, open land from timber harvest generates stronger radiative cooling and roughness warming (Fig. 3a) than fire (Fig. 3b). This is because the standing dead trees in the recently burnt site[17] partially mask winter snow cover and enhance turbulent mixing year round. The temperate site cluster (Fig. 3c) displays a weaker radiative cooling but stronger roughness warming than the boreal clusters. Over the broad parameter space shown in Fig. 3, the partitioning of the net temperature change bears remarkable resemblance to the results of a global-scale deforestation experiment in a climate model, but only after the sea-ice feedback has been included in the model[5].

Surprisingly, a diurnal asymmetry exists in the biophysical effect (Fig. 2c). Diurnal temperature range (DTR, the difference between the daily maximum and minimum temperature) is an important measure of surface climate variability[18,19] and we find that DTR is reduced with forest cover. At night, ΔS vanishes, surface evapotranspiration is generally negligible, and surface roughness is the main biophysical factor affecting the daily minimum temperature changes (Supplementary equation (14), noting $R_n < 0$). Even though the lower roughness contributes to a warming of the daily mean temperature (Fig. 3), at night open land cools more than forests in both the northern and the southern latitudes. We hypothesize that forests are warmer at night because in stable stratification the presence of trees causes turbulence, bringing heat from aloft to the surface. The mechanism underlying the daily maximum temperature changes is more complex. In the daytime, suppressed mixing due to a smaller surface roughness causes the surface temperature of the open land to rise faster than that of the forest. At the sites north of $45°$ N, this roughness effect is, however, nearly offset by cooling associated with albedo and Bowen ratio changes, resulting in almost identical daily maximum temperatures between the paired sites. The diurnal asymmetry emphasizes the importance of both daytime and night-time observations for obtaining an accurate assessment of the land-use effect.

Forests represent one of the most extensive land-use types, occupying about 30% of the terrestrial surface[1]. Our paired analysis
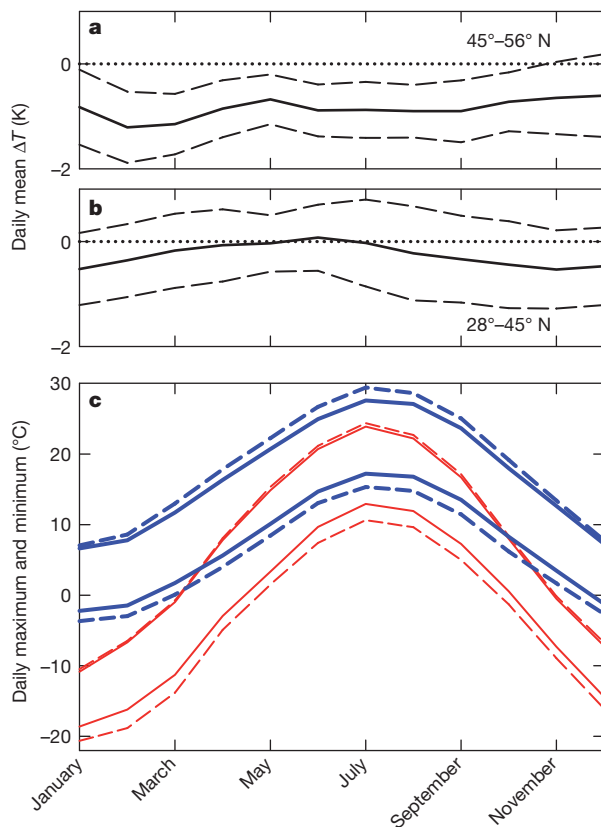

Figure 2 | Seasonal and diurnal patterns of surface air temperature. a and **b** show the mean temperature difference ± 1 s.d. for the site pairs north and south of $45°$ N. **c**, Mean daily maximum and minimum temperatures for the forests (solid lines) and the surface stations (dotted lines) for $28–45°$ N (blue lines) and $45–56°$ N (red lines).
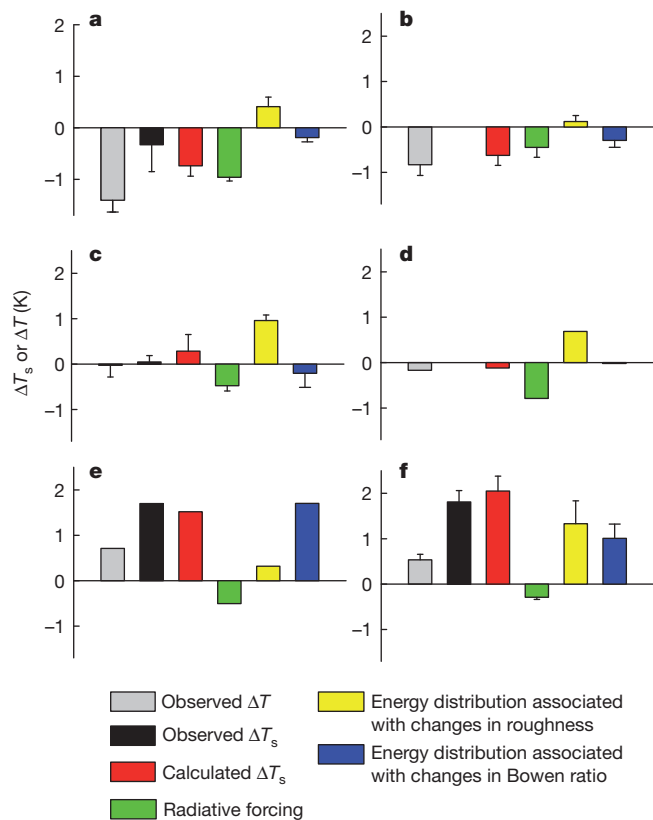
Figure 3 | Partition of the biophysical effect at six FLUXNET site clusters in four different climate zones. a, Boreal: harvested site versus jack pine forests[25]. **b,** Boreal: burnt site versus black spruce forests[17]. **c,** Temperate: grassland versus pine and oak/hickory forests[26]. **d,** Semi-arid: open shrub land versus pinyon juniper[27]. **e,** Tropical: pasture versus rainforest[14]. **f,** Tropical: farmland versus rainforest[28,29]. Temperatures are 24-h means. Error bars are given as 1 s.d. for the clusters with multiple site-year observations. No surface temperature measurements are available for **b** and **d**. For comparison, observed changes in surface air temperature (ΔT) are also shown.

indicates that biases exist in the climate station observations if they are used to represent the climate state of the forested land. These biases are manifested in several ways. First, the station network overestimates the north–south surface temperature gradient by 0.070 ± 0.010 K per °N (mean $\pm$ 1 s.e.) for this land type (Fig. 1a). Second, DTR is a variable sensitive to the biophysical properties of the surface above which the observation is made. The station DTR is biased high by an average of 2.8 ± 2.0 K (and up to 8 K in some locations) in comparison to that at
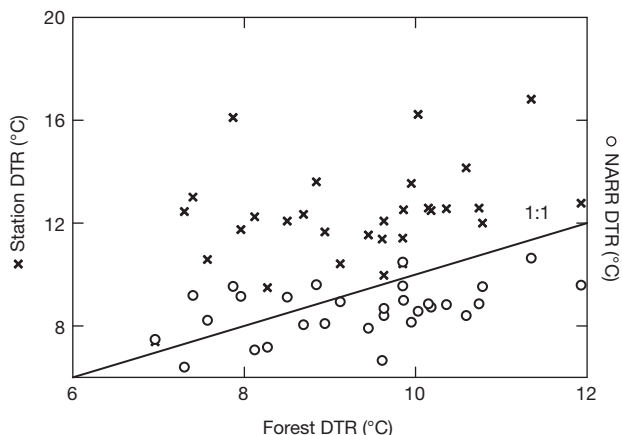
Figure 4 | Comparison of the DTR for the forests, the surface stations and the NARR model result.

the FLUXNET forests (Fig. 4). Third, these station biases can adversely affect model-data comparison. The models in question include both climate models and those used for atmospheric data assimilation. The modelled screen-height temperature is not compatible with the station observations because the grids prescribed as forest vegetation in the model domain have different biophysical properties from the surface of a weather station. For example, the DTR modelled by NARR (North American Regional Reanalysis)[20] is in much better agreement with the FLUXNET observations than with the surface station data (Fig. 4). Similar to the observed pattern (Fig. 1a), the station temperature becomes progressively lower with increasing latitude than the NARR-predicted screen-height (2.0 m above the vegetation surface) temperature (Supplementary Fig. 2). The model-data incompatibility may be one reason for why the DTR trends simulated by climate models do not agree with the observed trends[18,21], although firm evidence for this will need longer FLUXNET temperature records. It also provides additional evidence showing that the intrinsic biophysical mechanism can alter surface air temperatures in a predictive manner without influences originating from outside the atmospheric boundary layer.

The purpose of this analysis is to quantify the biophysical effect arising from spatial patterns of land use in the present climate. We assume that the adjacent land types share the same background state defined by the incoming solar radiation, the incoming longwave radiation and air temperature at the blending height[22] above the ground. Substitution of the spatial variations for time variations of land use must also consider that this background state may be changing due to large-scale variations in radiative forcing and climate feedbacks[23,24]. Conceptually, the intrinsic biophysical processes can be regarded as a local perturbation superimposed on the changing background. We postulate that at scales of ongoing land-use activities, the perturbation signals are much larger than the background changes. For example, clearing of a million hectares of forest (the size of a typical climate model grid) would reduce the global radiative forcing associated with albedo changes by 3×10^{-4} W m^{-2} (ref. 2), which is too weak to cause observable changes in surface temperature.

METHODS SUMMARY

FLUXNET and station data. Data obtained at 33 FLUXNET forest sites in the USA and Canada are used in this analysis. These sites have a minimum of three years of temperature and net radiation data. The surface weather station closest to every forest site was chosen for the paired analysis. The site pairs have a mean elevation difference of 59 m, a linear distance of 28 km and a latitudinal distance of 0.2 km. The height of the temperature measurement in the FLUXNET network varies from 2 to 15 m above the canopy. Correcting the measurement to the standard screen height (2.0 m above the vegetation) would change the annual mean temperature by no more than 0.1 K.

NARR data. NARR uses the NCEP (National Centers for Environmental Protection) Eta model and numerous data sources to produce outputs at a grid spacing of 32 km. Surface station observations of the screen-height temperature are not used to constrain the modelled fields. Each forest site is matched up with the closest NARR grid. At these grids, calculations of the NARR screen-height temperature are forced with a surface boundary with biophysical properties of forested landscapes.

Model of biophysical processes. Equation (1) is derived from a linearized version of the surface energy balance equation. It was assumed that in the vicinity of one another, a forest area and a piece of open land receive the same amounts of incoming shortwave and longwave radiation and that air is sufficiently mixed at the blending height. As a result, any difference in the surface temperature is caused by the intrinsic biophysical mechanism or changes in albedo, surface roughness and Bowen ratio. Evaluation of equation (1) for the six FLUXNET site clusters (Fig. 3) was done separately for the daytime and night-time periods to avoid nonlinear parameter interactions through the diurnal cycle.

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