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SUPPLEMENTARY MATERIALS

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FOREST MANAGEMENT

Europe's forest management did not mitigate climate warming

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Afforestation and forest management are considered to be key instruments in mitigating climate change. Here we show that since 1750, in spite of considerable afforestation, wood extraction has led to Europe's forests accumulating a carbon debt of 3.1 petagrams of carbon. We found that afforestation is responsible for an increase of 0.12 watts per square meter in the radiative imbalance at the top of the atmosphere, whereas an increase of 0.12 kelvin in summertime atmospheric boundary layer temperature was mainly caused by species conversion. Thus, two and a half centuries of forest management in Europe have not cooled the climate. The political imperative to mitigate climate change through afforestation and forest management therefore risks failure, unless it is recognized that not all forestry contributes to climate change mitigation.

During the past few decades, European forests have acted as a carbon sink (1). Forest management, however, can enhance (2) or weaken (3) this sink, which has put it on the political agenda as a mechanism for mitigating climate change (4). However, forest management not only influences the sink strength, it also changes forest structure, which affects the exchange of energy and water vapor with the overlying atmosphere (5–8). Therefore, the potential of forest management to mitigate climate change can only be fully assessed by accounting for the effects from both biogeochemical changes (greenhouse gas emissions) and biophysical changes (water and energy fluxes) (9, 10).

Whereas the effects of historical anthropogenic land-cover changes, such as deforestation and afforestation, on the carbon cycle and the contemporary climate are relatively well documented (11–13), the impacts of land-use changes that do not involve a change in land cover, such as forest management, are far less well understood. Forest management has been reported to affect water and energy fluxes to the atmosphere to the same extent as changes in land cover do (8), suggesting that centuries of forest management may have contributed to Europe's present-day climate.

Despite the well-known impact of forest management on site-level carbon, energy, and water exchanges (5–8), large-scale studies of the climate

effects of forest management were, until recently, hampered by restrictive model approaches and a lack of sufficiently detailed land-use reconstructions. We have addressed both of these limitations. We reconstructed the land-use history of Europe (defined as the land mass west of the Russian border) to take account of both land-cover changes (afforestation and deforestation) and forest management changes (tree species conversion, wood extraction via thinning and harvesting, and litter raking) (14). Among other developments [section 1 of (15)], we then replaced the big-leaf approach in the land-surface model ORCHIDEE-CAN (Organising Carbon and Hydrology In Dynamic Ecosystems–Canopy) with an explicit canopy representation to simulate the biogeochemical and biophysical effects of land-use change (16). The improved land-surface model was coupled to the atmospheric circulation model LMDZ (Laboratoire de Météorologie Dynamique Zoom) [section 2 of (15)] in a factorial simulation experiment to attribute climate change to global anthropogenic greenhouse gas emissions and European land-use change since 1750.

Increased atmospheric greenhouse gas concentrations from global fossil-fuel burning and land-use changes outside Europe are responsible for a change of 2.98 W m⁻² in the radiative imbalance at the top of the atmosphere, a significant increase of 1.71 K in summertime boundary layer temperature ($P < 0.05$, modified t test; Table 1), and an insignificant decrease of 6 mm in summertime precipitation ($P > 0.05$, modified t test; Table 1), relative to 1750. Enhanced plant growth caused by global warming and increased atmospheric CO₂ has resulted in a European forest-based carbon sink of 0.13 Pg C since 1750 (eq. S1), which is a negligible compensation for the contribution of 247 Pg C or 117 ppm CO₂ from global anthropogenic emissions (Table 1).

From 1750 to 1850, deforestation reduced Europe's forest area by 190,000 km². In the mid-19th century, the increasing use of fossil fuels

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for energy and, later, agricultural intensification halted net deforestation and even reverted the trend. In subsequent centuries, 386,000 km² of agricultural land was afforested (14), resulting in a net gain of forest area between 1750 and 2010 (17). Whereas deforestation between 1750 and 1850 mainly replaced broadleaved forests with agricultural land, afforestation from 1850 onward was often with coniferous species. Broadleaved forests were also directly converted to coniferous forests (18), resulting in a total increase of 633,000 km² in conifers at the expense of broadleaved forests (decreasing by 436,000 km²) (14). For centuries, foresters have favored a handful of commercially successful tree species (Scots pine, Norway spruce, and beech) and, in doing so, are largely responsible for the current distribution of conifers and broadleaved species in Europe (Fig. 1, A and B).

The species change thus reflects the onset of a more scientific and production-oriented approach to forestry (19). Through local production and trade, Europe tried to satisfy the wood demands of a population that grew from 140 million in 1750 to 580 million by 2010 (20). As a result, 417,000 km² of previously unmanaged forests were taken into production (Fig. 1, C and D), and 218,000 km² of coppices were converted to high stands, which, together with the 196,000 km² of afforestation, resulted in an 833,000 km² increase

in high-stand management (14). Within the same 260-year period, litter raking came into practice. It peaked around 1850, having transferred about 50 Tg of carbon from forests to agricultural land, and was progressively abandoned afterward with the increased availability of straw (21). Below, we discuss the climate effects of this afforestation, species conversion, and wood extraction in Europe between 1750 and 2010.

The net gain of 196,000 km² in forest area, with eastern Ukraine being a noteworthy exception, resulted in a 0.7-Pg carbon sink. At the same time, afforestation decreased the albedo of the land surface by 0.01 (i.e., 1% more solar radiation was absorbed). The decrease in albedo was not offset by the carbon sink, resulting in a net radiative imbalance of 0.11 W m⁻² ($P < 0.05$, modified t test; Table 1). After afforestation, atmospheric warming from changes in vegetation albedo and latent heat flux was largely offset by cooling from changes in sensible heat flux (fig. S1), resulting in a small summertime temperature increase of 0.02 K ($P < 0.05$, modified t test; Table 1). For temperate regions such as Europe, a small to nonexistent temperature effect after afforestation is consistent with observational studies (22–24).

Replacing broadleaved forests with conifers resulted in a simulated carbon sink of 0.6 Pg C (Table 1). Yet the summertime temperature in

the boundary layer increased by 0.08 K ($P < 0.05$, modified t test; Table 1). Temperature changes related to changes in sensible and latent heat flux, which can be triggered by species-specific changes in albedo (Fig. 2B) and canopy structure, were large but offset each other. However, a decrease in water vapor pressure due to reduced evapotranspiration decreased the atmosphere's ability to release thermal heat (atmospheric emissivity) (25), which explains the 0.08-K warming (Fig. 2A). Temperature changes follow a clear spatial pattern, with significant warming over central and eastern Europe (Fig. 2C). The strong correlation [coefficient of determination (R^2) = 0.56, $P < 0.05$, modified Pearson correlation] of the spatial patterns of land-use and species change suggests that the temperature effect of anthropogenic land use is largely determined by tree species conversion (Fig. 2D).

Almost 25% of the 633,000-km² increase in conifers occurred in northern Europe. Despite the lower albedo for coniferous relative to deciduous trees, the albedo over this region increased (Fig. 2B) due to a more than doubling of the surface area of young forests (forests with an average tree diameter <0.07 m) after the onset of widespread forest management. The sparse tree canopy of young forests allows more light to penetrate to the forest floor, which is generally more reflective than the tree cover (26), resulting in a higher albedo.

Putting 417,000 km² of previously unmanaged forest into production is estimated to have released 3.5 Pg of carbon to the atmosphere, because the carbon stock in living biomass, coarse woody debris, litter, and soil was simulated to be, respectively, 24, 43, 8, and 6% lower in managed forests compared with unmanaged forests. Differences in standing biomass between managed and unmanaged forests explain 38% of the total simulated 2.7-Pg increase in atmospheric carbon

Table 1. Attribution of biogeochemical, biophysical, and climatic effects between 1750 and 2010 to global greenhouse gas emissions and different factors of European anthropogenic land-use change. Land-use change includes both land-cover change and forest management, which was separated into species conversion and wood extraction (thinning, harvest, and litter raking). Contributions were calculated from eqs. S1 to S9 [section 3 of (15)]. The footnotes provide statistical information and indicate the main causes of the significant changes. Biogeochemical effects were discounted for the CO₂ emissions from the pressure-driven equilibrium between the oceans and the atmosphere. RF, radiative forcing; GHGs, greenhouse gases.

	Contribution to changes since 1750				
	Δ RF due to GHGs (W m ⁻²)	Δ RF due to surface change (W m ⁻²)	ΔT_a , summer (K)	Δ Precipitation, summer (mm per season)	Δ Atmospheric carbon (Pg C)†
Global					
Greenhouse gas emissions	2.98*‡	0.00	1.71*‡	-6	247§
European					
Land-use change	0.01*	0.11*¶	0.12*#	-3	3.1
Land-cover change	-0.01	0.12*¶	0.02*¶	0	-0.7**
Forest management	0.02	-0.01	0.10*#	-3*‡‡	1.9
Species conversion	-0.01	0.00	0.08*#	-4*‡‡	-0.6‡‡
Wood extraction	0.03	-0.01	0.02*	1	2.7

*Significant effects at the 0.05 significance level, as determined by a modified paired one-sample t test. †Effects for which statistical testing was not possible, because only a single realization was available. ‡Increased radiative forcing from increased atmospheric CO₂ concentrations due to fossil-fuel burning and land-use change. §Increased atmospheric CO₂ concentrations due to fossil-fuel burning and land-use change. ||Decreased carbon storage in vegetation caused by taking unmanaged forests into production. ¶Decreased vegetation albedo caused by large-scale afforestation. #Decreased atmospheric emissivity due to changes in albedo and canopy structure caused by replacing broadleaved deciduous with evergreen coniferous tree species. **Increased carbon sequestration in vegetation through large-scale afforestation. †‡Although statistically significant, these changes are unlikely to be relevant. ‡‡Increased carbon sequestration in vegetation caused by replacing broadleaved with fast-growing coniferous tree species.

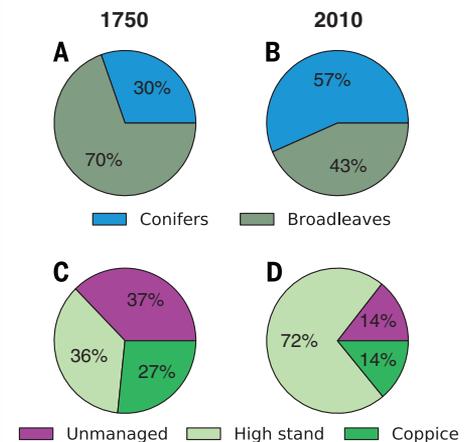


Fig. 1. Main changes in European forest management between 1750 and 2010. (A) Relative distribution (percent) of tree growth forms in 1750 and (B) 2010. Total forest area in 1750 was 1,929,000 km² and increased to 2,126,000 km² by 2010. (C) Relative distribution (percent) of wood extraction strategies in 1750 and (D) 2010.

due to wood extraction (Table 1). The decrease in carbon stocks caused by extracting wood from previously unmanaged forests could not be compensated for by building up a carbon stock in the wood-product pools (only 0.05 Pg C would be offset). The carbon released from wood extraction was, however, partly compensated for by the conversion from broadleaved to faster-growing coniferous species. Nevertheless, the combination of wood extraction and species conversion emitted 1.9 Pg C to the atmosphere (Table 1). Wood extraction only had minor effects on albedo ($P > 0.1$, modified t test), surface roughness, and evapotranspiration; the climate effect of wood extraction is therefore controlled by its carbon release.

Despite their present-day strength as carbon sinks (1), the distinctive history of afforestation, species conversion, and wood extraction from previously unmanaged forests nevertheless has resulted in European forests having a carbon debt of 3.1 Pg C, compared with 1750 (Table 1). A concurrent 0.12-K increase in summertime boundary layer temperature ($P < 0.05$, modified t test; Table 1) can be attributed only to a minor extent to afforestation (0.02 K) and is mainly due to

forest management (0.10 K; $P < 0.05$, modified t test; Table 1), more specifically to the conversion from broadleaved to coniferous species (0.08 K; $P < 0.05$, modified t test; Table 1). The radiative imbalance at the top of the atmosphere increased by 0.12 W m^{-2} as a result of land-use change ($P < 0.05$, modified t test; Table 1). Contrary to the temperature effect from land-use change that was largely explained by species conversion, the radiative imbalance can mainly be attributed to afforestation (0.11 W m^{-2}).

Although our analysis is restricted to Europe, similar effects are likely for regions where similar underlying processes are or have been occurring. Large-scale afforestation is ongoing in China (772,000 km²), the United States (254,000 km²), and the Russian Federation (170,000 km²) (17, 27). Wood extraction occurs in 64 to 72% of the 26.5 to 29.4 million km² of global forest area (8), and substantial species changes have occurred in China (216,000 km²), Brazil (71,000 km²), Chile (24,000 km²), New Zealand (18,000 km²), and South Africa (17,000 km²) (27).

Afforestation and forest management to maximize carbon sequestration are recognized as key strategies for climate mitigation by the Paris

agreement of the United Nations Framework Convention on Climate Change, because forest management and wood use are expected to slow global warming by removing CO₂ from the atmosphere. In Europe, two and a half centuries of land-use change increased the forest area by 10% and has put over 85% of the forests under management, but it has failed to result in net CO₂ removal from the atmosphere, because wood extraction released carbon otherwise stored in the biomass, litter, dead wood, and soil carbon pools. In addition, converting deciduous forests into coniferous forests resulted in changes in albedo, canopy roughness, and evapotranspiration from the land surface, which contributed to warming rather than mitigating it. Hence, any climate framework that includes land management as a pathway for climate mitigation should not only account for land-cover changes but also should equally address changes in forest management, because not all forest management contributes to climate change mitigation. The key question now is whether it is possible to design a forest management strategy that cools the climate and, at the same time, sustains wood production and other ecosystem services.

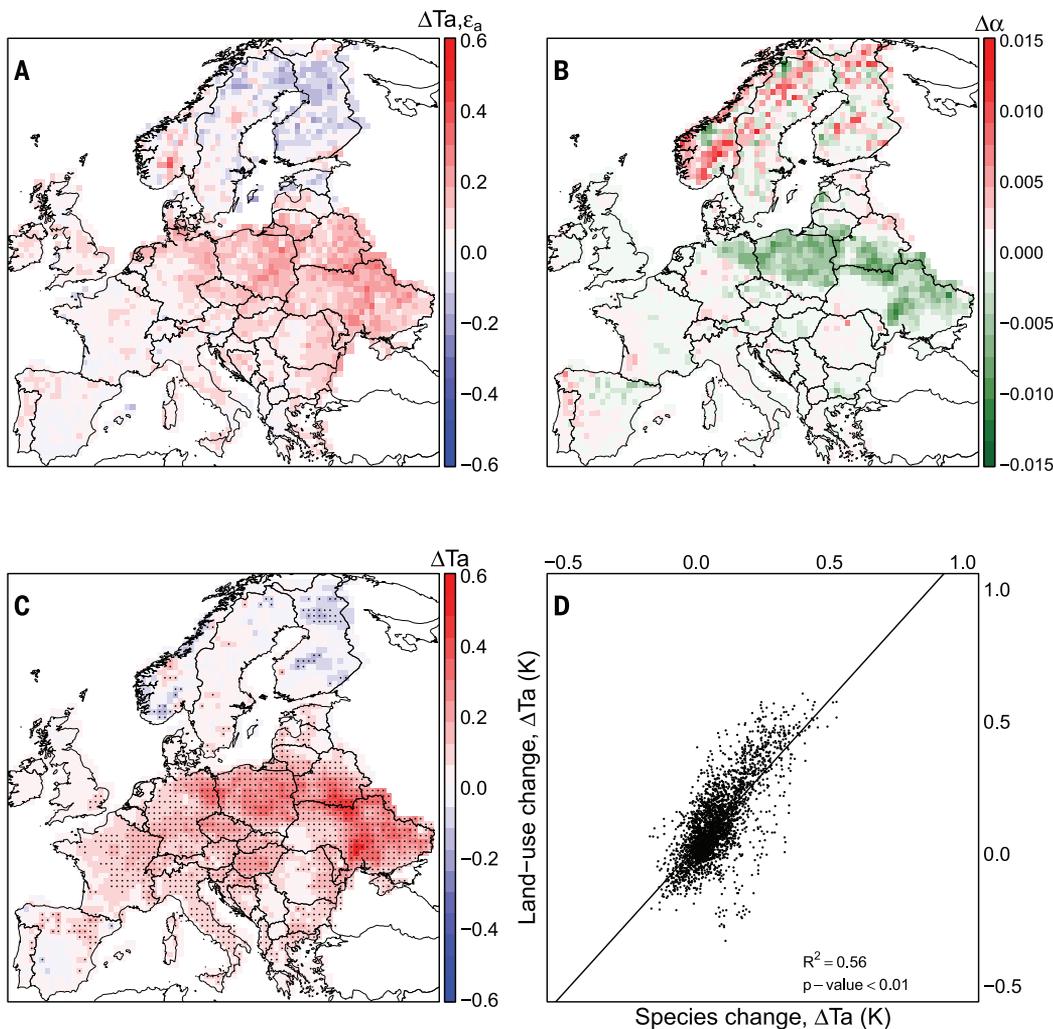


Fig. 2. Effects of species conversion in Europe since 1750. Temperature changes are for boundary layer temperature during summer (kelvin). (A) Temperature change due to changes in emissivity ($\Delta T_a, \epsilon_a$) caused by species conversion, (B) changes in albedo ($\Delta \alpha$) due to species conversion, (C) total temperature change (ΔT_a) due to species conversion, and (D) correlation between species-induced and land use-induced temperature change. In (C), black dots denote significant temperature changes at the 0.05 significance level, as determined by a modified paired one-sample t test.

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SUPPLEMENTARY MATERIALS

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CLIMATE CHANGE

Biophysical climate impacts of recent changes in global forest cover

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Changes in forest cover affect the local climate by modulating the land-atmosphere fluxes of energy and water. The magnitude of this biophysical effect is still debated in the scientific community and currently ignored in climate treaties. Here we present an observation-driven assessment of the climate impacts of recent forest losses and gains, based on Earth observations of global forest cover and land surface temperatures. Our results show that forest losses amplify the diurnal temperature variation and increase the mean and maximum air temperature, with the largest signal in arid zones, followed by temperate, tropical, and boreal zones. In the decade 2003–2012, variations of forest cover generated a mean biophysical warming on land corresponding to about 18% of the global biogeochemical signal due to CO₂ emission from land-use change.

Forests play a relevant role in the climate system by absorbing approximately one-fourth of anthropogenic CO₂ emissions (1), storing large carbon pools in tree biomass and forest soils (2), and modulating the land-atmosphere exchange of energy and water vapor (3). Given the important role of forests in the global carbon cycle, climate treaties account for land-based mitigation options such as afforestation, reforestation, and avoided deforestation or forest degradation (4, 5). On the contrary, the climate impacts of biophysical processes, such as the surface exchange of energy and water vapor (6), are still uncertain in sign and magnitude and therefore have not been considered in climate negotiations to date.

Over the past two decades, the biophysical effects of deforestation on climate have been assessed mainly by comparing paired model simulations with contrasting forest cover (7–12). These analyses have shown that, despite the increase in surface albedo, the net biophysical effects of tropical deforestation may increase surface temperature through the reduction of evapotranspiration (9, 13). On the contrary, boreal deforestation may lead to net climate cooling due to the high snow albedo in cleared areas during winter/spring and to the land-albedo/sea-temperature feedback (11, 12, 14). However, results of these numerical experiments are model-dependent, and the uncertainties in sign, magnitude, and spatial distribution of the predicted effects are very large (15–17). Therefore, direct observations of the biophysical climate effects of recent forest losses and gains are required to constrain predictions, reduce the uncertainty of model ensembles, and provide robust recommendations to climate policy.

To date, data-driven assessments based on in situ (18–20) or satellite observations (3, 21, 22) have adopted the space-for-time analogy, mean-

ing that spatial differences in surface temperature between areas with contrasting forest cover have been interpreted as the climate signal of hypothetical deforestation/afforestation. The substitution of space for time produces unbiased results only if forests are randomly distributed in the landscape. Conversely, the systematic location of forests in less favorable areas (such as steeper or colder slopes, shallow soils, etc.) may produce spatial gradients in surface climate that should not be attributed to changes in land cover (18). In addition, both model-based and observation-based assessments have focused so far on idealized scenarios of deforestation (10, 11) and on the estimation of climate sensitivities to land-use change (3, 18, 22), but the climate signal generated by the ongoing changes in forest cover has not yet been quantified.

To overcome the limits and uncertainties of past assessments, in this work we focused on areas that underwent recent land cover transitions, with the objective of providing a global, robust, and data-driven assessment of the biophysical climate impacts of observed forest gains and losses. The analysis builds on overlapping satellite retrievals of surface radiometric temperature (23) and of high-resolution variations in forest cover (24). A novel methodology has been developed to disentangle the effect of forest cover change from the global climate signal [details in supplementary materials (SM) text S1.2]. For this purpose, the temperature difference (ΔT) between two years at a given location is expressed as the effect of forest cover change (ΔT_{fcc}) plus the residual signal (ΔT_{res}) due to climate variability (Eq. 1)

$$\Delta T = \Delta T_{\text{fcc}} + \Delta T_{\text{res}} \rightarrow \Delta T_{\text{fcc}} = \Delta T - \Delta T_{\text{res}} \quad (1)$$

The temporal variation in air surface temperature (ΔT) is estimated from satellite retrievals of radiometric land surface temperature, evapotranspiration, and albedo, with semi-empirical models calibrated against in situ measurements of air temperature (SM text S1.1 and figs. S1 and S2). For a given location, we derive ΔT_{fcc} from Eq. 1 by estimating ΔT_{res} from adjacent areas with stable forest cover and therefore where $\Delta T_{\text{fcc}} \approx 0$

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