2021

Climate impacts of U.S. forest loss span net warming to net cooling

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CLIMATOLOGY

Climate impacts of U.S. forest loss span net warming to net cooling

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Storing carbon in forests is a leading land-based strategy to curb anthropogenic climate change, but its planetary cooling effect is opposed by warming from low albedo. Using detailed geospatial data from Earth-observing satellites and the national forest inventory, we quantify the net climate effect of losing forest across the conterminous United States. We find that forest loss in the intermountain and Rocky Mountain West causes net planetary cooling but losses east of the Mississippi River and in Pacific Coast states tend toward net warming. Actual U.S. forest conversions from 1986 to 2000 cause net cooling for a decade but then transition to a large net warming over a century. Avoiding these forest conversions could have yielded a 100-year average annual global cooling of 0.00088°C. This would offset 17% of the 100-year climate warming effect from a single year of U.S. fossil fuel emissions, underscoring the scale of the mitigation challenge.

INTRODUCTION

Protecting and expanding forest is promoted as a leading nature-based solution to help mitigate climate change (*1*–*3*), but there are several distinct mechanisms by which forests influence the climate system, with a range of effects that span cooling to warming (*4*–*6*). Most of the attention has focused on avoiding carbon release from deforestation (*7*, *8*), with some consideration of lost carbon sequestration typical in maturing, intact forests (*9*). Less attention is paid to the way forest loss increases surface albedo, reflecting more solar radiation out to space and cooling the planet (*10*–*20*). Furthermore, reduced evapotranspiration from conversion of forest to nonforest can cause warming through decreased cloud cover, particularly in the tropics, while carbon and surface albedo effects tend to dominate in temperate and boreal regions (*14*–*16*, *20*, *21*). Taking all of these factors into account, the Intergovernmental Panel on Climate Change (IPCC) in its synthesis concluded that historical forest losses have yielded a modest net planetary cooling (*19*), suggesting that reforestation of these locations would tend to cause warming (*22*, *23*), although some individual studies come to different conclusions (*18*, *24*).

Nonetheless, modeling studies reveal widespread geographic variation in the strength of these opposing climate effects (*14*–*18*, *25*, *26*), with forests in some locations causing net planetary cooling but forests in other locations causing net warming. Resolving these patterns is paramount to designing and implementing effective policies aiming to mitigate climate change with forest protection and expansion. The coarse spatial resolution and generic parameterization in climate models limit their utility in decision-making and motivates detailed, data-driven analyses as a needed alternative. In this study, we use detailed, geospatially explicit datasets on forest carbon stocks, forest carbon uptake, and the surface albedo changes caused by forest conversion to provide a thorough examination of their separate and combined effects on global climate as they vary across forestlands of the conterminous United States.

RESULTS

Forest loss initially causes net planetary cooling, averaging −8 W m^{-2} and ranging from −24 to 0 W m^{-2} across the United States (Table 1). Warming from the emission of forest carbon opposes cooling from albedo change; however, the albedo effect remains dominant even after 100 years for 27% (23 to 31%) of the country. Lost net ecosystem productivity (NEP) contributes substantially to the gross warming effect of forest loss, comprising about 46% (37 to 55%) of the gross warming by 50 years after conversion but with large spatial variability ranging from 22 to 73% for the 5th and 95th percentiles. Forest losses in West Coast states and east of the Mississippi River typically yield net warming after the first decade and a half, with a continued increase in net warming as the radiative forcing (RF) effects from carbon emissions and lost NEP accumulate over time (Fig. 1). In contrast, extensive snow cover and highly reflective post-conversion land cover types cause much of the western United States to exhibit persistent net cooling from forest loss. Thus, protecting Intermountain West and Rocky Mountain forests or expanding forest cover in these regions to combat climate change is likely to be counterproductive.

The United States annually experienced a gross loss of 380,417 ha of forest, averaged over 1986 to 2000 (see the Supplementary Materials). Losses were concentrated around urban centers, as well as some hot spots of rapid exurban development, and scattered clearings in semiarid Western regions and in some agricultural regions such as the Central Valley of California (figs. S1 and S2). The land cover types replacing lost forests vary geographically (fig. S3). Urban gain dominates near cities and across much of the upper Midwest, Northeast, and coastal Southeast. Outside of urban areas, shrubland gains dominated in the Pacific Coast states and in much of the intermountain and mountain west. Grassland gains, including pasturelands, dominated in much of the nonurban, central to southeastern United States, and cropland gains were widely scattered but with some hot spots in the Central Valley and along the Mississippi River.

Forest conversion in the United States over this 15-year period emitted 260 (208 to 312) Tg C in total, with a cumulative loss of 362 (274 to 465) Tg C that these forests would have removed from the atmosphere by the year 2100 (section S2.5). Together, these elevate globally averaged atmospheric CO_2 concentrations by 0.16 (0.19 to 0.23) parts per million in 2100, after accounting for ocean and land uptake of CO_2 (see the Supplementary Materials), which mitigates 37% (31 to 43%) of the total atmospheric loading from emissions and lost net uptake (section S2.5).

U.S. forest losses from 1986 to 2000 collectively cause local, mean annual RFs of 1.7 (−0.3 to 3.8) W m^{-2} 10 years after conversion,

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Table 1. Spatial statistics of potential instantaneous mean annual, local top-of-atmosphere radiative forcing caused by forest conversion across the United States with contributions from albedo, carbon emissions, lost NEP, and their combined net effect as they evolve over time (1, 10, 20, 50, and 100 years after conversion). Results correspond to the ensemble member with a stand age of 70 years, the middle biomass stock, the median Earth system uptake, and the Community Atmosphere Model CAM-5.0 (CAM5) radiative kernel.

	Year 1			Year 10			Year 20			Year 50			Year 100		
	5th	Mean	95th	5th	Mean	95th	5th	Mean	95th	5th	Mean	95th	5th	Mean	95th
Albedo	−24.1	**−9.2**	−1.5	−24.1	**−9.2**	−1.5	−24.1	**−9.2**	−1.5	−24.1	**−9.2**	−1.5	−24.1	**−9.2**	−1.5
C emission	0.4	**1.0**	1.9	2.2	**6.1**	11.3	2.9	**7.9**	14.8	3.0	**8.5**	15.7	2.8	**7.9**	14.6
Lost NEP	0.0	**0.3**	0.5	0.4	**2.2**	4.1	0.7	**4.0**	7.4	1.5	**8.0**	14.8	2.6	**11.9**	23.2
Net total	−23.9	**−8.2**	−0.3	−19.7	**−1.1**	10.9	−17.4	**2.7**	16.5	−15.3	**7.2**	23.6	−13.7	**10.5**	29.9

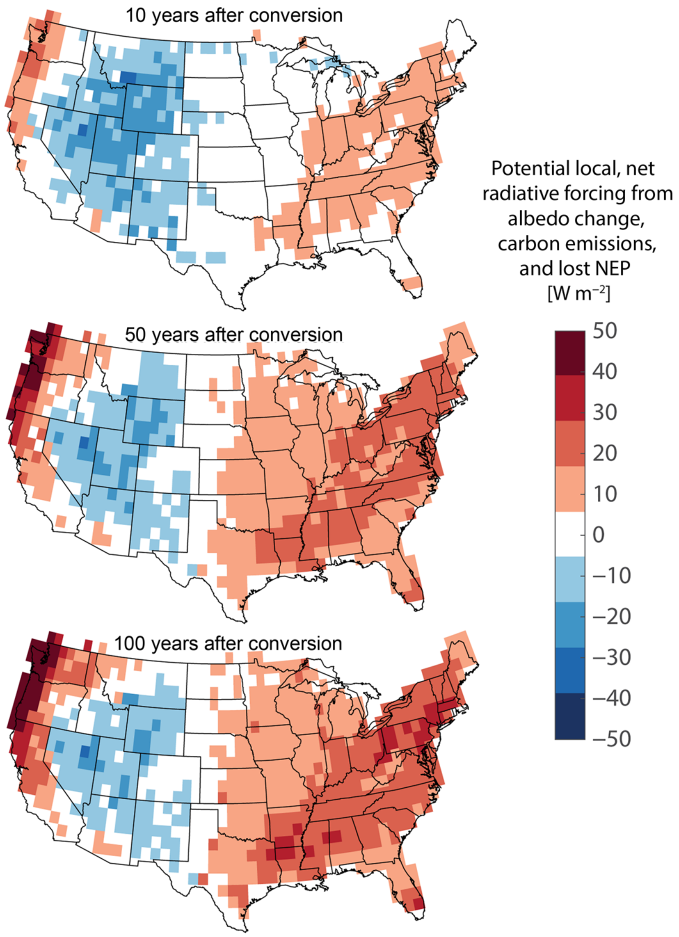

Fig. 1. Potential local, net RF from forest conversion considering albedo change, carbon emissions, and lost NEP. Results correspond to the ensemble member with a stand age of 70 years, the middle biomass stock, the median Earth system uptake, and the CAM5 radiative kernel.

11.3 (7.6 to 15.1) W m^{-2} after 50 years, and 15.4 (10.4 to 20.5) W m^{-2} after 100 years (Fig. 2). The global, mean annual RF for the century after forest conversion is 0.0011 W m^{-2} (0.0007 to 0.0015 W m^{-2}), constituting a small net planetary warming. Adopting an equilibrium climate sensitivity centered on 0.81°C per watt per square meter (see the Supplementary Materials), this global RF translates to 0.00088°C (0.00079° to 0.00099°C) of warming that could have been avoided by permanently preventing U.S. forest conversions from 1986 to 2000. The atmospheric CO_2 burden from 15 years of U.S. forest conversion amounts to 41% (31 to 52%) of 1 year's worth of U.S. fossil carbon emissions. However, the net warming, including albedo change, from 15 years of U.S. forest conversion amounts to only 17% (11 to 23%) of the RF (0.00574 W m^{-2}) caused by 1 year's worth of U.S. fossil carbon emissions.

DISCUSSION

These findings raise several important considerations for policy and management activities that aim to promote forests to mitigate climate change. First, forests can cause a net planetary warming compared to the climate effect of alternative land cover types, and this effect can reduce or even overwhelm the climate cooling effect of forest carbon storage. Thus, forestation and avoided deforestation should not be assumed to mitigate global warming. Land management policies aimed at climate mitigation, as well as carbon offset markets that pay for climate mitigation services provided by forests or forest expansion, would more effectively reach their goals by accounting for the climate impacts of changes in albedo. Datasets and methods are now readily available to identify where forest protection and forestation activities are best aligned with climate goals and where they are not. The approach demonstrated here can readily be adapted for formal, quantitative assessments worldwide.

Second, the climate effect of deforestation varies with time since conversion and, in many cases, changes sign from initial cooling to long-term warming. This indicates that the time scale chosen for a particular analysis strongly influences conclusions regarding net climate impacts. Adopting a 10- to 20-year time frame systematically biases interpretations toward net cooling effects of forest loss, while the medium- to long-term effect can remain a net cooling, or may become a sizeable net warming.

Third, the climate impact of forest conversion depends on the fate of the biomass cleared from forests. In this analysis, biomass removed from forests during conversion is assumed to have a fate that resembles national patterns of wood product uses, with three-quarters of the forest biomass carbon being emitted to the atmosphere within 100 years of conversion and assumed here to be emitted as CO_2 (see the Supplementary Materials). If biomass removals were actively directed toward long-lived wood products, particularly to substitute more greenhouse gas–intensive building materials, then the warming effect of forest loss would be directly reduced by 30 to 75% with some additional reduction due to the indirect effect of

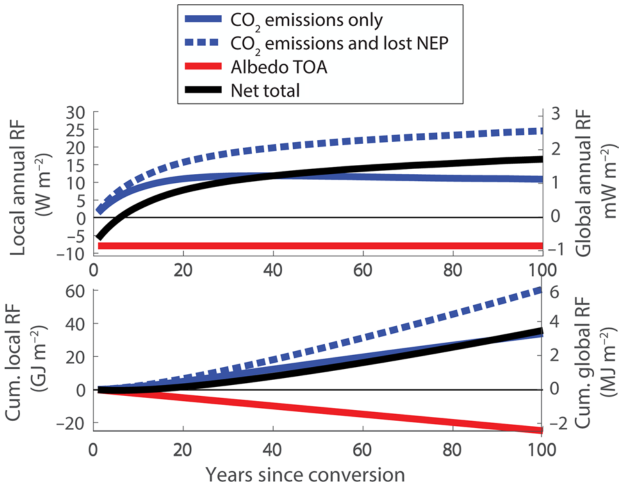

Fig. 2. Local mean annual instantaneous RFs from US forest conversions for the period 1986–2000 shown at local and global scales, and both annually and accumulated (Cum.) over years since conversion. Results correspond to the ensemble member with a stand age of 70 years, the middle biomass stock, the median Earth system uptake, and the CAM5 radiative kernel. TOA, top of atmosphere.

carbon emissions avoided by substitution of building materials (*27*, *28*). Together, this tilts the climate impacts of forest conversion toward cooling, but determining precisely how much would require detailed analysis.

Additional climate impacts of forest conversion warrant further study and could alter the summary conclusions presented here. While the soil carbon emissions from dead tree roots have been included in this study, it is unknown to what degree forest conversion produces additional carbon emissions from the organic and mineral soil that have not been included here. Recent studies report large spread and remain largely inconclusive (*29*–*31*). Long-term sequestration of atmospheric carbon in biomass or soils might resume in some post-conversion land cover types, potentially reducing the loss of NEP represented in this study. However, among global lands, forests represent the largest, most lasting sinks for atmospheric carbon (*9*), and thus, it is unlikely that postconversion sequestration would offset the loss of forest NEP. Emissions of volatile organic compounds (VOCs) by trees can warm or cool the planet via several unique mechanisms that have individual effects that can be as large as those of carbon emissions or surface albedo alone (*32*–*34*), and effects of VOCs have not been included here. Studies disagree about the magnitude of individual and combined effects of VOCs on climate and show large variation by region and forest type (*34*, *35*). This highlights an area in need of further study to reduce uncertainty and improve scientific understanding. Last, forest loss may decrease landscape-level evaporation, cloud formation, and planetary albedo, which have been shown to be particularly important in tropical regions but only a secondary factor in temperate and boreal zones (*14*, *25*, *26*). This may appear to be at odds with the conclusions from a number of recent observation-based studies (*36*, *37*), which suggest that nonradiative processes have a major influence even in temperate regions and that these processes can outweigh the albedo impact, for instance, by making trees cooler in summer compared to open land (despite the albedo-induced warming effect). However, the approach taken in those studies, of analyzing land surface temperature and the surface energy balance, does not quantify the global-scale climate change impact that can be equated to the effect of greenhouse gases in the atmosphere. Surface and planetary [top-of-atmosphere (TOA)] energy balance responses may oppose one another, and what matters most for the global mean climate is the radiative response at TOA.

RF remains a widely used and effective tool for assessing net climate impacts (*19*, *20*). However, nonadditivity of RF has been demonstrated and different RF agents such as local changes in surface albedo versus a well-mixed greenhouse gas can impose unique spatial patterns of global cooling or warming (*38*), making it an imperfect indicator. Future work may want to consider adopting the effective RF (ERF) concept to account for stratospheric adjustment, changes in tropospheric cloudiness, and other rapid adjustments in the climate system response to a forcing (*39*, *40*), thus reducing dependency of climate sensitivity on the agent causing the forcing, which helps mitigate issues with forcing-specific efficacy (*41*–*43*). However, the method for calculating ERF remains unsettled, ERFs can have a large spread across models due to rapid model-dependent feedbacks, and ERFs have large uncertainty relative to forcing when quantifying small forcings (*39*). Also, ERF radiative kernels would need to be made available for studies such as this, something that may be enabled by activities such as the recent Radiative Forcing Model Intercomparison Project whose simulations show that ERFs for historical land use tend to be about 70% as negative as IRFs (*40*).

This study shows that avoiding forest conversions can provide a modest climate change mitigation benefit in some regions of the United States but would be counterproductive in other regions. The mitigation benefits may be viewed as small when compared to U.S.-wide CO_2 emissions; however, this speaks more to the scale of the challenge of avoiding or offsetting those emissions as it does to the climate benefits of forest conservation. Furthermore, even where forest cover warms the planet, these forests may make important contributions to air and water quality, biodiversity, livelihoods, forest products, and recreation. Forest loss jeopardizes this suite of ecosystem service benefits, all of which deserve consideration alongside assessments of climate services.

MATERIALS AND METHODS

We adopt the widely used concept of RF to assess the climate impacts of forest conversion, including carbon emissions, lost carbon uptake, and albedo change. We compute the TOA radiative effect of changes in the global concentration of atmospheric CO_2 resulting from forest conversions and from changes in surface albedo with methods fully described in the Supplementary Materials and similar to those in prior studies (*44*, *45*). We apply these methods to consider the climate impact of hypothetical deforestation for any given location across the United States. Then, by pinpointing the actual locations of forest conversions with Landsat-based forest disturbance and land cover datasets, we quantify the actual climate impact of true forest conversions where they occurred from 1986 to 2000. We estimate carbon emissions with biomass from the North American Carbon Program (NACP) Aboveground Biomass and Carbon Baseline Dataset (*46*), adjusted to total live biomass based on U.S. Forest Service component ratios (*47*), and adopting emitted fractions consistent with the U.S. Forest Service Timber Products Output (*48*). We estimate annual NEP lost due to forest conversion based on a comprehensive set of published curves specific to regions and forest types (*49*). We computed the carbon-related forcing to Earth's TOA radiation budget imposed by a change in global atmospheric CO_2 concentration with the method of the IPCC (*50*), accounting for Earth system uptake of carbon emissions with CO_2 impulse response functions derived for 16 Earth system models (*51*). We estimated TOA RF from albedo changes based on blue-sky surface albedos derived from spaceborne observations of surface albedo under distinct illumination (direct or diffuse beam) and snow cover conditions (*52*), and extended to TOA with radiative kernels generated from general circulation model experiments involving each climate model's radiation code run off-line (*53*–*57*). We quantify uncertainty with a comprehensive ensemble from a full factorial combination of four dominant sources of uncertainty (108 members) reporting results for the median, 10th and 90th percentiles spanning the uncertainty range for (i) forest carbon stocks vulnerable to emission, (ii) forest carbon uptake that would be lost because of conversion, (iii) the rate at which the Earth system (ocean and land) removes anthropogenic emissions of CO_2, and (iv) the TOA RF resulting from a change in surface albedo. We adopted an equilibrium climate sensitivity (*58*, *59*) to estimate the mean 100-year global warming imposed by U.S. forest conversions from 1986 to 2000.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/7/7/eaax8859/DC1

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Acknowledgments: We thank P. Ellis of The Nature Conservancy for providing insights on methods for computing forest conversion rates and associated carbon emissions. We thank F. Zhao and C. Huang of the University of Maryland, College Park for providing maps of annual forest cover. **Funding:** This study was made possible by funding from NASA's Carbon Monitoring System program under awards NNX14AR39G and NNX16AQ25G. **Author contributions:** C.A.W. conceived the work, performed all analyses, generated figures, and wrote the manuscript. H.G. quantified forest loss and land cover types gained. T.J. prepared albedo change maps and datasets. All authors discussed methods and results and edited the manuscript. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 1 May 2019
Accepted 23 December 2020
Published 12 February 2021
10.1126/sciadv.aax8859

Citation: C. A. Williams, H. Gu, T. Jiao, Climate impacts of U.S. forest loss span net warming to net cooling. *Sci. Adv.* **7**, eaax8859 (2021).

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Sci. Adv., **7** (7), eaax8859.
DOI: 10.1126/sciadv.aax8859