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The Unseen Effects of Deforestation: Biophysical Effects on Climate

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Climate policy has thus far focused solely on carbon stocks and sequestration to evaluate the potential of forests to mitigate global warming. These factors are used to assess the impacts of different drivers of deforestation and forest degradation as well as alternative forest management. However, when forest cover, structure and composition change, shifts in biophysical processes (the water and energy balances) may enhance or diminish the climate effects of carbon released from forest aboveground biomass. The net climate impact of carbon effects and biophysical effects determines outcomes for forest and agricultural species as well as the humans who depend on them. Evaluating the net impact is complicated by the disparate spatio-temporal scales at which they operate. Here we review the biophysical mechanisms by which forests influence climate and synthesize recent work on the biophysical climate forcing of forests across latitudes. We then combine published data on the biophysical effects of deforestation on climate by latitude with a new analysis of the climate impact of the CO_2 in forest aboveground biomass by latitude to quantitatively assess how these processes combine to shape local and global climate. We find that tropical deforestation leads to strong net global warming as a result of both CO_2 and biophysical effects. From the tropics to a point between 30°N and 40°N, biophysical cooling by standing forests is both local and global, adding to the global cooling effect of CO_2 sequestered by forests. In the mid-latitudes up to 50°N, deforestation leads to modest net global warming as warming from released forest carbon outweighs a small opposing biophysical cooling. Beyond 50°N large scale deforestation leads to a net global cooling due to the dominance of biophysical processes (particularly increased albedo) over warming from CO_2 released. Locally at all latitudes, forest biophysical impacts far outweigh CO_2 effects, promoting local climate stability by reducing extreme temperatures in all seasons and times of day. The importance of forests for both global climate change mitigation and local adaptation by human and non-human species is not adequately captured by current carbon-centric metrics, particularly in the context of future climate warming.

Keywords: forest, biophysical effects, temperature, climate policy, deforestation/afforestation

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deforestation and all emitted CO_2 would have had an effect in a given band, but the point of the analysis was to isolate the temperature change caused by forests in a given latitude. We determined the latitudinal sensitivity to warming in response to added CO_2 from a re-analysis of global 2 m temperature data (CERA-20C) obtained from the European Centre for Medium-Range Weather https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/cera-20c. We compared average temperatures from 1901 to 1910 and 2001–2010, by latitude on land only (inadequate land only data for 50–60S and 80–90N; for those, we do not report a locally felt CO_2 effect). Then we divided the temperature change for each latitude band by the change in global temperature over the same period. We scaled the effect of CO_2 emitted by a given 10° latitude band by this sensitivity to represent the influence of non-linear responses such as polar amplification (see **Supplementary Information 1** and **Supplementary Table 2**).

RESULTS

Biophysical Effects of Deforestation on Local Climate: A Broader Context

Our analysis is the first to compare regional scale biophysical and CO_2 impacts from regional scale deforestation but the literature is replete with data on local biophysical impacts. The results for local biophysical effects (100s of m to 100s of km) agree with our results at the regional scale (below). **Figures 2, 3** synthesize local biophysically-driven temperature responses to deforestation, as indicated by forest/no-forest comparisons or forest change over time, from the scientific literature. Satellite and flux tower data indicate that surface temperatures in tropical forests are significantly lower than in cleared areas nearby. On an annual basis, local surface cooling of 0.2–2.4°C has been observed (mean 0.96°C; **Figure 2** and **Supplementary Information 2**). In the temperate zone, satellite studies of land surface temperature (which is more sensitive than the temperature of the air at 2 m) have shown biophysical cooling from forest cover, or biophysical warming from deforestation (0.02–1.0°C, mean of 0.4°C; see **Figure 2** and **Supplementary Information 2**). Both *in situ* and satellite data generally indicate an average annual cooling of under 1°C from boreal deforestation (**Figure 2**). Across latitudinal zones, warming from deforestation is generally greater during the day, and during the dry (hot) season (**Figure 3**).

CO_2-Induced Warming Versus Biophysical Effects on Regional (Local) Temperature From Deforestation by 10° Latitude Band

As expected, the regionally felt effect of regionally (10° band) produced CO_2 is very small compared to any individual biophysical effect or the sum of all non-CO_2 effects (**Figure 4**). These results indicate that the net impact of all non-CO_2 effects is negligible between 20 and 30N. Beyond 30N the local biophysical response to deforestation is cooling. In the broader literature, this latitude of net zero biophysical effect on local temperature is generally between 30 and 40N (**Figure 1**).

Biophysical Effects on Global Temperature From Deforestation by 10° Latitude Band

For most latitudinal bands, the strongest biophysical effect of deforestation is cooling from albedo changes. In the tropics, however, the warming effect of lost roughness is comparable to or greater than the albedo effect (**Figure 5A**). Adding the warming from lost evapotranspiration, the net biophysical effect from tropical deforestation is global warming, as much as 0.1°C contributed each by latitudes 0°–10°S and 0°–10°N. The net biophysical effect of intact tropical forest, therefore, is global cooling; slightly more cooling if BVOCs are also considered (see **Figure 5B**). Roughness effects are generally greater than evapotranspiration effects across latitudes providing a strong counterbalance to albedo effects (Davin and de Noblet-Ducoudré, 2010; Burakowski et al., 2018; Winckler et al., 2019b; **Figure 5A**). Albedo almost balances the combined effect of roughness, evapotranspiration, BVOC and non-linear effects between 20 and 30°N resulting in close to zero net biophysical effect on global temperature (**Figure 5B**). From 30–40°N and northward, albedo dominates, and the net biophysical effect of deforestation is cooling.

CO_2-Induced Warming Versus Biophysical Effects on Global Temperature From Deforestation by 10° Latitude Band

From 30°S to 30°N, the biophysical effect of deforesting a given 10° latitudinal band is about half as great and in the same direction as the CO_2 effect: global warming. Biophysical warming is around 60% as great as warming from released CO_2 in the outer tropics (20°S–10°S and 10°N–20°N) and about 35% as great in the heart of the tropics (10°S–10°N). Biophysical cooling due to deforestation from 30°N to 40°N offsets about 40% of the warming associated with carbon loss from deforestation; from 40°N to 50°N biophysical effects offset 85% of CO_2 effects (**Figure 5B**). Above 50°N, biophysical global cooling is 3–6 times as great as CO_2 induced global warming. The net impact of deforestation (effects of CO_2, biophysical processes and BVOC combined) is warming at all latitudes up to 50N (**Figure 5C**). Thus, from 50S to 50N, an area that encompasses approximately 65% of global forests (FAO, 2020), deforestation results in global warming (**Figure 5C**).

DISCUSSION

All Forests Provide Local Climate Benefits Through Biophysical Effects

Ignoring biophysical effects on local climate means casting aside a powerful inducement to promote global climate goals and advance forest conservation: local self-interest. The

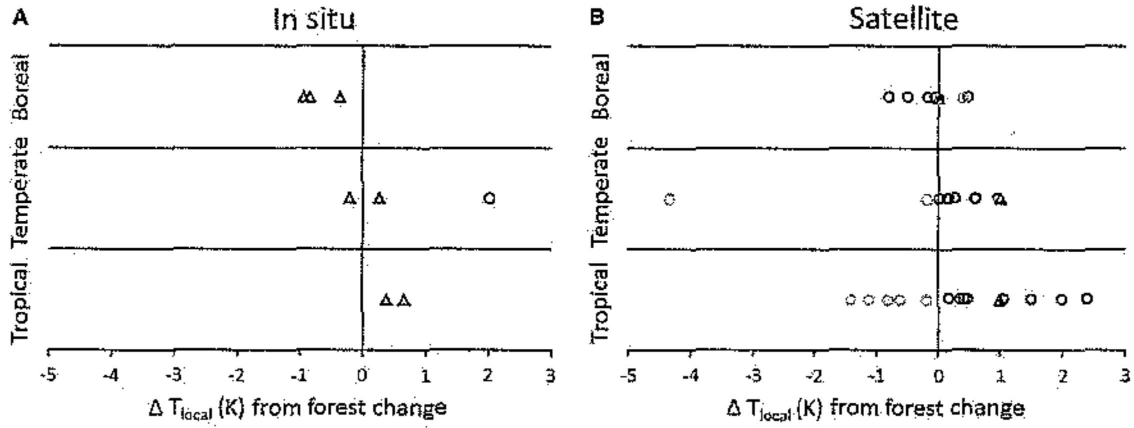

FIGURE 2 | Local average annual temperature change in response to deforestation (black symbols) or afforestation (green symbols) as determined by comparing neighboring forested and open land (space for time approach) or measuring forest change over time in the tropics, temperate and boreal zones, by **(A)** *in situ* or **(B)** satellite based land surface temperature measurements (0 m, triangles) or air temperature measurements (2 m, circles). See **Supplementary Information 2** for data sources.

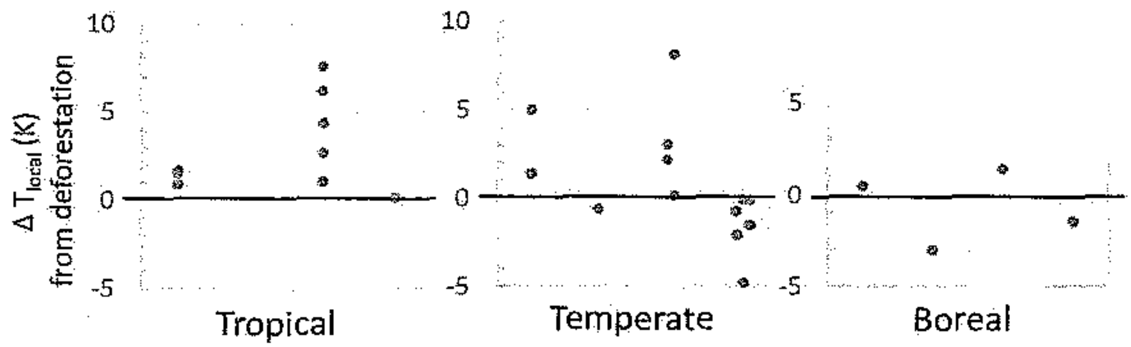

FIGURE 3 | Local temperature change in response to deforestation by season and time of day in the various climate zones as determined by comparing neighboring forested and open land (space for time approach) or measuring forest change over time. Warm/dry season response, averaged over the entire diurnal cycle, in red shading and cold/wet season response in blue shading. Daytime response, averaged over the entire annual cycle, in yellow shading and nighttime response in gray shading. See **Supplementary Information 3** for data sources.

biogeochemical effect of forests tends to dominate the biophysical effect at the global scale because physical effects in one region can cancel out effects in another. Nevertheless, biophysical effects are very important, and can be very large, at the local scale (e.g., Anderson-Teixeira et al., 2012; Bright et al., 2015; Jiao et al., 2017; **Figures 2–4**). The role of forests in maintaining critical habitat for biodiversity is well known, but new research on extinction confirms the role of forests in maintaining critical climates to support biodiversity. Changes in maximum temperature are driving extinction, not changes in average temperature (Román-Palacios and Wiens, 2020). Deforestation is associated with an increase in the maximum daily temperature throughout the year in the tropics and during the summer in higher latitudes (Lee et al., 2011; Zhang et al., 2014). Of course deforestation also increases average daytime temperatures in boreal, mid-latitude and tropical forests (**Figure 3**). The biophysical effects of forests also moderate local and regional temperature extremes such that extremely hot days are significantly more common following deforestation even in the mid- and high latitudes (Vogel et al., 2017; Stoy, 2018). Historical deforestation explains ~1/3 of the present day increase in the intensity of the hottest days of the year at a given location (Lejeune et al., 2018). It has also increased the frequency and intensity of hot dry summers two to four fold (Findell et al., 2017). Local increases in extreme temperatures due to forest loss are of comparable magnitude to changes caused by 0.5°C of global warming (Seneviratne et al., 2018). Forests provide local cooling during the hottest times of the year anywhere on the planet, improving the resilience of cities, agriculture, and conservation areas. Forests are critical for adapting to a warmer world.

Forests also minimize risks due to drought associated with heat extremes. Deep roots, high water use efficiency, and high surface roughness allow trees to continue transpiring during drought conditions and thus to dissipate heat and convey moisture to the atmosphere. In addition to this direct cooling, forest ET can influence cloud formation (Stoy, 2018), enhancing albedo and potentially promoting rainfall. The production of BVOCs and organic aerosols by forests accelerates with

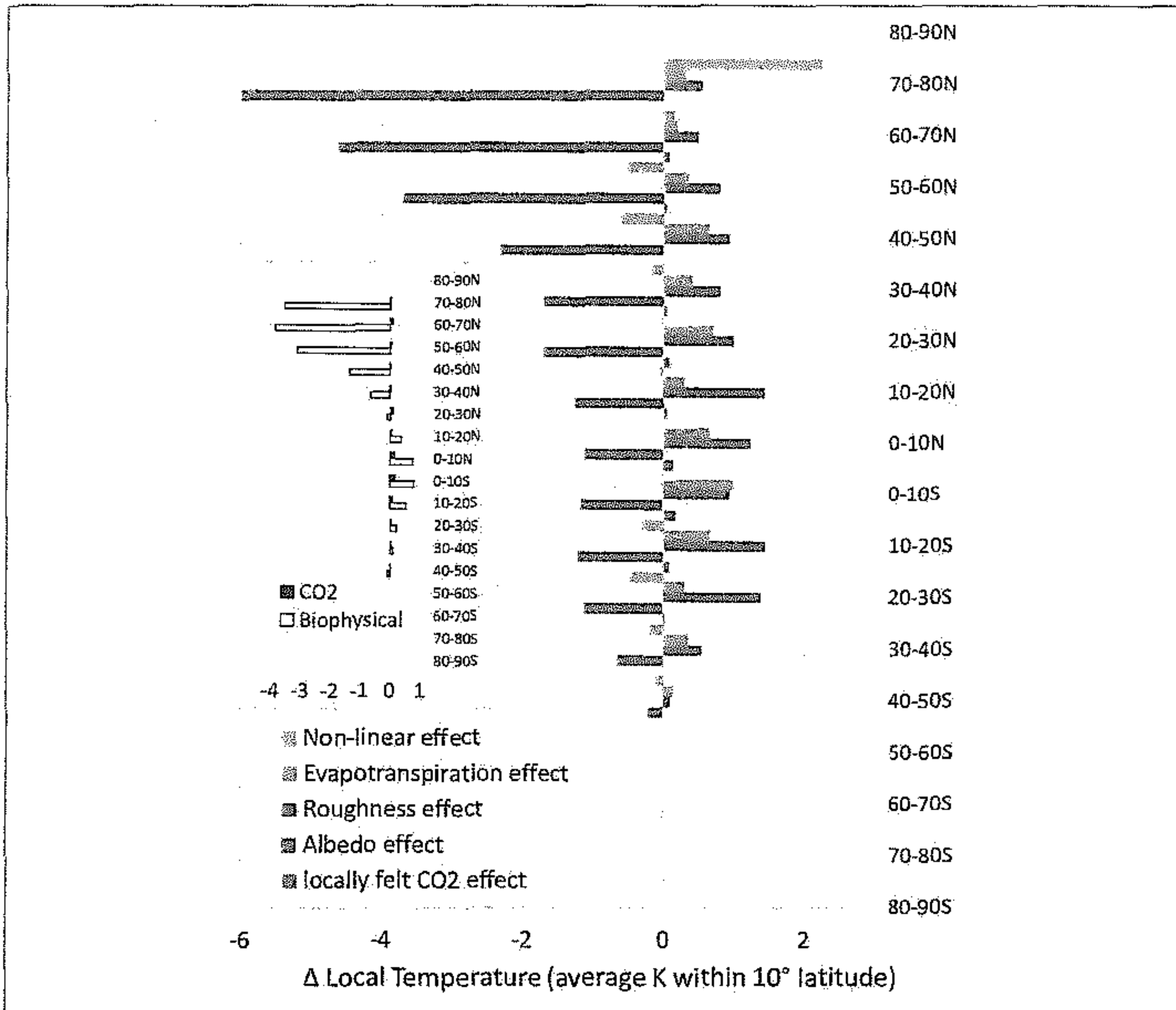

FIGURE 4 | Effect of complete deforestation on local annual temperature by climate factor, averaged across the land surface within a 10° latitudinal band. Complete deforestation was implemented globally and analyzed by 10° latitudinal bands (Davin and de Noblet-Ducoudré, 2010). The CO_2 effect was determined from total aboveground biomass in each 10° band after Walker et al. (2020) and scaled by CERA-derived sensitivity by latitude. Inset distinguishes the sum of all local biophysical effects from local CO_2 effects.

increasing temperatures, enhancing direct or indirect (cloud formation) albedo effects. This negative feedback on temperature has been observed to counter anomalous heat events in the mid-latitudes (Paasonen et al., 2013).

Some Forests Provide Global Climate Benefits Through Biophysical Effects

Disregarding the biophysical effects of specific forests on global climate means under-selling some forest actions and over-selling others. The response to local forest change is not equivalent for similar sized areas in different latitudes. According to Arora and Montenegro (2011) warming reductions per unit reforested area are three times greater in the tropics than in the boreal and northern temperate zone due to a faster carbon sequestration rate magnified by year-round biophysical cooling. Thus, considering biophysical effects significantly enhances both the local and global climate benefits of land-based mitigation projects in the tropics (see **Figures 4, 5**).

Constraints on Forest Climate Benefits in the Future

Climate change is likely to alter the biophysical effect of forests in a variety of ways. Deforestation in a future (warmer) climate could warm the tropical surface 25% more than deforestation

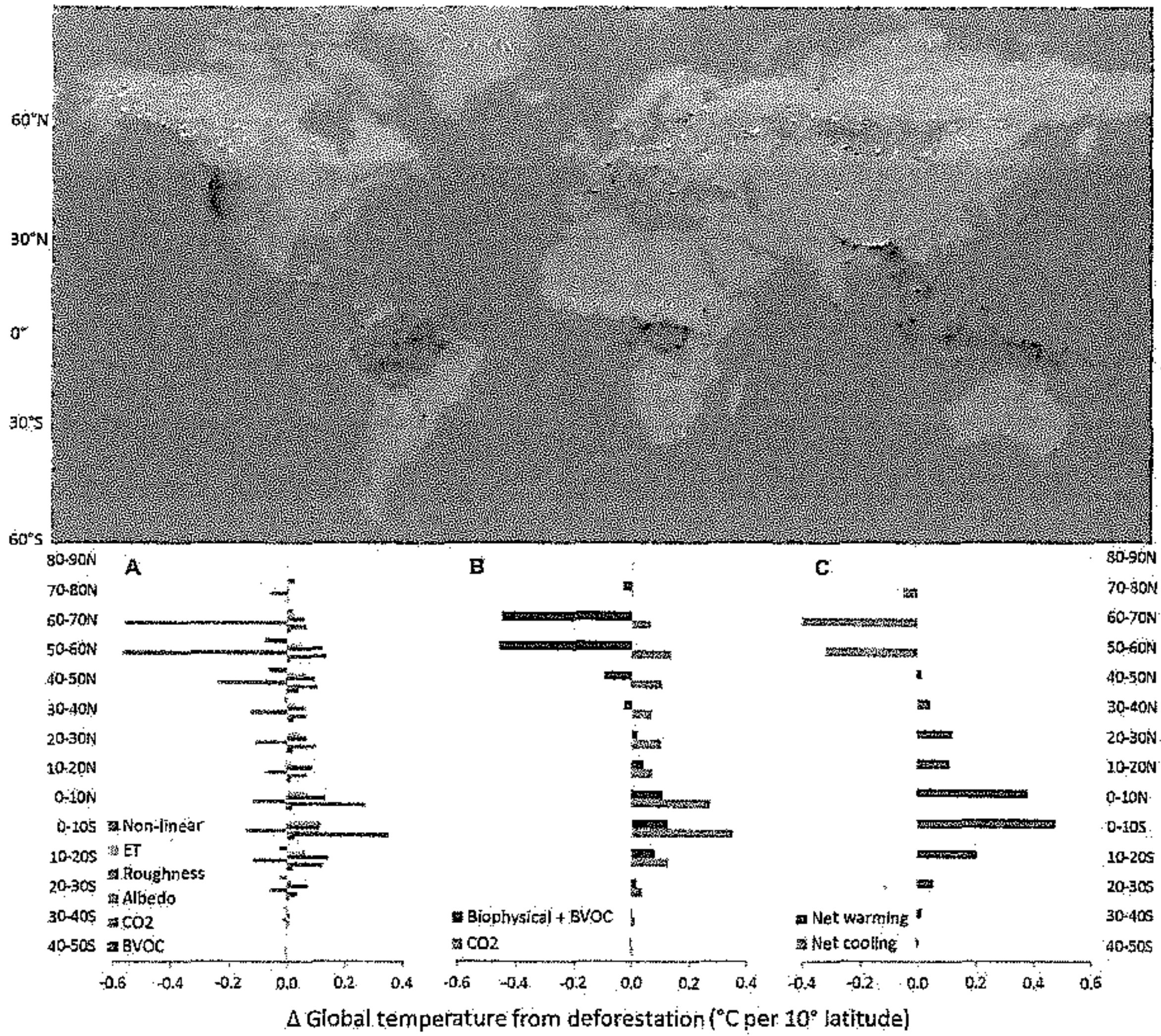

FIGURE 5 | Effect of complete deforestation on global temperature by 10° band of latitude. **(A)** Contribution to global temperature change by climate forcing factor. Biophysical factors are from Davin and de Noblet-Ducoudré, 2010, area-weighted. BVOC effects are estimated relative to albedo effects based on Scott et al., 2018. CO_2 effect is based on aboveground live biomass for each 10° latitudinal band following Baccini et al., 2017 and Walker et al., 2020. **(B)** Net biophysical and BVOC effect versus CO_2 effect. **(C)** Cooling or warming effects of deforestation by 10° latitudinal band (BVOC included). "Forests as mountains" map of aboveground biomass carbon in woody vegetation ca. 2016 courtesy of Woodwell Climate Research Center and shaded to indicate where deforestation results in net global warming. See **Supplementary Information 1** for details.

in a present-day climate due to stronger decreases in turbulent heat fluxes (Winckler et al., 2017b). In a warmer climate, reduced snow cover in the temperate and boreal regions will lead to a smaller albedo effect and thus less biophysical cooling with high latitude deforestation. In addition to snow cover change, future rainfall regimes will affect the response of climate to changes in forest cover (Pitman et al., 2011) as rainfall limits the supply of moisture available for evaporative cooling. Increases in water use efficiency due to increasing atmospheric CO_2 may reduce evapotranspiration (Keenan et al., 2013), potentially reducing the local cooling effect of forests and altering atmospheric moisture content and dynamics at local to global scales. Future BVOC production may increase due to warming and simultaneously decline due to CO_2 suppression (Lathière et al., 2010; Unger, 2014; Hantson et al., 2017). The physiological and ecological responses of forests to warming, rising atmospheric CO_2 and changing precipitation contribute to uncertainty in the biophysical effect of future forests on climate.

Forest persistence is essential for maintaining the global benefits of carbon removals from the atmosphere and the local and global benefits of the physical processes described above. Changing disturbance regimes may limit forest growth and regrowth in many parts of the world. Dynamic global vegetation models currently show an increasing terrestrial carbon sink in the future. This sink is thought to be due to the effects of fertilization by rising atmospheric CO_2 and N deposition on plant growth as well as the effects of climate change lengthening the growing season in northern temperate and boreal areas (Le Quéré et al., 2018). Free-air carbon dioxide enrichment (FACE) experiments often show increases in biomass accumulation under high CO_2 but results are highly variable due to nutrient limitations and climatic factors (Feng et al., 2015; Paschalis et al., 2017; Terrer et al., 2018). Climate change effects on the frequency and intensity of pest outbreaks are poorly studied, but are likely to be significant, particularly at the margins of host ranges. Warmer springs and winters are already increasing insect-related tree mortality in boreal forests through increased stress on the tree hosts and direct effects on insect populations (Volney and Fleming, 2000; Price et al., 2013).

Climate also affects fire regimes. In the tropics, fire regimes often follow El Niño cycles (van der Werf et al., 2017). As temperatures increase, however, fire and rainfall are decoupled as the flammability of forests increases even in normal rainfall years (Fernandes et al., 2017; Brando et al., 2019). Fire frequency is also increasing in some temperate and boreal forests, with a discernable climate change signal (Abatzoglou and Williams, 2016). Modeling exercises indicate that this trend is expected to continue with increasing damage to forests as temperatures rise and fire intensity increases (De Groot et al., 2013).

In addition to changes induced by warming, continued deforestation could severely stress remaining forests by warming and drying local and regional climates (Lawrence and Vandecar, 2015; Costa et al., 2019; Gatti et al., 2021). In the tropics, a tipping point may occur, potentially resulting in a shift to shorter, more savannah-like vegetation and altering the impact of vast, previously forested areas on global climate (Nobre et al., 2016; Brando et al., 2019). Some of these processes are included in climate models and some are not. The gaps leave considerable uncertainty. Nevertheless, a combination of observations, models, and theory gives us a solid understanding of the biophysical effects of forests on climate at local, regional and global scales. We can use that knowledge to plan forest-based climate mitigation and adaptation.

Mitigation Potential of Forests: Byond the Carbon/Biophysical Divide

If instead of focusing on the contrast between biophysical and biochemical impacts of forests and forest loss, we focus on the potential of forests to cool the planet through both pathways, another picture emerges. By our conservative estimate, through the combined effects on CO_2, BVOC, roughness and evapotranspiration, forests up to 50°N provide a net global cooling that is enough to offset warming associated with their low albedo. Given the most realistic pathways of forest change in the future (not complete deforestation of a 10° latitudinal band, or an entire biome), global climate stabilization benefits likely extend beyond 50°N. For the 29% of the global land surface that lies beyond 50°N, forests may warm the planet, but only as inferred from assessing the effects of complete zonal deforestation with all the associated, and powerful, land-ocean feedbacks spawned by largescale forest change in the boreal zone. Forests above 50°N, like forests everywhere, provide essential local climate stabilization benefits by reducing surface temperatures during the warm season as well as periods of extreme heat or drought. Indeed, they also reduce extreme cold.

Creating a fair and effective global arena for market-based solutions to climate change requires attention to all the ways that forests affect climate, including the biophysical effects. Future metrics of forest climate impacts should consider the effects of deforestation beyond CO_2. Only recently have modelers begun to include BVOC. Doing so means that the albedo of intact forests (or the atmosphere above them) is higher due to the creation of SOA and subsequent cloud formation. Modeled deforestation thus results in less of a change in albedo, reducing the biophysical cooling effect. Similarly, accounting for the ozone and methane effects of BVOC reduces the biogeochemical warming from deforestation (Scott et al., 2018). In addition, especially in the tropics, deforestation reduces the strength of the soil CH_4 sink (Dutaur and Verchot, 2007). While a small change relative to the atmospheric pool of CH_4 (the second most important greenhouse gas), the loss of this sink is equivalent to approximately 13% of the current rate of increase in atmospheric CH_4 (Saunois et al., 2016). We already have the data (**Figure 5**) to begin conceptualizing measures to coarsely scale CO_2 impacts of forest change by latitude. Finer resolution of latitude, background climate (current and future) and forest type would improve any such new, qualifying metric for the climate mitigation value of forests.

The role of forests in addressing climate change extends beyond the traditional concept of CO_2 mitigation which neglects the local climate regulation services they provide. The biophysical effects of forest cover can contribute significantly to solving local adaptation challenges, such as extreme heat and flooding, at any latitude. The carbon benefits of forests at any latitude contribute meaningfully to global climate mitigation. In the tropics, however, where forest carbon stocks and sequestration rates are highest, the biophysical effects of forests amplify the carbon benefits, thus underscoring the critical importance of protecting, expanding, and improving the management of tropical forests. Perhaps it is time to think more broadly about what constitutes global climate mitigation. If climate mitigation means limiting global warming, then clearly the biophysical effects of deforestation must be considered in addition to its effects on atmospheric CO_2. We may further consider whether mitigation is too narrow a scope for considering the climate benefits provided by forests. Climate policy often separates mitigation from adaptation, but the benefits of forests clearly extend into both realms.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

DL conceived the presented idea. All authors helped perform the computations, discussed the results, and contributed to the final manuscript.