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REVIEW

Even cooler insights: On the power of forests to (water the Earth and) cool the planet

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Abstract

Scientific innovation is overturning conventional paradigms of forest, water, and energy cycle interactions. This has implications for our understanding of the principal causal pathways by which tree, forest, and vegetation cover (TFVC) influence local and global warming/cooling. Many identify *surface albedo* and *carbon sequestration* as the principal causal pathways by which TFVC affects global warming/cooling. Moving toward the outer latitudes, in particular, where snow cover is more important, surface albedo effects are perceived to overpower carbon sequestration. By raising surface albedo, deforestation is thus predicted to lead to surface cooling, while increasing forest cover is assumed to result in warming. Observational data, however, generally support the opposite conclusion, suggesting surface albedo is poorly understood. Most accept that surface temperatures are influenced by the interplay of surface albedo, incoming shortwave (SW) radiation, and the partitioning of the remaining, *post-albedo*, SW radiation into latent and sensible heat. However, the extent to which the avoidance of sensible heat formation is first and foremost mediated by the presence (absence) of water and TFVC is not well understood. TFVC both mediates the availability of water on the land surface and drives the potential for latent heat production (evapotranspiration, ET). While latent heat is more directly linked to *local* than *global* cooling/warming, it is driven by photosynthesis and carbon sequestration and powers additional cloud formation and top-of-cloud reflectivity, both of which drive global cooling. TFVC loss reduces water storage, precipitation recycling, and downwind rainfall potential, thus driving the reduction of both ET (latent heat) and cloud formation. By reducing latent heat, cloud formation, and precipitation, deforestation thus powers warming (sensible heat formation), which further diminishes TFVC growth (carbon sequestration). Large-scale tree and forest restoration could, therefore, contribute significantly to both global and surface temperature cooling through the principal causal pathways of carbon sequestration and cloud formation.

KEYWORDS
boreal, carbon, clouds, deforestation, forest cooling, latent heat, latitude, planetary boundaries, reforestation, restoration, solar radiation, surface albedo, surface temperature, temperate, tropics

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1 | INTRODUCTION

The contributions of tree, forest, and vegetation cover (TFVC) to watering the Earth through the dynamics of infiltration and groundwater recharge, water storage on the land surface, rainfall triggering, precipitation recycling, and the regulation of the geographical distribution of precious water resources are increasingly well understood (Creed & van Noordwijk, 2018; Dada et al., 2023; Ellison et al., 2012, 2017, 2019; Hoek van Dijke et al., 2022; Keys et al., 2019; Makarieva et al., 2022; Meier et al., 2021; Morris, 2018; Morris et al., 2014; Sheil & Murdiyarso, 2009; Tanika et al., 2023). Though highly variable in the magnitude of their respective contributions and expressly subject to human modification via land use conversion, TFVC produce varying magnitudes of evapotranspiration (ET) (the total amount of stomatal *transpiration + evaporation* from leaf, bark, and soil surfaces, typically referred to as *evapotranspiration*), encourage infiltration and groundwater recharge, and promote the potential for precipitation recycling across the land surface. The flip side of this *watering the Earth* phenomenon, however, that is, the ability of TFVC to *cool the planet*, remains more hotly contested (Ban-Weiss et al., 2011; Bright et al., 2017; Davin & de Noblet-Ducoudré, 2010; Duveiller et al., 2021; Lawrence et al., 2022; Su et al., 2023; Windisch et al., 2021). Briefly highlighted in a previous publication (Ellison et al., 2017), the current paper identifies the causal pathways by which TFVC affects the climate; *carbon sequestration (and respiration)*, *surface albedo effects*, *latent heat production* (*evapotranspiration*), and *cloud formation*, and explicitly links these causal pathways with their surface temperature and climate impacts.

Since human capacity to withstand solar radiation is buffered by the TFVC-related albedo and latent heat impact on surface temperatures, average change in temperature is typically measured at the planet's surface (Rohde & Hausfather, 2020). Human welfare impacts alone may thus explain why the assessment of climate is primarily viewed through the lens of change in average, terrestrial, *surface* temperatures (see, e.g., Rohde & Hausfather, 2020; Trenberth, 2022). However, since changes in surface temperatures can be affected by more than just climate change, climate assessments based on surface temperature diagnostics are substantively more ambiguous. Such measurements easily conflate global warming/cooling with other impacts on temperature. Thus, a strategy capable of carefully distinguishing the different pathways by which TFVC can influence surface temperature differences, on the one hand, and TFVC factors that influence climate change on the other. A more disaggregated account of the principal TFVC causal pathways may help to better clarify the different types of *direct* (on global climate) and *indirect* (on temperature and potentially on climate) effects.

The analysis herein assesses the multiple causal pathways by which TFVC affects local *and* global warming/cooling and raises questions regarding "change in surface temperature" as the most appropriate diagnostic metric for understanding TFVC-related global warming and climate change impacts. We employ two alternative diagnostic criteria to assess the causal pathways by which TFVC effects are linked to impacts on temperature and the Earth's Energy Imbalance (EEI) (Trenberth, 2022)—atmospheric carbon dioxide (CO_2) and greenhouse gases (GHGs) concentrations, and global energy budget fluxes. These alternative diagnostics provide a more nuanced view of how different TFVC causal pathways affect both temperature and the EEI and thus improve our knowledge of what TFVC effects mean for global warming and climate change.

The TFVC drivers of change in the EEI operate through *largely independent*, but often *mutually reinforcing* causal pathways. In the broader literature, the analyzed mix of causal pathways varies importantly from study to study and individual impacts are frequently debated. Thus, precise estimates of the multiple causal pathways by which TFVC affects either surface temperature, climate, or both are frequently missing. Moreover, the effects of ET and cloud formation are frequently underestimated or entirely neglected and, for several reasons, may be the largest, most important outlier. To live up to their name, *net effect models* need to consider the combined effects of all relevant causal pathways. A comparatively small number of papers have, however, more strongly emphasized the roles of both ET and cloud cover and come to markedly different conclusions (Ban-Weiss et al., 2011; Duveiller et al., 2021; Xu et al., 2022; Zeng et al., 2017).

Most findings, however, suggest that, as one moves toward the outer latitudes, TFVC *surface albedo* effects begin to overpower forest cooling impacts (*carbon sequestration*), leading to increased warming. While reforestation is thus favored in the tropics, recommendations to "de-prioritize" reforestation across parts of the temperate boreal zones (Davin & de Noblet-Ducoudré, 2010; Lawrence et al., 2022; Windisch et al., 2021) represent a potential cause for concern. We highlight herein that the interplay of TFVC with surface albedo and the latent and sensible heat fluxes is poorly understood. Conversion of incoming SW radiation to sensible heat is first and foremost avoided by the availability of water and latent heat production potential. On land surfaces, TFVC drives the storage, circulation, and geographic distribution of water resources. Moreover, the extent and intensity of latent heat production is largely a by-product of the extent and geographic distribution of TFVC.

We begin with estimates of the forest role in atmospheric CO_2 concentrations and the EEI. We then detail the complexities of the surface albedo and the latent and sensible heat fluxes. We wrap up with a reflective analysis of latitude effects and conclude by suggesting that TFVC restoration presents a very real opportunity for addressing the climate challenge.

2 | TFVC CAUSAL PATHWAYS AND THE EEI: ALTERNATIVE ASSESSMENT CRITERIA

2.1 | Atmospheric CO_2 concentrations and the carbon drawdown

One alternative and potentially more reliable way to think about the EEI is via the rise of heat trapping and atmospheric CO_2 concentrations (Figure 1). In contrast to the easily confounded measure of

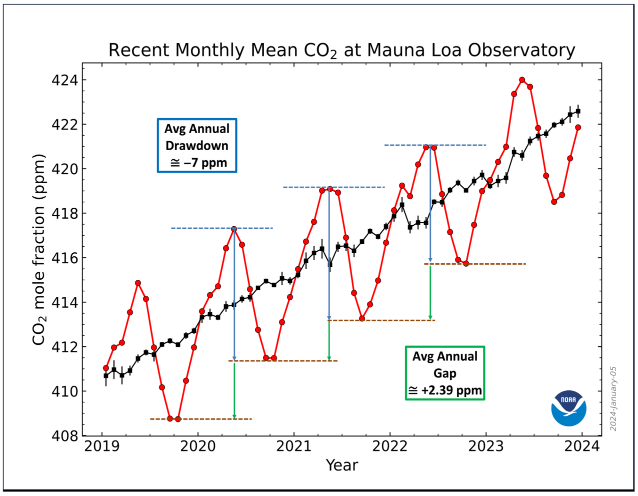

FIGURE 1 Atmospheric CO$_2$ concentrations, Mauna Loa Observatory. The figure shows mean monthly values (red) and 7-month smoothed values (black) of the so-called *Keeling* curve. *Source*: Adapted from NOAA. We have added the arrows illustrating the drawdown and the annual gap and added the estimates of the annual gap and the annual drawdown based on IPCC estimates (IPCC AR6 WGI Ch5).

surface temperature change, change in atmospheric CO$_2$ concentrations provides a comparatively more *direct* measure of one of the principal drivers of change in the EEI.

The annual CO$_2$ drawdown from the atmosphere by TFVC is driven by the growing season's binding of carbon and release of oxygen to produce living biomass. The combined TFVC and oceanic drawdown has been consistently recorded at approximately −7 ppm per annum. The amplitude of the TFVC drawdown may be increasing over time, but results remain inconclusive (Piao et al., 2018). Since respiration from the forest floor back into the atmosphere, as well as the anthropogenic emissions of CO$_2$ and other GHGs, exceed the annual drawdown, the heat-trapping potential of atmospheric GHG concentrations continuously rises. The total annual recorded drawdown and re-emission imbalance has grown from about +0.82 ppm to approximately +2.39 ppm per year between 1960 and 2020 (IPCC AR6 WGI Ch5).

As highlighted by the disaggregated Keeling curve, the global cooling effect of the carbon drawdown is *direct*, immediate, and unambiguous. Apart from the role of oceans which also absorb roughly equivalent amounts of carbon dioxide from the atmosphere, forest growth results in an annual drawdown of CO$_2$ from the atmosphere unparalleled by any other Earth system or technological device. While other factors (permanence, disturbances, etc.) may generate concerns about the long-term benefits of forest carbon, the climate impact of the natural carbon sequestration process itself is not in doubt.

The total gross annual TFVC drawdown of carbon dioxide amounts to approximately −12.5 ± 3.2 GtCO$_2$-eq year^{-1} (IPCC AR6 WGIII Ch7). This drawdown represents an important share of the total annual cooling impact of forests on the climate. The additional forest cover required to yield an additional annual drawdown of approximately −2.39 ppm CO$_2$, and thus a stabilization of current atmospheric CO$_2$, would have to generate an annual removal of approximately −8.53 GtCO$_2$-eq year^{-1} (calculated based on information provided in IPCC AR6 WGI Ch5).

Given that annual deforestation-related emissions are estimated at approximately +5.9 ± 4.1 GtCO$_2$-eq year^{-1} (IPCC AR6 WGIII Ch7), much of the additional required drawdown could be achieved by significantly reducing or eliminating ongoing deforestation and land use change. Roe et al. (2021), on the other hand, estimate the total *cost-effective* land-based mitigation potential at approximately −8 to −13.8 GtCO$_2$-eq year^{-1}. Likewise, as estimated in Table 1 below, restoring historically lost (pre-Anthropocene) TFVC would approximately add from −8.3 to −13.8 GtCO$_2$-eq year^{-1}. Moreover, TFVC thrives on increasing atmospheric CO$_2$ concentrations, which have significantly boosted TFVC greening (Zeng et al., 2017). Likewise resulting from absorbing excessive amounts of CO$_2$, ocean acidification, on the other hand, is comparatively harmful to life in the oceans (Kowalczyk & Lee, 2022), suggesting that absorbing more CO$_2$ with increasing TFVC could provide additional benefits.

Finally, though sometimes counterintuitive, strategies such as sustainable forest management and the innovation of the circular, bio-based economy, which reduces respiration and accelerates carbon sequestration, may help promote additional positive forest impacts on the Earth's radiative balance (Churkina et al., 2020; Gustavsson et al., 2021; Petersson et al., 2022). Forest resource use can potentially further accelerate atmospheric CO$_2$ drawdown through harvest, forest regeneration, and the reduction of respiration (since mature wood resources end up in wood-based products and do not decay in the forest). Producing and storing long-lived harvested wood products in the built environment (buildings, railroads, furniture, etc.), while substituting fossil fuel-intensive products (e.g., concrete, steel, glass, plastics) and using harvest residues and end-of-life-cycle wood resources for additional substitution (bioenergy production) likewise have additional positive mitigation benefits (Churkina et al., 2020; Gustavsson et al., 2021; Petersson et al., 2022; Sathre & O'Connor, 2010). Further, forest landscape restoration focused on deforested and degraded landscapes has important, positive climate benefits (Griscom et al., 2017; Mo et al., 2023; Roe et al., 2021).

2.2 | The Earth's Energy Imbalance

The estimated imbalance in the exchange of solar radiation between the sun, the Earth's surface, and the re-release of thermal longwave radiation back into space, provides a second alternative diagnostic (Figures 2 and 3). Long-term imbalances directly affect global warming/cooling. Increasing concentrations of CO$_2$ and other GHGs in the Earth's atmosphere create an important physical barrier to the release of thermal emissions back into space. The principal drivers of the EEI are thus increasing atmospheric CO$_2$ and other GHG concentrations. Not easily removed from the atmosphere and with variously long decay rates, CO$_2$ and GHGs are unambiguous, long-term EEI forcers.

TABLE 1 Estimating potential outgoing radiative flux from historical forest cover gain/(loss).

Estimated effect of increased forest cover on the net radiative balance (EEI) and TFVC drawdown	Estimated historical forest cover loss −30%	−40%	−50%	Formulas (FAO estimate)	Logic Cropland + urban settlement conversions
Land latent heat flux (LHF, Wm^2)	38.0	38.0	38.0	(Wild et al., 2015)	Terrestrial latent heat flux
Current annual TFVC CO_2 drawdown ($GtCO_2$-eq $year^{-1}$)	−12.5	−12.5	−12.5	IPCC AR6 WGIII Ch7	Annual TFVC drawdown
Lost latent heat flux (compared to 100% forest cover, Wm^2)	−16.3	−25.3	−38.0	=(LHF/FC) × (1 − FC)	Lost terrestrial latent heat flux (assuming all land can be converted)
Potential LHF (PLHF) with cropland conversion to forest (Wm^2)	6.5	10.1	15.2	=(*x* × 0.80) × (1–0.5)	Potential additional terrestrial latent heat flux assuming only agricultural land (80% of total loss) can be converted—Cropland LHF = 50% × forest LHF
% Increase in latent heat flux (assume 100% cropland conversion to forest, minus cropland evapotranspiration flux)	15%	21%	29%	=PLHF/LHF	Potential % increase in LHF
Change in top-of-cloud OLW (assuming initial 28 Wm^2 OLW flux)	1.2	1.7	2.3	=(28 × (PLHF/LHF)) × 0.29	Estimated change in outgoing longwave flux (adj. for 29% land cover)—increases in cloud cover reduce the OLW flux
Change in top-of-cloud OSW (assuming 64 Wm^2 outward reflectivity)	−2.7	−3.9	−5.3	= − (64 × (PLHF/LHF)) × 0.29	Estimated change in outgoing SW flux (adj. for 29% land cover)—increases in cloud cover increase the OSW flux
Estimated change in EEI from change in cloud cover (Wm^2)	−1.5	−2.2	−3.0	=SUM (ΔOLW + ΔOSW)	Potential change in EEI from increased cloud cover
Estimated change in total annual TFVC drawdown ($GtCO_2$ eq $year^{-1}$)	−5.4	−8.3	−12.5	=(DD/FC) × (1 − FC)	Potential change in TFVC drawdown from increased TFVC

Note: Based on assumptions about forest cover loss and the latent heat flux over land. Data on the land-based latent heat flux are taken from Wild et al. (2015). Initial top-of-cloud outward longwave (OLW) and shortwave fluxes (OSW) taken from Figure 1. Potential change in the global Earth's Energy Imbalance (EEI) based on net change in the principal OSW-OLW over land is highlighted in gold. Potential change in the tree, forest, and vegetation cover (TFVC) drawdown of carbon from the atmosphere is highlighted in green. Though the EEI and the TFVC drawdown are expressed in different units (Wm^2 vs. $GtCO_2$-eq), the impact of the current EEI is roughly equivalent to that of the total potential TFVC drawdown of approximately −8.53 $GtCO_2$-eq^{-1}.

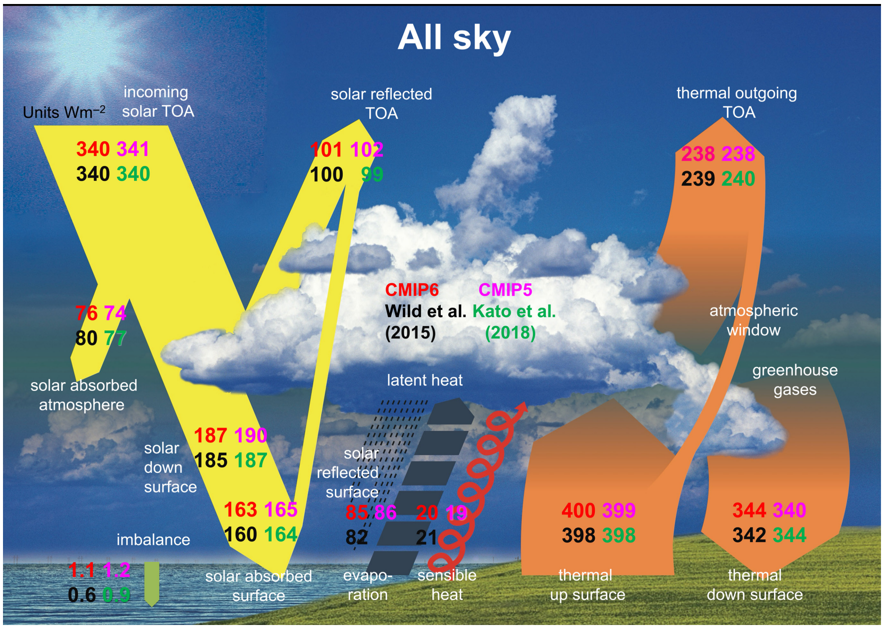

FIGURE 2 Earth's energy budget expressed as total, global amounts of incoming and outgoing shortwave radiation (yellow) and longwave emissions (orange). *Source*: Wild (2020). The energy flux values from different sources are represented in red (CMIP6 multi-model mean), pink (CMIP5 multi-model mean), black (Wild et al., 2019), and green (Kato et al., 2018). TOA, top-of-atmosphere.

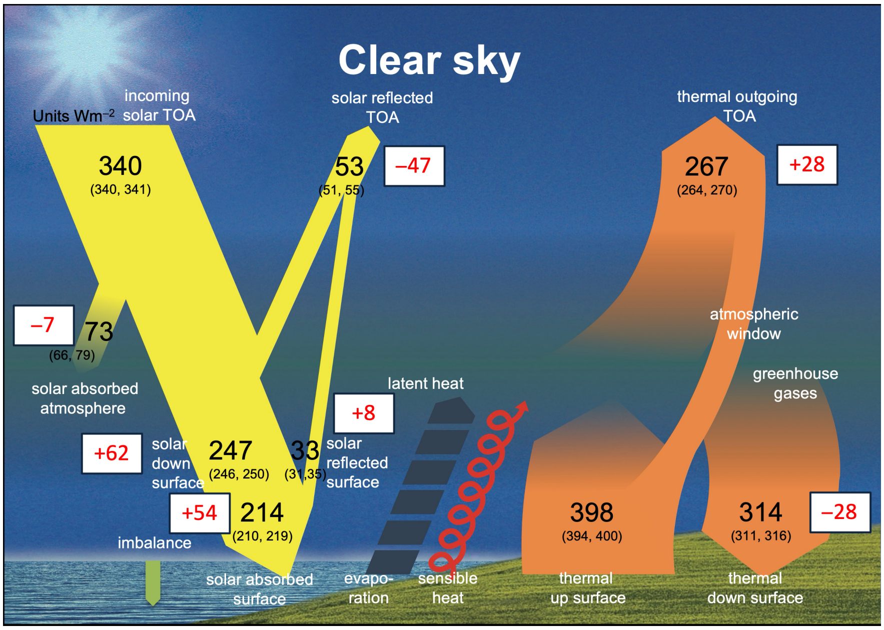

FIGURE 3 Global energy budget under clear skies. *Source*: Adapted from Wild (2020) and Wild et al. (2019). The numbers in red added here compare the clear sky change to Wild's representation of the conventional energy budget with clouds (Wild, 2020). TOA, top-of-atmosphere.

The annual net exchange of radiation between the Earth's surface and space is out of balance. This imbalance has grown over the last half-century from a total of approximately $+0.5 \pm 0.185\,\mathrm{Wm}^2$ for the period 1971–2006, to $+0.79 \pm 0.27\,\mathrm{Wm}^2$ per year for the period 2006–2018 (IPCC AR6 WGI Ch7). The energy fluxes that remain trapped within the Earth's atmosphere represent *direct* forcings with powerful climate impacts. Thus, while solar radiation provides the principal, regular energetic forcing which drives the slow-moving engine behind global warming and climate change, the principal drivers of the EEI are CO_2 and other GHGs, as well as changes in top-of-atmosphere (TOA) and surface albedo fluxes, in particular, top-of-cloud (often referred to as TOA) reflectivity (see Figures 2 and 3).

Currently estimated at about $0.79\,\mathrm{Wm}^2$, the overall size of the EEI relative to the major energy fluxes from space to the Earth's surface and back, is remarkably small. By way of example, the *latent heat flux* ($82\,\mathrm{Wm}^2$), triggered by ET and evaporation from terrestrial and ocean surfaces, the *amount of outgoing solar radiation originating from shortwave top-of-cloud surface reflectivity* ($75\,\mathrm{Wm}^2$), and *thermal longwave emissions from clouds* ($28\,\mathrm{Wm}^2$), are comparatively large. Variation in alternative estimates of each of these fluxes can likewise be larger than the estimated EEI (Figure 2 provides some examples of this variation).

Surprising things happen, however, when we compare the global energy budget under "clear" and "all sky" conditions (Figures 2 and 3). Due to the elimination of top-of-cloud reflectivity, reduced cloud formation has important impact on the total amount of shortwave (SW) radiation reaching the planet surface. Wild, for example, estimates the net radiative impact of clear sky increases in sensible surface heat at approximately +20 Wm^2 (Wild, 2020; Wild et al., 2019) (or approximately +5.8 Wm^2 over the land surface). Moreover, the loss of top-of-cloud reflectivity pales in comparison to the +54 Wm^2 increase in the SW sensible heat flux. Significant increases in SW radiation striking and being absorbed by significantly darker ocean surfaces (Figure 3), for example, may have decisive negative impacts on regional climate. This increase is partially compensated by an increase in outgoing longwave thermal emissions of −28 Wm^2 (since clouds no longer function as a heat barrier). However, the net estimated impact of the reduced latent heat flux loss and reduced cloud formation have profoundly negative impacts on the EEI.

Since declining TFVC (deforestation) leads to declining latent heat production and thus cloud cover loss, this representation has powerful implications for the potential consequences of deforestation over the land surface, suggesting that, at large scales, it will introduce significant warming. The compelling question, then, is the following: since the required margin of change needed to make a decisive impact on the EEI (0.79 Wm^2), and, thus, climate outcomes, is so small, to what extent can change in the various elements of the TFVC carbon, water, and energy cycle influence change in global climate outcomes?

The latent heat flux thus has an important though seemingly indirect impact on the EEI and global cooling/warming. The latent heat flux contributes to condensation and convergence, that is, cloud formation. As highlighted in Figure 2, the formation of low-lying clouds creates white top-of-cloud surfaces capable of reflecting incoming solar SW radiation back into space (Ban-Weiss et al., 2011; Duveiller et al., 2021; Wild et al., 2019; Xu et al., 2022; Zeng et al., 2017; Zheng et al., 2018, 2021). Though increasing cloud cover also reflects additional longwave radiation back toward the Earth's surface, a comparison of Figures 2 and 3 suggests top-of-cloud SW reflectivity has a comparatively greater impact. Thus, the net effect of the latent heat flux and albedo embodied in this top-of-cloud reflectivity represents a direct, unambiguous, beneficial impact on the EEI (Ban-Weiss et al., 2011; Duveiller et al., 2021; Xu et al., 2022).

3 | ESTIMATED EEI AND CARBON SEQUESTRATION IMPACTS OF RESTORED TFVC

Historically, estimates suggest human modification of the terrestrial surface for agricultural production and human settlements has resulted in the loss of some 40%–50% of pre-Anthropocene TFVC (FAO, 2001; Pongratz et al., 2010; Shvidenko et al., 2005). If the lost latent heat flux is roughly equivalent to the current latent heat flux, much has presumably been lost through land use conversion to agricultural production and urbanization. The UNCCD's *Global Land Outlook for 2022* argues "globally, food systems are responsible for 80% of deforestation" (United Nations Convention to Combat Desertification, 2022). If we assume cityscapes produce limited to no ET, while croplands and pasturelands produce about half the amount of ET ordinarily produced by tree and forest cover (see, e.g., the calculations in Ellison et al., 2012; Table 1), then the total lost ET-based latent heat flux from 40% or 50% historical deforestation, respectively, amounts to approximately 10.1–15.2 Wm^2 (Table 1).

Restoring this forest cover could potentially give rise to a +21% to +29% increase in the latent heat flux. Using this estimated percentage change to estimate the potential change in the top-of-cloud outgoing longwave radiation flux (increased downward LW radiation) and, given that land makes up approximately 29% of the Earth's surface, the total impact amounts to approximately +1.7 to +2.3 Wm^2. We further use this percent change to estimate the potential change in the top-of-cloud outward SW radiation (top-of-cloud reflectivity). This impact amounts to approximately −3.9 to −5.3 Wm^2. Summing these two effects, we estimate the total net impact on the EEI at approximately −2.2 to −3.0 Wm^2. This is more than enough to outweigh current net solar radiation absorption ($\mathrm{EEI} = +0.79 \pm 0.27\,\mathrm{Wm}^2$).

These *back-of-the-envelope* estimates may, however, over- or underestimate potential change. For one, we have not accounted for the latent heat flux over inland water bodies and wetlands. However, open water bodies only account for approximately 2% of the land surface and would not change importantly with forest landscape restoration. Wetland loss, however, like historical deforestation, has imposed similarly high losses on E and ET production (Fluet-Chouinard et al., 2023; Pokorný et al., 2016) and warrants equivalent attention. Further, reductions in surface temperature resulting from increased TFVC and cloud cover would likely diminish the surface energy balance, thereby reducing latent heat production and cloud cover, which in turn would reduce the potential change in the outward SW and downward longwave radiative fluxes. The question of magnitude is also important. The numbers in Table 1 assume a 1-to-1 relationship between increased ET, cloud formation, and increased top-of-cloud reflectivity. The relative magnitude of these relationships, however, may be larger or smaller. Thus, the total net EEI impact is also likely to be larger or smaller.

A growing literature emphasizes that the potential for cloud formation with increased forest cover is not everywhere equal (Duveiller et al., 2021; Xu et al., 2022). These authors emphasize, in particular, that there is strong seasonal variation across different settings. At the same time, in all cases, these authors note that cloud formation over forested areas appears to be strongest during the seasonal summer months and is either weaker or even inverted during seasonal winter months in some locations. However, far from suggesting that additional forest cover may, in some instances, have opposite effects, this literature strongly highlights the potential benefits of additional TFVC, even in drier locations.

Most importantly, perhaps, as the data in Table 1 suggests, the carbon and cloud cover-related impacts of TFVC are complementary and thus likely to positively reinforce each other. Based on these numbers, as long as the TFVC-driven intensification of the hydrologic cycle moves more water across terrestrial surfaces and recycles more rainfall (Ellison et al., 2012, 2017; Hoek van Dijke et al., 2022), the additional latent heat production (assuming adequate and large-scale change in TFVC) will likely increase cloud formation potential and top-of-cloud reflectivity. And increased TFVC will of course simultaneously and naturally improve the atmospheric CO_2 drawdown. We predict that, together, these two effects provide the principal combined impact of TFVC on the EEI and global cooling/warming.

4 | SURFACE ALBEDO, THE LATENT HEAT FLUX AND SENSIBLE HEAT

The above overview of the CO_2 drawdown and the EEI highlights the *direct*, *unambiguous*, causal pathways by which TFVC-related carbon, water, and energy cycles interact with the climate to influence global climate change. Surface albedo and the latent and sensible heat fluxes, on the other hand, are comparatively more complex and their effects on the climate both direct and indirect. Conceptualizations of surface albedo impacts have previously dominated thinking about TFVC warming/cooling, potentially misdirecting science, with the result that the interaction of *surface albedo*, and the *latent* and *sensible heat fluxes* are frequently misunderstood.

Apart from TOA interactions, how much SW radiation is reflected back into space or remains over the land surface is first determined by *surface albedo*. Postreflective surface albedo, remaining SW radiation is then partitioned into *latent* and *sensible heat*. While incoming solar radiation warms the Earth's surface as *sensible heat*, alternatively, TFVC and water produce *latent heat* (or ET). Photosynthesis is driven by the total amount of sunlight (heat) absorbed by leaf surfaces, triggering stomatal transpiration and binding carbon from atmospheric CO_2 (building biomass). How much *sensible heat* remains on the land surface is determined by the potential for TFVC and the remaining energy to convert water into *latent heat*. The presence (absence) of TFVC, water, and energy are thus the principal drivers of the partitioning of post-albedo SW radiation into *latent* and *sensible heat*.

Surface albedo, in a sense, represents an "evolutionary trait" determined by the natural interaction between TFVC, solar radiation, photosynthesis, and water. Trees and plants evolve darker and lighter colors to absorb adequate solar radiation to ensure competitive survival and reproduction. Faster-growing species tend to have darker colors to secure higher water use, whereas slower-growing species frequently have lighter colors. Surface albedo effects are thus modulated and regulated by the evolution of TFVC, which in turn modifies and regulates the total amount of incoming solar radiation partitioned into latent and sensible heat. The equilibrium conditions arising from this interaction govern the circulation of water, the binding of carbon in biomass, and the regulation of the surface energy balance (Köppen, 2011; Thornthwaite, 1948).

The progressive stages of forest development highlight this Darwinian competition for access to the sun's solar resources. Total forest-based ET production is essentially the expression of the outcome of this natural competition and, in later ("successional") stages, expresses the total potential (and, at least in natural settings, sustainable), use of available resources (energy and water).

On the other hand, both comparatively small and larger (interannual, and/or climate-driven) changes (perturbations) in temperature and rainfall can alter this delicate natural balance between TFVC, water, and the energy cycle, leading to potentially significant natural and anthropogenically driven disturbances in the surface energy balance. Natural climate variation, anthropogenic impacts, land use conversions to agriculture, and urban settlements with high water use/demand all create imbalances in this delicate interactive equilibrium, triggering potential reductions in ET, increased overland flows of water, elevated flood potential, elevated sensible surface heat, rising drought potential, and more extreme weather events. Such phenomena are thus naturally the outcome of both incidental interannual variation (due to natural variation in wind patterns, cloud formation, rainfall, and temperature) as well as anthropogenic modification of the natural landscape and can yield long-term, comparatively dramatic disturbances on the land surface.

Based on modeled results produced with the aid of Global Climate and Earth System Models (GCMs and ESMs), several decades of literature suggested early on that, by raising surface albedo, deforestation in the northern hemisphere led, historically, to surface cooling across the temperate and boreal regions (Bala et al., 2007; Betts, 2001; Betts et al., 2007; Bonan, 1999, 2008; Bonan et al., 1992; Brovkin et al., 1998, 2006; Burakowski et al., 2018; Davin et al., 2007; Davin & de Noblet-Ducoudré, 2010; Su et al., 2023). Publications from the 80s and 90s and on into the early 2000s suggest the surface albedo effects of TFVC outweigh carbon sequestration by warming surfaces where forests are planted (see, e.g., Bala & Nag, 2011; Bright et al., 2013, 2015; Jackson et al., 2008; Kirschbaum et al., 2011; Sjølie et al., 2013). The IPCC's AR6 WGI report similarly states, "land use and land cover changes over the industrial period introduce a negative radiative forcing by *increasing the surface albedo*. This effect has increased since 1750, reaching current values of about −0.20 Wm^2 (medium confidence)" (*my italics*). Zeng et al. highlight similar findings in the IPCC's AR5 report (Zeng et al., 2017). Many thus assume forest restoration warms the terrestrial surface by lowering surface albedo (reducing reflectivity), while the elimination of forest cover is expected to cool terrestrial surfaces due to raised surface albedo (increased reflectivity) (see, e.g., Davin & de Noblet-Ducoudré, 2010; Lawrence et al., 2022; Windisch et al., 2021).

The observational literature, however, highlights that deforestation drives increasing sensible heat formation on terrestrial surfaces (Barnes et al., 2023; Burakowski et al., 2018; Feng & Zou, 2019; Hesslerová et al., 2013; Lejeune et al., 2018; McAlpine et al., 2018; Pokorný et al., 2010, 2016). Infrared thermographic imagery (Figure 4), for example, finds cooler temperatures in well-watered forested landscapes, compared to cropland and barren surfaces (Ellison et al., 2017; Hesslerová et al., 2013; Pokorný et al., 2010, 2016). Surface albedo and sensible heat impacts thus appear to depend on the presence of well-watered TFVC and adequate soil water storage. Since soil moisture loss and the resulting decline in transpiration from closing stomata, on the other hand, favor the conversion of surplus solar radiation into sensible heat (van Heerwaarden & Teuling, 2014), drought conditions typically lead to divergent effects.

The interaction of plants with sunlight, carbon dioxide, and water captures an important share of the sun's *post-albedo* SW

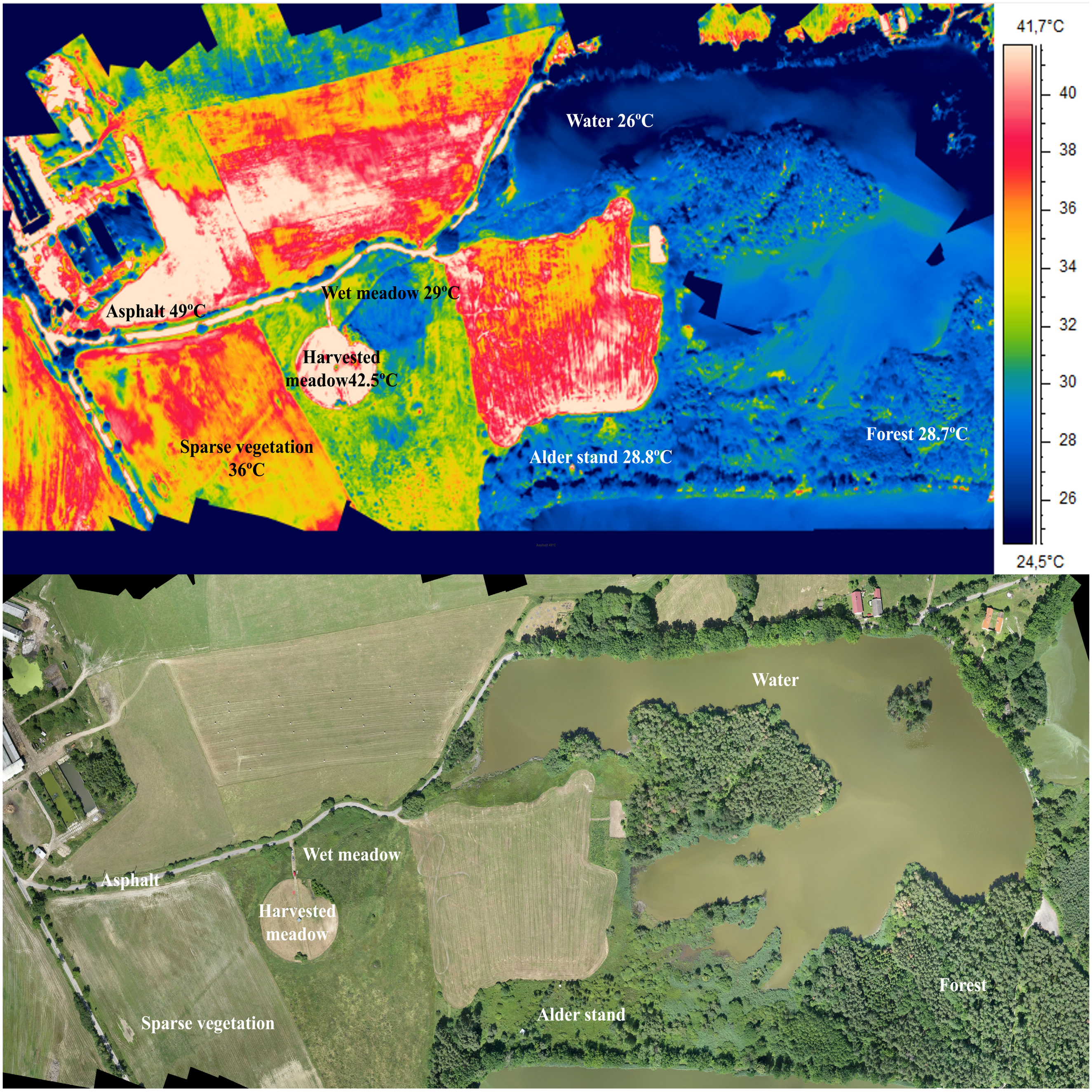

FIGURE 4 The temperature impact of surface albedo and the latent heat flux. *Source*: Adapted from Hesslerová et al. (2013), Huryna and Pokorný (2016), and Ellison et al. (2017).

radiative energy and releases it into the atmosphere as latent heat (ET), thereby reducing opportunities for sensible heat formation (fluxes) on terrestrial surfaces. This partitioning maintains cooler temperatures on terrestrial surfaces. The potential heat-related, sensible heat impact of forest cover is largely neutralized by massive upward fluxes of latent heat, which transfer energy from the land surface into the lower atmosphere (Pokorný et al., 2010, 2016). If, on the other hand, no latent heat transfer to the atmosphere occurs, for example, when water or soil moisture is unavailable, sensible heat formation on terrestrial surfaces will be significantly higher.

Over both dark *and light* surfaces with no evaporative or latent heat flux, remaining post-albedo solar radiation is converted into a sensible heat flux. Even highly reflective (high albedo), lighter-colored surfaces with no evaporative flux (e.g., the harvested meadow and road surfaces) drive greater sensible heat formation (Figure 4). However, due to low albedo, darker-colored surfaces (oceans, open water bodies, forested surfaces, etc.) can generate significant sensible heat fluxes, with adequate moisture they instead release latent heat energy into the atmosphere, thereby neutralizing sensible heat formation and contributing to surface cooling. Further, while sensible heat warming effects range from local to regional, latent heat effects are far more expansive, ranging far into the lower atmosphere. Conventional descriptions, however, frequently contrast sharply with this understanding (see, e.g., Jackson et al., 2008).

Though latent heat formation keeps the land surface cool, estimates of the potential *global* cooling/warming impact are more complicated. Increasing cloud production, as illustrated by a quick comparison with Figures 2 and 3 above, leads to increased downward LW radiation toward the land surface and a decline in outgoing LW radiation. Moreover, since increasing concentrations of CO_2/GHGs and clouds (water vapor) both act as GHGs, their persistent accumulation in the atmosphere appears to weaken any causal pathway (assuming one exists, see, e.g., Colman & Soden, 2021; Jeevanjee et al., 2021, 2022; Makarieva et al., 2023; Stevens & Bony, 2013) by which a share of the latent heat flux might move beyond the lower atmosphere and out into space. Thus, while Zeng et al., for example, suggest that increased ET is one of the principal drivers of cooling global temperatures (Zeng et al., 2017), the evidence presented here suggests something different: increasing latent heat production, cloud cover, and atmospheric CO_2/GHG concentrations hinders the potential space-bound release of outgoing LW radiation, further exacerbating the climate problem.

Thus, the steadily increasing gap between annual emissions and the CO_2 drawdown likely exacerbates atmospheric feedback, thereby strengthening the EEI. Moreover, evidence suggests the lower atmosphere has been warming over time, whereas the upper atmosphere has been cooling (Santer et al., 2023; Steiner et al., 2020). Though reduced CO_2 and GHG emissions could improve this situation, increases in the ET-based latent heat flux are likely neutral and potentially even negative with respect to global cooling. However, as highlighted above, increased ET production does drive increased cloud formation and thus top-of-cloud reflectivity. This phenomenon, along with carbon sequestration, appears to compensate for any warming effects of increased latent heat production and raises the potential for global cooling with increased ET production.

5 | SOIL- AND GROUND-WATER STORAGE AND THE VEGETATION DEPENDENCE OF E/ET

Observational data suggest that TFVC is integral to the storage and production of land surface E/ET (often referred to as terrestrial evaporation, E), precipitation recycling, and the availability of water across the land surface. Without latent heat production, what little rainfall originates from ocean E would travel primarily as overland flows to surface waters and eventually the oceans, thereby reducing TFVC cooling impacts and rainfall and further promoting the surface-related sensible heat flux.

As a concept, *E-vegetation dependence* is not well recognized. However, transpiration has been estimated to represent 60%–64% of terrestrial E (Good et al., 2015; Jasechko et al., 2013; Jones et al., 2022; Schlesinger & Jasechko, 2014). The remainder is made up of interception, which ranges more broadly from 18% to 25% in different locations (Jones et al., 2022; Wang-Erlandsson et al., 2014), and soil evaporation, which may represent another 10% (Wang-Erlandsson et al., 2014). The remaining E comes from land and freshwater surfaces. Since the share of water bodies in the total land mass is very small (approximately 2%, if wetlands are included, 3%), this remainder is likewise very small (Ellison et al., 2012). Moreover, like transpiration, E from interception and soil evaporation primarily depend on the presence of vegetation. Soil evaporation further strongly depends on the soil's infiltration capacity (favored by preferential pathways built by TFVC-based root systems) and water holding potential (favored by decomposed litterfall from vegetated surfaces and soil carbon content) (Bargués-Tobella et al., 2020; Ellison et al., 2017; Ilstedt et al., 2016). Thus, without vegetation, interception and soil evaporation will approach 0.

TFVC is more commonly thought of as the natural outcome of water availability on land surfaces. Yet TFVC presence (absence) simultaneously drives (limits) the availability of water by contributing to infiltration, soil moisture storage, and precipitation recycling. Without infiltration potential and with degrading and compacting soils—all consequences of deforestation and landscape degradation—emaining rainfall will quickly turn into overland flows, moving rapidly to surface waters. E from surface waters, however, is fixed by surface area, temperature, and turbulence and represents a comparatively small share of land-based E. If *vegetation-dependent E* (summing transpiration, interception, and soil evaporation) ranges between 88% and 99% of total terrestrial E, then the total share of terrestrial E produced without TFVC ranges from approximately 1%–12% of total (reduced) terrestrial E.

The occurrence of E in any magnitude on land surfaces thus requires some degree of infiltration, soil moisture storage and precipitation recycling, all of which are TFVC-dependent (Asbjornsen et al., 2022; Bargués Tobella et al., 2014, 2020; Bruijnzeel, 2004; Ellison et al., 2017; Ellison & Ifejika Speranza, 2020; Ilstedt et al., 2016; Sheil & Bargués-Tobella, 2020). Because terrestrial surface water availability (i.e., storage), soil water infiltration and groundwater recharge are largely vegetation-dependent, soil water content is likewise largely a function of TFVC presence (absence). Figure 5 highlights these basic relationships and contrasts a *dominant paradigm* with an *updated paradigm*. The relative importance of this shift in thinking about TFVC–water relationships at the level of soil–water interactions and precipitation recycling potential cannot be overstated. Previous models suggest soil water infiltration and groundwater recharge were at their maximum without TFVC. We now know this is not the case. Without TFVC, soil surfaces degrade and compact, further facilitating overland flow. Without TFVC, rainfall turns almost immediately into overland flow and surface runoff, thereby returning more rapidly to the oceans without being stored on terrestrial surfaces or recycled for additional downwind rainfall.

The presence (absence) of TFVC, thus, determines variation in the availability of water and the recycling of water (rainfall) on the land surface. Due to the role water storage and precipitation recycling play in total rainfall over land surfaces, without TFVC, annual rainfall amounts would decline significantly. The complete loss of

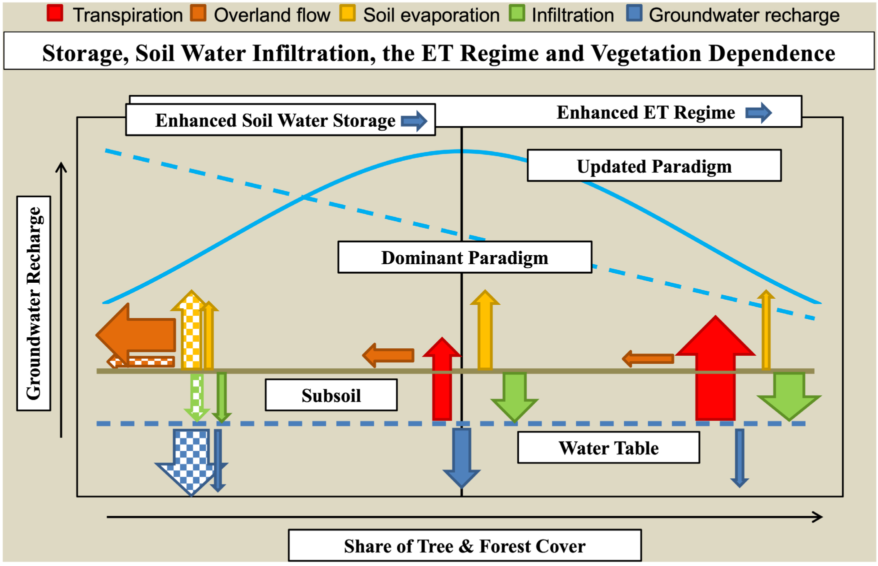

FIGURE 5 Dominant and updated paradigms: soil water infiltration, groundwater recharge and the evapotranspiration (ET) regime. Adapted on the basis of multiple sources (Asbjornsen et al., 2022; Bargués Tobella et al., 2014, 2020; Ellison et al., 2017; Ellison & Ifejika Speranza, 2020; Ilstedt et al., 2016; Sheil & Bargués-Tobella, 2020). Cross-hatching indicates dominant paradigm at lower levels of tree and forest cover, while solid colors indicate the updated view. Controversy about soil water infiltration, groundwater recharge and soil evaporation generally concern; (1) what happens with less tree, forest, and vegetation cover (TFVC) and (2) the principal differences between outcomes under low and median TFVC conditions. There is general agreement about high TFVC conditions, but much of the literature has tended to neglect study of the larger-scale TFVC impacts on the ET regime, downwind rainfall, and water supply.

TFVC and precipitation recycling would ultimately mean that land-based rainfall would decline by as much as 60%, approximating the oceanic contribution to rainfall on land, approx. 45,000 km^3 (compared to today's 112,000 km^3). Thus, while some expect E to occur even without TFVC (dominant paradigm), the updated paradigm strongly suggests the opposite.

The potential range of variation in rainfall and water availability is immense. Currently, annual rainfall over land surfaces is somewhere around 112,000 km^3. However, as suggested in Table 1 above, TFVC loss has presumably led to a significant decline in both annual rainfall and the availability of water on the land surface. Though estimates like those in Table 1 have previously been generated (Ellison et al., 2019; Kleidon et al., 2000; Wang-Erlandsson et al., 2018), records of the total annual rainfall that occurred with preanthropogenic modification of the natural landscape are inadequate and the potential extent of additional rainfall with additional TFVC remains uncertain.

One point is clear: if the relative extent, availability, and circulation of water drive temperature change, then surface albedo is not the predominant factor driving local and global warming/cooling. The inverse logic inherent in this discussion requires greater attention. Since raised albedo is perceived to drive local and global cooling potential toward the outer latitudes, the supposed link between lowered albedo and surface and climate warming suggests that we should deforest terrestrial landscapes. If, on the other hand, the extent, availability, and circulation of water drives surface and climate cooling/warming, then TFVC loss across the land surface would ultimately have dire consequences.

These points have important implications for the likely (under-) representation of the consequences of deforestation in climate models and require further study. Progressive deforestation has two major consequences for changes in the Earth's energetic exchange between the terrestrial surface and the atmosphere. For one, by reducing the latent heat flux, deforestation allows sensible heat to invade the land surface. For another, the loss of TFVC further means the loss of water storage and circulation across terrestrial surfaces. Less water will thus be available for E/ET heat transfer into the atmosphere. Most importantly, the progressive loss of TFVC means that both precipitation recycling and cooling potential will be reduced to a minimum, further raising the relative sensible heat flux on the land surface.

The maximum potential climate benefit is thus presumably achieved when the greatest potential TFVC is present on the land surface. Moreover, the relative intensity of the hydrologic cycle across the land surface determines the potential extent and magnitude of biomass production (carbon sequestration) on the land surface. The sequestration of additional carbon and the circulation of additional water resources are explicitly interactive and interdependent processes with enormous and direct cooling/warming potential. Not only will such systems store more water across terrestrial surfaces, likewise, they will recycle larger amounts of precipitation and make more water available to downwind locations. Such systems will further provide greater amounts of latent heat production and surface cooling power and are therefore likely to maximize carbon sequestration, atmospheric moisture production, cloud formation, and thus, global cooling.

Presumably, the availability of land and the ability of sunlight to reach the land surface set limits to the potential expansion and intensification of carbon and water resource use. Temperature variations resulting from the expansion (contraction) of TFVC and relative hydrologic intensity, set additional limits on photosynthesis: increasing cloud cover, for example, creates limits to photosynthesis by reducing incoming SW radiation and lowering temperatures.

Such a view contrasts sharply with suggestions that deforestation raises surface albedo and leads to surface cooling. On the contrary, forest surface albedo is largely neutralized by the TFVC interaction with water, the production of latent heat, its energetic transfer from the surface to the lower atmosphere, and cloud formation. Such a perspective is supported by the observational record, which suggests deforestation leads to warming surface temperatures (Barnes et al., 2023; Burakowski et al., 2018; Hesslerová et al., 2013; Lejeune et al., 2018; McAlpine et al., 2018; Pokorný et al., 2010, 2016; Winckler et al., 2019; Zeng et al., 2017).

6 | LATITUDE EFFECTS ON SURFACE ALBEDO AND THE LATENT HEAT FLUX

Toward the outer latitudes, TFVC is increasingly perceived to have potentially conflicting impacts on global warming (Davin & de Noblet-Ducoudré, 2010; Lawrence et al., 2022; Windisch et al., 2021). Two to three factors drive these competing claims about forest impacts. One is reduced latent heat (ET) production as one moves toward the outer latitudes. The second is the increased potential for snow cover, which is diminished/improved by raising/lowering forest cover. Third, some argue that deforestation drives cooling because reduced atmospheric moisture (due to reduced ET) has the effect of reducing the total amount of longwave radiation transferred from the atmosphere back to the ocean surface (Davin & de Noblet-Ducoudré, 2010).

Though in summertime, forest cover is, overall, still expected to have a cooling effect, wintertime impacts are more complex. Boreal forest cover has winter warming impacts because, with reduced wintertime ET, forest surface albedo warms the surrounding environment. Likewise, increases in forest cover reduce the extent of reflective, snow-covered surfaces. Outer latitude surface albedo warming effects are thus reportedly more intense and some suggest wintertime TFVC warming can even be transferred to the regional atmosphere and ocean surfaces (Davin & de Noblet-Ducoudré, 2010; Lawrence et al., 2022; Lee et al., 2011; Windisch et al., 2021).

Seen, however, from the perspective of the clear and all sky energy budgets (Figures 2 and 3 above), such concerns seem ill-founded. While the thermal exchange of LW radiation from the surface to space is facilitated by the reduction of TFVC, the simultaneous increase in SW radiation to the surface due to the loss of ET production and cloud formation is significantly greater, far outweighing any benefits from the release of outgoing LW radiation. Such factors are compounded by the comparatively long period of summertime sun exposure. A second issue concerns the perception that the outer latitudes produce "less" ET. While this is true, these regions are well known to be "energy limited" (as well as nutrient limited Högberg et al., 2017; Norby et al., 2010), but not "water limited," meaning they produce less ET in part because they receive less incoming SW radiation (Trenberth, 2022), which further impacts the partitioning of SW radiation into sensible and latent heat. Simply put, less energy is available for sensible heat formation. Likewise, wintertime solar radiation potential is further reduced by the Earth's tilt and surface curvature, and by the reduced amount of time during sunlight falls on the outer reaches of the Northern Hemisphere (NH). For these reasons, TFVC-based surface albedo effects are likely to have only limited impacts on total, net cooling/warming potential.

The focus on the surface albedo benefits of snow-covered surfaces is not surprising given their significant and comparatively dramatic cooling benefits. However, an alternative analysis might consider how best to promote increased snowfall, as opposed to how to reduce forest restoration in the NH, and/or promote the removal of tree cover and other vegetated surfaces. Snow deposition, like rainfall, is driven by total amounts of moisture present in the atmosphere. With reduced TFVC, we should expect reductions in atmospheric moisture and cloud cover. Moreover, in the outer latitudes, to some degree, wintertime TFVC warming and reduced ET production are presumably welcome, since, in some of the colder northern regions of the boreal, temperatures can exceed −30°C (e.g., across much of northern Scandinavia, Russia, Canada).

Increased ET from greater amounts of forest cover has important advantages, that is, increased atmospheric moisture production and cloud cover. These factors (1) keep Earth surfaces from gathering sensible heat and (2) increase total amounts of top-of-cloud SW reflectivity back toward space. Moreover, the increased carbon sequestration that accompanies increased forest cover further improves the annual drawdown of atmospheric CO_2. Finally, the loss of cloud cover associated with reduced total amounts of ET production may be quite negative for things like solar radiation falling on the Arctic Circle and Greenland. Hofer et al. (2017), for example, find that recent declines in cloud cover are driving abrupt increases in the Greenland ice melt. Zeng et al. (2017) likewise suggest that reduced ET is likely to have negative warming effects. These studies further overlap neatly with the analysis of Figures 2 and 3, and further suggest such analyses should be extended to impacts related to the progressive loss of the Arctic Ice Shelf and increasing SW radiation uptake from darker Arctic Ocean surfaces.

Arguments for the cooling benefits of mid- and high-latitude deforestation across the temperate and boreal zones are thus troubling. Encouraging additional loss of net annual carbon sequestration and latent heat production represents a potential threat to the surface energy balance and global warming more generally. Historical TFVC loss from progressive deforestation and land use conversion has presumably had very *direct* impacts on the drawdown of atmospheric CO_2 and the loss of cloud reflectivity. Thus, historically, solutions that may improve food security have progressively reduced the land cover's climate change mitigation potential. With significantly shorter growth cycles, greatly reduced leaf area index (LAI), shorter root systems, and greatly reduced levels of ET production, conversions from forest to croplands and urban settlements have presumably had significant negative impacts on both above- and below-ground biomass, latent heat production, and the surface energy balance across the outer latitudes.

Boreal forests comprise approximately 33% of the world's forests and an even larger share of the world's soil-based carbon stores (Chapin et al., 2011). Moreover, boreal forests sequester carbon stores on the order of 272 ± 23 Pg C and contribute an annual flux (removals of atmospheric CO_2 concentrations) of approximately −3.4 to −4.4 $GtCO_2^{-1}$ (Pan et al., 2011). Finally, changes in forest law in many of the boreal countries in the late 19th and early 20th century greatly encouraged productive forestry practices that have contributed substantially to both dramatic increases in rates of carbon accumulation (productivity/growth coefficients) as well as significant forest regrowth and the rapid accumulation of carbon stocks across the Nordic countries (Ellison et al., 2022; Högberg et al., 2021).

"De-prioritizing" boreal forest cover (Lawrence et al., 2022; Seymour et al., 2022; Windisch et al., 2021) would seriously reduce these carbon fluxes and latent heat production. Deforestation already represents a global problem for carbon emissions into the atmosphere (Friedlingstein et al., 2020; Houghton & Nassikas, 2017). Though the albedo-related benefits of snow cover presumably concern the outermost reaches of the boreal, reforestation efforts are far more likely to focus on the southern regions since this is where tree cover has the greatest potential for rapid carbon accumulation and growth. Current changes at the outermost Boreal are far more likely driven by global warming and the gradual northward shift of the boreal biome and not direct human intervention per se. Put in other words, the northward expansion of the boreal is a climate problem and, to the extent that it needs to be slowed or reversed, is best addressed by reducing CO_2/GHG emissions, increasing latent heat production, and eliminating the EEI. Removing more carbon sequestration and ET production potential will likely have the opposite effect.

6.1 | Increasing vulnerability of the inner (not the outer) latitudes?

Despite the positive benefits of increasing forest cover, one caveat regarding the inner latitudes is worth considering. The increasing heat generated by the EEI leads to increasing limitations on water availability, that is, the principal factor limiting forest growth, precipitation recycling and the cooling power of forests. As temperatures rise in drier, and more *water limited*, regions, increased ET production begins to dry out the landscape, rainfall declines and the likelihood of drought increases (see, e.g., Denissen et al., 2022; Staal et al., 2020; Taufik et al., 2017; Van Lanen et al., 2013). Such phenomena upset the delicate, natural, preanthropogenic surface energy equilibrium described above and established over millennia. Increasing heat wave invasions radiate out from the inner latitudes toward the poles, posing the greatest threats to the cooling power of forests, not to mention tree and forest survival, *from the inner latitudes on out* (and *not* from the outer latitudes on in) (see, e.g., Hsu & Dirmeyer, 2023; Li et al., 2022).

Starting from the inner latitudes, rising temperatures, aridity, and declining water availability drive the opposite set of interactions and feedbacks. Under these conditions, increasing TFVC may result in greater drying of the landscape through increased ET production potential, declines in rainfall, water availability, reduced TFVC, and, because of increasing drought potential, greater increases in sensible heat, aridity, and feedback-driven drought potential. For this reason, reforestation efforts in the inner latitudes, and radiating outward toward the poles, should perhaps be the principal focus of concern. Such an assessment of vulnerability resonates with repeated concerns about failing to consider the water consequences of reforestation efforts—in particular at the basin scale (Bennett & Barton, 2018; Farley et al., 2005; Filoso et al., 2017; Hoek van Dijke et al., 2022; Jackson et al., 2005; Sheil et al., 2019; Vose et al., 2011). On the other hand, even with increasing aridity, reforestation efforts may, in many cases, have positive impacts on downwind conditions (Creed & van Noordwijk, 2018; Ellison et al., 2019; Ellison & Ifejika Speranza, 2020; Pranindita et al., 2022).

This trend is the opposite of the one predicted by the presumed warming trends generated by forest cover and lowered surface albedo in the outer latitudes. Even though greater temperature changes are occurring across the boreal, both forest cover and *increasing* forest cover are presumably highly beneficial. Moreover, increasing forest cover is a logical outcome of the increased rainfall, rising temperatures, and longer growing seasons in the outer latitudes. The problem in the inner latitudes, on the other hand, is the opposite. Declining water availability means forest-related surface albedo effects have a greater impact: less ET potential equals reduced cooling power, with the unused solar energy thus being converted into sensible heat, and further raising sensible heat formation and drought potential. Likewise, toward the inner latitudes and especially under the conditions of declining TFVC, rising temperatures alter the density and composition of atmospheric moisture, thereby reducing the potential for latent heat to generate condensation and drive cloud formation (see, e.g., Makarieva et al., 2022).

The driving factor in these relationships is the increased ET potential in drier regions and the loss of water availability, which then allows surface albedo effects to favor sensible heat formation and dominate local and regional temperatures. Presumably, these factors create a tipping mechanism whose feedback effects function like a self-fulfilling prophecy (Lovejoy & Nobre, 2018). As more heat is generated by declining water availability, reduced ET potential and the increasing power of surface albedo, this drives a vicious cycle of warming that further accelerates the process of declining water availability, increased surface albedo effects, further increasing the likelihood of drought. Such phenomena, in fact, have already pervaded both the inner and, to some extent, even the outer latitudes, though clearly in declining proportion (Allen, 2009). The heatwaves descending upon parts of the drier inner latitudes, the temperate zone and out into the southern reaches of the boreal are increasingly followed by periods of extended drought. This analysis is reflected in the literature, for example, on forest dieback and declining forest resilience (Allen, 2009; Forzieri et al., 2021, 2022), increasing drought potential (Bagley et al., 2013; Dai, 2010, 2013), the increasing likelihood of forest shifts from sink to source (Anderegg et al., 2020; Baccini et al., 2017; Ciais et al., 2005; Hadden & Grelle, 2016), as well as the increasing likelihood of wildfire (IUFRO, 2018; Taufik et al., 2017).

The literature on predictions of future rainfall potential in the very dry regions of the inner latitudes provides a second caveat. One question has been why oceans do not evaporate more with rising temperatures, thus producing more clouds and rainfall. One response highlights the role of reflective sulfur-based aerosols from fossil fuel-based energy production in reducing sea surface temperatures (SSTs), which reduce ocean warming and lower than expected evaporation. The decline of coal-based power production in the US and Europe, for example, has led to reductions in the amount of reflective aerosols in the atmosphere, suggesting SSTs will again rise and generate more rain-producing atmospheric moisture (Biasutti, 2019; Giannini & Kaplan, 2019). Declining atmospheric SO_2 may thus explain the recent uptick in rainfall over the last couple of decades in the Sahel region of West Africa and argue it will progress.

7 | DISCUSSION

In a sense, one can think of the principal global cooling and warming effects as those that affect the EEI, that is, what we here refer to as the "climatic envelope." Within this envelope, smaller-scale local and regional cooling/warming phenomena occur (Lawrence & Vandecar, 2015; Zeng et al., 2017) but are likely to have more limited effects on the global climate. As far as the global climate is concerned, the principal focus should be on the large-scale TFVC interactions that drive change in the EEI, that is, on carbon sequestration and the potential for promoting increased cloud formation, primarily through increased TFVC-based latent heat production, and the multiplier effects from increased latent heat production (precipitation recycling) on rainfall and TFVC growth. Since CO_2 drawdown and top-of-cloud reflectivity provide the principal, direct engines for reducing the EEI, these principal TFVC pathways matter for global warming/cooling and climate change. While smaller-scale phenomena (surface albedo warming and the latent heat flux) can have short-term impacts on surface temperature variation, only the global effects contribute to long-term global climate change mitigation (or its opposite, warming).

TFVC surface temperature and climate impact perspectives are complicated by the competing views generated via modeled (GCMs/ESMs) and observational data. Perhaps the most extraordinary inelegance in older GCMs was to simplify the E/ET and TFVC relationship by assuming terrestrial evaporation (E) was adequately estimated by setting it equivalent to "potential evapotranspiration" (PET), the amount of water that *can be evaporated* given a specific temperature (T), amount of solar radiation and adequate water supply (Dickinson, 1984; NRC, 2005). If E is assessed as independent of TFVC, then all findings will be based on the awkward, misleading assumption that vegetation is irrelevant to the latent heat flux, or that the latent heat flux is detached from the role and importance of TFVC. The consequence of such models is to deny/erase the role of TFVC in surface warming/cooling. Such models further disturb the linkage between the latent heat flux and surface albedo effects. Failing to capture these fundamental relationships underestimates or entirely misses the TFVC impact on both surface temperature and the climate.

While large and complex fluxes should ideally be estimated using GCMs and ESMs, inelegant modeling of terrestrial land–atmosphere coupling and the latent heat flux, as well as significant data insufficiencies, represent a significant barrier to modeled climate results. Problems with the estimation of E, ET, and surface temperature persist in the newer generation of land–atmosphere interaction models (e.g., CMIP5, CMIP6). Though significantly better at representing TFVC and the land–atmosphere interaction, these models still bear testament to significant deviations between modeled and observed results (Baker & Spracklen, 2022; Berg & Sheffield, 2019; Lejeune et al., 2020; Scafetta, 2021). As IPCC authors highlight, the role and impact of clouds and water vapor on global temperatures, "has long been the biggest source of uncertainty in climate projections" (IPCC AR6 WGI Ch7). Though climate models rapidly multiply and improve, the impact of atmospheric moisture and clouds continues to represent one of the most significant unknowns (Trenberth, 2022). Further, the resolution of GCMs and ESMs is such that connecting ET fluxes to specific land cover and tree types down to tree scale is virtually impossible. Yet, to adequately mimic the E-vegetation dependence identified above, this is presumably what is required. Estimating E-vegetation dependence is thus rendered problematic by difficulties linking the latent heat flux (E/ET) and surface albedo phenomena with surface temperature and climate change (Bright et al., 2022; Chen & Dirmeyer, 2020; Duveiller et al., 2022).

The unreliability of E/ET estimates suggests the observational data provides a more reliable foundation upon which to build theoretical insights about forest–water interactions and their impacts on the climate and surface temperatures. Considered in the context of the relative partitioning between latent and sensible heat, such inaccuracies have the consequence of underestimating TFVC-related surface cooling impacts and overestimating forest-related albedo warming effects. Additional problems, such as the difficulty of estimating both carbon sequestration and albedo effects, likewise generate variation in climate model predictions (Lejeune et al., 2020; Montenegro et al., 2009).

Several important realizations flow from this description of TFVC impacts. Most importantly historical TFVC loss, in addition to the continuous emission of CO_2 and GHGs this implies (Arneth et al., 2017; Kaplan et al., 2011; Ruddiman, 2003), has presumably had significant and devastating impacts on the integrity of the global *climate envelope*. Significant reductions in the global TFVC CO_2 drawdown potentially exacerbate the increasing accumulation of CO_2 in the upper atmosphere. With the steady increase in CO_2 and GHG production over time, further reductions of this drawdown capacity should (and have) raise(d) alarms. Likewise, though the lack of an adequate record makes it difficult to assess, the historical loss of significant amounts of low-lying cloud cover has presumably had similarly significant impacts on top-of-cloud reflectivity (Millán et al., 2005; Takata et al., 2009).

The repeated suggestions that forest surface albedo represents a barrier to increased reforestation and forest landscape restoration are concerning. Lowered surface albedo (reduced reflectivity) can of course warm terrestrial surfaces at the local and regional scale, in particular as the warming and drought phenomena driven by progressive climate change worsen opportunities for TFVC surface temperature and global climate cooling. Warming, however, is significantly neutralized by the latent heat flux and further primarily affects surface temperatures at the local to regional scale. Though such warming affects temperatures *within* the *global climate envelope*, these fluxes have a far more *indirect and ambiguous impact on the porosity of the envelope itself* and thus are unlikely to have any significant long-term impact on the EEI. Both carbon sequestration and latent heat production, on the other hand, which (1) draw down additional carbon and (2) transfer ET from the terrestrial surface into the atmosphere where it can trigger cloud formation, do have the potential to affect the climate envelope.

8 | CONCLUSIONS

Many predict benefits from increasing forest cover, in particular for the purposes of climate change mitigation (Bastin et al., 2019; Ellison et al., 2011, 2013; Griscom et al., 2017; Mo et al., 2023; Nabuurs et al., 2017; Roe et al., 2021). Predictions of forest benefits are likewise increasingly linked with advantages for the water cycle (Creed & van Noordwijk, 2018; Ellison et al., 2012, 2017, 2019; Gebrehiwot et al., 2018; Hoek van Dijke et al., 2022). Though this image is complicated by the frequent disconnect between basin level, "demand side," and larger-scale regional to continental, "supply side" forest-water impacts, the precipitation-cycling perspective suggest that we can promote a safe, strategic framework for pursuing intensification of the hydrologic cycle (Ellison, 2018; Ellison et al., 2012; Filoso et al., 2017; Hoek van Dijke et al., 2022; Jackson et al., 2005). The strategic placement of forest, its suitability to the local environment, as well as required consideration of the 20th and 21st century anthropogenic modification of demand placed on the catchment water balance, are the principal lessons from these many references to the water-related challenges of forest landscape restoration.

The only caveat here may be the difficulty in determining the suitability of forest cover to the local environment since this remains a moving target (Ellison et al., 2012; Hoek van Dijke et al., 2022). Global warming and climate change are rapidly altering ecosystems and the boundaries of biomes. This is rapidly transforming the equilibrium balance between tree and forest types and the zones in which they normally thrive. Selecting appropriate species for reforestation has thus become a complex problem linked to the rate and extent of global warming and climate change. This, and being able to accurately determine the limits for tree survival in changing climates, represent perhaps the two greatest challenges to future forest restoration efforts and climate change mitigation goals.

The observational data strongly support the power of forests to cool the planetary surface and promote improvements in the radiative (im-)balance through carbon sequestration, ET production, and cloud formation. Decades of discussion about the effects of land cover change have encouraged us to weigh surface albedo effects over the benefits of carbon sequestration. Where surface albedo effects, however, are neutralized by the evaporative transfer of latent heat into the atmosphere, TFVC effectively cools surface temperatures. Moreover, carbon sequestration and top-of-cloud reflectivity are directly and unambiguously linked with the EEI, and thus climate change impacts. TFVC loss should therefore be expected to have positive and significant effects on the EEI.

Prioritizing forest restoration should further consider extensive, multiple TFVC benefits, not all of which are related to surface temperature and the EEI. Thus, in addition to precipitation recycling, the accelerated carbon, water and energy cycle benefits linked to forest growth, the atmospheric CO_2 drawdown, latent heat production, surface cooling, condensation and cloud formation, and top-of-cloud surface reflectivity, one should also consider soil water infiltration, groundwater recharge, water purification, harvested wood products and the HWP carbon pool, substitution, renewable energy production, etc. (for a more extensive list, see, e.g., Ellison, 2010). In this regard, and assuming food production remains secure, systematic forest landscape restoration efforts and increased TFVC are presumably favorable in and across all historically forested locations (and *not* just in the tropics). In fact, the most heavily deforested and anthropogenically modified region of the world is clearly the temperate zone.

Disaggregating the discussion of TFVC, water, and energy cycle interactions into their *direct* and *indirect* effects on temperature and the climate further suggests that continued forest loss could be disastrous for the planet. The continued production of CO_2 and other GHGs, as well as the progressive reduction in cloud cover through reduced ET (latent heat) production, would further strengthen sensible heat formation and global warming. Removing TFVC heightens sensible impacts and reduces the surface cooling important to human welfare and basic survival. In this regard, the massive reforestation efforts currently promoted through multiple venues (New York Declaration on Forests, the Bonn Challenge, the Trillion Tree Initiative, the focus on Nature-Based Solutions to Climate Change to emerge out of the 2021 COP26 in Glasgow, and the UN's Decade of Ecosystem Restoration), all point in potential directions that can significantly benefit the Earth's energy balance and humanity.

AUTHOR CONTRIBUTIONS

David Ellison: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing – original draft; writing – review and editing. **Jan Pokorny:** Data curation; writing – review and editing. **Martin Wild:** Data curation; investigation; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The Authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Please note that there is no external data that would require archiving.

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