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Is Forestation Still Good Climate Policy Despite Increasing Forest Fires?

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Abstract

Despite the global increase in forest fires in recent years, forestation—the planting of trees in new areas (afforestation) and previously deforested areas (reforestation)—remains a major and relatively low-cost approach for sequestering carbon dioxide. High-resolution satellite data show that the annual incidence of tree death and corresponding carbon dioxide release from stand-replacement forest fires remains low. The analysis applies this incidence as a "hazard rate" in the actuarial sense and arrives at cumulative probabilities of the burning of newly planted trees over time. Even with projected increases in response to global warming, this hazard rate would not reach levels that would substantially negate sequestration gains from forestation. Estimates based on past US experience further suggest that health, property, and other damages from forestation's addition of potential forest area fuel to burn would be much smaller than the benefit from the additional carbon sequestration resulting from the forestation.

Keywords

Climate Change, Forest Fires, Carbon Sequestration

1. Introduction

It has long been recognized that reforestation and afforestation are relatively low-cost means of sequestering carbon dioxide[1]. The most recent Assessment Review of the Intergovernmental Panel on Climate Change judged that over the next 30 years, some 5.5 billion tons of carbon dioxide ($GtCO_2$) could be sequestered (or their emissions avoided) annually through forestry measures at a cost of about $75 US per ton. In comparison, a central global emissions baseline for this period an-

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[1] For an early discussion, see Cline (1992, chapter 5).

ticipates a plateau of about 40 $GtCO_2$ annually; and the cost of direct air capture and carbon sequestration (DACCS) would likely be \$100 to \$300 per ton (IPCC 2022, p. 36)[2]. By implication, forestation can make an important contribution to curbing global warming, even though cutbacks in fossil fuel emissions will be much more important.

However, the increased salience of forest fires and other wildfires has raised the question of whether forestation would be a mistaken strategy[3]. The most direct reason for this concern is the possibility that in the warmer climate of the future, any carbon dioxide sequestered in the near term would simply return to the atmosphere in the future as a consequence of fire. In this respect, carbon dioxide sequestered in trees can be seen as vulnerable to "fire leakage" analogous to leakage of carbon dioxide sequestered in underground caverns[4]. An additional possible concern is that under future conditions, damages from the extra forest fires associated with additional forest area would exceed the benefits of sequestration.

Citing the large scale of Canadian wildfires in 2023, prominent climate journalist David Wallace-Wells argued that "Forests Are No Longer Our Climate Friends"[5]. Canadian novelist and journalist Claire Cameron similarly cited that year's "plumes of gases and soot from Québec and northern Ontario that plagued Canada [and] also blanketed the American Midwest and East Coast" in lamenting "planting a time bomb" three decades earlier in summer projects reforesting clear-cut logging areas[6].

For climate modeling, an important question is whether the main Integrated Assessment Models of costs and benefits of curbing greenhouse gas emissions have adequately taken into account the prospective increases in forest fires in warmer future climates. Models featuring the use of forestation as a substantial means of sequestering carbon dioxide could be misleading if not.

A rising incidence of forest fires would not turn forestation into a poor seques-

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[2] The IPCC review cited the reduction of tropical deforestation as having the largest mitigation potential. Its summary for policy-makers nonetheless struck a relatively cautionary tone on the practical scope for forestation measures. It cited "insufficient institutional and financial support, uncertainty over long-term additionality and trade-offs, weak governance, insecure land ownership, low incomes and the lack of access to alternative sources of income, and the risk of reversal" (p. 33).

[3] In 2023, summer temperatures in the Northern Hemisphere reached their highest in about 175 years and perhaps in 2000 years. Delger Erdenesanaa, "Summer 2023 Was the Northern Hemisphere's Hottest in 2000 years, Study Finds," *New York Times,* May 14, 2024. Wildfires in Canada spiked to burn 11.9 million hectares in 2023, compared to annual averages of 1.5 million in 1984-93 and 2.5 million in 1994-2022. (Calculated from CIFFC, 2024). The wildfire in Maui in August 2023 caused at least 114 deaths, the most US deaths from a single fire in more than a century. Stephen Culp, "Maui Wildfires: What Are the Deadliest Wildfires in US History?", *Reuters*, August 21, 2023. In January 2025, the Pacific Palisades and Eaton fires caused the greatest wildfire destruction in the history of Los Angeles. *Reuters,* "The worst Wildfires in Los Angeles History Are Raging On" (video), January 9, 2025.

[4] Liquid compressed carbon dioxide can be transported in pipelines and injected into underground systems such as saline formations or former oil and gas reservoirs (International Energy Forum, 2022).

[5] David Wallace-Wells, "Forests Are No Longer Our Climate Friends," *New York Times*, September 6, 2023. However, he also acknowledged that planting trees was still good, albeit of more limited benefit than in optimistic assessments.

[6] Claire Cameron, "We Thought We Were Saving the Planet, but We Were Planting a Time Bomb, *New York Times,* September 15, 2023. She reports that replanting using a monoculture of black spruce saplings spaced six feet apart in neat rows "made wildfires much more likely and much worse…"

tration method unless it made the probability of the burning of the new forested area high enough to sharply reduce any net sequestration expected. Alternatively, or in addition, the damage from the burning of the additional forest area might be so severe that it would exceed the benefit of the net sequestration achieved.

Assessing the first question requires examining the path of the probability of fire incidence as a function of rising global temperatures. This study suggests using a "hazard rate" for this purpose, similar to the actuarial concept of the annual probability of a person's death at a given age. It turns out that the hazard rate for tree death by fire in forests, properly measured, is currently low, and that likely increases from future warming would be too small to reverse advantages of forestation as a sequestration method.

This study first presents a brief review of recent literature on forest fire trends and their implications for climate models. It then discusses the notion of a relevant "hazard rate" for emissions of carbon dioxide from forest fires based on global forest fire incidence by region, and, alternatively, on US "carbon flux" data. The analysis then turns to alternative estimates of the response of fire incidence to rising global temperatures. It then considers whether the future hazard rates would be likely to rise so much that forestation would be likely to become a high-cost rather than low-cost means of carbon sequestration.

The analysis then considers the extra fire damages from the addition of more forest area to burn in comparison to the extra benefits from more carbon dioxide sequestered. An illustrative set of calculations suggests that by mid-century, the social cost of carbon dioxide as estimated by the US Environmental Protection Agency (EPA, 2023b) would be sufficiently high that the benefit of sequestration through forestation would substantially exceed damages from the fires on forest area added.

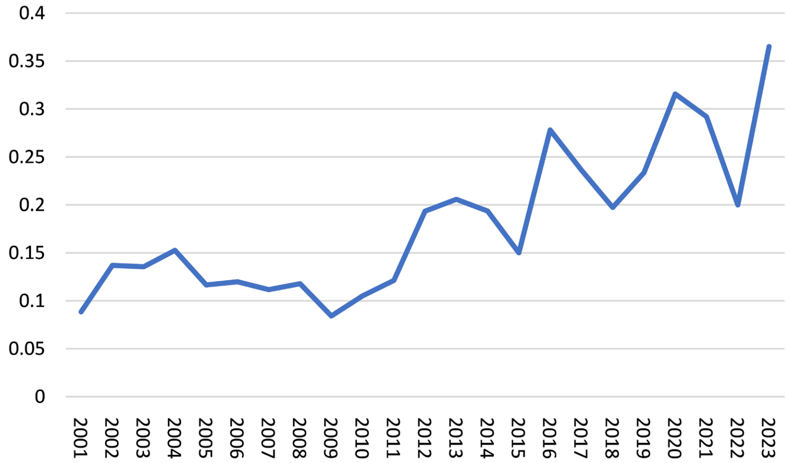
A final section briefly discusses further considerations about forestation. These include regional differences in the consequences for albedo (reflectiveness of earth's surface), the role of preventive maintenance in reducing fire severity, recent official estimates of increased needs for reforestation in view of rising fire incidence, and the need for monitoring forestation initiatives for additionality and permanence. The central question is whether consideration of forest fires substantially undermines the case for forestation after taking into account the more familiar caveats about its scope. The estimates of this study indicate not.

2. Global Trends in Forest Fires

In contrast to the salience of forest fires in Canada and the United States in 2023, 2024, and early 2025, the most recent assessment of global forests by the United Nations Food and Agriculture Organization, in 2020, showed no upward trend in the total area of land burned annually. The five-year average area of land burned instead declined by about 15 percent from 2001-05 to 2014-2018 (FAO, 2020, p. 90). However, this measure includes large wildfire areas of savanna and grassland (p. 91), and vastly overstates the area of forest fires. Specifically, the FAO (2020, p. xi) estimates global forest area in 2020 at 4.07 billion hectares, so the average global land area burned at 400 million hectares annually from 2001 through 2018 would amount to about 10 percent of all forest area annually if the metric just included forest fires. Instead, the FAO estimates that in 2015, "tree-covered burned area" only accounted for 29 percent of the total, representing only 3 percent of forest area (p. 92).

More recent estimates using a more narrowly defined concept of forest fires arrive at a far smaller fraction of forest area burned each year. (Tyukavina et al., 2022; Tyukavina, 2024). These estimates, in the University of Maryland Global Land Analysis and Discovery (GLAD) dataset, apply higher-resolution satellite data to measure "forest fires resulting in tree-cover loss (stand-replacement fires)", excluding those that do not (Tyukavina et al., 2022, p. 2)[7]. They thus exclude "low-intensity and understory forest fires that do not result in substantial tree-canopy loss," as well as "burning of felled logs following mechanical canopy removal" common in slash-and-burn agriculture (p. 2)[8].

Figure 1 shows the percent of global forest area burned annually in the Tyukavina et al. (2022) and updated Tyukavina (2024) estimates[9]. In this narrower measure of forest area lost to wildfires, there is a clear increase, from around 0.1 percent annual loss to forest fires in 2001-2011 to around 0.2 percent in 2013-2019 and 0.3 percent in 2020-2023[10].



Source: Calculated from Tyukavina (2024) and FAO (2020).

Figure 1. Percent of global forest area lost to wildfires, 2001-2023.

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[7] The authors apply 30-meter resolution data, in contrast to 250 - 500 m resolution in previous maps of global burned area. They critique the FAO estimates for not distinguishing between stand-replacement and non-stand-replacement fires such as those in "fire-adapted parkland and woodland savannas with little or no tree mortality" (p. 2).

[8] The high-resolution, stand-replacement approach follows Hansen et al. (2013) and annual updates in the Global Forest Watch initiative (https://www.globalforestwatch.org/).

[9] University of Maryland GLAD estimates, provided by Tyukavina (2024), show global forest area lost to fire rose from an average of 4.8 million hectares annually in 2001 through 2011 to a high of 14.8 million hectares in 2023. These estimates are taken as a percent of global forest area, using straight-line interpolation between the estimates in FAO (2020) namely: 4.158 billion hectares in 2000, 4.106 billion in 2010, and 4.059 billion in 2020 (FAO, 2020, p. 16). The average annual change in global forest area during 2010-2020 is assumed to have continued during 2021-2023.

[10] Also see MacCarthy et al. (2023) regarding the rising forest fire incidence observed in this database.

Table 1 provides detail on the sharp difference between the estimates of Tyukavina et al. (2022) and those of the FAO (2020) for 2015, the only year for which the FAO reports estimates on burned forest area. The most dramatic difference is between the FAO's estimate of about 73 million hectares lost to fires in tropical areas in that year, and the corresponding estimate of only 0.8 million hectares lost in that ecological domain in the UMD-GLAD database. The closest estimates between the two sources are for boreal forests, which lost 6 million hectares to fire in the FAO estimates and 4.5 million in the UMD-GLAD estimates.

Table 1. FAO versus university of maryland-GLAD estimates of forest fire area in 2015 (thousand ha).

Ecological domain	FAO: forest area *affected by* fire	% of forest area	UMD-GLAD: forest area lost to *stand-replacement* fire	% of forest area
Tropical	72,860	4	810	na
Subtropical	9760	2	440	na
Temperate	9390	1	380	na
Boreal	6030	1	4,500	na
TOTAL	98,040	3	6,130	0.15[a]

n.a. Not available; a. See note 9 regarding global forest area. Source: FAO, 2020 (p. 92); Tyukavina et al., 2022 (p. 10, fig. 8).

The stand-replacement loss to fire is the most relevant to measuring the leakage of forest-sequestered carbon to wildfires, so the analysis of this study is based primarily on the UMD-GLAD estimates (Tyukavina et al., 2022; Tyukavina, 2024).

Alternative satellite-based estimates by Chen et al. (2023) show a much larger area forest burned annually, but no trend. The authors use MODIS (Moderate Resolution Imaging Spectroradiometer) data[11] and do not remove non-stand-replacement fires. As a consequence, the estimates are likely to overstate the incidence of forest loss to wildfires, for the reasons discussed by Tyukavina et al. (2022). For 2001-2020, Chen et al. show an average of 87 million hectares of forest burned annually (their Figure S14), or 2.1 percent of global forest area.

3. The Forest Fire Tree Death Hazard Rate

The life insurance industry applies the concept of the 'hazard rate" defined as the probability that a person of a given age will die within a specified period of time[12]. US Social Security officials apply an "actuarial life table" to assess the projected finances of Social Security and Medicare each year (US Social Security Administration, 2024). For example, their table for 2021 indicates that a male 65 years old faces a probability of 1.99 percent of dying within the next year. By age 75, this year-ahead death probability rises to 4.06 percent; and by age 82, it reaches 7.78 percent. The 65-year-old male has a cumulative probability of 50 percent for dying

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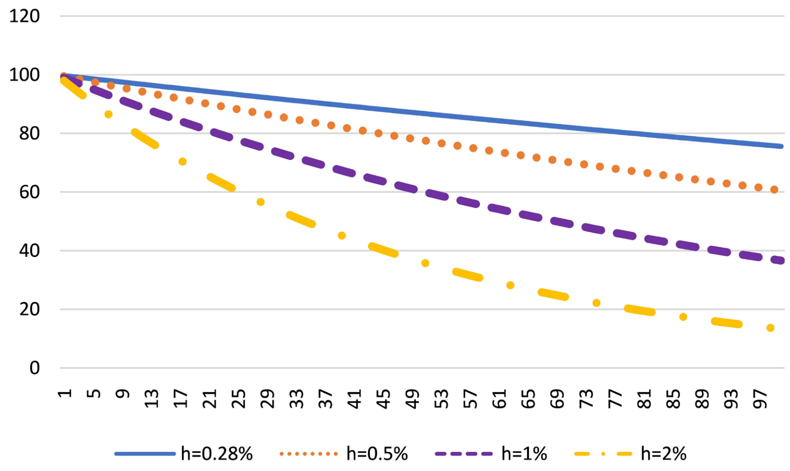
[11] See NASA (2024).

[12] See for example Liberto (2022).

within the next 16.95 years, the period defined as his prospective "life expectancy"[13].

Whether it makes sense to plant trees as a means of sequestering carbon depends in part on whether rising temperatures from global warming will increase the rate of forest loss to fires so much that the expected years of continued sequestration would be sharply reduced in comparison to past experience. Lutter et al. (2021) identify the larch and the Norway spruce as the best species in northern Europe for carbon sequestration in biomass and harvested wood substitution in products over a 100-year period. The lifespan of the larch is some 250 years (Woodland Trust, 2024), and that of the Norway spruce, some 200 - 300 years (Sullivan, 1994)[14].

Figure 2 shows the probability for survival of a long-lifespan tree over 100 years under alternative assumptions about the annual hazard rate for tree death by wildfire[15]. The choice of a 100-year horizon is meant to reflect the centennial life scale of the relevant trees for forestation while remaining broadly within the typical horizon in, for example, the more detailed projections of the IPCC. The highest survival path (lowest hazard rate path) uses a constant annual hazard rate of 0.28 percent, the global average rate in 2019-2023 rate based on the Tyukavina (2024) high-resolution, stand-replacement calculations (see **Figure 1** above). The lowest survival path (highest hazard rate path) applies the Chen et al. (2023) moderate-resolution all-fires estimate of about 2 percent.



Source: author's calculations.

Figure 2. Probability of tree survival under alternative annual fire loss hazard rates (percent, vertical, and year, horizontal).

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[13] Expectancy designates what can typically be expected, indicating a cumulative 50 percent probability. This cumulative probability is less than the sum of the individual annual probabilities, because in each successive year the new annual hazard rate applies to a smaller base of "survivors" than the full base at the beginning of the 65-year-old's horizon.

[14] Note however, that Sullivan also reported that the Norway spruce was not well adapted to survive fire, despite having been widely planted in reforestation programs in the eastern United States.

[15] At a constant annual hazard rate of h, at the end of the first year the fraction surviving will be $1 - h$; at the end of the second year, $(1 - h)$ times the previous year's surviving fraction, or $(1 - h)^2$; and so forth. At the end of year n, the fraction surviving will be $(1 - h)^n$.

The scope for rising incidence of forest fires to undermine effective sequestration through forestation can then be examined by considering the prospective rise in the hazard rate. In broad terms, and without adjusting for the time delay for the warming and hence the rise in the hazard rate, the impact on effectiveness of forestation sequestration can be seen as loss of the area under the survival curve from transiting from a lower hazard rate to a higher one. For example, if the rate were to surge from 0.28 percent annually to 1.0 percent (from the highest curve to the next-to-lowest), then, evaluated at the midpoint of 50 years, survival would fall from 86.9 percent to 60.5 percent. As a consequence, the effective sequestration would fall by nearly one-third. The resulting effective unit cost of sequestered carbon would be 50 percent higher than the baseline estimate ignoring the prospective increase in fire incidence from warming[16]. The analysis below returns to alternative prospective hazard rate paths incorporating rising fire incidence from future global warming.

4. Estimating a Direct Emissions Hazard Rate for the United States

The US Environmental Protection Agency issues annual estimates of greenhouse gas emissions and sinks in its "inventory" submitted to the Intergovernmental Panel on Climate Change. Its most recent issue includes estimates of annual emissions of carbon dioxide from forest fires (EPA, 2024, pp. 6-31, 6-33). **Table 2** shows these estimates, as well as the EPA estimates for the existing stocks of above-ground carbon in forest areas[17].

Over the past two decades, US forest area as measured by the EPA has been approximately constant at about 282 million hectares. (In comparison, total US land area including Alaska and Hawaii is 936.2 million ha; EPA, 2024, pp. 6-11.) In 2023 the above-ground forest carbon stocks shown in **Table 2** amounted to 24,702 million metric tons of carbon (corresponding to 90,656 million metric tons of carbon dioxide).

The EPA estimates of annual emissions from fires on forest land show a sharp surge in 2021, followed by a decline in 2022 (emissions estimates are not yet available for 2023). At their 2021 peak, these emissions amounted to 164 million metric tons of carbon dioxide, or 0.18 percent of the total relevant pool of carbon in US forests. This fraction can be interpreted as a direct calculation of an "emissions hazard rate".

The US EPA estimates of CO_2 emissions from US forest fires provide an indirect test of whether the UMD-GLAD estimates of stand-replacement fires represent an appropriate metric, or whether instead they seriously understate fire loss in

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[16] If the total cost of the planting remains unchanged at C, but sequestration falls from Q_0 to 0.67 Q_0, unit cost of sequestered carbon rises from $c_0 = C/Q_0$ to $c_1 = C/(0.67\ Q_0)$. This approximation treats the relevant hazard curves as straight lines. Incorporating nonlinearity (most evident in the lowest curve in **Figure 2**), the proportionate unit cost increase would be somewhat higher.

[17] Adding below-ground biomass (3233 mmt C in 2023), soil-mineral (28,401 mmt C), and soil-organic (5983 mmt C) would more than double the estimate of the carbon stock in the forest ecosystem, but these stocks are unlikely to be susceptible to generating emissions from fires.

view of the much higher FAO estimates and moderate-resolution estimates such as Chen et al. (2023). **Table 2** shows that in 2020-2022, average CO_2 emissions from US forest fires were 139 million metric tons annually. The Tyukavina (2024) estimates show US forest area lost to fire at an average of 993,000 hectares annually in this period. The corresponding implied average fire emissions amounted to 140 metric tons of CO_2 per hectare. This amount represents 44 percent of the average relevant carbon dioxide pool (317 mt/ha in this period; **Table 2**). This fraction is reasonable for a stand-replacing fire. Far larger estimates would imply implausible amounts of emissions exceeding the relevant carbon pool. Appendix A shows further that a relatively good statistical fit can be obtained by relating the time series of EPA forest-fire emissions estimates to the UMD-GLAD time series for US forest area lost to fire.

Table 2. US forest area and forest fire emissions, 1990-2023.

	1990	2005	2019	2020	2021	2022	2023
Forest area (1000 ha)	283,500	282,521	281,137	281,779	281,780	281,752	281,724
Carbon pool (mmtC)[a]							
Biomass[b]	12,739	15,122	17,199	17,340	17,483	17,622	17,757
Dead Wood	1977	2521	3038	3074	3111	3148	3184
Litter	3789	3794	3775	3767	3768	3768	3761
Total	18,505	21,437	24,012	24,181	24,362	24,538	24,702
total, mmt CO_2[c]	67,913	78,674	88,124	88,744	89,409	90,054	90,656
avg mt CO_2 per ha	240	278	313	315	317	320	322
Fire emissions[d]	55.1	142.2	53.0	124.4	163.5	129.2	…
Percent of carbon pool	0.081	0.181	0.060	0.140	0.183	0.143	…

a. Million metric tons of carbon; b. Above ground only; c. mmt of carbon × 3.67; d. mmt CO_2. Source: EPA, 2024 (pp. 6-31, 6-33).

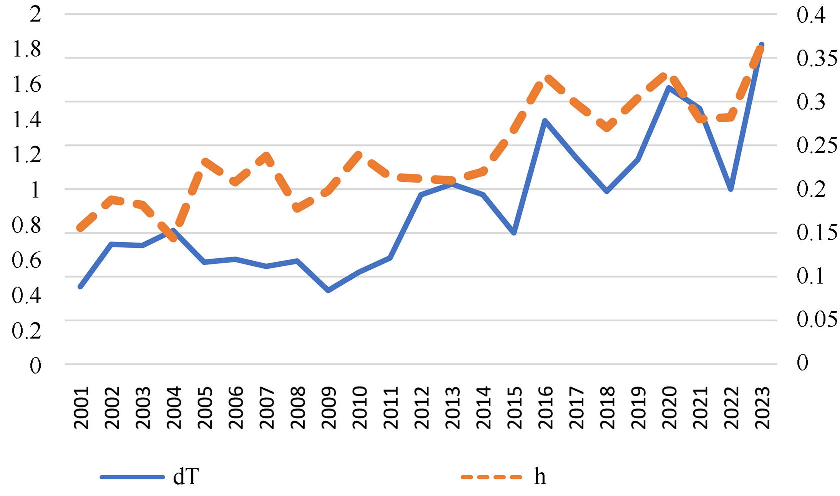
5. Prospective Impact of Global Warming on the Tree Death Hazard Rate from Forest Fires

The updated UMD-GLAD data can be combined with NOAA (2024) estimates of global temperature trends to examine the influence of a warming climate on the hazard rate for tree death from forest fires. **Figure 3** repeats the information in **Figure 1** on the right axis, for forest area lost to stand-replacing forest fires expressed as a percent of global forest area. The left axis adds information on the excess of the global average land temperature in a given year above the 1901-2000 average level (the year's temperature "anomaly").

A broad positive correlation between forest lost to fire and global land temperature anomaly is evident in **Figure 3**. The exception is in the period 2005-2011, when temperatures plateaued but fire incidence declined.

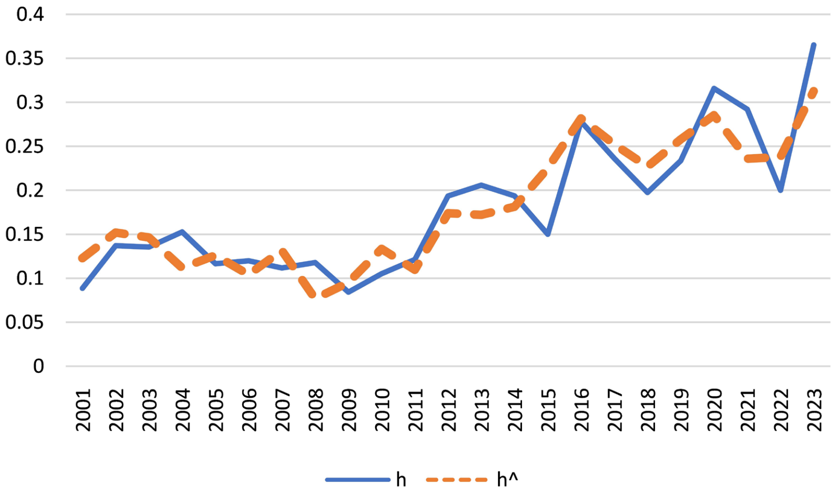
A simple linear regression of the fire loss hazard rate on the global land temperature anomaly and a dummy variable for 2005-11 yields the result shown in

Equation (1). **Figure 4** shows the actual path of the hazard rate (h) and the path predicted by the regression (h^). In this regression, an increase in global land temperature by 1 degree Celsius above the 1901-2000 average increases the hazard rate for tree death by forest fire by 0.183, with a high statistical significance (t-ratio of about 7).



Source: NOAA (2024); and calculated from Tyukavina (2024) and FAO (2020).

Figure 3. Global land temperature anomaly from 1901-2000 average (Left, ˚C) and forest loss to fire as percent of global forest area (Right).



a. Forest area lost to fire as percent of global forest area. Source: calculated from Tyukavina (2024), NOAA (2024), and FAO (2020).

Figure 4. Forest fire hazard rate[a], 2001-2023 (Percent) actual and predicted by warming anomaly.

$$h = -0.020 + 0.1827dT - 0.0660 \cdot D_{2005\text{-}11} \rightarrow \text{adj.}R^2 = 0.799 \qquad (1)$$

$$(-0.58)(6.98)(-4.02) \rightarrow \text{t-statistics in parentheses}$$

Equation (1) provides a basis for projecting the future increase in the forest fire hazard rate that might be expected from climate model projections of future global warming. The most recent estimates of the IPCC place cumulative warming above average global surface temperatures in 1850-1900 at 1.18˚C in 2020. The IPCC projects additional global surface warming of 0.52˚C by 2050 in the moderate scenario SSP1-2.6, reaching cumulative warming of 1.7˚C. The corresponding projection in the high emissions scenario SSP5-8.5 is an increment of 1.07˚C above the 2020 level, to cumulative warming of 2.25˚C above the 1850-1900 average by 2050 (IPCC, 2021, p. SPM28).

To apply Equation (1), the IPCC projections need to be converted to temperature anomalies against the period 1901-2000, and the global land and ocean anomaly needs to be converted to a land-only anomaly[18]. The 2020 anomaly cited by IPCC (2021) becomes 1.006˚C. The observed 2020 anomaly above 1901-2000 for global land was 1.67˚C. The projected increases in global land and ocean temperature remain unchanged from the corresponding changes when applying the 1850-1900 base (0.52˚C or 1.07˚C). The projected increase in land temperature can be estimated by applying the 1.64 factor observed over the past 6 decades (see note 18). The increase in the land temperature anomaly against 1901-2000 by 2050 then becomes 0.852˚C for SSP1-2.6 and 1.755˚C for SSP5-8.5, placing the anomaly levels by 2050 at 2.52˚C and 3.42˚C respectively. Applying Equation (1), expected forest loss to fire would rise from h^ = 0.285 percent in 2020 to 0.44 percent in the moderate scenario and to 0.604 percent in the severe scenario. A reasonable broad range for the change in the forest fire hazard ratio by 2050 is a near-doubling from its 2020 level, to about 0.5 percent. This rate would represent approximately the second path shown in **Figure 1** (round-dot).

The linear relationship of the hazard rate to the warming anomaly indicated in Equation (1) suggests that if there is a prospective "tipping point" of steep, nonlinear acceleration of forest fire incidence, it is not yet identifiable.

6. Impact of Rising Fire Loss on Cost Effectiveness of Carbon Sequestration by Forestation

Jäger et al. (2024) argue that the integrated assessment models (IAMs) applied to evaluate alternative mitigation pathways "project global forest area to be expanded vastly" in order to limit global warming to the 1.5 to 2.0-degree Celsius range endorsed internationally in the 2015 Paris Agreement. They critique the model estimates for insufficient attention to likely increases in forest fires at warmer tem-

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[18] During 1850-1900 average global surface temperature was 0.174˚C lower than the average for 1901-2000, so this magnitude needs to be subtracted from the IPCC anomaly estimates using the 1850-1900 base. (Note that for land surface only, the 1850-1900 average was 0.455˚C lower than the 1901-2000 average. Both calculations are from NOAA 2024 data). Both land and global surface temperatures remained relatively flat on average from 1850 to 1918, but then by 1944 rose to local peaks of about 0.4˚C above the 1850-1900 average (global land and ocean) and 0.7˚C (global land). By 1964 these anomalies had fallen back to zero (land & ocean) and 0.1˚C. However, for the past 60 years there has been an upward trend in the temperatures. From the period 1963-73 to the period 2013-2023, the average anomalies from 1850-1900 have risen from 0.185˚C to 1.098˚C for land-ocean, and from 0.395˚C to 1.892˚C for land. During this period the ratio of land temperature increases to the global land-ocean surface increase amounted to a factor of 1.64.

peratures, and, they imply, a corresponding unreliability of forestation as a mitigation instrument. They find that in the scenario SSP1-2.6 designed to meet the 2˚ limit to global warming above pre-industrial temperatures, six leading IAMs rely on global forest expansion ranging from 3 to 10 million square kilometers, or to 7 to 22 percent above present forest area[19].

The authors estimate the Canadian Fire Weather Index (FWI) as a function of temperature, precipitation, relative humidity, and surface winds (p. 11)[20]. They then apply projections of these variables in Earth System Models participating in the IPCC's Coupled Model Intercomparison Project (CMIP). The resulting global forest area weighted mean FWI stood at 13.7 in 2020. In climate scenario SSP1-2.6, this average rises to 14.35 by 2050 and then remains at that plateau (their Figure 3).

In six IAMs, the median outcome indicates a resulting rise of 10 percent in the global mean FWI by 2050, reaching a 25 percent increase by 2090 (their Figure 4(b)). The corresponding median increases in predicted global annual burned area on existing forested area as a consequence of climate change is 8 percent by 2050 and 25 percent by 2090 (their Figure 4(e)). Once the additional forest area is taken into account, the median overall increase in burned forest area amounts to 24 percent by 2050 and 60 percent by 2090. The disproportionate jump in projected burned forest area from the forestation reflects the fact that "most of the increase in danger under SSP1-2.6 is driven by A/R [afforestation and reforestation] in regions of already high and/or intensifying fire weather" (p. 6).

If the Jäger et al. projections are applied to the Tyukavina (2024) average of 0.27 percent of global forest area lost to wildfires annually in 2020-2023 (**Figure 1** above), the SSP1-2.6 scenario would correspondingly be expected to boost the fire loss hazard rate to about 0.33 percent by 2050 and about 0.43 percent by 2090. In terms of the survival path shown in **Figure 1** above, setting 2021 as year 1, by year 70 the survival rate would still be above the second from top path (for h = 0.5%), and still near the top path.

However, the six IAMs examined in Jäger et al. have a higher 2020 base rate of fire incidence, with central estimates of the share of annual burned forest area ranging from 0.6 percent ("IMAGE") to 1.8 percent ("MESSAGE-GLOBIUM) (Jäger et al., 2024, Figure S3). **Figure 5** shows three alternative paths of tree survival rates to provide further comparison of the estimates of this study and those in Jäger et al. In the first, "J1," the hazard rate for tree death by forest fire begins at the average between the low and high IAM estimates for 2020, a base rate of 1.2 percent. By 2050 the rate rises by 24 percent to 1.49%, and by 2090 it rises by a

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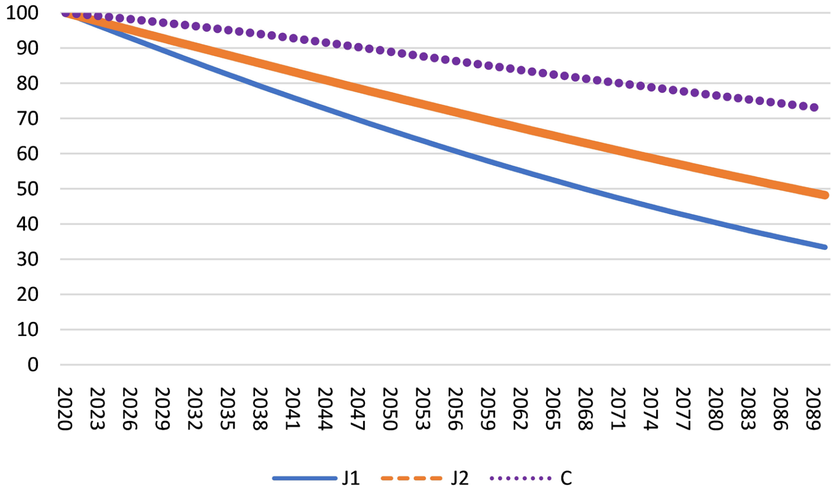
[19] SSP refers to "shared socio-economic pathway;" "1" refers to the first ("sustainability" or "green road") of 5 scenarios examined in the IPCC's sixth assessment report; and "2.6" refers to radiative forcing of 2.6 watts per square meter as the level reached by 2100. The six IAM models considered in Jäger et al. (2024) begin from estimates of current forest extent ranging from 37.5 Mkm^2 to 43.5 Mkm^2; by 2100, two of the models (IMAGE and AIM) show global forest area as high as 53 to 55 Mkm^2 respectively for SSP1-2.6 (p. 3).

[20] For the United States, this index was less than 5 for the Eastern states and Alaska, but in the range of 25 - 35 for California and the Southwest (their Figure 3).

cumulative 60 percent, to 1.92%. The second scenario based on the Jäger et al. estimates ("J2") simply applies annual hazard rate two-thirds as large as those in J1. The basis for this shrinkage is that the 2020 base rates in the IAMs are likely overstated by the same problems as the FAO and Chen et al. estimates discussed above, including failure to remove fire loss to intentional slash and burn, or to planned maintenance burn. The third path in the figure ("C") applies the rise in the base rate from 0.28 percent in 2020 to 0.5 percent by 2050 in the estimates of the present study, as discussed above. It assumes no further increase in the hazard rate after 2050, under the optimistic assumption that "net zero" for emissions is achieved by 2050[21].



a. "J" refers to Jäger et al.; "C" refers to this study. See text. Source: author's calculations.

Figure 5. Forestation tree survival rates (percent) under three fire hazard rate scenarios[a].

If one sums the survival-percent-years under each path in **Figure 5**, the result provides a basis for inferring the overall carbon leakage rate for forestation measures. In the most pessimistic path, J1, survival falls from 100 percent at the start (2020) to 67 percent by 2050 and 33 percent by 2090, yielding a cumulative percent-survival years of 4500 out of maximum potential of 7000 over 70 years. In the more optimistic path J2, the corresponding sum is 5185; and in path C, the sum is 6157. On this basis, and assuming an estimate of $75 per ton of CO_2 for sequestration by forestation before accounting for fire loss, the corresponding estimates over the next 70 years (at constant dollars) would be $117, $101, and $85 respectively. This range of adjusted costs seems unlikely to be so high that it would broadly negate forestation as an attractive strategy. In the likely range between paths C and J2, only 12 percent to 26 percent of gross sequestration from forestation would be lost to fire[22].

In contrast, Jäger et al. imply that forestation is unlikely to be an attractive

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[21] The premise of "TCRE" (Transient Climate Response to cumulative Emissions) that future additional warming stops approximately when net emissions reach zero has been maintained in the most recent IPCC assessment report (IPCC, 2021, pp. 22, 28). Also see Cline, 2022 (chapter 5).

[22] That is: [1 − (6157/7000)] to [1 − (5185/7000)] respectively.

means of carbon sequestration because of rising fire incidence. They state: "We showed the forestation potential under SSP1-2.6 modeled in the presented IAM simulations to be severely compromised by fire risk. Including such risk into the assessment will likely diminish the role of forestation in the mitigation portfolio." The exercise here suggests their inference is too pessimistic. Two additional considerations concern extent and location of forestation efforts. First, the upper end of the range of addition to forest area in Jäger et al., expansion by 22 percent might indeed push forestation to a range of rapidly diminishing returns. Second, the study's finding that most of the increase in fire incidence would be attributable to locating most of the new forest area in areas that already have high fire risk could be too pessimistic. As discussed below, some recent studies find greater potential than usually assumed for additional forestation in geographic areas not already subject to relatively high fire risk[23].

7. More Fuel for the Fires versus Less Carbon Dioxide in the Atmosphere

Nonetheless, the primary concern of such observers as David Wallace-Wells may not be that warming and fires will negate the sequestration potential of forestation by raising the tree-death hazard rate. Rather, the concern may be that prospective damage from wildfires is already so large that additional damage from increasing the area and density of forests available to be burned would be more costly than the benefit from the additional carbon sequestered.

Global forested area of 4.06 billion hectares currently sequesters an estimated 662 billion metric tons of carbon (GtC), of which 295 GtC is in biomass (FAO, 2020, p. 129). By implication, if forestation expanded the forest area by 10 percent, the eventual sequestration potential would amount to an additional 29.5 GtC in biomass beyond current levels[24]. In comparison, the remaining carbon budget to limit global warming above pre-industrial levels to 2˚ Celsius is on the order of 500 GtC (59 billion tons of carbon-dioxide equivalent; IPCC, 2013, p. 1033; Cline, 2022, p. 147). Global emissions of greenhouse gases were 16 billion tons of carbon in 2019 (59 billion tons of carbon-dioxide-equivalent; IPCC, 2023, p. 4). At this rate, only about 30 years remained before exhaustion of the carbon budget even with no further increase in the annual rate. Forestation expanding the forest base by 10 percent could increase the effective remaining carbon budget by about 6 percent[25].

The EPA estimates that at a discount rate of 2 percent, the 2050 social cost of carbon would stand at $310 per ton of carbon dioxide in 2020 dollars (EPA, 2023b, p. 4). At that price, sequestration of 29.5 GtC, corresponding to 108 billion metric

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[23] Moreover, severity of fire risk in the tropics may be overstated in the moderate as opposed to high-resolution satellite analyses, as strongly suggested by the FAO versus UMD-GLAD comparison in **Table 1** above.

[24] As noted above, the IPCC (2022, p. 33) estimates that 5 to 6 billion tons of carbon dioxide could be sequestered annually over the next 30 years at a cost of about $75 per ton. The cumulative sequestration would amount to 45 GtC (= [30 × 5.5/3.67]), and hence an expansion of forested area by as much as 15 percent.

[25] That is: 29.5 GtC/500GtC.

tons of carbon dioxide, would constitute creation of a global asset worth \$33.5 trillion at 2020 prices, or \$38.6 trillion at 2023 prices[26].

For the United States, researchers at the National Institute of Standards and Technology have estimated that the "costs and losses of wildfire" are between \$73 billion and \$348 billion annually, at 2016 prices (Thomas et al., 2017, pp. 45-50). The category of largest potential loss is death from wildfire smoke, at \$203 billion for the high estimate but only \$29 billion for the low estimate[27]. In the high estimates, the next two largest categories are evacuation costs (\$42.5 billion) and potential impact on housing price (\$28.3 billion). In addition to fire losses, there are costs associated with preventing wildfires. In the high estimates, the largest category is converting terrain to defensible space, which would amount to a high of \$53 billion but a low of \$1.7 billion)[28]. The average of the high and low estimates is \$210 billion in annual costs and losses. At 2023 prices, these costs and losses amount to \$267 billion, or 1.0 percent of 2023 GDP[29].

Table 3 compiles an illustrative set of estimates of the carbon sequestration benefits of an expansion of global forest area by 10 percent, and the extra costs of fire damage this forestation might cause. The first entry in the table is the \$267 billion in annual costs and losses of US wildfires. The second entry reduces this figure by half to take account of wildfires not in forested areas. On the basis of area burned the reduction would be greater, but the amount of smoke and emissions per hectare from forest fires is much greater than that from grassland fires[30].

The third entry in **Table 3** shows the total US forested area as estimated by the FAO (2020, p. 15). The fourth entry is the implied average of annual forest fire costs and losses per hectare for the United States (entry 2 divided by entry 3).

Row 5 in the table shows the FAO estimate of global forested area. Row 6 multiplies this area by the US costs and losses per hectare in row 4 to arrive at a rough estimate of annual world forest fire damage applying US rates, amounting to \$1.76 trillion. Row 7 estimates that forestation amounting to 10 percent of current world forest area would sequester 108 billion metric tons of carbon dioxide[31]. Row 8

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[26] US consumer prices rose by 17.7 percent from 2020 to 2023 (BLS, 2024).

[27] The authors apply a value of a statistical life of \$9.6 million. They report that whereas the high estimate imputes 21,095 annual deaths to wildfire smoke, the annual number of direct deaths from wildfire is exceedingly low, at 15 for civilians and 18 for firefighters.

[28] Measures to create defensible space from wildfires include firewise landscaping, in which plants are placed a few feet away from the house, followed by a zone of 30 feet dominated by a green mowed lawn excluding evergreen trees (see e.g. Maryland, 2024).

[29] Consumer prices rose 27.0 percent from 2016 to 2023 (BLS, 2024). US GDP was \$27.36 trillion in 2023 (BEA, 2024).

[30] On average, for 2001-2023 the total US land area burned by wildfires annually was 2.78 million hectares (NICC, 2024). In the same period, the annual average forest area lost to fires in the UMD-GLAD dataset was 0.64 million hectares, or 24.5 percent (calculated from Tyukavina, 2024). However, "… trees have a larger fuel load and lose more carbon to the atmosphere than grasses per unit of area burned" (Zheng et al., 2021, p. 2). In view of the key role of smoke in the damage estimates, the share of damage from forest fires would be expected to exceed their share in total land area burned. Globally, the density of CO and CO_2 emissions from forest fires is about 4 times that from grassland fires (ibid).

[31] As discussed above, the world forest total of 4.06 billion hectares sequesters 295 GtC; the 10 percent forestation measure would sequester another 29.5 GtC, corresponding to 29.5 × 3.67 = 108.3 $GtCO_2$.

shows the EPA (2023b) intermediate estimate of the social cost of carbon dioxide in 2050, $365 per metric ton at 2023 prices[32]. Row 9 then multiplies this unit social value to the cumulative quantity of carbon dioxide sequestered by forestation in the 10 percent expansion exercise (row 7) to arrive at the social value of the sequestration achieved: $39.4 trillion at 2023 prices.

Table 3. Illustrative global forestation benefits of carbon sequestration versus additional fire costs (in 2023 US dollars) applying US parameters.

1	Annual costs and losses of US wildfires	$267 billion
2	Likely share attributable to forests: one-half (?)	$133.5 billion
3	US forest area	310 million ha
4	Forest fire costs and losses per hectare, US	$431/ha
5	World forest area	4.06 billion ha
6	World forest fire damage at US rate	$1.75 trillion
7	CO_2 sequestration from 10% increase in world forested area	108.2 $GtCO_2$[a]
8	Social cost of carbon dioxide by 2050 (discounting at 2%)	$365/metric ton
9	Social value of sequestration added	$39.4 trillion
10	Annual fire costs and damage from 10% increase in forest base:	
10a	At current climate conditions: US	$13.35 billion
10b	World	$175 billion
10c	At future climate conditions assuming double fire incidence: US	$26.7 billion
10d	World	$350 billion
11	Cumulative additional costs and damages over 30 years	
11a	US	$601 billion
11b	World	$7.88 trillion

a. Gt = billion metric tons.

Section 10 of the table considers the annual damage by mid-century from additional forest fires associated with 10 percent expansion of forest area. Rows 10a and 10b are simply 10 percent of rows 2 and 6, estimating 10 percent increase in forest area in the United States and the world respectively but with no allowance for greater fire incidence from global warming. In contrast, rows 10c and 10d show the annual damage by mid-century for the United States and the world respectively under the assumption that the warmer world doubles the forest fire incidence from recent levels.

Section 11 of the table translates the mid-century estimates of annual damages into cumulative damages over 30 years, applying linear annual increments between the estimates 10a, 10b and the estimates 10c, 10d. In this illustrative exercise, by mid-century *the value of carbon dioxide sequestered globally,* $39 *trillion*

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[32] The intermediate estimate discounts at 2 percent per annum, and is $310 per metric ton in 2020 prices.

(*row* 9), *is five times as large as the cumulative fire damage from additional forest area available for wildfires to burn*, \$7.9 trillion (row 11b).

Consideration of possible biases in this illustrative calculation suggests that benefits of the forestation scenario would continue substantially to outweigh additional fire costs under reasonable alternative assumptions. One alternative that would reduce the benefit/cost ratio would be to assume a considerably larger increment than a doubling in the incidence of fire for the marginal 10 percent of global forest area in this forestation scenario. As noted above, the Jäger et al. (2024) estimates of disproportionately large increase in global forest fires from increasing forested area are driven by concentration of the expanded area in regions with already high fire weather. However, pursuing a 10 percent expansion in global forest area rather than the 15 percent implied in IPCC (2022) would mean more flexibility to avoid concentrating expansion in such regions.

On the damages side, an important potential bias in the estimates of **Table 2** is toward overstatement because of the use of US parameters (rows 6, 10b, and 10d). In particular, valuation of human life lost to increased smoke is priced based on the value of a US statistical life in the Thomas et al. (2017) estimates. In contrast, on the benefit side, the draft EPA social cost of carbon dioxide applies a lower statistical value of life for lower income countries. The result is to understate the benefit/cost ratio unless the costs were adjusted to similarly weigh the rest of the world in the damage estimates. However, the severity of fires in more recent years than the period covered by that study, including in Maui in 2023 and Pacific Palisades in early 2025, may have raised the appropriate damage estimates significantly.

A possible upward bias in the benefit/cost comparison is comparing the total mid-century sequestration stock with cumulative incremental fire damage annual flows by that time, without taking account of damage flows in subsequent decades. Whereas the stock of carbon dioxide sequestered would be unlikely to rise much after mid-century, annual flows of damage from fires on the added forest area would continue (and grow, in the Jäger et al. estimates). Even so, the five-fold gap between benefits and costs (or more if the cost is adjusted downward for global statistical life valuation) is so large that incorporating the subsequent decades would be unlikely to eliminate the net forestation benefit. Moreover, the draft EPA social cost of carbon dioxide also rises after 2050, with the increase from 2050 to 2080 amounting to 32 percent (EPA, 2023b, p. 4)[33].

8. Further Considerations

This study examines whether increases in wildfires associated with a warmer

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[33] More specifically, if the annual flow of global damages from extra fires associated with extra forest area were to plateau at the \$350 billion shown in row 11 of **Table 2**, an additional 30 years for the horizon would add \$10.5 trillion to cumulative damages. In comparison, a 32 percent increase in the social cost valuation of the stock of carbon dioxide sequestered by 2050 would add \$12.6 trillion to the benefit of the sequestration, placing the (broad rough) benefit/cost ratio at (39.4 + 12.6)/(7.88 + 10.5) = \$52 trillion/\$15.4 trillion = 2.83, not as high as the 5:1 ratio in **Table 2** but still close to 3:1. (A constant rather than rising annual damage flow after 2050 would be consistent with the ambitious international target of zero net emissions by 2050; see e.g. IEA (2023, p. 7).

world should sharply reduce expectations of the scope for afforestation and reforestation to contribute to limiting global warming. The tentative conclusion is in the negative, for two reasons. First, the hazard rate for forest tree-death has been so low that even a major increase such as a doubling would not reduce net sequestration of carbon dioxide sufficiently to turn forestation into an unattractive policy. Second, although forestation would increase the forest base in area and density, and hence biomass available to be burned, the climate benefits of the net sequestration would greatly exceed the additional fire damages from this increase in the fuel available.

These diagnoses do not address the usual set of caveats about the potential of forestation, including concerns about additionality, credibility, competition for agricultural land, institutional obstacles such as land rights of indigenous communities, and the net radiative effects if the area's reflectivity (albedo) declines when forest replaces open land[34]. Nor do they address whether afforestation of grassy ecosystems in the tropics has potential adverse effects on biodiversity and water availability to streams[35]. Instead, the analysis here implies that concern about future wildfires should not become a new and predominant addition to these policy caveats.

The issue of albedo warrants special comment. Recent research suggests that the previous tendency to focus this concern on high latitude boreal forests because of the reflective role of snow cover of open areas has not been sufficiently nuanced. Mykleby, Snyder, and Twine (2017) find high potential for sequestration in some mid- to higher-latitude areas even after taking account of albedo effects[36]. Hasler et al. (2024) find that "[W]hile dryland and boreal settings have especially severe albedo offsets, it is possible to find places that provide net-positive climate mitigation in all biomes," but that although "on-the-ground projects are concentrated in these more climate-positive locations, …the majority still face at least a 20% albedo offset" (p. 1).

Two recent studies further suggest continued relevance of forestation despite rising fire incidence. In the first, a year-long review of US reforestation by the Departments of Interior and Agriculture set reforestation targets at a total of 72.3 million acres by 2030 (US DOI-DOA, 2023, pp. 3-4), representing 9.4 percent of existing forest area. These included targets for federal land (2.3 million acres, of which the National Forest Service would account for 1.8 million); and indicative goals of 51.4 million acres for private timberland, 5.1 million for state timberland, 5.7 mil-

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[34] A forestation project may not be additional to carbon sequestration if the trees would have been planted anyway. It may not credibly secure legal assurance that the newly planted area will remain in forest over many decades. For a discussion of these and other obstacles, see Mendelsohn, Sedjo, and Sohngen (2012). The authors nonetheless judged that an efficient forest carbon sequestration program could provide as much as one-fourth of CO_2 emissions reduction needed over this century, with more than 40 percent from reduced deforestation and the rest about evenly divided between improved forest management and afforestation.

[35] See for example Kate Parr and Caroline Lehmann, "When Tree Planting Actually Damages Ecosystems," *The Conversation*, July 26, 2019.

[36] These include New England, the Great Lakes states, and to a lesser extent the Pacific Coast, in the United States; and Novia Scotia and New Brunswick in Canada (p. 2498).

lion for private and tribal drinking water basins, and 7.8 million for urban reforestation. The report recognized that "wildfires increased reforestation needs," for example by over 1.5 million acres in California and Oregon after 2020-21 wildfires (p. 2). The study made no mention at all of a proposition that reforestation efforts should be *reduced* because wildfires had turned a remedy into a threat.

The second study with a similar implication found that management interventions that reduce wildfire severity can partially offset climate-related declines in tree regeneration (Davis, Robles, Kemp, Higuera, Chapman et al., 2023)[37]. The study found declining conifer postfire regeneration in Western US forests over the past four decades. It indicated that "Changes to fire regimes resulting from fire suppression, past management practices, …that have increased the likelihood of high fire severity …may be playing a larger role driving reductions in postfire conifer regeneration than direct climate impacts alone" (p. 4). Using climate model projections through 2050 (with scenario RCP4.5), and models of post-fire regeneration for 8 species of conifers, it found that "median recruitment probability decreased by 0.34 with a change from low to high fire severity, as opposed to a decline of only 0.12 on average due to climate change in successive time periods"… (p. 3). However, the study also warned of "a limited time window over which management actions that reduce fire severity may effectively support postfire conifer regeneration"[38].

9. Conclusion

Despite the global increase in forest fires in recent years, forestation remains a major and relatively low-cost approach for sequestering carbon dioxide. The 165 billion tons of carbon dioxide (45 billion tons of carbon) that the IPCC (2022) estimates could be sequestered over the next 30 years at a cost of about US $75 per ton of CO_2 would constitute about one-tenth of the remaining carbon emissions budget of about 500 billion tons of carbon before global warming would exceed a limit of 2˚C above pre-industrial temperatures, at a cost much lower than alternative carbon capture approaches. The global "hazard rate" for carbon dioxide release from tree death caused by wildfires remains low, at about 0.3 percent annually. Even with projected increases in response to global warming, such as a doubling by 2050, this hazard rate would not reach levels that would substantially negate sequestration gains from forestation. Moreover, an illustrative exercise applying US parameters suggests that globally the damage from additional fires associated with increased forest area would be only a small fraction of the benefits from additional carbon sequestration resulting from the forestation, probably one-fifth or less.

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[37] The study indicated that "[T]here is substantial evidence that fuel reduction treatments, especially those using prescribed burning, effectively reduce local wildfire severity in dry forests" (p. 2). For 334 wildfires from.

[38] Based on the finding that the percent of the study area "unlikely to experience conifer regeneration, regardless of fire severity," was projected to rise from 5% in the 1981-2000 base period to 26 - 31% by mid-century.

Increased salience of public awareness of forest fires such as those in Canada and Hawaii in 2023 and the Western United States in 2024 and early 2025 should not halt efforts to use forestation as an important strategy in helping curb global warming. Nonetheless, forestation efforts will need to be accompanied by measures to address other obstacles. These measures include certification of additionality and credibility of projects, increased sophistication in calculations of vulnerability to offsetting reductions in land reflectivity (albedo) in locating projects, and (although not addressed in this study) broader development of carbon offset markets[39]. More fundamentally, the estimates here do not alter the diagnosis that reducing fossil fuel emissions remains by far the most important policy approach to limiting global warming, even with help still available from potential forestation despite forest fires.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

BLS (US Bureau of Labor Statistics) (2024). *Consumer Price Index for All Urban Consumers (CPI-U).*

Chen, Y., Hall, J., van Wees, D. et al. (2023). Multi-Decadal Trends and Variability in Burned Area from the 5th Version of the Global Fire Emissions Database (GFED5). *Earth System Science Data, 15,* 1-51. https://doi.org/10.5194/essd-2023-182

CIFFC (Canadian Interagency Forest Fire Centre) (2024). *Annual Burned Area in Canada.*

Cline, W. R. (1992). *The Economics of Global Warming.* Peterson Institute for International Economics.

Cline, W. R. (2022). *Median Incomes, China Shock, Climate Metrics, and Debt Sustainability: Collected Papers, 2018-2021.* Economics International Inc.

Davis, K. T., Robles, M. D., Kemp, K. B., Higuera, P. E., Chapman, T., Metlen, K. L. et al. (2023). Reduced Fire Severity Offers Near-Term Buffer to Climate-Driven Declines in Conifer Resilience across the Western United States. *Proceedings of the National Academy of Sciences, 120,* e2208120120. https://doi.org/10.1073/pnas.2208120120

EPA (2023a). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.*

EPA (2023b). *Report on the Cost of Greenhouse Gases: Estimates Incorporating Recent*

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[39] In the United States, the executive branch has recently set forth principles for evaluating the "integrity" of voluntary carbon credit markets (White House, 2024). Several carbon credit rating entities have emerged. Their disparate methods suggest a need for more systematic practices in this nascent field (see for example Wawrzynowicz, Krey, and Samaniego, 2023).

Scientific Advances. https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf

EPA (2024). *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022.*

EPA (US Environmental Protection Agency) (2015). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013.*

FAO (Food and Agriculture Organization of the United Nations) (2020). *Global Forest Resources Assessment 2020: Key Findings*. https://doi.org/10.4060/ca8/53en

Hasler, N., Williams, C. A., Denney, V. C., Ellis, P. W., Shrestha, S., Terasaki Hart, D. E. et al. (2024). Accounting for Albedo Change to Identify Climate-Positive Tree Cover Restoration. *Nature Communications, 15,* Article No. 2275. https://doi.org/10.1038/s41467-024-46577-1

IEA (International Energy Agency) (2023). *Global Energy and Climate Model: Documentation-2023.*

International Energy Forum (2022). *Caverns, Concrete and Carbonate: The Future of Storing Captured Carbon.*

IPCC (2013). *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report.*

IPCC (2022). *Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the Sixth Assessment Report.*

IPCC (2023). *Climate Change 2023: Synthesis Report, Summary for Policymakers.*

IPCC (Intergovernmental Panel on Climate Change) (2021). *Climate Change 2021: The Physical Science Basis. Working Group I Contribution to the Sixth Assessment Report.*

Jäger, F., Schwaab, J., Quilcaille, Y., Windisch, M. et al. (2024). *Fire Weather Compromises Forestation-Reliant Climate Mitigation Pathways.*

Liberto, R. (2022). *Hazard Rate: Definition, How to Calculate, and Example*. Investopedia.

Lutter, R., Stål, G., Arnesson Ceder, L., Lim, H., Padari, A., Tullus, H. et al. (2021). Climate Benefit of Different Tree Species on Former Agricultural Land in Northern Europe. *Forests, 12,* Article No. 1810. https://doi.org/10.3390/f12121810

MacCarthy, J., Richter, J., Tyukavina, S., Weisse, M., & Harris, N. (2023). *The Latest Data Confirms: Forest Fires Are Getting Worse*. World Resources Institute.

Maryland (Maryland Department of Natural Resources) (2024). *Firewise Landscaping.* https://dnr.maryland.gov/forests/Documents/fire/Firewise_LandscapingFactsheet.pdf

Mendelsohn, R., Sedjo, R., & Sohngen, B. (2012). Forest Carbon Sequestration. In R. A. de Mooij, M. Keen, & I. W. H. Parry (Eds.), *Fiscal Policy to Mitigate Climate Change: A Guide for Policymakers* (pp. 89-102). International Monetary Fund.

Mykleby, P. M., Snyder, P. K., & Twine, T. E. (2017). Quantifying the Trade-Off between Carbon Sequestration and Albedo in Midlatitude and High-Latitude North American Forests. *Geophysical Research Letters, 44,* 2493-2501. https://doi.org/10.1002/2016gl071459

NASA (National Aeronautics and Space Administration) (2024). *MODIS: Moderate Resolution Imaging Spectroradiometer.* https://modis.gsfc.nasa.gov/about

NOAA (2024). *NOAAGlobalTemp.* https://www.ncei.noaa.gov/products/land-based-station/noaa-global-temp

Sullivan, J. (1994). Picea Abies. In *Fire Effects Information System* (pp. 1-12). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). https://www.fs.usda.gov/database/feis/plants/tree/picabi/all.html

Thomas, D., Butry, D., Gilbert, S., Webb, D., & Fung, J. (2017). *The Costs and Losses of Wildfires: A Literature Survey*. National Institute of Standards and Technology.

Tyukavina, A. (2024). *2001-2023 Forest Loss Due to Fire*. Database Provided by Special Communication.

Tyukavina, A., Potapov, P., Hansen, M. C., Pickens, A. H., Stehman, S. V., Turubanova, S. et al. (2022). Global Trends of Forest Loss Due to Fire from 2001 to 2019. *Frontiers in Remote Sensing, 3,* Article ID: 825190. https://doi.org/10.3389/frsen.2022.825190

US DOI-DOA (US Department of the Interior and US Department of Agriculture) (2023). *Reforestation Goals and Assessments, and a Climate-Informed Plan to Increase Federal Seed and Nursery Capacity*.

US Social Security Administration (2024). *Actuarial Life Table*. https://ssa.gov/oact/STATS/table4c6.html

Wawrzynowicz, I., Krey, M., & Samaniego, X. (2023). *Assessing and Comparing Carbon Credit Rating Agencies*. Perspectives Climate Group.

White House (2024). *Voluntary Carbon Markets Joint Policy Statement and Principles*. https://home.treasury.gov/system/files/136/VCM-Joint-Policy-Statement-and-Principles.pdf

Woodland Trust (2024). *European Larch.* https://www.woodlandtrust.org.uk/trees-woods-and-wildlife/british-trees/a-z-of-british-trees/european-larch/

Zheng, B., Ciais, P., Chevallier, F., Chuvieco, E., Chen, Y., & Yang, H. (2021). Increasing Forest Fire Emissions Despite the Decline in Global Burned Area. *Science Advances, 7,* eabh2646. https://doi.org/10.1126/sciadv.abh2646

Appendix A

US Forest Fire Incidence and CO_2 Emissions

The data on carbon dioxide emissions from US forest fires reported by the US Environmental Protection Agency provide one possible basis for checking the accuracy of the University of Maryland GLAD data on forest fires by country. Table A1 shows the annual estimates of forest area lost to fires in the UMD database, in thousand hectares, and the annual EPA estimates of CO_2 emissions from forest fires for the same years when available.

Table A1. US forest area lost to fire and associated carbon dioxide emissions.

	UMD-GLAD forest area loss to fire (1000 ha)	EPA CO_2 emissions from forest fires (million metric tons)	metric tons per ha
2001	348	…	…
2002	672	…	…
2003	423	…	…
2004	926	…	…
2005	918	142.2	155
2006	901	…	…
2007	663	…	…
2008	452	…	…
2009	263	77.9	297
2010	583	63.4	109
2011	268	76.4	285
2012	373	86.1	231
2013	461	97.8	212
2014	295	41.7	141
2015	1079	239.9	222
2016	713	50.9	71
2017	677	123.5	182
2018	653	84.6	130
2019	759	53.0	70
2020	812	124.4	153
2021	997	168.3	169
2022	1171	129.2	110
2023	325	…	…

Source: Tyukavina (2024); EPA (2024, 2023a, 2015)[40].

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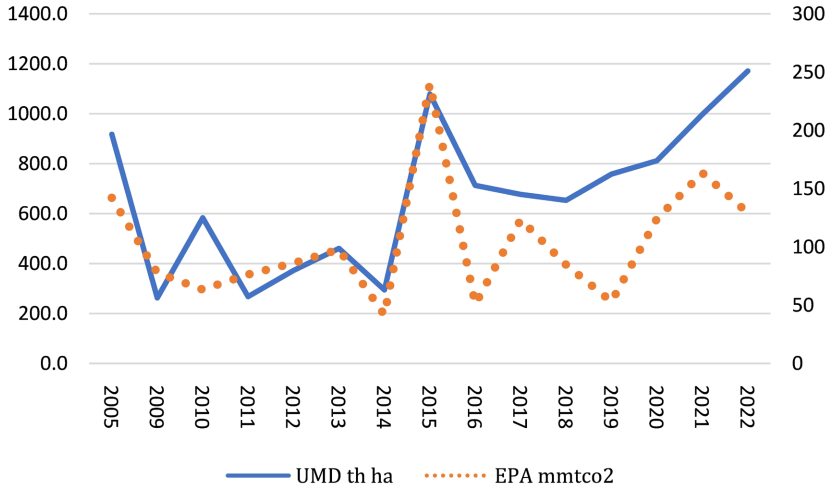
[40] Emissions data are from EPA (2024) for 2005 and 2018-22; EPA (2023) for 2011-2017; and EPA (2015) for 2009-10.

The emissions estimates are for carbon dioxide. In addition, forest fires cause emissions of methane and nitrous oxide, which the EPA estimates separately[41]. The final column of the table shows the ratio of the CO_2 emissions to the forest area lost to fire. This ratio eased from an average of 214 metric tons per hectare in 2009-2015 to 126 metric tons per hectare in 2016-2022. In comparison, above-ground biomass, plus dead wood and litter, has averaged about 300 metric tons of CO_2 in the US forest carbon pool (text **Table 2**). The relatively high ratio of emissions to burnable carbon stock is consistent with the UMD focus on "stand-replacement" fires.

Figure A1 shows these data with area lost to fire on the left axis and CO_2 emissions on the right axis[42]. The broad correlation is suggestive of supportive emissions evidence consistent with estimated fire area. The principal caveat is a tendency for lower emissions to occur after 2015 than would have been expected from the pattern before then.



Source: see **Table A1**.

Figure A1 UMD-GLAD fire loss area (1000 ha, left) and EPA forest fire CO_2 emissions (million metric tons, right).

A simple linear regression predicting CO_2 emissions given forest area lost to fire, and incorporating a dummy variable after 2015, achieves reasonably high explanation. With E as CO_2 emissions from forest fires (million metric tons) and F as US forest area lost to fires (thousand hectares):

$$E = 15.9 + 0.1647F - 47.8 \cdot D_{2016\text{-}22} \rightarrow \text{adj.}R^2 = 0.58 \qquad \text{(A1)}$$

$$(0.71)(4.62)(-2.34) \rightarrow \text{t-statistics in parentheses}$$

Figure A2 shows the paths of actual and predicted emissions applying this

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[41] In 2021, these emissions amounted to CO_2 equivalents of 12.7 million metric tons and 7.2 million metric tons, respectively, representing an increase of about 12 percent in total carbon dioxide equivalent emissions above the amount for CO_2 alone. EPA (2024, pp. 6-45).

[42] Note that the first observation is for 2005; the next is for 2009 and then all years are included through 2022.

equation.

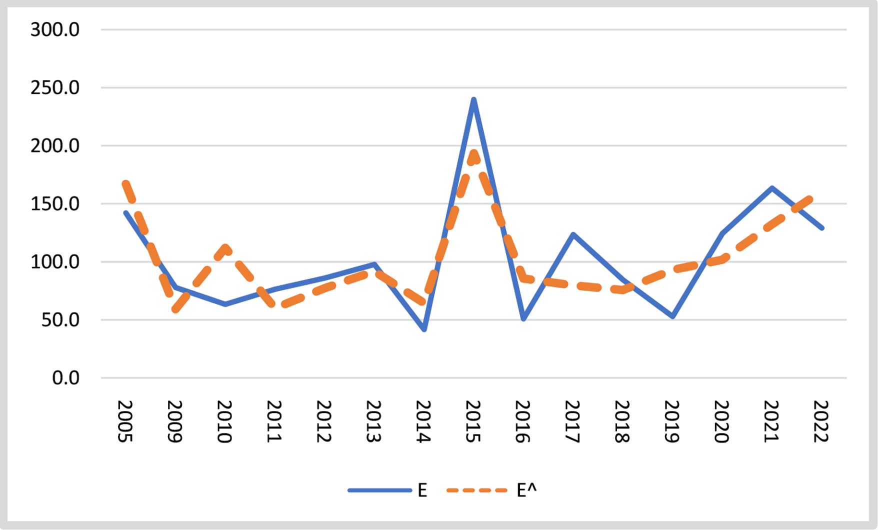

Figure A2 Actual and predicted emissions of CO_2 from US forest fires (million metric tons).

These results suggest that US EPA data on emissions from forest fires provide evidence supporting the University of Maryland-GLAD high-resolution satellite data estimates of annual losses of forest area to fire.