



**Economics
International
Inc**

Working Paper 24-1

Forest Fires and Carbon Sequestration

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July 22, 2024; rv. November 6

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. The “hazard rate” for carbon dioxide release from tree death caused by wildfires remains low. Even with projected increases in response to global warming, this hazard rate would not reach levels that would substantially negate sequestration gains from forestation. The damage from additional fires associated with increased forest area would be much smaller than the benefit from additional carbon sequestration resulting from the forestation.

Keywords: {Climate Change, Forest Fires}
JEL Q23, Q54

Introduction

It has long been recognized that reforestation and afforestation are relatively low-cost means of sequestering carbon dioxide.² As discussed in Appendix A, 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 (GtCO₂) 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 anticipates a plateau of about 40 GtCO₂ annually; and the cost of direct air capture and carbon sequestration (DACCS) would likely be \$100 to \$300 per ton (IPCC 2022, p. 36).

¹ President, Economics International Inc., and Senior Fellow Emeritus, Peterson Institute for International Economics. For comments on an earlier draft, I thank without implicating Yang Chen, James MacCarthy, William Nordhaus, and Jessica Richter. I thank Alexandra Tyukavina, Associate Research Professor at the University of Maryland, for providing updated data on forest loss due to fire, from the Global Land Analysis and Discovery (GLAD) high-resolution satellite dataset.

² For an early discussion, see Cline (1992, chapter 5).

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 sequestration 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

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 2,000 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.

⁴ “Captured CO₂ can be compressed until it reaches a fluid state suitable for transporting in pipelines and injecting into underground systems like 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 is still good, all else being equal, and can offer some climate benefits, if more limited ones than optimistic assessments suggest.”

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 ...”

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 the more usual caveats about forestation, such as its potential competition for land area otherwise in food production, and regional differences such as the consideration of loss of albedo (reflectiveness of earth’s surface).

Global Trends in Forest Fires

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, and 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

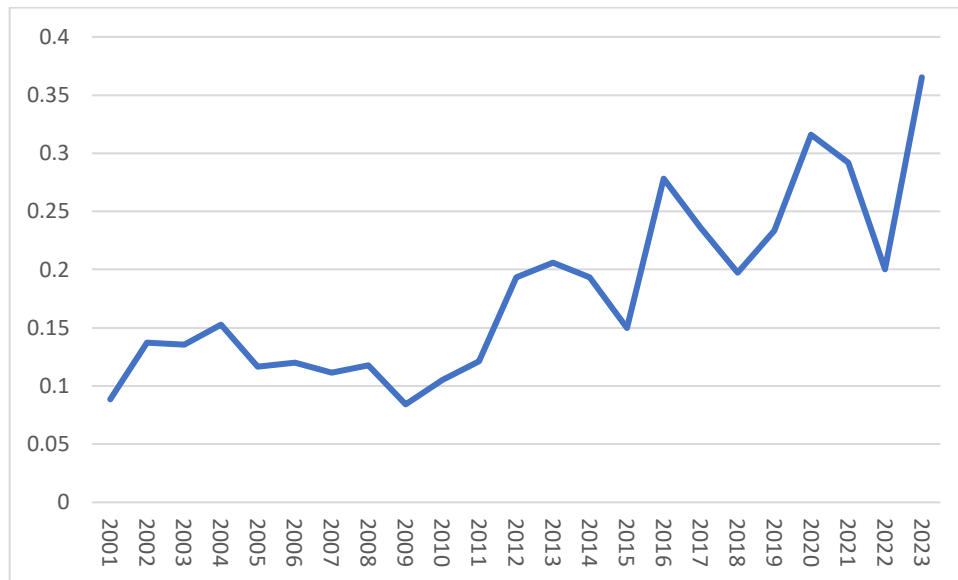
⁷ The authors apply 30-meter resolution data, in contrast to 250-500 m resolution in previous maps of global burned area. They critique the FAO estimates for not distinguishing between stand-replacement and non-stand-replacement fires such as those in “fire-adapted parkland and woodland savannas with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

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

Figure 1

Percent of Global Forest Area Lost to Wildfires, 2001-2023



Source: calculated from Tyukavina (2024) and FAO (2020)

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.

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

FAO versus University of Maryland-GLAD Estimates of Forest Fire Area in 2015
(thousand ha)

Ecological domain	FAO: forest area <i>affected by fire</i>	% of forest area	UMD-GLAD: forest area lost to <i>stand- replacement</i> fire	% of forest area
Tropical	72,860	4	810	na
Subtropical	9,760	2	440	na
Temperate	9,390	1	380	na
Boreal	6,030	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) data¹¹ 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.

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. 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 within the next 16.95 years, the period defined as his prospective “life expectancy”.¹³

¹¹ See NASA (2024).

¹² See for example Liberto (2022).

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.

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 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 path applies the Chen et al (2023) moderate-resolution all-fires estimate of about 2 percent.

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.

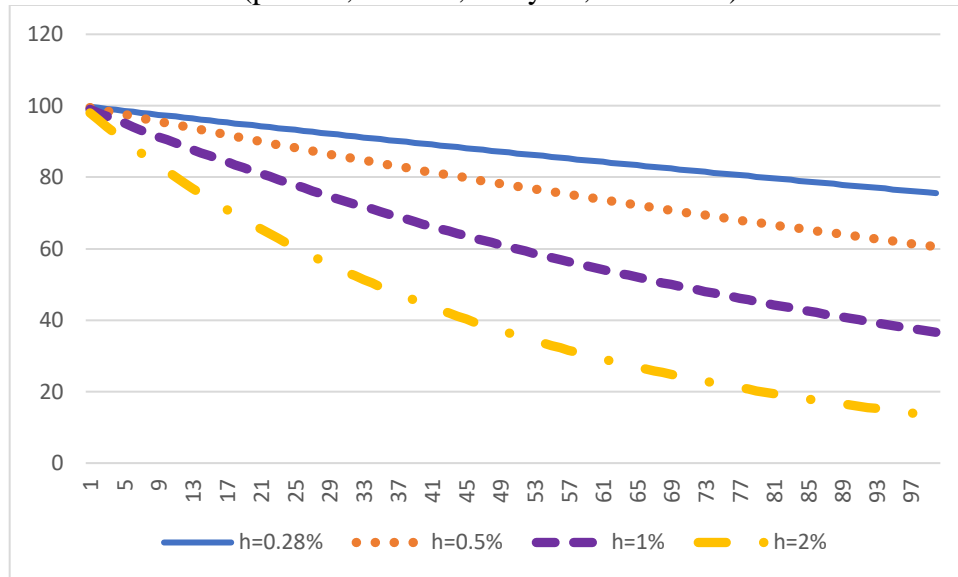
¹⁴ Note however, that Sullivan (1994) reports that the Norway spruce is “not well adapted to survive fire” even though “it has been widely planted in reforestation programs in the eastern United States.”

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 $(1-h)^n$.

¹⁶ If the total cost of the planting remains unchanged at C , but sequestration falls from Q_0 to $0.67Q_0$, 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.

Figure 2

Probability of Tree Survival under Alternative Annual Fire Loss Hazard Rates (percent, vertical, and year, horizontal)



Source: author's calculations

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, p. 6-11.) In 2023 the above-ground forest carbon stocks shown in table 1 amounted to 24,703 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”.

¹⁷ Adding below-ground biomass (3,233 mmt C in 2023), soil-mineral (28,401 mmt C), and soil-organic (5,983 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.

Table 2

US Forest Area and Forest Fire Emissions, 1990-2023

	1990	2005	2019	2020	2021	2022	2023
Forest area (1,000 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	1,977	2,521	3,038	3,074	3,111	3,148	3,184
Litter	3,789	3,794	3,775	3,767	3,768	3,768	3,761
Total	18,505	21,437	24,012	24,181	24,362	24,538	24,702
total, mmtCO 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 x 3.67

d. Mmt CO₂

Source: EPA (2024, pp. 6-31, 6-33)

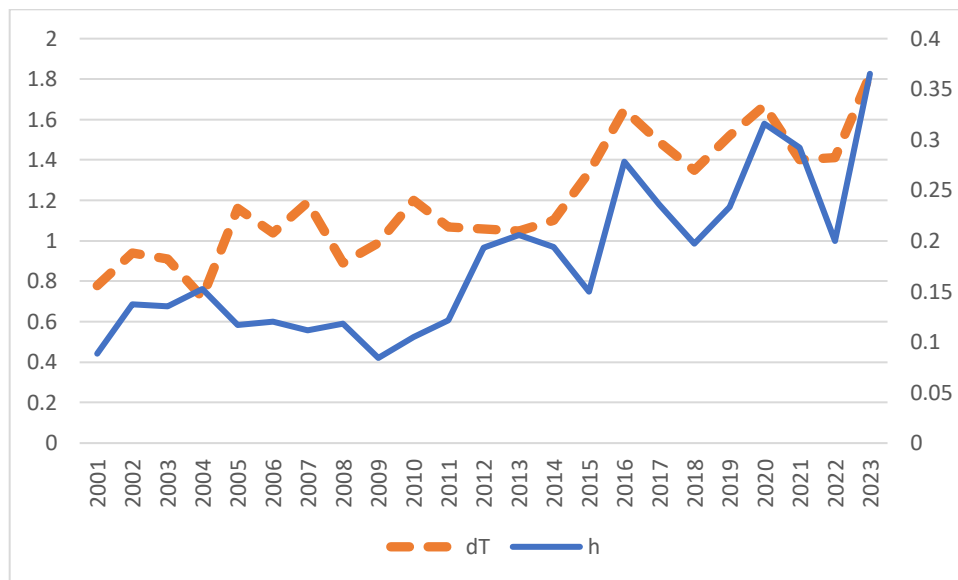
The US EPA estimates of CO₂ emissions from US forest fires provide an indirect test of whether the UMD-GLAD estimates of stand-replacement fires represent an appropriate metric, or whether instead they seriously understate fire loss in view of the much higher FAO estimates and moderate-resolution estimates such as Chen et al (2023). Table 2 shows that in 2020-2022, average CO₂ 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 CO₂ 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 B 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.

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").

Figure 3

Global Land Temperature Anomaly from 1901-2000 Average (Left, "dT", °C)
And Forest Loss to Fire as Percent of Global Forest Area (Right, "h")



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

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.

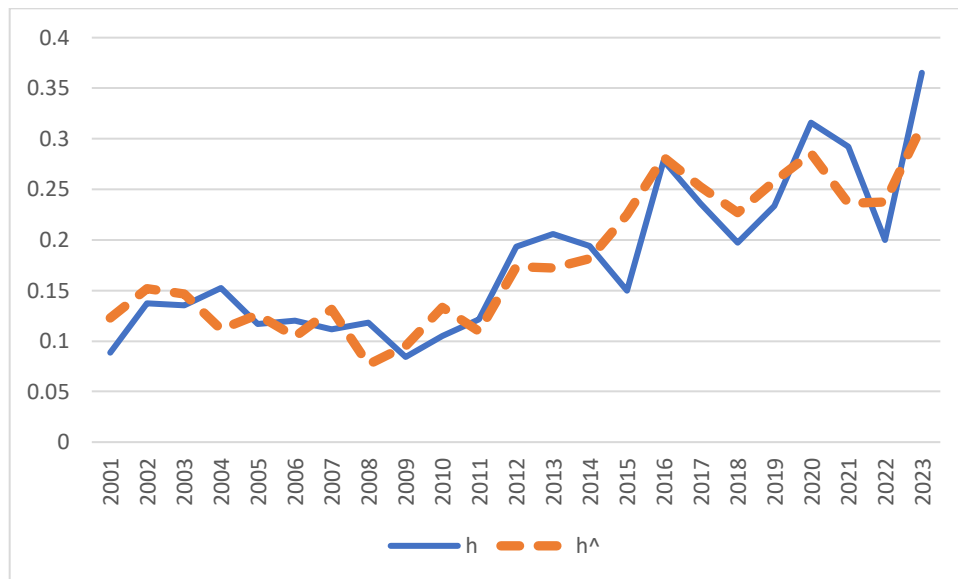
A simple linear regression of the fire loss hazard rate on the global land temperature anomaly and a dummy variable for 2005-11 yields the result shown in equation 3. Figure 4 shows the actual path of the hazard rate (h) and the path predicted by the regression (h^). In this regression, an increase in 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).

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

(-0.58) (6.98) (-4.02) (t-statistics in parentheses)

Figure 4

Forest Fire Hazard Rate^a, 2001-2023 (Percent)
Actual and Predicted by Warming Anomaly



a. Forest area lost to fire as percent of global forest area.

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

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 $h^{\wedge} = 0.285$ 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).

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

Jäger et al (2023) 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 temperatures, 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

¹⁸During 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.

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 (2023) begin from estimates of current forest extent ranging from 37.5 Mkm² to 43.5 Mkm²; by 2100, two of the models (IMAGE and AIM) show global forest area as high as 53 to 55 Mkm² 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).

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).

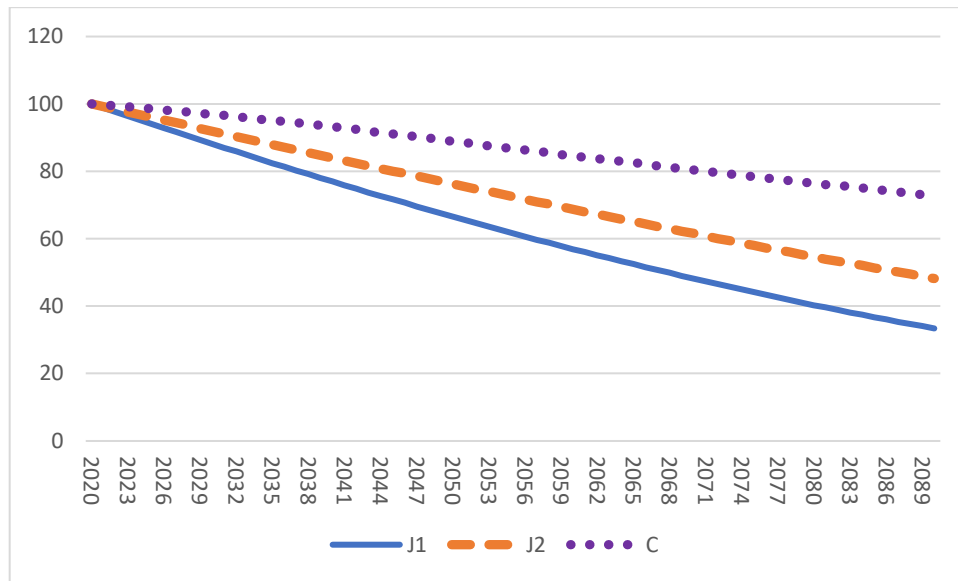
If the Jäger et al projections are applied to the Tyukavina (2024) average of 0.27 percent of global forest area lost to wildfires annually in 2020-2023 (Figure 1 above, path h[^]), the SSP1-2.6 scenario would correspondingly be expected to boost the fire loss hazard rate to about 0.33 percent by 2050 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 “share of annual burned forest area” ranging from 0.6 percent (“IMAGE”) to 1.8 percent (“MESSAGE-GLOBIUM”) (Jäger et al, 2023, 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 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

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).

Figure 5

Forestation Tree Survival Rates under Three Fire Hazard Rate Scenarios^a



a. “J” refers to Jäger et al; “C” refers to this study. See text.

Source: author’s calculations

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 CO₂ 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 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

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

find greater potential than usually assumed for additional forestation in geographic areas not already subject to relatively high fire risk.²³

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 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

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 and discussed in Appendix A, the IPCC (2022b, 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 x 5.5/3.67]), and hence an expansion of forested area by as much as 15 percent.

²⁵ That is: 29.5GtC/500GtC

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.

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 shows the EPA (2023b) estimate 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.

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.

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 CO₂ 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 $29.5 \times 3.67 = 108.3$ GtCO₂.

³² The intermediate estimate discounts at 2 percent per annum, and is \$310 per metric ton in 2020 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 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 (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 (2023) 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.

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

Caveats

This study examines whether increases in wildfires associated with a warmer 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 does it address whether afforestation of grassy ecosystems in the tropics has potential adverse effects on biodiversity and

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 $(39.4+12.6)/(7.88+10.5) = \$52 \text{ trillion}/\$15.4 \text{ trillion} = 2.83$, 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).

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 CO₂ 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.

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).

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 CO₂ 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.

Increased salience of public awareness of forest fires such as those in Canada and Hawaii in 2023 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.³⁷

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 Nova Scotia and New Brunswick in Canada (p. 2498).

³⁷ 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).

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Appendix A

Forestation and Forest Fires in the IPCC's Sixth Assessment Report

In its 2022 mitigation report of more than 2,000 pages (IPCC, 2022b), Working Group III of the Intergovernmental Panel on Climate Change reaffirmed the relatively low cost of carbon sequestration through forestation measures. Nonetheless, the report's introductory summary for policy-makers struck a relatively cautionary tone on the practical scope of these measures. Although the chapter on Agriculture, Forestry, and Other Land Uses (AFOLU) discussed rising incidence of forest fires, the report did not assess the potential increase in sequestration costs that could be associated with rising fire hazard at higher future temperatures.

This appendix comprises relevant quotations from the report.

Summary for Policymakers

p. 33: “The projected economic mitigation potential of AFOLU options between 2020 and 2050 at costs below USD100 tCO₂-eq⁻¹, is 8-14 GtCO₂-eq yr⁻¹ ...³⁸ 30-50% of this potential is available at less than USD20 tCO₂-eq⁻¹. ... The largest share ... (4.2-7.4 GtCO₂-eq yr⁻¹) comes from the conservation, improved management, and restoration of forests and other ecosystems ..., with reduced deforestation in tropical regions having the highest total mitigation. ... Persistent region-specific barriers continue to hamper the economic and political feasibility of deploying AFOLU mitigation options.

... Barriers ...include 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.

... Net costs of delivering 5-6 GtCO₂ yr⁻¹ of forest-related carbon sequestration and emissions reduction as assessed with sectoral models are estimated to reach about USD400 billion yr⁻¹ by 2050.”

p. 34: “Indigenous Peoples, private forest owners, local farmers and communities manage a significant share of global forests and agricultural land and play a central role in land-based mitigation options.”

Fire Regime Changes

p. 770: Wildland fires account for approximately 70% of the global biomass burned annually ... Although fires are part of the natural system, the frequency of fires has increased in many areas, exacerbated by decreases in precipitation, including in many regions with humid and temperate

³⁸ GtCO₂-eq yr⁻¹ refers to billion tons of carbon-dioxide-equivalent greenhouse gases per year. In comparison, the 2021 IPCC report of Working Group I (on The Physical Science Basis) placed baseline carbon-dioxide emissions from 2015 through 2050 at a plateau slightly above 40 GtCO₂ annually in its intermediate scenario (SSP2-4.5). IPCC (2021, p. 13).

forests that rarely experience large-scale fires naturally. ... [A] study over 14 years indicated, on average, the largest fires in Australia, boreal North America and Northern Hemisphere Africa ...

... About 98 Mha of forest and savannahs are estimated to have been affected by fire in 2015 ... Fire is a prevalent forest disturbance in the tropics where about 4% of the total forest and savannah area in that year was burned and more than two-thirds of the total area affected was in Africa and South America ... [L]and clearing for agriculture [has been] the primary driver in tropical regions, for example, clearance for industrial oil-palm and paper-pulp plantations in Indonesia ... or for pastures in the Amazon ... [I]n the last years, fire seasons of unprecedented magnitude occurred in diverse regions as California ..., the Mediterranean basin ..., Canada ... with unprecedented fires in British Columbia in 2021, the Arctic and Siberia ..., Brazilian Amazon ... and Pantanal, Chile ... and Australia Lightning plays an important role in the ignition of wildfires, with the incidence of lightning igniting wildfires predicted to increase with rises in global average air temperatures ...

Appendix B

US Forest Fire Incidence and CO₂ 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 B.1 shows the annual estimates of forest area lost to fires in the UMD database, in thousand hectares, and the annual EPA estimates of CO₂ emissions from forest fires for the same years when available.

Table B.1
US Forest Area Lost to Fire and Associated Carbon Dioxide Emissions

	UMD-GLAD forest area loss to fire (1,000 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, 2023, 2015).³⁹

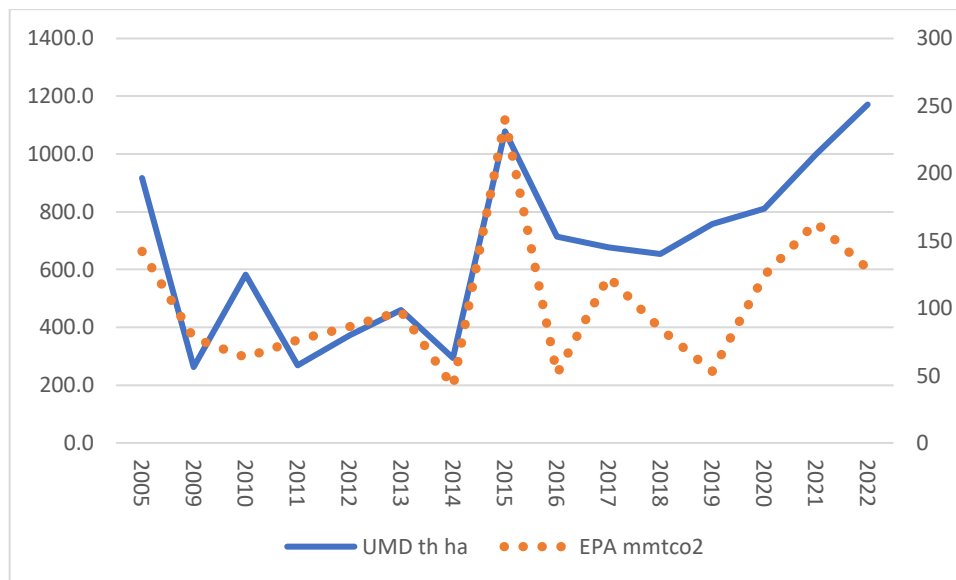
³⁹ Emissions data are from EPA (2024) for 2005 and 2018-22; EPA (2023) for 2011-2017; and EPA (2015) for 2009-10.

The emissions estimates are for carbon dioxide. In addition, forest fires cause emissions of methane and nitrous oxide, which the EPA estimates separately.⁴⁰ The final column of the table shows the ratio of the CO₂ 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 CO₂ in the US forest carbon pool (text table 1). The relatively high ratio of emissions to burnable carbon stock is consistent with the UMD focus on “stand-replacement” fires.

Figure B.1 shows these data with area lost to fire on the left axis and CO₂ emissions on the right axis.⁴¹ 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.

Figure B.1

UMD-GLAD Fire Loss Area (1,000 ha, left) and EPA Forest Fire CO₂ Emissions (million metric tons, right)



Source: see table B.1.

⁴⁰ In 2021, these emissions amounted to CO₂ 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 CO₂ alone. EPA (2024, p. 6-45).

⁴¹ Note that the first observation is for 2005; the next is for 2009 and then all years are included through 2022.

A simple linear regression predicting CO₂ emissions given forest area lost to fire, and incorporating a dummy variable after 2015, achieves reasonably high explanation. With E as CO₂ emissions from forest fires (million metric tons) and F as US forest area lost to fires (thousand hectares):

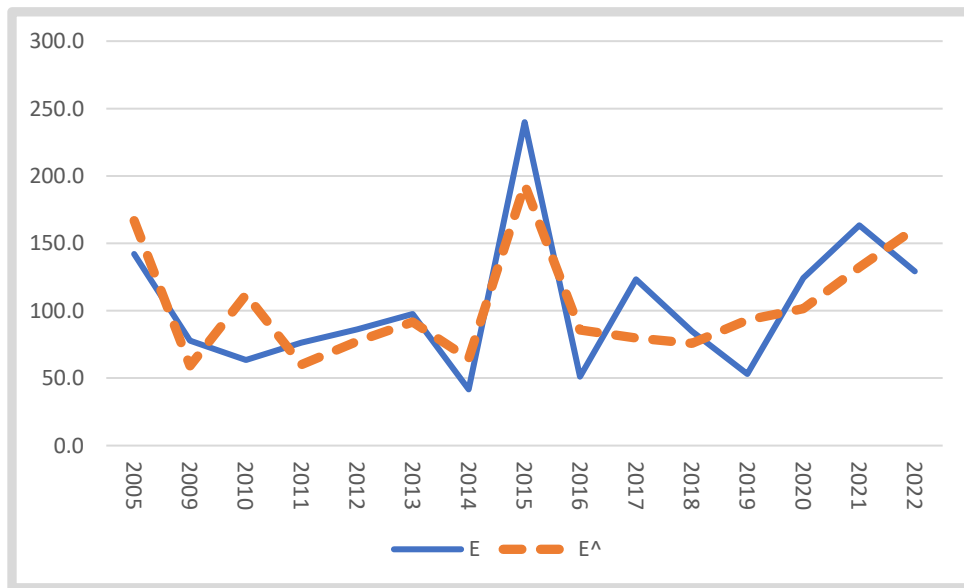
$$B. 1) E = 15.9 + 0.1647 F - 47.8 D_{2016-22} \quad \text{adj. } R^2 = 0.58$$

(0.71 (4.62) (-2.34) (t-statistics in parentheses)

Figure B.2 shows the paths of actual and predicted emissions applying this equation.

Figure B.2

Actual and Predicted Emissions of CO₂ 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.