

Article

Long-Term Socioeconomic Damages Attributable to Future Wildfire Carbon Emissions Under SSP2-4.5 and SSP5-8.5

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Abstract

Wildfires are an increasingly important carbon source under climate change, yet their long-term climate-mediated socioeconomic costs remain poorly quantified. Here, we used the PAGE-ICE integrated assessment model to estimate the economic damages attributable to projected wildfire CO₂ emissions under SSP2-4.5 and SSP5-8.5. Wildfire emissions were introduced through paired simulations with and without these emissions, allowing their marginal effects on atmospheric CO₂ concentration, radiative forcing, warming, and damages to be quantified. By 2100, wildfire emissions increased atmospheric CO₂ by 50.7 ppm under SSP2-4.5 and 56.1 ppm under SSP5-8.5, producing additional warming of 0.233 °C and 0.169 °C, respectively. Although wildfire emissions were higher under SSP5-8.5, their marginal climate effects were stronger under SSP2-4.5 because additional CO₂ produces a larger forcing increment when background concentrations are lower. By 2100, wildfire-attributable annual damages reached 8.11 trillion USD yr^{−1} under SSP2-4.5 and 6.63 trillion USD yr^{−1} under SSP5-8.5. Discounted cumulative damages were 144.0 and 130.3 trillion USD, respectively. Damages were unevenly distributed, with the largest absolute losses in Africa and the Middle East and India and Southeast Asia. These upper-bound estimates indicate that wildfire carbon emissions can impose substantial long-term socioeconomic costs and should be more explicitly represented in climate–economy assessments, residual-emission accounting, and sustainability-oriented fire and land-management strategies.

Keywords: wildfire emissions; climate change damages; integrated assessment model; PAGE-ICE; socioeconomic impacts; SSP scenarios; sustainability assessment



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1. Introduction

Wildfires have long shaped the structure and functioning of many terrestrial ecosystems, but their frequency, intensity, and spatial extent have changed substantially in recent decades under a warming climate [1,2]. Rising temperatures, prolonged droughts, declining snow cover, and increasing vapor pressure deficits have contributed to more favorable fire weather conditions across many regions, particularly in boreal forests and other high-latitude ecosystems [3,4]. Large wildfires have become increasingly common in North America, Siberia, Australia, and parts of the Mediterranean, causing extensive ecological and socioeconomic disruption [5–8]. Recent events illustrate the scale of these impacts. The 2019–2020 Australian bushfires burned more than 18 million hectares of land and generated substantial sectoral losses, including estimated agricultural losses of AUD 4–5 billion

and tourism-related output losses of about AUD 2.8 billion [9,10]. The 2025 Los Angeles wildfires were estimated to have caused tens of billions to more than one hundred billion USD in property and capital losses [11]. The unprecedented Canadian wildfire season in 2023 emitted more carbon than the annual fossil-fuel emissions of many industrialized countries and temporarily ranked among the largest national-scale carbon sources globally [12]. Beyond direct damage to infrastructure, forests, and human livelihoods, wildfires influence atmospheric composition, ecosystem carbon storage, hydrological processes, and land–atmosphere interactions, thereby creating feedbacks that can further amplify climate change [13].

The carbon released during wildfires represents a major perturbation to the global carbon cycle. Fire emissions consist primarily of carbon dioxide (CO₂), together with methane (CH₄), carbon monoxide, and aerosols [14]. Wildfire-induced combustion of biomass and organic soils can rapidly transfer carbon accumulated over decades or centuries back to the atmosphere [15,16]. Boreal forests are of particular importance because they store vast quantities of carbon in vegetation, soils, and permafrost [17]. In some regions, repeated burning may reduce ecosystem carbon sinks and accelerate permafrost degradation, leading to additional greenhouse gas emissions and longer-term climate feedbacks [18]. Consequently, wildfire emissions are increasingly recognized as a non-negligible component of the global carbon budget and a source of uncertainty in future climate projections [19].

Considerable effort has been devoted to understanding recent and future wildfire activity. Previous studies have examined trends in burned area, fire weather conditions, fire severity, and carbon emissions using observations, process-based models, and Earth system models [20]. Recent assessments suggest that climate change is likely to increase wildfire risk across many regions during the twenty-first century, although the magnitude of change varies among ecosystems and emission scenarios [21]. A growing body of research has also focused on the consequences of wildfire smoke exposure, linking wildfire-derived particulate matter to respiratory diseases, premature mortality, and increasing public health burdens [22,23]. For example, Zhao et al. (2025) projected future wildfire carbon emissions and smoke-related health impacts under different socioeconomic pathways, highlighting substantial increases in exposure and associated inequalities across regions [24]. Other studies have emphasized the role of wildfire emissions in altering atmospheric greenhouse gas concentrations, weakening terrestrial carbon sinks, and amplifying climate feedbacks [25,26].

Despite these advances, the economic assessment of wildfire impacts remains uneven across damage pathways. One group of studies has focused on direct wildfire losses, including suppression costs, property damage, infrastructure losses, and sectoral disruption. A second group has examined smoke-related health impacts, especially mortality and morbidity associated with wildfire-derived particulate matter. A third group has evaluated wildfire carbon emissions, burned area, fire severity, and ecosystem carbon feedbacks. However, these strands of research are rarely integrated in a way that quantifies the long-term climate-mediated economic damages caused specifically by wildfire carbon emissions [27–29]. In particular, carbon released during wildfires contributes to atmospheric greenhouse gas accumulation and can influence future warming trajectories, yet the resulting climate damages are rarely estimated in monetary terms [30,31]. This leaves a gap between wildfire carbon cycle research and climate–economy assessment. Quantifying this pathway is necessary for evaluating the broader sustainability implications of future wildfire activity, beyond direct fire damage and smoke-related health effects.

Integrated assessment models (IAMs) provide a framework for linking greenhouse gas emissions, climate responses, and socioeconomic outcomes within a consistent analytical system [32,33]. By translating additional emissions into atmospheric concentrations,

radiative forcing, temperature changes, and economic impacts, IAMs allow the long-term consequences of specific emission sources to be evaluated in monetary terms [34]. Among available IAMs, the Policy Analysis of the Greenhouse Effect (PAGE) model and its updated PAGE-ICE framework have been widely used in climate policy analysis, including assessments of climate damages, the social cost of carbon, Arctic feedbacks, permafrost carbon release, and geoengineering scenarios [35,36]. PAGE-ICE incorporates updated climate parameters, regional socioeconomic projections, revised CO₂ cycle equations, empirically constrained damage functions, and cryosphere-related processes that are particularly relevant to high-latitude regions [35,37]. These features make PAGE-ICE suitable for estimating the long-term climate and economic consequences of additional carbon emissions from future wildfires.

Here, we quantify the socioeconomic damages attributable to projected wildfire carbon emissions under future climate scenarios. Rather than projecting wildfire activity itself, we use wildfire carbon emission projections from Zhao et al. (2025) [24] as external inputs to the PAGE-ICE integrated assessment model. By comparing simulations with and without wildfire emissions under SSP-based scenarios, we estimate the marginal contribution of future wildfire carbon releases to atmospheric CO₂ concentration, radiative forcing, warming, and economic damages. The novelty of this study is that it isolates the climate-mediated economic cost of wildfire carbon emissions, rather than focusing on direct fire losses, suppression costs, ecosystem damage, or smoke-related health effects. This perspective is relevant for sustainability because wildfire carbon emissions can affect long-term climate risk, residual-emission accounting, and the evaluation of land- and fire-management strategies under future mitigation pathways. We focus on the SSP2-4.5 and SSP5-8.5 scenarios and examine both global and regional impacts.

2. Materials and Methods

Figure 1 summarizes the overall workflow, including data inputs, scenario construction, PAGE-ICE simulations, uncertainty analysis, and the main climate and economic outputs.

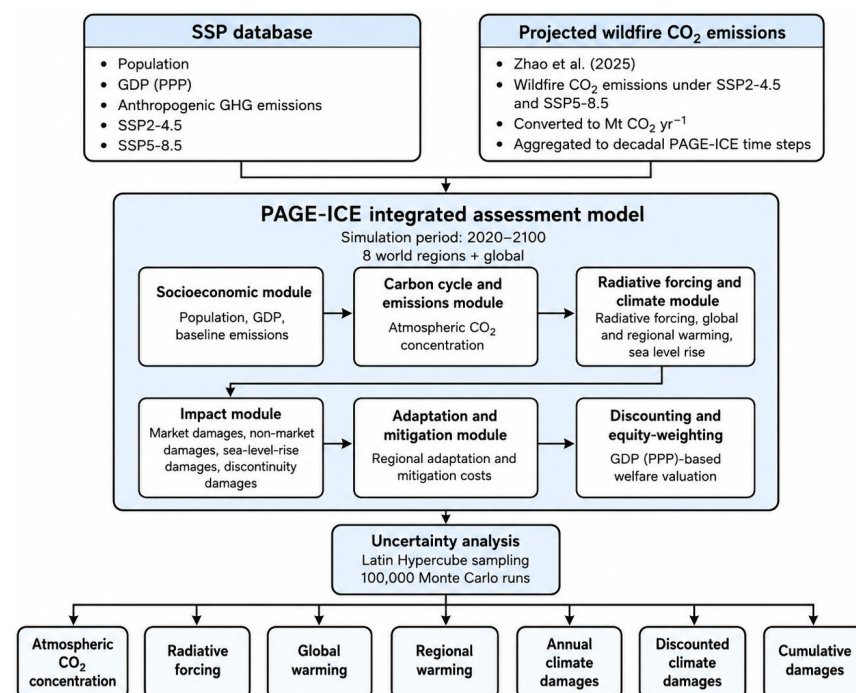


Figure 1. The overall workflow of this study.

2.1. Input Data

The model inputs used in this study include socioeconomic projections, anthropogenic greenhouse gas emissions, and projected wildfire carbon emissions under SSP2-4.5 and SSP5-8.5. Socioeconomic and anthropogenic emission data were obtained from the Shared Socioeconomic Pathways database [38]. The SSP database provides harmonized projections of population, gross domestic product (GDP), urbanization, greenhouse gas emissions, and radiative forcing under alternative socioeconomic narratives and climate forcing pathways [39]. These data were used to provide the baseline demographic, economic, and anthropogenic emission pathways required by PAGE-ICE. Following the regional structure of PAGE-ICE, country-level socioeconomic projections and harmonized emissions were aggregated into eight world regions (Figure A1) [40].

Wildfire carbon emission projections were obtained from Zhao et al. (2025) [24]. Their study developed an interpretable machine-learning framework to project global burned area and wildfire emissions under future warming scenarios, using historical wildfire information and climate-sensitive drivers derived from remote sensing, reanalysis products, and Earth system model simulations [24]. The resulting dataset provides future wildfire carbon emissions under SSP-based scenarios, including SSP2-4.5 and SSP5-8.5, and was used here as the external wildfire emission input for PAGE-ICE. We used this dataset because it provides a recent, internally consistent, global projection of future wildfire carbon emissions that can be linked directly with SSP-based PAGE-ICE simulations. To avoid mixing scenario differences with differences among fire emission models, we did not combine it with alternative wildfire datasets that differ in spatial coverage, scenario design, variable definition, or modeling framework. Because the wildfire dataset reports gross fire-related carbon emissions, our PAGE-ICE experiment treats these emissions as an additional atmospheric CO₂ perturbation. This assumption does not explicitly account for post-fire vegetation regrowth or ecosystem carbon recovery, and may therefore overestimate the long-lived atmospheric burden where regrowth offsets part of the initial fire emissions. Accordingly, the primary simulations are interpreted as a gross-emission perturbation case and provide upper-bound estimates.

The wildfire emission data were originally reported as carbon emissions and were converted to CO₂ emissions before being introduced into PAGE-ICE. In the input table used in this study, wildfire emissions are expressed in Mt CO₂ yr^{−1}. PAGE-ICE represents climate and economic processes at discrete simulation periods from 2020 to 2100. For model periods expressed at decadal intervals, wildfire emissions were aggregated to match the temporal structure of PAGE-ICE.

2.2. PAGE-ICE Integrated Assessment Model

We used the PAGE-ICE model to quantify the climate and economic consequences of future wildfire carbon emissions [40]. PAGE is one of the major integrated assessment models used in climate policy analysis and has been used in governmental estimates of the social cost of carbon [41,42]. PAGE-ICE is an updated version of the PAGE model that incorporates revised climate-response parameters, CO₂ cycle equations, regional socioeconomic projections, damage functions, and cryosphere-related processes [43]. It has been applied to assess climate damages, the social cost of carbon, Arctic feedbacks, permafrost carbon release, and the economic implications of geoengineering and carbon removal scenarios [35,44–47].

PAGE-ICE links emissions to atmospheric concentrations, radiative forcing, global and regional temperature change, sea level rise, and economic damages. The model contains four main components relevant to this study: a socioeconomic module that describes regional population and economic development, an emission and climate module that trans-

lates greenhouse gas emissions into atmospheric concentrations and temperature changes, an impact module that estimates climate-related damages through damage functions, and a discounting module that converts future losses into present values [48]. Regional impacts are calculated for eight world regions and then aggregated to the global level.

Climate damages in PAGE-ICE are represented through several broad categories, including market impacts, non-market impacts, sea-level-rise damages, and discontinuity damages associated with large-scale climatic and socioeconomic risks [45]. In this study, we used the “PAGE09 & IPCC AR5 & Burke” damage-function setting provided by PAGE-ICE. This setting was selected for three reasons. First, it retains the PAGE09 damage structure, which allows market, non-market, sea-level-rise, and discontinuity damages to be estimated within the standard PAGE-ICE framework. Second, it incorporates IPCC AR5-based updates and the Burke temperature–damage relationship, thereby linking the PAGE damage structure with an empirically informed representation of temperature-related economic losses. Third, this setting has been used in previous PAGE-ICE-based assessments of climate damages under future emission scenarios, making our estimates more comparable with earlier studies [37]. Alternative damage-function settings could produce different absolute damage levels, but a systematic intercomparison of all PAGE-ICE damage-function settings would shift this paper away from its main purpose, which is to isolate the marginal climate–economic effect of wildfire CO₂ emissions under a consistent modeling framework.

Economic losses are reported in purchasing power parity dollars rather than market exchange rate dollars. This choice is appropriate because the analysis focuses on the relative welfare losses across economies rather than international trade values [49,50]. Global and regional damages were calculated using the equity-weighting and discounting scheme implemented in PAGE-ICE, namely “Equity-weighting ON, PTP discounting”. Equity weighting gives higher weight to losses in poorer regions, reflecting the fact that the same monetary loss can imply different welfare impacts across regions with different income levels [51]. Future damages were discounted to the base year 2015 using the PAGE-ICE discounting framework.

2.3. Scenario Construction

We constructed paired simulations for SSP2-4.5 and SSP5-8.5 over the period 2020–2100. These two scenarios were selected for two reasons. First, the wildfire emission dataset used in this study provides internally consistent projected wildfire CO₂ emissions for SSP2-4.5 and SSP5-8.5, allowing the same fire emission projection framework to be linked with PAGE-ICE across scenarios. Second, the two scenarios provide a clear contrast between an intermediate forcing pathway and a high-emission fossil-fuel-intensive pathway. SSP2-4.5 is widely used as an intermediate pathway in CMIP6/ScenarioMIP [39,52], whereas SSP5-8.5 represents an upper-end high-emission pathway with fossil-fueled development and limited mitigation [53]. We therefore use these scenarios to examine how the marginal climate and economic effects of wildfire CO₂ emissions differ under lower- and higher-background-concentration pathways.

For each SSP scenario, two PAGE-ICE simulations were conducted. The first simulation used the standard SSP socioeconomic and anthropogenic emission inputs and served as the baseline experiment. The second simulation added the projected wildfire CO₂ emissions from Zhao et al. (2025) [24] to the corresponding SSP emission pathway. The difference between the wildfire emission experiment and the baseline experiment was interpreted as the climate and socioeconomic effect attributable to future wildfire carbon emissions. In this study, “attributable” refers to the marginal contribution estimated from paired PAGE-ICE simulations, rather than statistical causal attribution from observed wildfire events.

The wildfire emissions were introduced as an additional CO₂ emission source while keeping the underlying SSP socioeconomic assumptions unchanged. This design isolates the effect of projected wildfire carbon emissions from differences in population, GDP, and anthropogenic greenhouse gas pathways. It also avoids attributing changes in climate damages to socioeconomic differences that are already embedded in SSP2-4.5 and SSP5-8.5. A remaining caveat is that the harmonized SSP baseline emissions and the external wildfire emission dataset are compiled using different source classifications. Potential overlap with land-use, biomass-burning, or deforestation-related emissions already embedded in the SSP baseline therefore cannot be fully excluded. A complete removal of overlapping components would require detailed source-category matching between the SSP emission inputs and the wildfire projection dataset, which is not available from the published data. For this reason, the primary simulations should be interpreted as a gross-emission perturbation experiment rather than a fully source-separated net carbon accounting exercise.

2.4. Damage Metrics and Uncertainty Analysis

The outputs from PAGE-ICE include atmospheric CO₂ concentration, radiative forcing, global mean temperature change, regional temperature change, and climate-related economic damages. For each scenario, wildfire-attributable climate responses were calculated as the difference between the simulation with wildfire emissions and the corresponding baseline SSP simulation.

We evaluated four groups of indicators. First, the additional climate response was measured using changes in atmospheric CO₂ concentration, radiative forcing, global mean temperature, and regional temperature. Second, annual economic damages were extracted for each PAGE-ICE simulation year between 2020 and 2100. Third, cumulative damages were calculated by summing annual damages across the study period. Fourth, discounted damages were calculated as net present values using the PAGE-ICE discounting scheme. These indicators were reported at both global and regional scales.

Regional results were used to examine whether the climate damages from wildfire carbon emissions are evenly distributed across the eight PAGE-ICE regions. We also calculated damages as absolute losses, per capita losses, and losses relative to regional GDP where appropriate. Absolute losses reflect the total economic burden, per capita losses describe the average welfare burden borne by individuals, and GDP-relative losses provide a measure of regional economic vulnerability.

Uncertainty was assessed using the probabilistic structure of PAGE-ICE. The model represents uncertainties in climate sensitivity, carbon cycle response, damage functions, adaptation, and discounting parameters through predefined probability distributions [46]. We performed 100,000 Monte Carlo simulations with Latin Hypercube sampling for each scenario. Results are reported as the mean or median values together with uncertainty ranges, depending on the figure or table design.

To evaluate the influence of post-fire ecosystem carbon recovery on the estimated damages, we conducted an additional gross-to-net perturbation sensitivity analysis. The primary simulation was defined as the gross-emission perturbation case (G100), in which 100% of the projected gross wildfire CO₂ emissions were introduced into PAGE-ICE. We then defined two additional sensitivity cases: an intermediate-net-perturbation case (G50), in which 50% of the gross wildfire CO₂ emissions were introduced, and a low-net-perturbation case (G25), in which 25% were introduced. These gross-to-net factors were used as illustrative sensitivity assumptions rather than source-specific estimates of post-fire recovery. The G25 case is informed by historical fire emission studies showing that deforestation/degradation and peat fires, which are less likely to be fully offset by post-fire regrowth, account for roughly one-quarter of global fire carbon emissions [54,55]. The G50 case represents a

higher-net-perturbation sensitivity case, allowing for the possibility that future wildfire emissions may increasingly involve longer-lived carbon losses from forests, peatlands, permafrost-affected regions, or repeatedly burned ecosystems [25]. For both SSP2-4.5 and SSP5-8.5, PAGE-ICE was re-run under the G50 and G25 cases using the same socioeconomic pathways, model settings, uncertainty distributions, and Monte Carlo sampling design as in the primary simulations.

3. Results

3.1. Emission Pathways and Atmospheric CO₂ Response

Projected wildfire CO₂ emissions increased under both SSP2-4.5 and SSP5-8.5, although the magnitude of change differed between the two scenarios (Figure 2). Under SSP2-4.5, mean wildfire emissions increased from 7.64 Gt CO₂ yr⁻¹ in 2020 to 8.94 Gt CO₂ yr⁻¹ in 2100. Under SSP5-8.5, the increase was larger, from 7.67 to 11.11 Gt CO₂ yr⁻¹ over the same period. By contrast, anthropogenic CO₂ emissions diverged strongly between the two scenarios. Anthropogenic emissions under SSP2-4.5 rose slightly from 41.04 Gt CO₂ yr⁻¹ in 2020 to a peak of 49.40 Gt CO₂ yr⁻¹ around 2050, and then declined to 15.04 Gt CO₂ yr⁻¹ by 2100. Under SSP5-8.5, anthropogenic emissions increased continuously from 43.95 Gt CO₂ yr⁻¹ in 2020 to 153.56 Gt CO₂ yr⁻¹ in 2100.

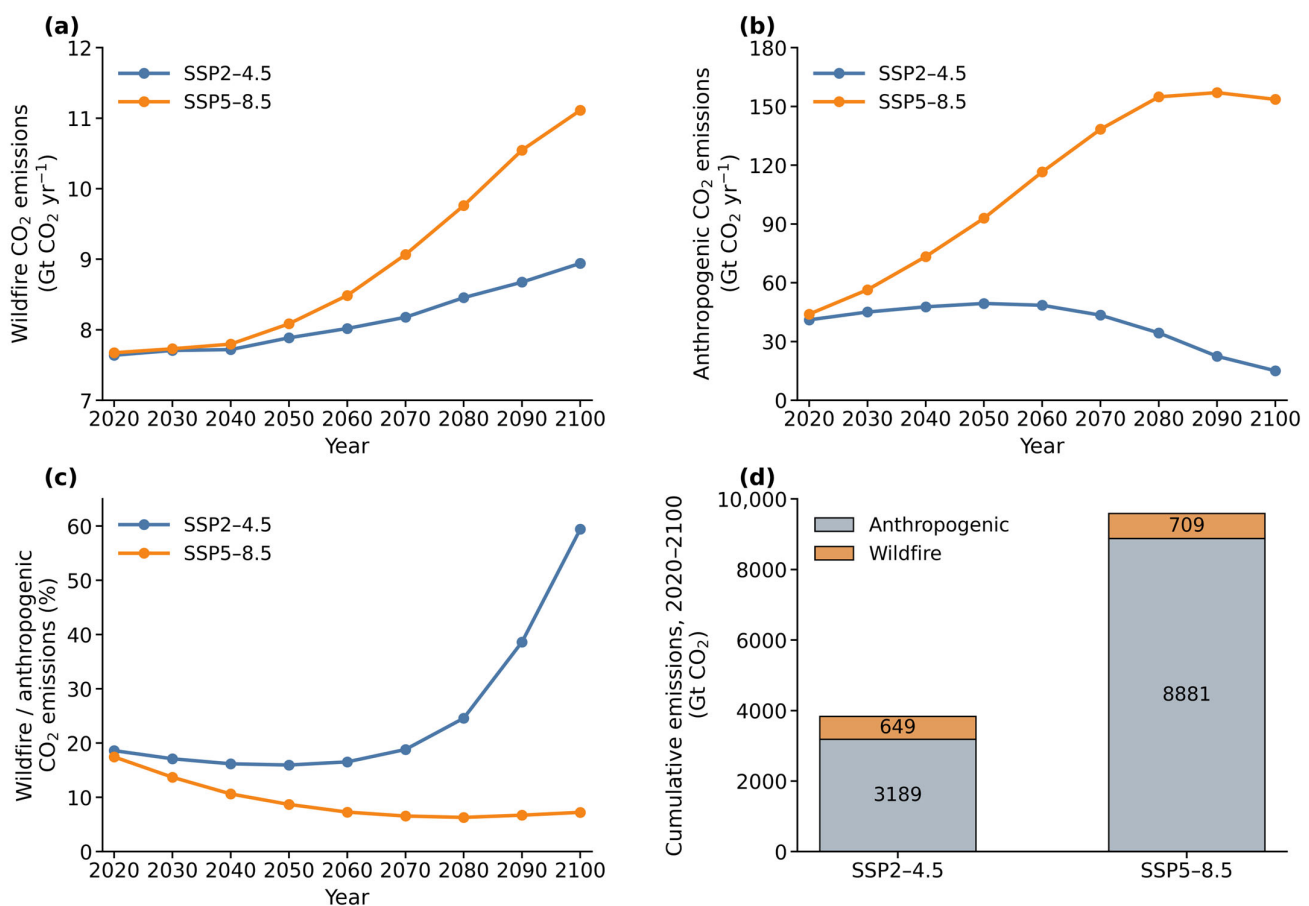


Figure 2. Anthropogenic and wildfire CO₂ emission pathways under SSP2-4.5 and SSP5-8.5. (a) Wildfire CO₂ emissions. (b) Anthropogenic CO₂ emissions. (c) Wildfire emissions as a percentage of anthropogenic emissions. (d) Cumulative anthropogenic and wildfire CO₂ emissions during 2020–2100.

Because anthropogenic emissions decline substantially under SSP2-4.5, wildfire emissions account for an increasingly large share of total carbon emissions in the late twenty-

first century. The ratio of wildfire to anthropogenic emissions under SSP2-4.5 decreased slightly from 18.6% in 2020 to 16.0% in 2050, but then increased rapidly to 59.4% by 2100. Under SSP5-8.5, the corresponding ratio declined from 17.5% in 2020 to 6.3% in 2080, followed by a slight increase to 7.2% in 2100. Over 2020–2100, cumulative wildfire emissions reached 649 Gt CO₂ under SSP2-4.5 and 709 Gt CO₂ under SSP5-8.5, compared with cumulative anthropogenic emissions of 3189 and 8881 Gt CO₂, respectively. This contrast suggests that wildfire carbon becomes relatively more important in mitigation pathways where anthropogenic emissions decline, making it a residual-emission issue in late-century climate policy.

The PAGE-ICE simulations indicate that wildfire emissions produce a persistent increase in atmospheric CO₂ concentration under both scenarios (Figure 3). Under SSP2-4.5, mean atmospheric CO₂ concentration increased from 416.6 ppm to 604.0 ppm in the baseline simulation, and from 418.8 ppm to 654.7 ppm when wildfire emissions were included. The corresponding wildfire-attributable increase rose from 2.21 ppm in 2020 to 50.73 ppm in 2100, with a 5th–95th percentile range of 1.86–2.61 ppm in 2020 and 40.97–60.74 ppm in 2100. Under SSP5-8.5, mean atmospheric CO₂ concentration increased from 417.4 ppm to 1061.7 ppm without wildfire emissions, and from 419.6 ppm to 1117.8 ppm with wildfire emissions. The corresponding wildfire-attributable increase rose from 2.22 ppm in 2020 to 56.10 ppm in 2100, with a 5th–95th percentile range of 1.86–2.63 ppm in 2020 and 45.49–67.10 ppm in 2100. These results indicate that projected wildfire emissions add a substantial atmospheric carbon burden under both scenarios, with a larger absolute CO₂ perturbation under SSP5-8.5 and a stronger relative importance under SSP2-4.5.

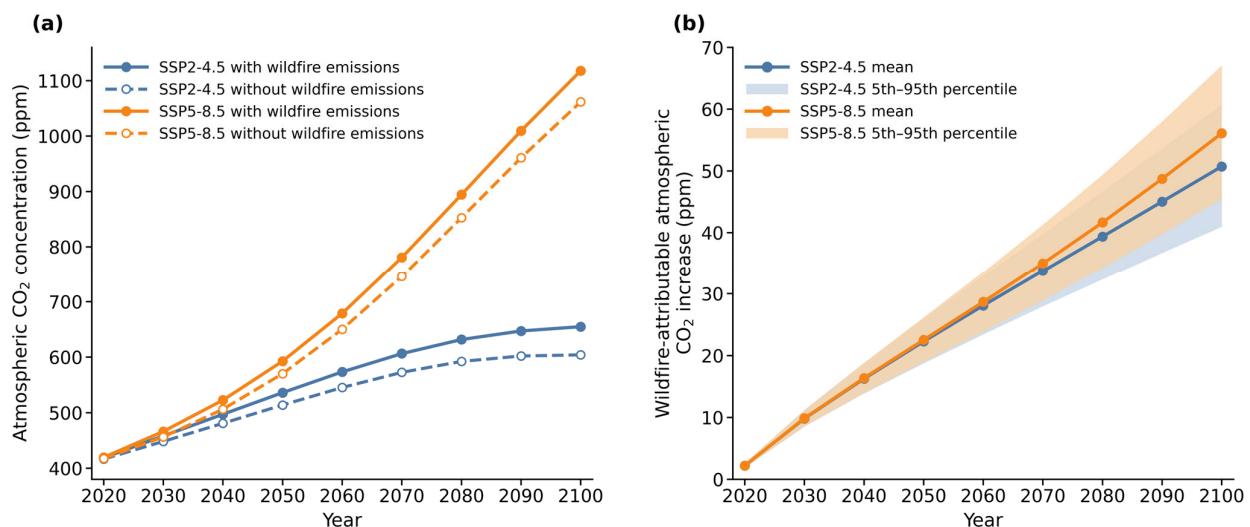


Figure 3. Atmospheric CO₂ responses to projected wildfire emissions under SSP2-4.5 and SSP5-8.5. (a) Atmospheric CO₂ concentration simulated with and without wildfire emissions. (b) Wildfire-attributable increase in atmospheric CO₂ concentration under the two scenarios. Solid lines indicate mean values, and shaded areas indicate the 5th–95th percentile ranges derived from 100,000 Monte Carlo simulations.

3.2. Radiative Forcing and Warming Attributable to Wildfire Carbon Emissions

Projected wildfire carbon emissions generated persistent positive radiative forcing under both SSP2-4.5 and SSP5-8.5 (Figure 4). In the baseline simulations without wildfire emissions, total radiative forcing increased from 1.89 to 3.93 W m^{−2} under SSP2-4.5 and from 1.90 to 7.02 W m^{−2} under SSP5-8.5 between 2020 and 2100. When wildfire emissions were included, the corresponding values increased to 4.37 and 7.30 W m^{−2}, respectively. The wildfire-attributable component rose steadily through the century. Under SSP2-4.5, the mean additional radiative forcing increased from 0.029 W m^{−2} in 2020 to 0.442 W m^{−2}

in 2100, with a 5th–95th percentile range of 0.396–0.487 W m^{-2} in 2100 based on 100,000 Monte Carlo simulations. Under SSP5-8.5, the corresponding increase was from 0.029 to 0.282 W m^{-2} , with a 5th–95th percentile range of 0.258–0.307 W m^{-2} in 2100.

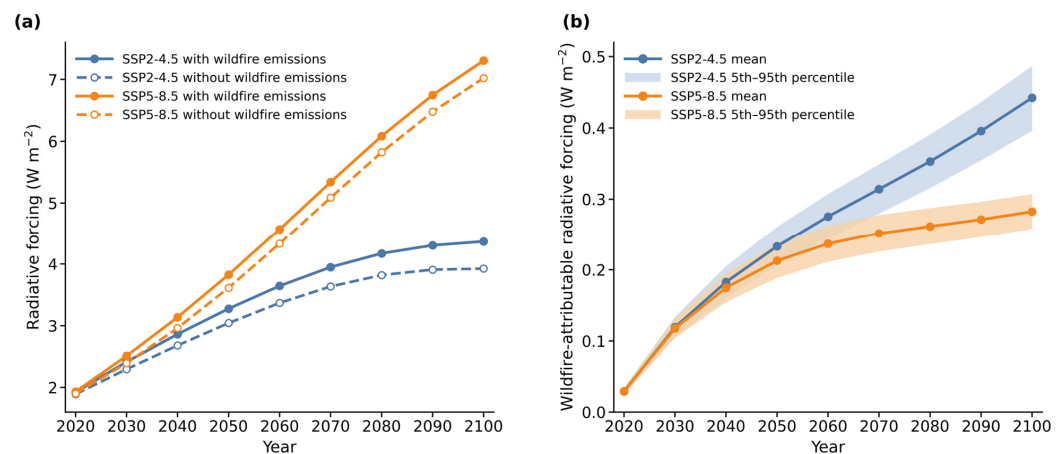


Figure 4. Radiative forcing attributable to projected wildfire carbon emissions under SSP2-4.5 and SSP5-8.5. (a) Total radiative forcing simulated with and without wildfire emissions under SSP2-4.5 and SSP5-8.5. (b) Wildfire-attributable radiative forcing under the two scenarios. Solid lines indicate mean values, and shaded areas indicate the 5th–95th percentile ranges derived from 100,000 Monte Carlo simulations.

A notable feature is that the marginal radiative effect of wildfire emissions was stronger under SSP2-4.5, even though absolute wildfire emissions were higher under SSP5-8.5. This pattern is consistent with the logarithmic dependence of CO_2 radiative forcing on atmospheric concentration. The radiative forcing from CO_2 is approximately logarithmic with respect to atmospheric concentration [56,57], so the same or even a somewhat larger increment in atmospheric CO_2 produces a smaller forcing increment when the background concentration is already high. Under SSP5-8.5, the climate system is already subject to a much larger anthropogenic forcing background, and therefore the incremental forcing associated with additional wildfire-derived CO_2 is relatively muted. Under SSP2-4.5, by contrast, the lower background concentration makes each additional unit of CO_2 more effective in altering the radiative balance. In that sense, the larger marginal forcing under SSP2-4.5 is consistent with the general expectation that the climate response to added CO_2 becomes less sensitive in forcing terms as background concentrations rise.

This additional forcing translated into a sustained warming contribution over the twenty-first century (Figure 5). In the simulations without wildfire emissions, global mean temperature change reached 3.30 $^{\circ}\text{C}$ under SSP2-4.5 and 4.86 $^{\circ}\text{C}$ under SSP5-8.5 by 2100. When wildfire emissions were included, the corresponding warming increased to 3.53 and 5.03 $^{\circ}\text{C}$. The wildfire-attributable global warming component increased from nearly zero in 2020 to 0.233 $^{\circ}\text{C}$ under SSP2-4.5 and 0.169 $^{\circ}\text{C}$ under SSP5-8.5 by 2100. The 5th–95th percentile range in 2100 was 0.145–0.321 $^{\circ}\text{C}$ for SSP2-4.5 and 0.106–0.231 $^{\circ}\text{C}$ for SSP5-8.5. The divergence between the two scenarios became more pronounced after the mid-century, which mirrors the radiative forcing results.

The stronger warming increment under SSP2-4.5 should not be interpreted as meaning that this scenario is more strongly affected in absolute climate terms than SSP5-8.5. Rather, it indicates that the marginal effect of wildfire carbon emissions is more pronounced against a lower-forcing background. Under SSP5-8.5, the climate system still experiences much greater total warming overall, but the additional warming attributable specifically to wildfire emissions is smaller on the margin. This distinction is important because it shows that the climatic significance of wildfire emissions depends not only on the magnitude of

the wildfire source itself, but also on the broader emission pathway into which that source is introduced.

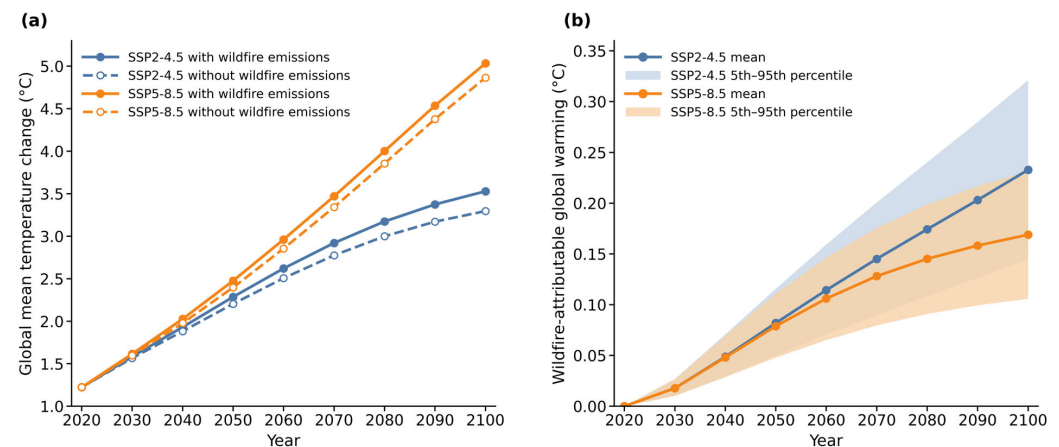


Figure 5. Global warming attributable to projected wildfire carbon emissions under SSP2-4.5 and SSP5-8.5. (a) Global mean temperature change simulated with and without wildfire emissions under SSP2-4.5 and SSP5-8.5. (b) Wildfire-attributable global warming under the two scenarios. Solid lines indicate mean values, and shaded areas indicate the 5th–95th percentile ranges derived from 100,000 Monte Carlo simulations.

Regional warming responses in 2100 were spatially heterogeneous (Figure 6). Under SSP2-4.5, the largest wildfire-attributable warming occurred in Eastern Europe and the former Soviet Union, with a mean increase of 0.384 °C and a 5th–95th percentile range of 0.237–0.537 °C. The United States and Europe also showed relatively high mean warming increments of 0.312 and 0.296 °C, respectively. Lower values were found in India and Southeast Asia, Latin America, and China and centrally planned Asia, where mean additional warming ranged from 0.235 to 0.272 °C. A similar ranking appeared under SSP5-8.5, although the magnitudes were consistently lower, ranging from 0.171 °C in India and South-east Asia to 0.279 °C in Eastern Europe and the former Soviet Union. The land-average additional warming reached 0.292 °C under SSP2-4.5 and 0.212 °C under SSP5-8.5.

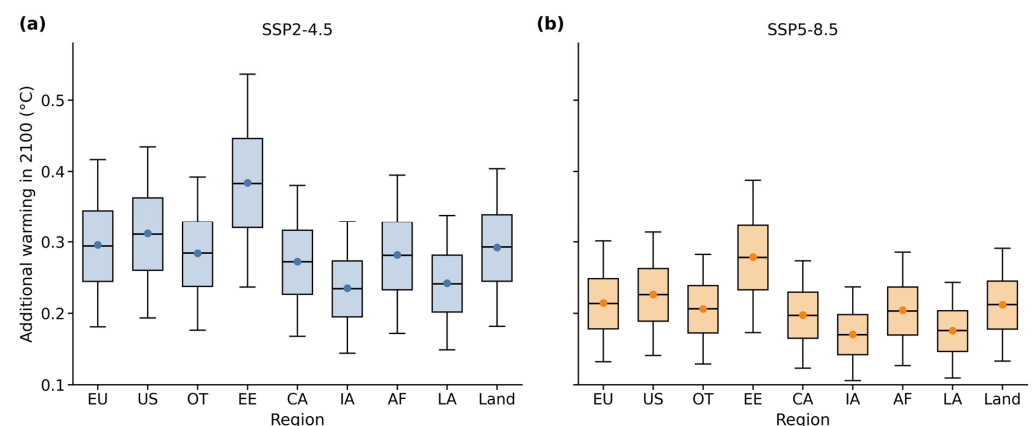


Figure 6. Regional additional warming in 2100 attributable to projected wildfire carbon emissions under (a) SSP2-4.5 and (b) SSP5-8.5. Additional warming is calculated as the difference between paired simulations with and without projected wildfire CO₂ emissions. Boxes indicate the 25th–75th percentiles, whiskers indicate the 5th and 95th percentiles, horizontal lines indicate the median, and dots indicate the mean, based on 100,000 Monte Carlo simulations. Region abbreviations: EU, Europe; US, United States; OT, Other OECD; EE, Eastern Europe and former Soviet Union; CA, China and centrally planned Asia; IA, India and Southeast Asia; AF, Africa and Middle East; LA, Latin America; Land, global land area.

The pronounced regional contrast is likely related to the stronger sensitivity of high-latitude land areas to additional radiative forcing. The Eastern Europe and former Soviet Union region includes extensive northern continental areas adjacent to the Arctic, where Arctic amplification, snow and ice albedo feedbacks, and strong land–atmosphere coupling can enhance warming [58]. These mechanisms tend to amplify temperature responses over northern land regions relative to lower-latitude or more maritime regions. By contrast, regions such as India and Southeast Asia or Latin America are less directly influenced by high-latitude amplification processes, and their additional warming increments are correspondingly smaller. PAGE-ICE does not resolve fine-scale physical processes in the same way as an Earth system model, so this interpretation should be treated as a plausible explanation rather than a direct mechanistic attribution. Still, the regional pattern is broadly consistent with the expected tendency for high-latitude continental regions to exhibit stronger warming responses to additional greenhouse forcing. These results show that future wildfire carbon emissions can produce a measurable increment in radiative forcing and warming at both global and regional scales. More importantly, the magnitude of that increment depends on the background emission pathway, while its regional expression is shaped by spatial differences in climate sensitivity.

3.3. Annual Climate Damages and End-Century Socioeconomic Burden

Annual climate damages increased strongly through the twenty-first century under both SSP2-4.5 and SSP5-8.5 (Figure 7). These values refer to the primary G100 gross-emission perturbation case. When wildfire emissions were included, mean annual climate damages under SSP2-4.5 reached 10.21 trillion USD yr^{−1} in 2050 and 42.68 trillion USD yr^{−1} in 2100. Without wildfire emissions, the corresponding values were 8.60 and 34.57 trillion USD yr^{−1}. Under SSP5-8.5, mean annual damages increased more rapidly, reaching 11.85 trillion USD yr^{−1} in 2050 and 80.53 trillion USD yr^{−1} in 2100 when wildfire emissions were included, compared with 10.33 and 73.89 trillion USD yr^{−1} without wildfire emissions.

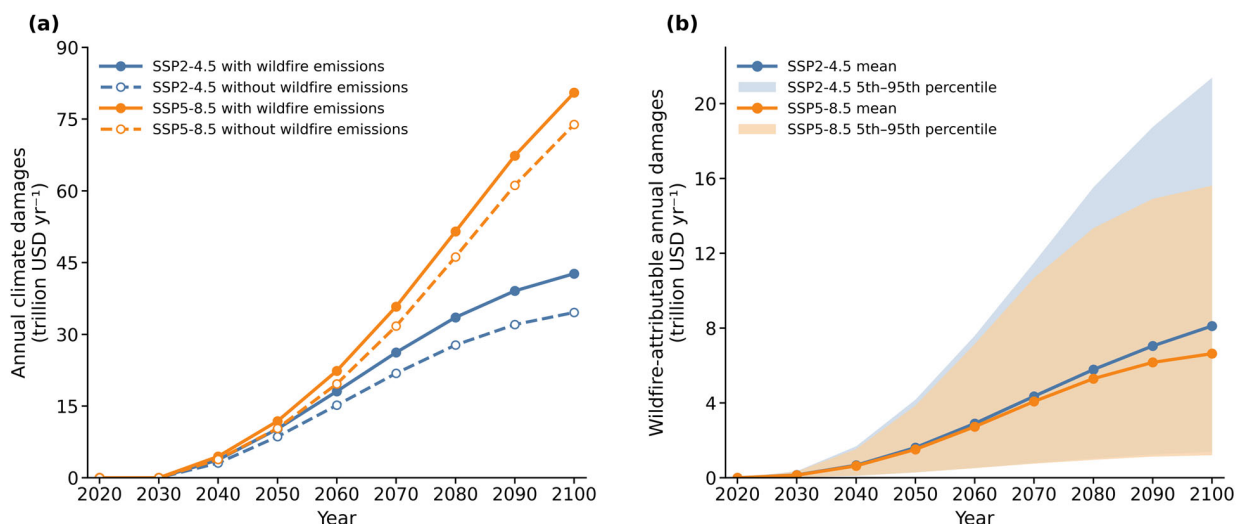


Figure 7. Temporal evolution of annual climate damages attributable to wildfire carbon emissions under SSP2-4.5 and SSP5-8.5. (a) Annual climate damages in simulations with and without projected wildfire carbon emissions. (b) Annual damages attributable to wildfire carbon emissions. Attributable damages are calculated as the difference between paired simulations with and without projected wildfire CO₂ emissions. Solid lines indicate mean values, and shaded areas indicate the 5th–95th percentile ranges derived from 100,000 Monte Carlo simulations. Damages are undiscounted and expressed in trillion USD yr^{−1}.

The difference between the paired simulations gives the annual damages attributable to wildfire carbon emissions. Under SSP2-4.5, mean wildfire-attributable annual damages increased to 1.61 trillion USD yr⁻¹ in 2050 and 8.11 trillion USD yr⁻¹ in 2100. The 5th–95th percentile range widened from 0.29–4.18 trillion USD yr⁻¹ in 2050 to 1.39–21.39 trillion USD yr⁻¹ in 2100. Under SSP5-8.5, mean wildfire-attributable annual damages reached 1.52 trillion USD yr⁻¹ in 2050 and 6.63 trillion USD yr⁻¹ in 2100, with a 5th–95th percentile range of 1.21–15.62 trillion USD yr⁻¹ in 2100.

The larger wildfire-attributable annual damages under SSP2-4.5 after the mid-century are consistent with the stronger marginal forcing and warming response discussed above. However, this does not mean that the damage pattern simply follows the warming response. In PAGE-ICE, estimated damages also reflect regional population, GDP, baseline temperature, income level, and adaptation assumptions. A warmer region may experience larger losses from an additional temperature increment because it is already closer to heat-related damage thresholds. A richer region may have greater adaptive capacity, but it also has more economic output, infrastructure, and consumption exposed to climate risk. Therefore, the monetary damages reflect both the physical climate response and the socioeconomic setting in which that response occurs.

The end-century results provide a more direct view of the socioeconomic burden during 2090–2100 (Table 1). Globally, wildfire-attributable annual damages averaged 8113 billion USD yr⁻¹ under SSP2-4.5 and 6633 billion USD yr⁻¹ under SSP5-8.5. These losses corresponded to 1.35% and 0.63% of global GDP, respectively. The lower GDP-relative loss under SSP5-8.5 mainly reflects the much larger projected global economy in that scenario, rather than a lower level of total climate risk.

Table 1. Wildfire-attributable economic damages during 2090–2100 under SSP2-4.5 and SSP5-8.5.

Region	Annual Damages Under SSP2-4.5 (Billion USD yr ⁻¹)	GDP-Relative Damages Under SSP2-4.5 (%)	Per Capita Damages Under SSP2-4.5 (Thousand USD Person ⁻¹ yr ⁻¹)	Annual Damages Under SSP5-8.5 (Billion USD yr ⁻¹)	GDP-Relative Damages Under SSP5-8.5 (%)	Per Capita Damages Under SSP5-8.5 (Thousand USD Person ⁻¹ yr ⁻¹)
EU	507 (76–1408)	0.87 (0.13–2.40)	1.01 (0.15–2.79)	745 (123–1774)	0.55 (0.09–1.31)	1.01 (0.17–2.40)
US	520 (80–1397)	0.97 (0.15–2.59)	1.13 (0.17–3.03)	779 (132–1807)	0.57 (0.10–1.32)	1.09 (0.18–2.53)
OT	281 (45–772)	0.91 (0.15–2.51)	0.92 (0.15–2.54)	355 (59–852)	0.52 (0.09–1.25)	0.94 (0.16–2.25)
EE	459 (86–1042)	2.49 (0.47–5.65)	1.90 (0.36–4.31)	294 (70–585)	1.12 (0.27–2.23)	1.58 (0.38–3.14)
CA	663 (105–1865)	0.94 (0.15–2.64)	0.85 (0.14–2.40)	574 (95–1401)	0.53 (0.09–1.29)	0.88 (0.15–2.15)
IA	1909 (305–5370)	1.06 (0.17–2.99)	0.64 (0.10–1.80)	1442 (230–3690)	0.52 (0.08–1.33)	0.68 (0.11–1.75)
AF	3340 (571–8836)	2.36 (0.40–6.25)	1.09 (0.19–2.89)	2127 (394–4868)	0.90 (0.17–2.06)	1.00 (0.18–2.29)
LA	433 (69–1224)	0.87 (0.14–2.46)	0.65 (0.10–1.83)	318 (51–812)	0.48 (0.08–1.23)	0.70 (0.11–1.80)
Global	8113 (1391–21,389)	1.35 (0.23–3.55)	0.90 (0.15–2.38)	6633 (1206–15,618)	0.63 (0.11–1.48)	0.90 (0.16–2.12)

Note: Values are mean estimates, with 5th–95th percentile ranges in parentheses, based on 100,000 Monte Carlo simulations. EU, Europe; US, United States; OT, Other OECD; EE, Eastern Europe and former Soviet Union; CA, China and centrally planned Asia; IA, India and Southeast Asia; AF, Africa and Middle East; LA, Latin America.

Africa and the Middle East had the largest absolute annual damages, reaching 3340 billion USD yr⁻¹ under SSP2-4.5 and 2127 billion USD yr⁻¹ under SSP5-8.5. India and Southeast Asia ranked second, with 1909 and 1442 billion USD yr⁻¹, respectively. These two regions accounted for a large share of global wildfire-attributable damages because they combine large population exposure with high sensitivity to additional warming. Their GDP-relative losses were also substantial, especially for Africa and the Middle East under SSP2-4.5, where damages reached 2.36% of regional GDP.

The ranking changes when damages are expressed relative to GDP or population. Eastern Europe and the former Soviet Union showed the highest GDP-relative damage under SSP2-4.5, at 2.49% of regional GDP, despite having lower absolute damages than Africa and the Middle East or India and Southeast Asia. The same region also had the highest per capita damage under SSP2-4.5, reaching 1.90 thousand USD person⁻¹ yr⁻¹. This

reflects the combination of strong regional warming, regional economic exposure, per capita normalization, and the PAGE-ICE regional damage structure. The high per capita damages in Eastern Europe and the former Soviet Union should therefore not be interpreted as an observed ranking of social vulnerability. They reflect the way PAGE-ICE combines regional temperature response, income, GDP exposure, adaptation assumptions, and valuation settings before damages are divided by regional population. Under SSP5-8.5, per capita damages were generally lower or similar, with the United States, Europe, Africa and the Middle East, and Other OECD all around 0.94–1.09 thousand USD person^{−1} yr^{−1}. This is partly because SSP5 assumes rapid economic growth, higher income levels, and stronger convergence in regional development [53]. These assumptions increase total exposed economic value, but they can also reduce the average burden per person through higher income and stronger adaptive capacity. The relatively lower per capita damages under SSP5-8.5 therefore reflect the socioeconomic pathway rather than a weaker climate impact. These regional rankings also depend on the PAGE-ICE valuation settings. Because the main simulations use PPP-based damages with equity-weighting ON, losses in lower-income regions receive greater welfare weight than they would under an equity-weighting-off or market-exchange-rate accounting setting. The high damages estimated for Africa and the Middle East and India and Southeast Asia therefore reflect both exposure and vulnerability and the welfare-valuation structure of PAGE-ICE.

3.4. Discounted Cumulative Damages and Regional Distribution

To compare damages occurring at different points in time, future losses were converted into present-value terms through discounting. In this framework, losses occurring late in the century carry a different weight from near-term losses because the assessment accounts for time preference, future consumption growth, and intergenerational welfare assumptions. Discounted cumulative damages therefore provide a welfare-weighted measure of long-term socioeconomic cost, rather than a direct sum of annual future losses.

At the global scale, discounted cumulative climate damages were higher when wildfire emissions were included (Figure 8). Under SSP2-4.5, mean cumulative damages increased from 649.5 trillion USD without wildfire emissions to 793.6 trillion USD with wildfire emissions. The wildfire-attributable component was 144.0 trillion USD, with a 5th–95th percentile range of 24.6–386.7 trillion USD. Under SSP5-8.5, mean cumulative damages increased from 1082.6 to 1212.9 trillion USD when wildfire emissions were included. The wildfire-attributable component was 130.3 trillion USD, with a 5th–95th percentile range of 23.6–334.6 trillion USD.

The total discounted cumulative climate damages are much larger under SSP5-8.5, but the wildfire-attributable component is slightly larger under SSP2-4.5. Total damages reflect the full climate pathway, including much stronger baseline warming under SSP5-8.5. The wildfire-attributable component reflects only the marginal effect of adding projected wildfire carbon emissions to each baseline pathway. Because the marginal forcing and warming effect of wildfire CO₂ is stronger under SSP2-4.5, the global discounted cost of wildfire emissions is also slightly higher in that scenario.

The decomposition of discounted cumulative damages provides additional context for the economic interpretation of the results (Table A1). Market damages dominate under both scenarios, accounting for 88.9% of total damages under SSP2-4.5 and 75.1% under SSP5-8.5. The discontinuity component is negligible under SSP2-4.5 (0.01%) but increases to 17.5% under SSP5-8.5, suggesting that high-emission pathways increase the relative importance of large-scale discontinuity risks within the PAGE-ICE damage structure.

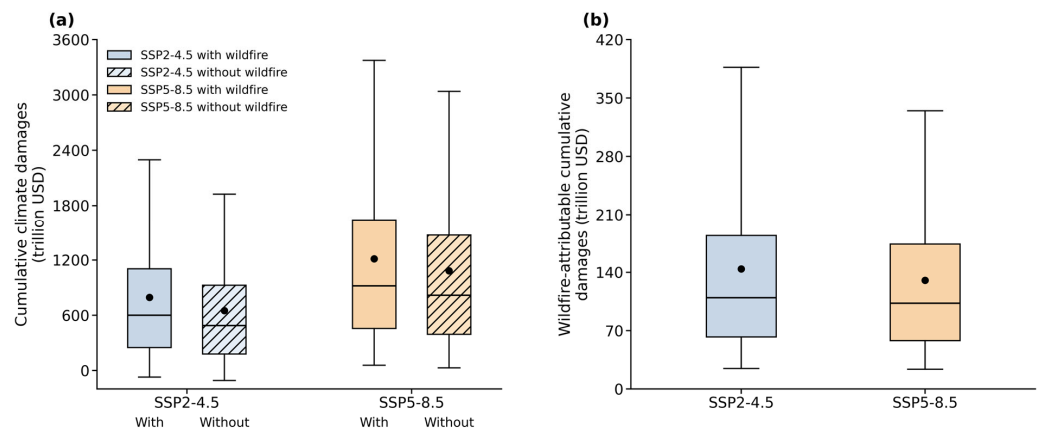


Figure 8. Accumulated global climate damages associated with projected wildfire carbon emissions. (a) Global cumulative climate damages in simulations with and without projected wildfire carbon emissions. (b) Global cumulative damages attributable to wildfire carbon emissions. Values are discounted cumulative damages. Boxes indicate the 25th–75th percentiles, whiskers indicate the 5th and 95th percentiles, horizontal lines indicate the median, and dots indicate the mean, based on 100,000 Monte Carlo simulations.

Regional wildfire-attributable cumulative damages were unevenly distributed (Figure 9). Africa and the Middle East had the largest damages in both scenarios, with mean values of 57.1 trillion USD under SSP2-4.5 and 42.4 trillion USD under SSP5-8.5. India and Southeast Asia ranked second, with 34.3 and 29.1 trillion USD, respectively. These large regional damages reflect the combined influence of population exposure, income growth, baseline climate, and regional damage functions. These regional damages should not be interpreted as a map of wildfire occurrence or direct fire impacts. Once wildfire CO₂ is emitted, it is treated as a global atmospheric perturbation in PAGE-ICE.

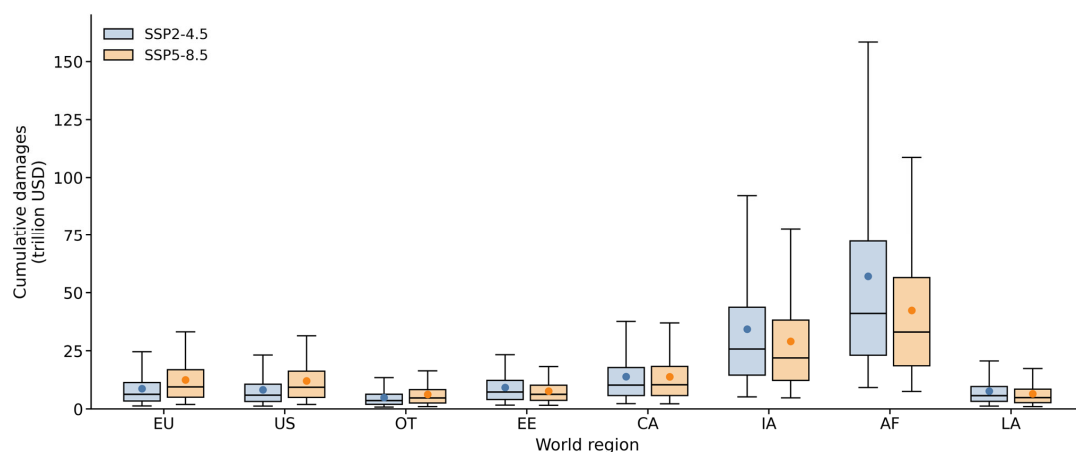


Figure 9. Regional cumulative damages attributable to projected wildfire carbon emissions. Values are discounted cumulative damages. Boxes indicate the 25th–75th percentiles, whiskers indicate the 5th and 95th percentiles, horizontal lines indicate the median, and dots indicate the mean, based on 100,000 Monte Carlo simulations. Region abbreviations: EU, Europe; US, United States; OT, Other OECD; EE, Eastern Europe and former Soviet Union; CA, China and centrally planned Asia; IA, India and Southeast Asia; AF, Africa and Middle East; LA, Latin America.

The comparison between SSP2-4.5 and SSP5-8.5 also shows that regional economic damages do not follow regional warming increments mechanically. Most regions had larger wildfire-attributable cumulative damages under SSP2-4.5, consistent with the stronger marginal climate response in that scenario. Europe, the United States, and Other OECD were exceptions. Their cumulative damages were higher under SSP5-8.5, increasing from

8.7 to 12.5 trillion USD in Europe, from 8.2 to 12.1 trillion USD in the United States, and from 4.9 to 6.2 trillion USD in Other OECD. These developed economies have much larger projected GDP under SSP5-8.5. A smaller marginal warming increment can therefore still translate into larger absolute monetary losses when the exposed economic base is much larger.

This result also points to a broader interpretation issue. Economic damages are not determined by temperature change alone. They also depend on baseline climate, income level, population, sectoral exposure, and adaptation capacity. Warming in already-hot regions can generate large welfare losses because it pushes labor productivity, health, agriculture, and energy demand closer to damaging thresholds. In contrast, high-latitude regions may experience stronger physical warming, but the economic damage response can differ because of lower baseline temperatures, different exposure structures, and stronger adaptive capacity in some cases. The regional damage pattern should therefore be interpreted as a combined climate–economic outcome rather than a direct map of regional temperature response.

4. Discussion

4.1. Climate-Mediated Economic Costs of Wildfire Carbon Emissions

This study quantifies the long-term socioeconomic damages attributable to projected wildfire carbon emissions by introducing wildfire CO₂ emissions into PAGE-ICE under SSP2-4.5 and SSP5-8.5. The results show that future wildfire emissions add a persistent atmospheric CO₂ burden, produce additional radiative forcing and warming, and generate measurable economic damages at both global and regional scales. By 2100, wildfire emissions increased atmospheric CO₂ concentration by 50.7 ppm under SSP2-4.5 and 56.1 ppm under SSP5-8.5. The resulting wildfire-attributable warming reached 0.233 °C and 0.169 °C, respectively. These increments are smaller than total anthropogenic warming under the two SSP pathways, but they are not negligible when translated into long-term economic damages.

Previous wildfire impact studies have mostly focused on burned area, fire weather, suppression costs, property losses, ecosystem impacts, or smoke-related mortality. Howard (2014) [59] argued that wildfire damages were largely omitted from social-cost-of-carbon (SCC) calculations and that this omission could lead to an underestimation of climate damages. That report estimated global climate-change-induced wildfire damages of roughly 50–300 billion USD annually by 2050, but the estimates were based on broad damage ratios and wildfire expansion assumptions rather than explicit carbon emission perturbation experiments in an IAM. More recent work has estimated the economic value of carbon released by individual fires by applying SCC estimates to fire-related carbon losses. For example, Sweeney et al. [29] estimated that the 2017 Eagle Creek Fire in Oregon generated 187.2 million USD in carbon-related losses, illustrating that wildfire carbon emissions can be economically meaningful even at the event scale. Other recent work [23] has focused on wildfire smoke mortality and shown that adding smoke-related damages can substantially increase SCC estimates, but those studies address health damages from smoke exposure rather than the climate damages caused by wildfire carbon emissions.

Our analysis differs from these studies in two respects. First, it isolates the climate-mediated effect of wildfire carbon emissions rather than valuing direct fire damage, suppression cost, property loss, or smoke mortality. Second, it evaluates future wildfire emissions under SSP-based pathways using a paired PAGE-ICE design, which allows the marginal contribution of wildfire CO₂ to atmospheric concentration, radiative forcing, warming, and economic damages to be traced consistently. The discounted cumulative damages attributable to wildfire emissions reached 144.0 trillion USD under SSP2-4.5 and 130.3 tril-

lion USD under SSP5-8.5. These estimates are not directly comparable to event-level SCC applications or smoke–health damage estimates, but they show that the climate component of wildfire emissions represents a substantial long-term cost.

To provide a more comparable scale for climate–economy interpretation, we further calculated an illustrative wildfire-specific discounted damage intensity. This metric is defined as discounted cumulative wildfire-attributable damages divided by cumulative gross wildfire CO₂ emissions during 2020–2100. In the primary G100 case, cumulative wildfire emissions reached 649 Gt CO₂ under SSP2-4.5 and 709 Gt CO₂ under SSP5-8.5, while discounted cumulative damages reached 144.0 and 130.3 trillion USD, respectively. The resulting damage intensities are therefore approximately 222 USD t CO₂^{−1} under SSP2-4.5 and 184 USD t CO₂^{−1} under SSP5-8.5. These values are not formal SCC estimates, because the numerator is a discounted cumulative damage estimate whereas the denominator is undiscounted cumulative gross wildfire CO₂ emissions. They also depend on the PAGE-ICE damage functions, discounting and equity-weighting settings, and the gross-to-net wildfire carbon perturbation assumption. Nevertheless, the metric helps place the magnitude of wildfire carbon damages in a form that can be compared more easily with climate–economy and social-cost-of-carbon studies.

These results can be interpreted in line with earlier PAGE-ICE studies of Earth system feedbacks, especially those on permafrost carbon emissions [35,60]. Those studies introduced additional carbon from Earth system processes into PAGE-ICE and estimated the incremental climate and economic damages relative to a baseline pathway. Here, we apply the same attribution logic to wildfire carbon emissions. The comparison is useful because both permafrost carbon release and wildfire emissions are often treated as feedback-related or semi-natural carbon sources, rather than conventional fossil-fuel emissions.

4.2. Why Lower-Background Pathways Can Show Larger Marginal Damages

A consistent result across the climate and economic outputs is that wildfire-attributable forcing, warming, and damages are larger under SSP2-4.5 than under SSP5-8.5, despite higher absolute wildfire emissions under SSP5-8.5. This does not mean that SSP2-4.5 produces more total climate damage. Total climate damages are much higher under SSP5-8.5 because baseline anthropogenic emissions and warming are much larger. The result refers only to the marginal effect of adding wildfire CO₂ to each scenario.

The underlying reason is the logarithmic relationship between atmospheric CO₂ concentration and radiative forcing. When background CO₂ concentration is already high, as under SSP5-8.5, an additional unit of CO₂ produces a smaller increment in radiative forcing than the same unit added under a lower-concentration pathway. This is why wildfire emissions can have a stronger marginal forcing effect under SSP2-4.5. The warming response follows the same logic, because the temperature increment is driven by the additional forcing generated by wildfire emissions. The economic damages then inherit this marginal climate signal through the damage functions in PAGE-ICE.

The result should therefore be interpreted as a marginal effect, not as evidence that SSP2-4.5 produces larger total climate damages. A lower-emission world does not make wildfire emissions unimportant. On the contrary, as anthropogenic emissions decline, remaining non-fossil carbon sources such as wildfire emissions become more visible in relative terms. In this study, wildfire emissions reached 59.4% of anthropogenic CO₂ emissions by 2100 under SSP2-4.5, compared with only 7.2% under SSP5-8.5. This does not mean that wildfire emissions dominate the carbon budget, but it indicates that wildfire carbon can become a residual-emission issue under mitigation pathways. This interpretation is consistent with recent evidence that fire activity can weaken terrestrial carbon sinks before the 1.5 °C warming level is reached, indicating that fire-related carbon feedbacks can become

relevant even under moderate-warming pathways [25]. Recent evidence that moderate global warming does not rule out extreme global climate outcomes further supports the need to evaluate residual carbon sources such as wildfire emissions under intermediate pathways [61].

4.3. Regional Damages Reflect Both Climate Response and Socioeconomic Exposure

The regional results show that physical warming and monetary damages are related but not identical. Eastern Europe and the former Soviet Union showed the largest wildfire-attributable regional warming in 2100, which is consistent with the strong sensitivity of high-latitude land areas to greenhouse forcing. The region includes large northern continental areas, where snow and ice albedo feedbacks, land–atmosphere coupling, and Arctic amplification can enhance warming responses. However, the largest economic damages occurred in Africa and the Middle East and India and Southeast Asia, rather than in the region with the largest warming increment. The relatively high per capita damages in Eastern Europe and the former Soviet Union should be interpreted with the PAGE-ICE model structure in mind. Per capita damages are not determined by income level alone. They also depend on regional warming, the damage-function response to baseline temperature, exposed economic output, adaptation assumptions, PPP-based valuation, equity weighting, and the population denominator used to express total damages on a per capita basis. The comparison with Africa and the Middle East therefore does not imply that Eastern Europe and the former Soviet Union are objectively more vulnerable in an observational sense. It indicates that, under the PAGE-ICE regional damage and valuation structure used here, this region has a higher modeled per capita burden under SSP2-4.5.

This difference is expected in an integrated assessment framework. Economic damages depend not only on the amount of additional warming, but also on baseline temperature, population, income, sectoral exposure, and adaptation capacity. Additional warming in already-hot regions can impose larger losses through heat stress, labor productivity decline, agricultural impacts, health risks, and energy demand. By contrast, warming in colder high-latitude regions may have a different damage profile in the model, even if the physical warming is stronger. This is why interpreting regional economic damages as a direct map of regional temperature response would be misleading.

The comparison between SSP2-4.5 and SSP5-8.5 also shows the role of socioeconomic exposure. Most regions had larger wildfire-attributable cumulative damages under SSP2-4.5, consistent with the larger marginal warming response. Europe, the United States, and Other OECD were exceptions. Their cumulative damages were higher under SSP5-8.5 because these developed economies have much larger projected GDP under the SSP5 narrative. A smaller temperature increment can still produce larger absolute monetary losses when the exposed economic base is much larger. It reflects the fact that climate damages are valued against future economic activity, not only against degrees of warming.

4.4. Uncertainty and Sensitivity of the PAGE-ICE Estimates

In PAGE-ICE, wildfire emissions first affect atmospheric composition and temperature, and the resulting climate signal is then translated into regional economic damages. Uncertainty is introduced at each step, including the carbon cycle response, climate sensitivity, regional exposure, damage functions, adaptation assumptions, and discounting [34]. This matters most for damages in the second half of the century, when socioeconomic conditions and adaptive capacity become increasingly uncertain. The resulting ranges therefore reflect not only model uncertainty, but also the broader uncertainty in how future societies may be exposed to and affected by additional warming.

The sensitivity analysis identifies the parameters most closely associated with the spread in wildfire-attributable discounted cumulative damages (Figure 10). Transient climate response (TCR) showed the largest positive sensitivity contribution, at 40.6%. This result is consistent with the structure of the analysis, since wildfire emissions affect economic damages primarily through their effects on radiative forcing and temperature. Pure time preference (PTP) showed the second-largest contribution, but with a negative association (−17.5%). Higher PTP values place less weight on future losses and therefore reduce the present value of damages, particularly when a large share of wildfire-attributable impacts occurs after the mid-century.

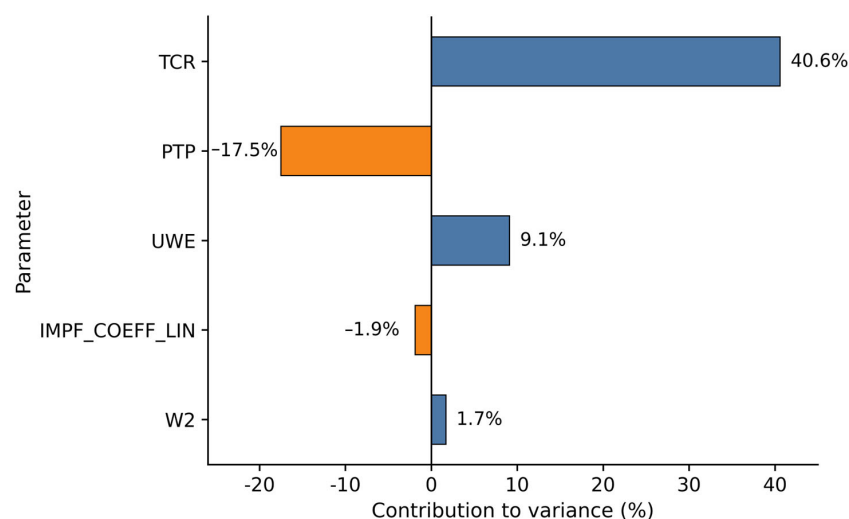


Figure 10. Sensitivity contributions of key uncertain parameters to wildfire-attributable discounted cumulative damages. Positive and negative values indicate the direction of association between each uncertain parameter and the model output. TCR, transient climate response; PTP, pure time preference; UWE, uncertainty in wildfire emissions; IMPF_COEFF_LIN, linear coefficient in the PAGE-ICE impact function; W2, PAGE-ICE weighting parameter.

The uncertainty in wildfire emissions (UWE) had a positive sensitivity contribution of 9.1%, indicating that the spread in the wildfire emission input does affect the estimated damages. However, its contribution was clearly smaller than those of TCR and PTP. This result suggests that the uncertainty in wildfire-attributable damages is not driven primarily by the wildfire emission range itself. Rather, the final monetary estimates are shaped more strongly by how PAGE-ICE translates additional CO₂ emissions into warming and how future welfare losses are valued in present-value terms. The smaller contributions of the linear impact-function coefficient (IMPF_COEFF_LIN, 1.9%) and W2 (1.7%) further indicate that these damage-function parameters played a limited role in the simulations.

This pattern is important for interpreting the large uncertainty ranges in the damage estimates. Better wildfire emission projections would improve the emission input, but they would not be sufficient to tightly constrain the economic estimates on their own. The larger sources of uncertainty lie in the climate-response and valuation structure of the IAM, especially TCR and discounting-related assumptions. The sensitivity analysis therefore shows that the trillion-dollar estimates should be read not only as a function of projected wildfire emissions, but also as outcomes conditioned by the climate and welfare assumptions embedded in PAGE-ICE.

4.5. Implications of Post-Fire Carbon Recovery for Damage Estimates

The primary damage estimates reported above are based on the G100 gross-emission perturbation case. They should therefore be interpreted as upper-bound estimates of the

climate-mediated damages associated with projected gross wildfire CO₂ emissions. This qualification is important because the wildfire input data report gross fire-related carbon emissions, whereas post-fire vegetation regrowth, soil-carbon recovery, delayed decomposition, and longer-term ecosystem carbon compensation are not explicitly represented at the fire-source location. In rapidly recovering ecosystems, especially grasslands and savannas, a substantial part of the carbon released during fire may be reabsorbed over relatively short-to-medium timescales [55]. By contrast, fires involving peat, permafrost carbon, repeated high-severity forest burning, or deforestation-related land-use change are more likely to produce longer-lived net carbon losses.

The future wildfire emission dataset used in this study does not provide source-specific emissions for grassland/savanna, forest, peat, permafrost, or deforestation-related fires [24]. We therefore did not assign biome-specific recovery fractions. Instead, we used G50 and G25 as gross-to-net perturbation sensitivity cases. The G25 case provides a literature-informed low-net-perturbation case, consistent with historical fire emission estimates showing that deforestation/degradation and peat fires account for approximately one-quarter of global fire carbon emissions [54,55]. The G50 case provides an intermediate sensitivity case in which a larger share of gross wildfire CO₂ is treated as a long-lived net atmospheric perturbation. This higher-retained-perturbation assumption is relevant because future fire activity may increasingly affect forests, peatlands, permafrost-affected regions, or repeatedly burned ecosystems, where carbon recovery can be slower and long-term carbon losses may be larger [25].

The sensitivity experiments show an approximately proportional response of the climate and economic outcomes to the gross-to-net perturbation factor (Table 2). Under SSP2-4.5, the 2100 atmospheric CO₂ concentration increase declines from 51 ppm in G100 to 25 ppm in G50 and 13 ppm in G25, while additional global warming declines from 0.23 °C to 0.12 °C and 0.06 °C. The corresponding discounted cumulative damages decline from 144 trillion USD in G100 to 71 trillion USD in G50 and 35 trillion USD in G25. Under SSP5-8.5, discounted cumulative damages decline from 130 trillion USD in G100 to 65 trillion USD in G50 and 33 trillion USD in G25.

Table 2. Sensitivity of climate and economic damages to gross-to-net wildfire CO₂ perturbation assumptions.

Scenario	Gross-to-Net Factor	2100 Atmospheric CO ₂ Concentration Increase (ppm)	2100 Additional Global Warming (°C)	2100 Annual Additional Climate Damages (Trillion USD yr ^{−1})	Discounted Cumulative Damages by 2100 (Trillion USD)
SSP2-4.5	100% (Gross-emission perturbation)	51 (41–61)	0.23 (0.14–0.32)	8.11 (1.39–21.39)	144 (25–387)
SSP2-4.5	50% (Intermediate net perturbation)	25 (20–30)	0.12 (0.07–0.16)	4.03 (0.65–10.72)	71 (12–194)
SSP2-4.5	25% (Low net perturbation)	13 (10–15)	0.06 (0.04–0.08)	2.00 (0.33–5.45)	35 (6–96)
SSP5-8.5	100% (Gross-emission perturbation)	56 (46–67)	0.17 (0.11–0.23)	6.63 (1.21–15.62)	130 (24–335)
SSP5-8.5	50% (Intermediate net perturbation)	28 (23–34)	0.09 (0.05–0.12)	3.34 (0.58–7.96)	65 (11–168)
SSP5-8.5	25% (Low net perturbation)	14 (11–17)	0.04 (0.03–0.06)	1.68 (0.29–3.99)	33 (6–85)

Note: Values are mean estimates, with 5th–95th percentile ranges in parentheses, based on 100,000 Monte Carlo simulations. The gross-to-net factor is a multiplier applied to the wildfire CO₂ input before running PAGE-ICE. It should not be interpreted as the fraction of emitted CO₂ permanently remaining in the atmosphere, because PAGE-ICE still simulates atmospheric carbon cycle uptake. Instead, it represents the fraction of gross wildfire CO₂ treated as an additional net perturbation after allowing for possible post-fire vegetation regrowth and ecosystem carbon recovery.

The approximately proportional response is consistent with the marginal nature of the perturbation experiment. The G50 and G25 simulations modify only the wildfire CO₂ input, while the background SSP pathway, socioeconomic assumptions, damage

functions, discounting settings, and uncertainty distributions remain unchanged. These results confirm that the headline damage estimates are sensitive to the fraction of gross wildfire CO₂ treated as a long-lived net perturbation. At the same time, the G25 case still produces discounted cumulative damages of 35 trillion USD under SSP2-4.5 and 33 trillion USD under SSP5-8.5, indicating that wildfire carbon emissions remain economically relevant even under partial post-fire recovery assumptions.

4.6. Limitations and Implications

The results should be interpreted with several methodological assumptions in mind. First, the wildfire emission pathways were taken from Zhao et al. (2025) [24], and we did not develop an independent wildfire emission model. This was intentional, because the purpose of this study was to assess the socioeconomic consequences of projected wildfire carbon emissions rather than to re-project wildfire activity. In addition, possible overlap between wildfire-related carbon in the SSP baseline and the external wildfire emission input cannot be fully excluded because the two inputs use different source classifications. This potential overlap may bias the G100 carbon-mediated damage estimates upward and is one reason why the primary results are framed as upper-bound perturbation estimates. Future work should test whether the results are robust to alternative wildfire emission datasets, Earth system models, fire modules, and more detailed source-category matching between baseline and wildfire-related emissions. Extending the analysis to low-emission pathways such as SSP1-2.6 would also be valuable once consistent wildfire CO₂ projection inputs are available for such scenarios.

Second, the analysis focuses on climate-mediated damages from wildfire carbon emissions rather than the full societal cost of wildfire activity. Direct fire damages, suppression costs, property losses, smoke-related health impacts, biodiversity losses, and ecosystem service damages are not included in the PAGE-ICE simulations. Previous studies suggest that some of these omitted costs can be large, including direct disaster losses and smoke-related health burdens reaching hundreds of billions of USD in specific regions or periods [62,63]. These values are not directly comparable with our estimates because they differ in spatial coverage, time horizon, valuation method, and damage category. They nevertheless show that the damages estimated here represent only one component of broader wildfire costs. Meanwhile, the G100 case may overstate the carbon-mediated component where post-fire ecosystem recovery offsets part of the initial fire emissions, or where wildfire-related emissions overlap with components already represented in the SSP baseline. The paired PAGE-ICE design also does not feed the additional wildfire-induced warming back into future wildfire activity, which may omit a second-order climate–fire feedback. The estimates should therefore be interpreted as climate damages under specified carbon perturbation assumptions, not as a complete valuation of all wildfire impacts.

Third, PAGE-ICE operates at a coarse regional scale. This is appropriate for global IAM analysis, but it cannot resolve sub-national heterogeneity in local fire regimes, income distribution, exposure, infrastructure, institutional capacity, or adaptation capacity. This limitation is particularly relevant for large and diverse regions such as Africa and the Middle East, where vulnerability can vary substantially within the same PAGE-ICE region. The regional damages reported here should therefore be understood as broad climate–economic estimates rather than location-specific wildfire risk assessments.

Fourth, discounted damage estimates are sensitive to the choice of discounting and equity-weighting settings. In this study, this issue is particularly important because wildfire-attributable damages increase mainly in the second half of the century. Discounting converts those future losses into present-value terms, but it also reduces the weight assigned to late-century damages. As a result, the final monetary estimates are strongly affected by

assumptions about how future welfare is valued relative to present welfare. The sensitivity result for PTP makes this point clear, showing that discounting is one of the main determinants of the estimated damages.

Future wildfire carbon emissions can impose measurable climate damages through their contribution to atmospheric CO₂, radiative forcing, and warming. The estimated damage intensities reported in Section 4.1 should not be interpreted as direct wildfire-specific carbon prices, but they suggest that wildfire carbon should be considered more explicitly in climate–economy assessment, residual-emission accounting, and SCC-related discussions. For carbon-pricing applications, the figures should be used only with caution because they depend on the PAGE-ICE damage functions, discounting settings, equity-weighting assumptions, and gross-to-net wildfire carbon perturbation factors. For land-based mitigation, the results support closer integration between wildfire management, ecosystem carbon protection, REDD+-type carbon permanence safeguards, and broader climate mitigation strategies [64,65].

5. Conclusions

This study assessed the long-term climate-mediated socioeconomic damages caused by projected wildfire carbon emissions under SSP2-4.5 and SSP5-8.5 using PAGE-ICE. The main conclusions are as follows:

- (1) Future wildfire CO₂ emissions add a persistent atmospheric carbon burden. By 2100, they increased atmospheric CO₂ concentration by 50.7 ppm under SSP2-4.5 and 56.1 ppm under SSP5-8.5.
- (2) The marginal climate response was stronger under SSP2-4.5, even though wildfire emissions were higher under SSP5-8.5. This is mainly because additional CO₂ produces a larger radiative forcing increment when background CO₂ concentration is lower.
- (3) In the primary G100 case, wildfire emissions produced non-negligible economic damages. By 2100, annual damages reached 8.11 trillion USD yr^{−1} under SSP2-4.5 and 6.63 trillion USD yr^{−1} under SSP5-8.5. Discounted cumulative damages reached 144.0 and 130.3 trillion USD, respectively. The G50 and G25 simulations show that lower-gross-to-net-perturbation assumptions substantially reduce the monetary estimates, but do not eliminate the climate–economic relevance of wildfire carbon emissions.
- (4) Regional damages were shaped by both climate response and socioeconomic exposure. Africa and the Middle East and India and Southeast Asia had the largest absolute losses, while differences in GDP-relative and per capita damages reflected regional population, income, baseline climate, exposure, and adaptation capacity.
- (5) The estimated damages remain only one component of the broader cost of wildfires. Direct fire damage, suppression costs, ecosystem degradation, and smoke-related health impacts were not included. The full societal cost of future wildfires is therefore likely higher than the climate-mediated damages estimated here.

These findings suggest that wildfire carbon emissions should be represented more explicitly in climate–economy assessments and residual-emission discussions. Meanwhile, their interpretation in carbon-pricing or SCC-related applications should account for gross-to-net carbon uncertainty, discounting assumptions, equity weighting, and regional valuation choices.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18146952/s1>, Table S1: SSP245-Wildfire_G100; Table S2: SSP585-Wildfire_G100 [35,39,51,66–75].

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W.T.; supervision, A.L.; project administration, A.L.; funding acquisition, A.L. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

AF	Africa and the Middle East
CA	China and centrally planned Asia
EE	Eastern Europe and former Soviet Union
EU	Europe
GDP	Gross domestic product
IA	India and Southeast Asia
IAM	Integrated assessment model
IMPF_COEFF_LIN	Linear coefficient in the PAGE-ICE impact function
LA	Latin America
OT	Other OECD
PAGE-ICE	Policy Analysis of the Greenhouse Effect with Ice, Climate, and Economics
PPP	Purchasing power parity
PTP	Pure time preference
SCC	Social cost of carbon
SSP	Shared Socioeconomic Pathway
TCR	Transient climate response
US	United States
UWE	Uncertainty in wildfire emissions
W2	PAGE-ICE weighting parameter

Appendix A

Table A1. Percentage contribution of damage components to wildfire-attributable discounted cumulative damages under SSP2-4.5 and SSP5-8.5.

Damage Component	SSP2-4.5 (%)	SSP5-8.5 (%)
Market damages	88.91	75.12
Non-market damages	9.02	5.42
Sea-level-rise damages	2.06	1.95
Discontinuity damages	0.01	17.51

Note: Values show the percentage contribution of each damage component to total wildfire-attributable discounted cumulative damages in the primary G100 gross-emission perturbation case.

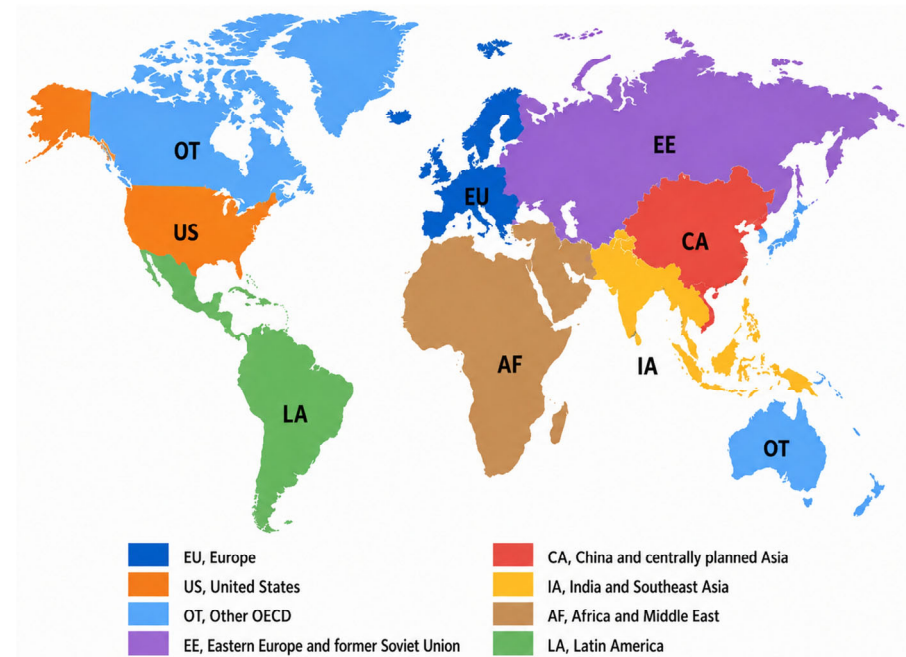


Figure A1. Reference map of the eight PAGE-ICE world regions.

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