Forest Fire Carbon Emissions: Impacts and Mitigation Strategies (Postprint)

Authors: Liu Zhihua, He Hongshi, Xu Wenru, Liang Yu, Jiaojun Zhu, Wang Gaofeng, Wei Wei, Wang Zifa, HAN Yongming

Date: 2023-12-03T00:00:00+00:00

Abstract

From 2002 to 2020, global wildfires emitted approximately 7.32 billion tons of carbon dioxide (CO2) annually, accounting for 18.5% of CO2 emissions from fossil fuels; among these, forest fire carbon emissions accounted for approximately 20% of wildfire carbon emissions (1.5 billion tons of CO2). In recent years, with intensifying climate change and human activities, CO2 released by forest fires has exhibited an increasing trend. For example, the Canadian forest fires since May 2023 have cumulatively emitted 1.268 billion tons of CO2 as of August 29. Against the backdrop of achieving "dual growth" in forest area and stock volume, China has seen a significant reduction in the frequency and area of forest fires since 2010, making important contributions to reducing forest fire carbon emissions and addressing global climate change. Given that forest fires have become a non-negligible source of greenhouse gas emissions, it is necessary to establish a comprehensive, objective, and equitable carbon emission monitoring and accounting system that takes into account both anthropogenic activities (such as fossil fuel emissions, industrial emissions) and natural forest fire carbon emissions; particularly through effective measures such as reducing the frequency of forest fires and decreasing fire intensity to lower forest fire carbon emissions. Addressing the global challenge of predicting and preventing extreme forest fires, there is an urgent need to construct a technical system for forest fire risk identification, early warning-prediction, and prevention and control, and to strengthen research on carbon emissions from forest fire processes, establishing a more scientific, comprehensive, and autonomous carbon accounting system.

Full Text

Preamble

Citation Format: Liu Z H, He H S, Xu W R, et al. Impacts of forest fire carbon emission and mitigation strategies. *Bulletin of Chinese Academy of*

Sciences, 2023, 38(10): 1552-1560, doi: 10.16418/j.issn.1000-3045.20230823001. (in Chinese)

Impacts of Forest Fire Carbon Emissions and Mitigation Strategies

Liu Zhihua[1], He Hongshi[2], Xu Wenru[1], Liang Yu[1], Zhu Jiaojun[1]*, Wang Geoff G.[1], Wei Wei[3], Wang Zifa[4], Han Yongming[5]

[1]Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China
[4]Institute of Earth Environment, Chinese Academy of Sciences, Xi' an 710061, China

Abstract

Between 2002 and 2020, global wildfires emitted approximately 7.32 billion tons of carbon dioxide (CO_2) annually, representing 18.5% of CO_2 emissions from fossil fuel combustion. Forest fires accounted for about 20% of these wildfire emissions, releasing roughly 1.5 billion tons of CO_2 per year. In recent years, CO_2 emissions from forest fires have shown an increasing trend due to climate change and intensified human activities. For instance, the Canadian wildfires that began in May 2023 had cumulatively emitted 1.268 billion tons of CO_2 by August 29. In contrast, China has achieved a remarkable reduction in both the frequency and area of forest fires since 2010, despite simultaneous growth in forest area and stock volume, making significant contributions to global efforts to mitigate forest fire carbon emissions and address climate change. Given that forest fires have become a non-negligible source of greenhouse gas emissions, it is imperative to establish a comprehensive, objective, and equitable carbon emission monitoring and accounting system that considers both anthropogenic sources (such as fossil fuel and industrial emissions) and natural forest fire emissions. Effective measures must be implemented to reduce the frequency and intensity of forest fires, thereby decreasing their carbon emissions. To address the worldwide challenge of predicting and preventing extreme forest fires, there is an urgent need to develop a technical system for forest fire risk identification, early warning, prediction, and prevention, while strengthening research on carbon emissions from fire processes to establish a more scientific, comprehensive, and domestically controllable carbon accounting system.

Keywords: wildfire, carbon emission, climate change, carbon neutrality

1. The Role of Forest Fire Carbon Emissions in the Global Carbon Cycle

1.1 Global Trends in Forest Fire Area and Carbon Emissions

Wildfire is one of the most important natural disturbance processes in global ecosystems and the primary natural disturbance affecting forests and grasslands, playing a significant role in terrestrial ecosystem carbon cycling. Fire destroys surface vegetation, releasing substantial amounts of greenhouse gases, particulate matter, and other trace gases, exacerbating soil erosion and air pollution, and representing a key driver of global environmental and climate security. Between 2002 and 2020, global wildfires emitted (7.32 ± 0.732) billion tons of CO_2 annually, approximately 18.5% of fossil fuel emissions, contributing significantly to rising atmospheric CO_2 concentrations. Notably, wildfire carbon emissions exhibit substantial interannual variability driven by climate change. For example, during the 1997–1998 El Niño event, wildfire emissions reached 11.712 billion tons of CO_2, whereas the annual average from 2001–2009 was 5.86 billion tons, making wildfire carbon emissions a major factor driving variations in terrestrial carbon sinks. Although post-fire vegetation recovery can offset a portion of direct carbon emissions, vegetation requires increasingly longer periods to compensate for carbon releases under conditions of climate warming, shortened fire return intervals, and intensified fire severity. Particularly in boreal and tropical rainforest regions, climate warming and drying, combined with human activities, have increased the frequency, extent, and intensity of forest fires, causing a sharp rise in carbon emissions. Forest regeneration in these areas may require over a century to offset fire-induced carbon release, lagging behind the timeframe established for limiting temperature rise to 1.5°C. Therefore, wildfire carbon emissions cannot be ignored in the context of "dual carbon" accounting systems.

Forest fires occur primarily across three major ecosystems: grasslands, savannas, and forests, with the African continent accounting for over three-quarters of global burned area. Satellite data indicate that global wildfire area has generally declined since 2000, mainly due to reduced burning in African grasslands and savannas resulting from agricultural management practices. However, global forest fire area has increased, particularly in western North America and Australia, where catastrophic fires have become more frequent. Although forest fires constitute only about 5% of global burned area, they contribute 20% of global wildfire CO_2 emissions—approximately 1.5 billion tons annually—due to high forest biomass. Recent studies show that CO_2 emissions from forest fires are increasing at a rate of about 1% per year (approximately 15 million tons of CO_2), establishing them as a significant and growing carbon source. Boreal coniferous forests are particularly concerning, as climate warming and drought intensification have significantly increased fire frequency. Between 2000 and 2020, boreal forest fires contributed 10% of global wildfire CO_2 emissions, but this proportion rose to 23% in 2021, releasing 1.76 billion tons of CO_2. Moreover, fire-prone areas are expanding into high-latitude tundra regions, where increased fire activity accelerates permafrost thaw and enhances emissions of potent greenhouse gases such as methane and nitrogen oxides.

1.2 Factors Influencing Forest Fire Occurrence

Forest fire occurrence is influenced by meteorological conditions, fuel characteristics, and ignition sources. Climate warming leads to elevated temperatures, heatwaves, and drought, reducing fuel moisture content while increasing atmospheric lightning frequency, which collectively increases fire frequency, spread rate, and energy release. Simultaneously, rising temperatures promote vegetation growth at high latitudes, increasing fuel loads and further intensifying fire severity. Due to the "Arctic amplification effect"—whereby high-latitude regions warm faster than the global average—future heatwaves and drought events in the Northern Hemisphere high latitudes may become more frequent, potentially leading to sustained increases in extreme wildfire frequency and intensity. The positive feedback mechanism between climate warming and wildfire carbon emissions could transform high-latitude regions into hotspots for fire-related carbon emissions.

2. Carbon Emission Estimation from the 2023 Canadian Extreme Forest Fires

2.1 Methods for Estimating Forest Fire Carbon Emissions

Forest fire is an essential natural disturbance process in boreal ecosystems, crucial for maintaining forest ecosystem diversity and health. It regulates forest species composition, age structure, and spatial (landscape) patterns through various forms ranging from ground fires to crown fires. Canada' s active fire season extends from May to October. Global climate change has caused persistent high temperatures across North America; in spring 2023, several Canadian provinces experienced temperatures significantly higher than average, with exceptionally hot and dry conditions increasing fire frequency and intensity. According to the Canadian Interagency Forest Fire Centre, as of August 29, 2023, the country had experienced 5,900 fires, with a cumulative burned area of approximately 150,000 km^2. Such large-scale, high-intensity fires can cause ecosystem destruction, biodiversity loss, and irreversible ecosystem degradation.

Primary methods for calculating forest fire carbon emissions include emission factor approaches, remote sensing observations, model simulations, and monitoring inversion techniques. Emission factor methods, remote sensing observations, and model simulations are "bottom-up" approaches that estimate emissions by combining burned area or fire radiative power with parameters such as biomass, combustion efficiency, and emission factors. These methods offer high spatial resolution (100 m^2-1 km^2) but require precise data on burned area, biomass, and emission factors. Monitoring inversion methods are "top-down" approaches that use atmospheric greenhouse gas concentrations and meteorological field data combined with atmospheric chemistry transport models and data assimilation techniques to rapidly estimate fire emissions. However, these methods have coarse spatial resolution (>0.25°) and are affected by the atmospheric boundary layer, making it difficult to quantify source-sink changes in CO_2 emissions. Due to limited information on forest structure, stand density, and combustion ratios in Canadian burned areas, different estimation methods yield varying results.

Remote sensing data currently provides an effective means for estimating large-scale forest fire carbon emissions. This study employs a fire carbon emission intensity method for rapid and accurate preliminary assessment. The approach first calculates a carbon emission intensity map for Canada using the Global Fire Emissions Database (GFED), a high-precision, internationally recognized dataset that serves as the primary data source for IPCC fire carbon emission estimates. This is then combined with remote sensing observations and Canadian national fire data to estimate cumulative carbon emissions in near real-time. The calculations are performed using the following formulas:

$$EFireC = E_{intensity} \times S$$

$$EFireCO_2 = 3.66 \times EFireC$$

where $EFireC$ represents fire carbon emissions (carbon equivalent), $EFireCO_2$ represents fire CO_2 emissions (CO_2 equivalent), $E_{intensity}$ is the regional fire carbon emission intensity for Canada (Figure 1 [Figure 1: see original paper]), and S is the burned area.

This study uses carbon emission data from the Copernicus Atmosphere Monitoring Service (CAMS) Global Fire Assimilation System (GFAS) for validation. GFAS converts Fire Radiative Power (FRP) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) into dry matter consumption using emission factor methods, then calculates fire carbon emissions based on published data. GFAS is widely applied in monitoring fire carbon emissions, air quality forecasting, and atmospheric chemistry modeling, representing one of the most authoritative international fire carbon emission databases.

Our estimation indicates that as of August 29, 2023, Canadian fires had cumulatively emitted approximately 1.268 billion tons of CO_2, about 9% lower than the CAMS estimate of 1.394 billion tons. This emission total is more than five times the average emissions during the same period from 2002–2022 (Figure 2 [Figure 2: see original paper]), exceeding the total energy-related CO_2 emissions of both Canada (546 million tons) and Germany (674 million tons) in 2021, according to 2022 data from the Global Carbon Project. Germany ranks seventh globally in energy-related CO_2 emissions.

2.2 Air Quality Impacts of Canadian Forest Fires

In addition to CO_2 and methane, Canadian forest fires generate substantial particulate matter, including fine particulates ($PM_{2\cdot5}$), inhalable particles (PM_{10}), black carbon (BC), and volatile organic compounds (VOCs). These pollutants significantly impact local and downwind air quality, directly affecting human health. Using the Earth System Model (IAP-AACM), this study simulated the global $PM_{2\cdot5}$ concentration impacts from Canadian fire pollutants. Results show that $PM_{2\cdot5}$ from Canadian forest fires undergoes long-range transboundary transport via westerly circulation and atmospheric dynamics, affecting not only the eastern United States but also crossing the Atlantic to reach densely populated regions in Western Europe and Eurasia, causing extensive air pollution. Four major transboundary transport events were identified: May 17-26, June 6-19, June 23-30, and July 16-20. The June 27-30 event significantly impacted European $PM_{2\cdot5}$ concentrations (exceeding 5 g/m^3), while U.S. air quality was affected earlier ($PM_{2\cdot5}$ concentrations reaching over 50 g/m^3). Canadian fires also influenced $PM_{2\cdot5}$ concentrations in North Africa and Asia, including western China with contributions below 5 g/m^3. By July 20, 2023, Canadian fires had caused $PM_{2\cdot5}$ exceedances over more than 3 million km^2 of land, affecting over 80 million people.

3. Current Status of Forest Fire Carbon Emissions in China

Through persistent afforestation and forest protection efforts, China has achieved over 30 consecutive years of "dual growth" in forest area and stock volume. According to the Ninth National Forest Inventory, China' s natural forest area totals 140 million hectares, with plantation forest area of 80 million hectares, yielding a forest coverage rate of approximately 23%. China contributed about one-quarter of global greening area from 2000–2017, ranking first worldwide and making substantial contributions to carbon sequestration. The *14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives Through 2035* proposes increasing forest coverage to 24.1% during the 14th Five-Year Plan period.

While continuous growth in forest area and stock volume has greatly contributed to carbon sequestration and ecological improvement, it also presents significant challenges for forest fire prevention. Despite severe challenges from combined natural and social factors, China' s forest and grassland fire prevention capabilities have improved substantially through collaborative efforts. Between 2000 and 2021, China experienced an average of 6,088 $\pm$ 3,948 forest fires annually, with over 95% affecting areas smaller than 100 hectares. The average annual burned area was (72,000 $\pm$ 120,000) hectares, with particularly significant reductions in both fire frequency and area since 2010 (Figure 4 [Figure 4: see original paper]). This reduction in burned area has substantially decreased forest fire carbon emissions, which currently average (15 $\pm$ 1.6) million tons of CO_2 annually. China' s "greening for carbon sequestration" ecological engineering measures and "prevention-first, combine prevention with suppression" fire management policy have thus made tremendous contributions to global environmental governance, carbon sink enhancement, and forest fire carbon emission reduction.

4. Strengthening Forest Fire Carbon Research to Reduce Natural Process Emissions

Forest fires have become a significant carbon emission source that cannot be ignored, particularly as extreme fire events have increased in frequency (e.g., Amazon fires in 2019, Australian fires in 2019–2020, Siberian fires in 2022, and Canadian fires in 2023), directly emitting massive quantities of greenhouse gases. Additionally, forest fires accelerate permafrost thaw, releasing substantial amounts of potent greenhouse gases such as methane and nitrous oxide. Other natural processes like volcanic eruptions and active fault zones also emit greenhouse gases. Therefore, strengthening research on forest fire carbon emissions and reducing natural process carbon emissions is imperative. We propose three recommendations:

1. **Integrate forest fire carbon emissions into national emission inventories.** Establish a comprehensive, objective, and equitable carbon emission monitoring and accounting system that considers both anthropogenic sources (fossil fuel and industrial emissions) and natural process emissions. This will support the development of a fair, reasonable, and cooperative global climate governance system.

2. **Implement effective measures to reduce natural process carbon emissions.** Although predicting and controlling forest fires remains a challenge for academia and forestry agencies, scientific and effective prevention measures can be adopted. These include fuel treatment in forests to reduce fuel loads through prescribed burning, mechanical removal, stand thinning, natural fire utilization, and establishment of firebreaks. Adjusting forest species composition to create fire-resistant forest belts can also build natural "green fire barriers." The May 2023 *Opinions on Comprehensively Strengthening Forest and Grassland Fire Prevention and Control Under New Situations* demonstrates China's commitment to mitigating major forest and grassland fire risks and safeguarding lives, property, and ecological security.

3. **Strengthen international cooperation.** The impacts of extreme forest fires extend beyond individual regions, becoming global environmental and climate governance emergencies requiring urgent attention from all nations. Enhanced cooperation and practical measures are needed to mitigate carbon emissions from natural factors. To address the worldwide challenge of predicting and preventing extreme forest fires, researchers should be organized to develop forest fire risk identification, early warning, prediction, and prevention technology systems. Furthermore, research on carbon emissions from fire processes should be strengthened to estab-

lish a more scientific, comprehensive, and domestically controllable carbon accounting system.

References

1. IPCC. *Climate Change 2021: The Physical Science Basis.* Cambridge: Cambridge University Press, 2021.

2. Fang J Y. Ecological perspectives of carbon neutrality. *Chinese Journal of Plant Ecology*, 2021, 45(11): 1173-1176. (in Chinese)

3. Friedlingstein P, O' Sullivan M, Jones M W, et al. Global carbon budget 2022. *Earth System Science Data*, 2022, 14(11): 4811-4900.

4. Bowman D M J S, Kolden C A, Abatzoglou J T, et al. Vegetation fires in the Anthropocene. *Nature Reviews Earth & Environment*, 2020, 1(10): 500-515.

5. Yang J, Tian H Q, Tao B, et al. Century-scale patterns and trends of global pyrogenic carbon emissions and fire influences on terrestrial carbon balance. *Global Biogeochemical Cycles*, 2015, 29(9): 1549-1566.

6. Clarke H, Nolan R H, De Dios V R, et al. Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand. *Nature Communications*, 2022, 13: 7161.

7. van Lierop P, Lindquist E, Sathyapala S, et al. Global forest area disturbance from fire, insect pests, diseases and severe weather events. *Forest Ecology and Management*, 2015, 352: 78-88.

8. Langmann B, Duncan B, Textor C, et al. Vegetation fire emissions and their impact on air pollution and climate. *Atmospheric Environment*, 2009, 43(1): 107-116.

9. van Wees D, van der Werf G R, Randerson J T, et al. Global biomass burning fuel consumption and emissions at 500 m spatial resolution based on the Global Fire Emissions Database (GFED). *Geoscientific Model Development*, 2022, 15(22): 8411-8437.

10. van der Werf G R, Randerson J T, Giglio L, et al. Interannual variability in global biomass burning emissions from 1997 to 2004. *Atmospheric Chemistry and Physics*, 2006, 6(68): 3423-3440.

11. van der Werf G R, Randerson J T, Giglio L, et al. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmospheric Chemistry and Physics*, 2010, 10(23): 11707-11735.

12. Gatti L V, Gloor M, Miller J B, et al. Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements. *Nature*, 2014, 506: 76-80.

13. Xu W R, He H S, Hawbaker T J, et al. Estimating burn severity and carbon emissions from a historic megafire in boreal forests of China. *Science of the Total Environment*, 2020, 716: 136534.

14. Wu C, Venevsky S, Sitch S, et al. Historical and future global burned area, fire emissions, and seasonality derived from changing climate and human demography. *One Earth*, 2021, 4(4): 517-530.

15. Zheng B, Ciais P, Chevallier F, et al. Increasing forest fire emissions despite the decline in global burned area. *Science Advances*, 2021, 7(39): eabh2646.

16. Zheng B, Ciais P, Chevallier F, et al. Record-high CO_2 emissions from boreal fires in 2021. *Science*, 2023, 379: 200-200.

17. Wotton B M, Nock C A, Flannigan M D. International Journal of Wildland Fire, 2010, 19(3): 253-271.

18. Flannigan M, Stocks B, Turetsky M, et al. Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology*, 2009, 15(3): 549-560.

19. Abatzoglou J T, Williams A P. Impact of anthropogenic climate change on wildfire across western US forests. *PNAS*, 2016, 113(42): 11770-11775.

20. Mouillot F, Field C B. Fire history and the global carbon budget: A 1°$×$1° fire history reconstruction for the 20th century. *Global Change Biology*, 2005, 11(3): 398-420.

21. Kaiser J W, Heil A, Andreae M O, et al. Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. *Biogeosciences*, 2012, 9: 527-554.

22. Yin L, Tian X R, Kang L, et al. Research development of carbon emissions from forest fires. *World Forestry Research*, 2009, 22(3): 46-51. (in Chinese)

23. Peuch V, Engelen R, Rixen M, et al. The Copernicus Atmosphere Monitoring Service: From research to operations. *Bulletin of the American Meteorological Society*, 2022, 103(12): E2650-E2668.

24. Rorig M L, Ferguson S A. Characteristics of lightning and wildland fire ignition in the Pacific Northwest. *Journal of Applied Meteorology*, 1999, 38(11): 1565-1575.

25. Calkin D E, Gebert K M, Jones J G, et al. Forest Service large fire area burned and suppression expenditure trends, 1970–2002. *Journal of Forestry*, 2005, 103(4): 179-183.

26. National Forestry and Grassland Administration. *China Forest Resources Report (2014-2018)*. Beijing: China Forestry Publishing House, 2019. (in Chinese)

27. Chen C, Park T, Wang X H, et al. China and India lead in greening of the world through land-use management. *Nature Sustainability*, 2019, 2(2): 122-129.

28. He H S, Chang Y, Hu Y M, et al. Contemporary studies and future perspectives of forest fuel and fuel management. *Chinese Journal of Plant Ecology*, 2010, 34(6): 741-752. (in Chinese)

Author Introduction

Liu Zhihua, Ph.D. in Ecology, Professor at the Institute of Applied Ecology, Chinese Academy of Sciences. Research focuses on forest fire and carbon cycle. E-mail: liuzh@iae.ac.cn

Zhu Jiaojun, Ph.D. in Ecology, Professor at the Institute of Applied Ecology, Chinese Academy of Sciences. Research focuses on forest ecology. E-mail: jiaojunzhu@iae.ac.cn

*Corresponding author

Note: Figure translations are in progress. See original paper for figures.