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Wildfires are testing the limits of emission-control gains

Nan Wang,[1,*] Fumo Yang,[1,*] Song Liu,[1] Yaohan Xian,[1] and Xin Huang[2,*]

[1]College of carbon Neutrality Future Technology, Sichuan University, Chengdu 610065, China

[2]School of Atmospheric Sciences, Nanjing University, Nanjing 210023, China

*Correspondence: nan.wang@scu.edu.cn (N.W.); fmyang@scu.edu.cn (F. Y.); xinhuang@nju.edu.cn (X.H.)

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Wildfires are increasingly recognized as an important driver of atmospheric composition and air quality, with implications for climate, ecosystems, and human health. Although substantial progress has been made in understanding wildfire emissions, smoke transport, and smoke-driven atmospheric chemistry, comparatively less attention has been paid to a more fundamental question: can increasing wildfire emissions undermine the long-term air-quality benefits achieved through anthropogenic emission controls?

Deng et al.[1] address this question through a comprehensive assessment that combines high-resolution ozone reconstruction with source attribution, health-impact assessment, and regulatory analysis. Their analysis indicates that wildfire influence has offset, and in some regions reversed, recent policy-relevant ozone pollution mitigation across the contiguous United States despite continued reductions in anthropogenic precursor emissions. More importantly, the study identifies wildfire influence as a measurable constraint on regulatory attainment, highlighting its potential to weaken the real-world effectiveness of emission-control strategies. Figure 1 summarizes this emerging divergence between declining anthropogenic emissions and wildfire influence, as well as its consequences for surface ozone pollution.

SEEING WHAT MONITORING SYSTEMS ALONE CANNOT

Understanding the long-term wildfire influences on ozone requires observations that are both temporally consistent and spatially representative. Yet the U.S. Environmental Protection Agency network covers only about 2% of the continental U.S. land area and 26% of its population, and only 35% of stations provide continuous records for 2003–2024. Ground-based measurements are direct but spatially uneven, particularly across inland, rural, fire-prone, and downwind regions. Reanalyses and satellite-derived products provide broader atmospheric and surface coverage, but no single observing system offers a long-term, daily, high-resolution record of surface maximum daily 8-hour average (MDA8) ozone.

Deng et al. address these limitations using a multilayer perceptron trained on EPA daily MDA8 ozone measurements and predictors from atmospheric and meteorological reanalyses and remotely sensed products. A custom cost function gives greater weight to rare high-ozone events, increasing the hit rate for exceedance events from 45.8% to 75.3% and enabling a gapless daily 1-km ozone dataset for 2003–2024. The reconstruction showed little overall bias against EPA observations (mean bias = −0.03 ppb; regression slope = 0.98), and its spatial trend directions agreed strongly with EPA stations. However, its influence on baseline ozone and long-term trends remains uncertain because an otherwise identical unweighted reconstruction was not reported. Machine learning thus functions as an observational integrator, enabling full-coverage, neighborhood-scale assessments of ozone attainment, exposure, and health impacts. These improvements are particularly important for regulatory assessments, in which accurate representation of rare exceedance events is more consequential than average predictive performance.

WHEN EMISSION-CONTROL GAINS ARE OFFSET

Independent satellite and inventory evidence provides context for the changing balance between anthropogenic and wildfire influences. VIIRS and MODIS observations indicate that burned area and active-fire counts during the latter decade of 2003–2024 were 3.6% and 6.6% higher, respectively, than during the first decade. CONUS-wide burned area showed a positive but nonsignificant tendency of 491.5 km^2 yr^{-1} (p = 0.407), although significant local increases occurred across several fire-prone regions (Figure 1B). CAMS-GLOB-ANT shows continued declines in U.S. anthropogenic CO, NO_x, and NMVOC emissions, with decreases of 24.9%, 19.6%, and 8.8%, respectively, during the latter decade (Figure 1D), whereas GFED5.1 indicates positive but nonsignificant tendencies in wildfire NMVOC and NO_x emissions (Figure 1E). These emission trends characterize a changing emissions landscape but do not translate directly into ozone production, which depends on NO_x–VOC chemistry, plume evolution, meteorology, transport, and background composition.

Against this background, policy-relevant ozone declined by 0.65 ppb yr^{-1} during 2003–2015 but increased by 0.13 ppb yr^{-1} during 2015–2024; the counterfactual trend without wildfire influence remained negative at −0.25 ppb yr^{-1} (Figure 1C). Nationally, Deng et al. estimate that wildfire influence offset 3.9 years of ozone-control progress. The reversal was spatially heterogeneous. In the western United States, the trend shifted from −0.44 to +0.13 ppb yr^{-1}, compared with −0.22 ppb yr^{-1} without wildfire influence; in the Midwest, it shifted from −0.54 to +0.26 ppb yr^{-1}, compared with −0.30 ppb yr^{-1} without wildfire influence. Wildfires consequently offset approximately 6.2 and 5.3 years of ozone-control progress in these regions, respectively.

Importantly, the ozone reversal itself is derived from an observation-informed reconstruction, whereas the magnitude of the wildfire contribution is inferred from counterfactual and chemical-transport-model analyses. Two independent attribution approaches yielded highly consistent counterfactual results (R = 0.99), providing a robustness check, but uncertainties remain in fire emissions, meteorology, atmospheric transport and chemistry, background composition, biogenic VOCs, and the separation of wildfire effects from concurrent anthropogenic and meteorological changes. More broadly, these findings illustrate how climate-sensitive emission sources may complicate the relationship between anthropogenic emission controls and ambient air-quality outcomes.

FROM OZONE TRENDS TO POLICY RELEVANCE

The significance of wildfire-driven ozone change lies not only in the trend itself, but in whether it alters exposure, health burden, and regulatory attainment. Deng et al. translate fire-sourced ozone into these policy-relevant outcomes, showing that premature deaths attributable to long-term exposure have increased by about 318 deaths per year since 2013, with average mortality during 2013–2023 being 46% higher than during 2003–2013. During 2022–2024, wildfire emissions placed an additional 43 million people in ozone-nonattainment areas. The resulting attainment burden was comparable to that expected under a 66-ppb standard without wildfire influence, implying that wildfire emissions effectively prevented an approximately 4-ppb tightening of the current 70-ppb standard.

These results move wildfire-driven ozone from an atmospheric-chemistry issue into the domain of health protection and regulatory decision-making. A similar erosion of environmental gains has been reported for $PM_{2.5}$, for which increasing wildfire smoke offset approximately one-quarter of previous long-term improvements in the United States.[2] Together, these studies indicate that wildfire can affect not only atmospheric composition, but also the public-health protection and regulatory progress expected from anthropogenic emission-control policies.

This has a concrete regulatory analogue. Under the U.S. EPA's Exceptional Events Rule, wildfire-influenced monitoring data may, following an approved exceptional-events demonstration, be excluded from specific NAAQS regulatory determinations; this regulatory treatment should not be interpreted as systematic removal of wildfire-affected episodes from the observational record. Deng et al.'s assessment explicitly considers wildfire-related ozone exceedances.[1] Their finding that wildfire emissions have offset years of ozone-control progress raises a broader regulatory question about how increasingly recurrent wildfire-related ozone should be considered in attainment and exceptional-event determinations, a question that extends beyond the atmospheric evidence discussed here.

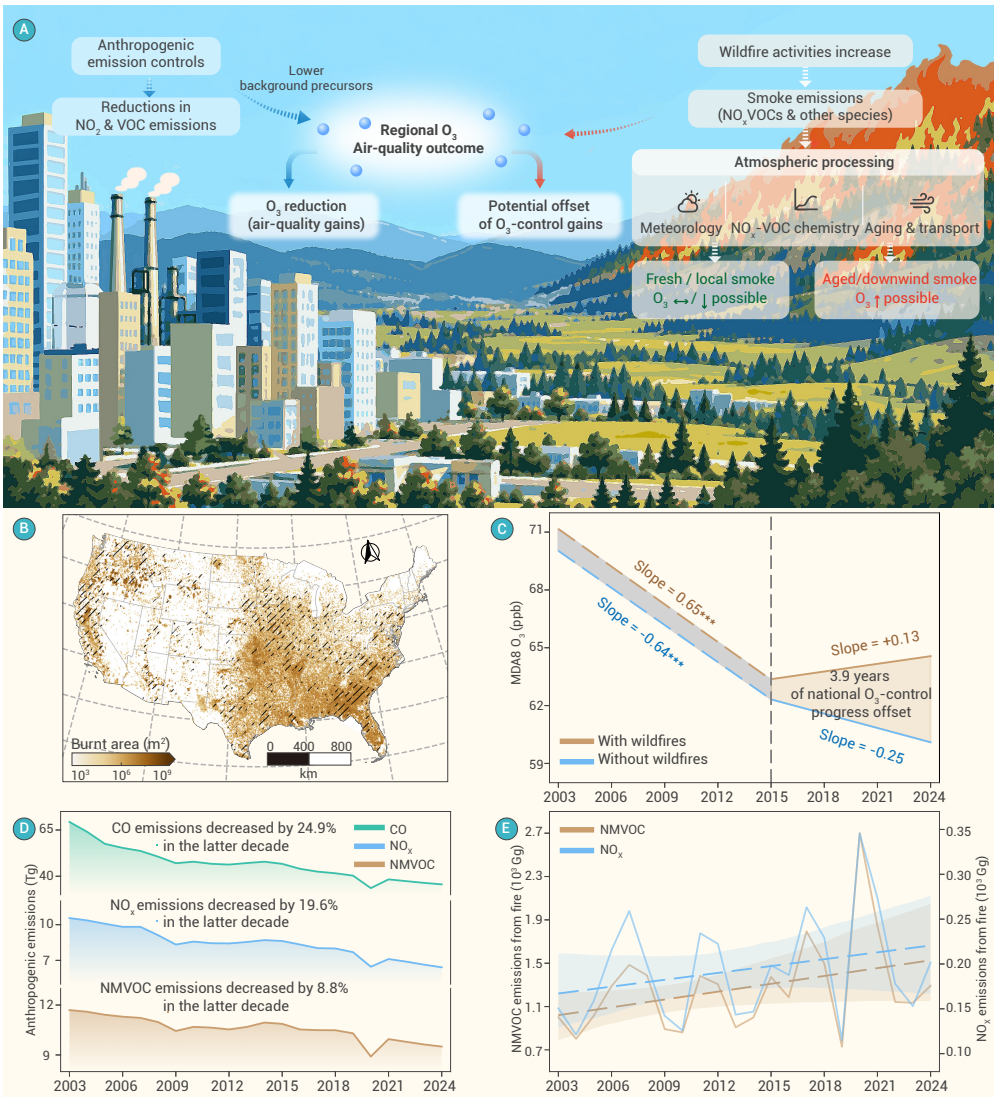

Figure 1. Wildfire influence can offset ozone improvements achieved through anthropogenic emission controls (A) Conceptual illustration showing how anthropogenic emission controls reduce surface ozone, whereas wildfire-related ozone responses depend on atmospheric processing and can potentially offset part of these gains. (B) Spatial distribution of burned area detected by VIIRS and MODIS in 2024. Hatched areas indicate grid cells where annual burned area increased significantly ($p < 0.05$) during 2003–2024. (C) Annual policy-relevant ozone over the contiguous United States with and without wildfire influence. Policy-relevant ozone is defined as the 3-year running average of the annual fourth-highest maximum daily 8-hour average ozone concentration. Trend slopes are shown for 2003–2015 and 2015–2024. Data are derived from Deng et al.[1] (D) Annual U.S. anthropogenic CO, NO_x, and NMVOC emissions from CAMS-GLOB-ANT. (E) Annual U.S. wildfire NMVOC and NO_x emissions from GFED5.1. Dashed lines indicate fitted trends, and shaded areas show the corresponding 95% confidence intervals.

LOOKING BEYOND THE CURRENT OZONE REVERSAL

The implications of Deng et al. extend beyond the recent ozone reversal. Climate change has increased the likelihood of extreme regional wildfire years worldwide,[3] while the 2023 Canadian wildfire season illustrates how rapidly wildfire can reshape atmospheric composition at continental scales.[4] Smoke–weather feedbacks further show that wildfire can reinforce atmospheric conditions favorable for extreme fire activity.[5] These studies do not themselves establish future ozone trends or regulatory outcomes. Future wildfire-related ozone will depend not only on changes in fire activity, but also on emission composition, atmospheric chemistry and transport, meteorology, background ozone, and future anthropogenic precursor emissions.

The U.S. case examined by Deng et al. nevertheless suggests a broader lesson: future air-quality management may increasingly need to consider anthropogenic emission reductions and climate-sensitive emission sources within the same framework. Distinguishing controllable emission-driven improvements from wildfire-driven losses will be important for interpreting long-term changes in exposure, mortality, and attainment, while sustaining future gains will require closer coordination among conventional emission control, climate mitigation and adaptation, and wildfire-risk reduction.

CONCLUSION

Deng et al. do more than identify a reversal in policy-relevant ozone.[1] By combining observation-informed ozone reconstruction with wildfire attribution, health assessment, and attainment analysis, they show that wildfire influence can materially constrain the air-quality gains delivered by anthropogenic emission controls.

The U.S. case should not be interpreted as implying a universal ozone response to wildfire emissions. Rather, it demonstrates that climate-sensitive emission sources can become consequential for the realized benefits of conventional controls when atmospheric and chemical conditions favor ozone enhancement. The effectiveness of future air-quality strategies may therefore depend increasingly on accounting for wildfire alongside controllable anthropogenic emissions, while recognizing that the magnitude of wildfire-related ozone remains strongly context dependent.

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AUTHOR CONTRIBUTIONS

Nan Wang: Writing draft, Investigation, Validation, Formal analysis, Data curation, Project administration, and Funding acquisition. Song Liu: Visualization, Software, Investigation and Data curation. Yaohan Xian: Visualization. Fumo Yang: Resources, Conceptualization, Investigation and Validation. Xin Huang: Conceptualization. Editing, Investigation and Writing draft. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.