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Wildfire Pollution Emissions, Exposure, and Human Health: A Growing Air Quality Control Issue

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Abstract: Wildfires emit large quantities of air pollutants into the atmosphere. As wildfires increase in frequency, intensity, duration, and coverage area, the emissions from these fires have become a significant control issue and health hazard for residential populations, especially the vulnerable groups. A critical barrier to addressing the health impacts of air pollution caused by wildfires lies in our limited understanding of its true extent. This problem is expected to be exacerbated by additional factors such as the anticipated increase in wildfire intensity due to climate change, and the associated rise in fine particulate matter ($PM_{2.5}$) in wildfire smoke, which, according to recent toxicological studies, could be more harmful than typical ambient PM2.5. The primary goal of our study is to develop a novel statistical framework that enables the forecasting of future emissions from active wildfires. This research aims to address the unquantified impacts of wildfire emissions and is a priority research area for many US federal agencies e.g., NIEHS, US EPA, and NOAA. The framework integrates physicochemical models of emissions and satellite observations with forecasting models based on spatial statistics and machine learning models. Through the incorporation of these diverse datasets, we aim to improve the accuracy and reliability of our predictions regarding the spatio-temporal distribution of wildfire emissions. The potential human health impacts resulting from poor air quality during wildfires are also explored. By modeling the relationship between environmental exposures and disease risk, the burden of disease attributed to both short- and long-term impacts of exposure to wildfire events will be assessed.

1. Wildfires and Human Health

Wildfires are emerging as an increasingly critical global concern, likely intensified by changing erratic climatic patterns (1). The increase in intensity, frequency, and duration of global fire activities have been a significant contributor in the increase of noxious emission of various air pollutants (1,2). A major health concern resulting from these wildfire emissions is the release of fine particulate matter under 2.5 micron ($PM_{2.5}$) specifically from these fires, which, according to recent toxicological studies, is potentially more harmful than typical ambient $PM_{2.5}$ (3). Beyond $PM_{2.5}$, these wildfires also emit a variety of other harmful pollutants and stroke dust emissions leading to additional public health concerns. Interestingly, these pollutants do not stay localized but can undergo significant long-range transport. This long-range transport is greatly influenced by wind patterns and atmospheric conditions, spreading the impact far beyond the fire's origin. For instance, the nutrients in the smoke can fall onto distant oceans and lakes, potentially triggering harmful algal blooms that disrupt aquatic life and ecosystems. On a human health front, even communities miles away from a wildfire can experience deteriorated air quality, leading to a range of health issues from respiratory problems to more serious cardiovascular conditions. Quantifying these impacts is a complex task due to the variable nature and widespread dispersal of pollutants, highlighting a pressing need for more robust tracking and analysis methods to fully understand and mitigate the far-reaching impacts of wildfire pollution on a global scale (2–4).

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The health impacts of wildfires are primarily manifesting as respiratory ailments, cardiovascular dysfunction, and notable mental health challenges. However, specific demographics, such as children, the elderly, and individuals harboring pre-existing health conditions, find themselves at a higher risk. This brings to light an additional issue, that is, the most vulnerable sectors of the population are at a disproportionate risk of wildfires. These risks must be identified to implement effective mitigation measures. However, due to the intricate and dynamic nature of wildfires, coupled with the influence of ever-changing weather patterns, fluctuating vegetation states, and the inherently unpredictable behavior of fires, reliably forecasting wildfire emissions remains a formidable challenge. This complexity results in significant difficulty in not only predicting but also controlling these emissions. It is imperative to address this existing knowledge gap to establish adequate pollution control methods (5).

Thus, this research pivots towards addressing a critical question: How can the uncertainties in calculating wildfire emissions be mitigated through the integration of advanced computational techniques, such as Artificial Neural Networks (ANN)?

2. Background

Wildfires have always played a crucial role in global bio-geochemical systems, with many ecosystem services being driven by the emission and transport of nutrients released during these events (6–8). Historically, wildfires have been harnessed as an ecosystem management tool by nature, early human civilizations, and many modern societies. This showcases their intrinsic connection with natural ecosystems and landscapes(9).

However, in the past century, strategies focused on fire suppression and, more specifically, fire exclusion have disrupted this balance and have resulted in significant carbon accumulation in many ecosystems, especially forest ecosystems. Fires in these carbon-overloaded ecosystems can lead to unstable fire regimes, potentially causing a negative carbon balance and uncontrollable blazes. This makes such ecosystems heavily dependent on human intervention, with the absence of controlled fires potentially leading to mega fires(10). These megafires pose a significant threat to populations who have been encroaching into the wildland urban interface.

The escalating effects of climate change on these carbon-rich ecosystems are pushing us steadily towards an era dominated by mega fires. These fires profoundly affect the health and well-being of people, not just in the immediate vicinity, but globally. Yet, our current estimation methods fall short in truly assessing the health costs linked to these disasters. Due to the uncertainties inherent in climate models, forecasting accurate future impacts remains challenging. Consequently, a more advanced approach is imperative. With the emergence of cloud computing and Artificial Neural Networks, we believe these technologies might offer enhancements in wildfire monitoring.

3. How Wildfires Are Undoing Our Air Quality Gains?

The health effects of wildfires have become more significant due to major megafire events. There's concern that the rise in these fires might undo the progress made by the Clean Air Act and years of environmental policies (11).

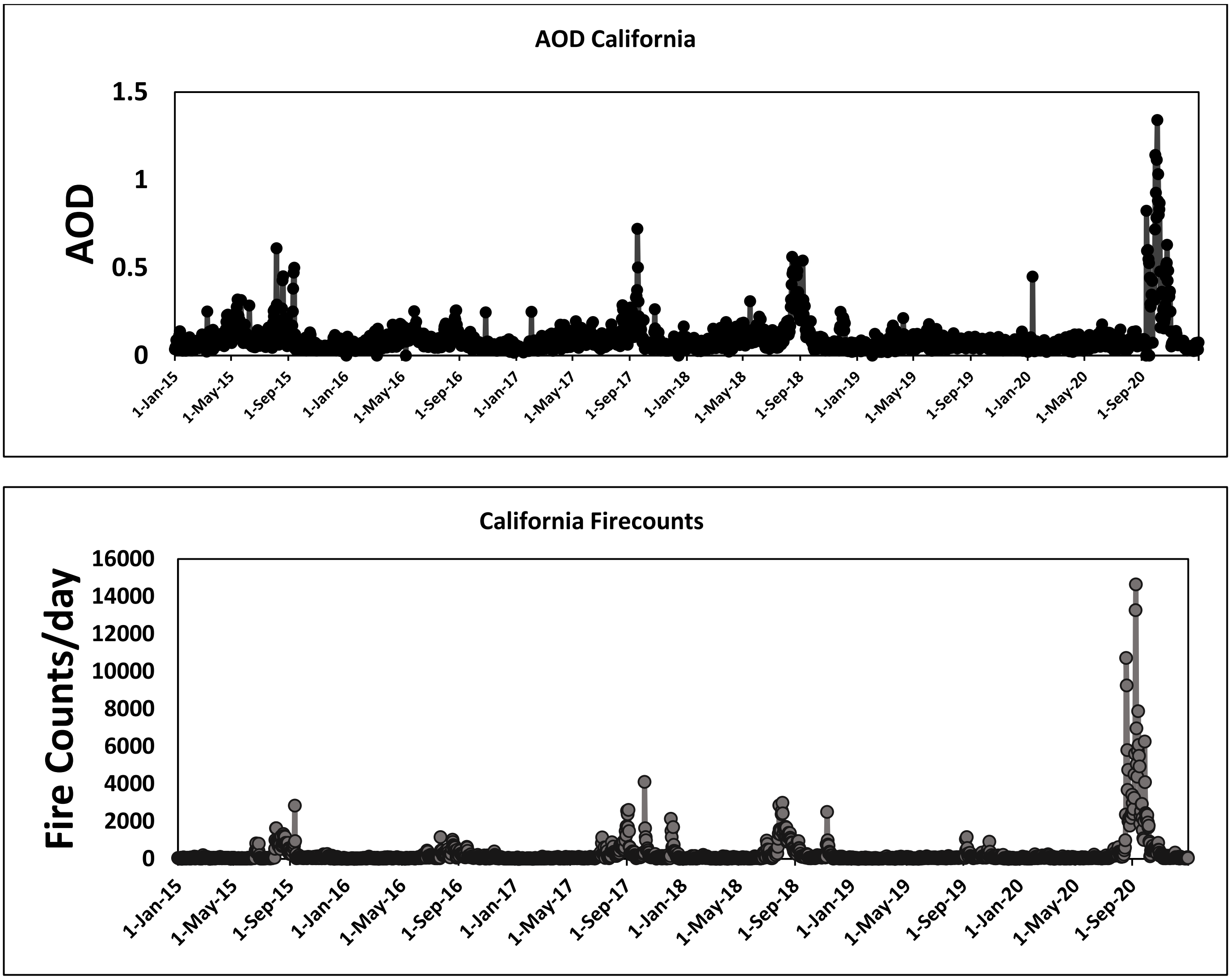

Figure 1. Comparison of wildfire counts and Aerosol Optical depth (AOD) from January 1, 2015, to December 31, 2020, using data from MODIS FIRMS (Fire Information for Resource Management System) and MODIS MCD19A2.

Figure 1 illustrates the correlation between wildfire events and AOD (used here as an indicator of pollution).

4. Estimating Wildfire Emissions

Traditionally, wildfire emission estimations have relied on empirical approaches, as demonstrated by the widespread use of Equations 1 and 2 rooted in observed data and well-established relationships. However, these empirical methods have inherent limitations, often stemming from the constraints of the data and assumptions they are based on. Because of these limitations and the inherent uncertainty associated with climate change the predictions based on these models are vastly different from one another, these differences could stem from the different assumptions in the dynamic vegetation models and future landscape models and offer wildly relatively different results as emphasized by(12).

$$Ei = FRE \times CF \times EFi \tag{1}$$

$$Ei = BA \times AFL \times CC \times EFi \tag{2}$$

Ei = Emissions of specie i [Kg(species i)]

BA = Burned Area
AFL = Available fuel load [Kg(biomass)/m^2]
CC = Combustion completeness
EFi = Emission factor for of specie i [Kg(species i)/ Kg(biomass)]
FRP = Fire radiative power [W]
FRE = Fire radiative energy [J]
CF = Conversion factor [Kg(biomass)/W(FRE)]

With the advent of algorithmic methodologies, particularly Artificial Neural Networks (ANNs), we are presented with an opportunity to significantly improve the accuracy of these predictions. ANNs, with their ability to detect intricate patterns in large datasets, can be finely tuned to deliver superior forecasting accuracy. This opens up not only the prospect of fully leveraging these cutting-edge algorithms but also the potential for a hybrid approach, seamlessly combining the reliability of empirical models with the flexibility and precision of ANNs. The following analytical approach has potential for predicting the impacts of wildfires on human health using Artificial Neural networks trained on data from previous wildfire data (Figure 2).

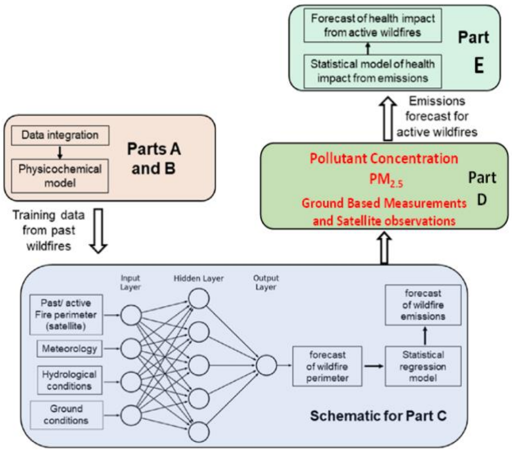

Figure 2. Proposed approach for better wildfire predictions and assessment of human health.

5. How To Manage Wildfires In An Increasingly Warming Earth?

Wildfires, especially in the context of our rapidly warming planet, present a complex challenge that goes beyond mere containment. Historically, our approach to fire management, dominated by fire exclusion strategies, has inadvertently created overstocked carbon systems in our forests. This not only amplifies the risk of intense wildfires but also jeopardizes the equilibrium of forest ecosystems. A shift in our managerial approaches is imperative. Techniques such as controlled burns and thinning can play a pivotal role in restoring the natural balance and reducing the accumulated fuel loads. Additionally, with the increasing encroachment of the Wildland-Urban Interface (WUI), infrastructure planning becomes paramount. Urban development should be in harmony with fire-resilient strategies, ensuring that communities are not only safe but also educated about the inherent risks and the necessary precautions.

With the technological advancements at our disposal, Artificial Neural Networks (ANNs) stand out as a promising tool to further our capabilities in wildfire management. ANNs can be harnessed for early wildfire detection and ensuring a rapid response. Their ability to process vast datasets in real-time allows us not only to anticipate fires but also to predict their subsequent community health impacts. Furthermore, the adaptability of ANNs makes them invaluable for research and continuous monitoring, ensuring that our strategies evolve in tandem with the changing dynamics of wildfires. In essence, while wildfires are a multifaceted dilemma, a combination of traditional forest management practices, community engagement, and state-of-the-art technologies like ANNs can pave the way for a more proactive and effective approach.

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