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$PM_{2.5}$ from wildfires as a potential phosphorus source for Lake Ohrid

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ABSTRACT

During the summer of 2024, forest fires in North Macedonia and Albania were associated with a noticeable increase in atmospheric loading, directly affecting air quality and the ecological processes of Lake Ohrid. The analysis of satellite data combined with kinetic modeling shows an increase in average $PM_{2.5}$ concentrations from 16.7 µg/m³ to around 40 µg/m³ during intense fire episodes. In a 60-day simulation, biodiversity decreased by 24.7% in the baseline scenario and by 70.5% in the fire scenario, while dissolved oxygen dropped from 8.5 to 7.24 mg/L, raising the risk of hypoxia by 2–3 times. The study highlights the high sensitivity of the oligotrophic lake to nutrient deposition from $PM_{2.5}$ and provides a simple prediction tool for environmental management. The purpose of this study is to investigate a previously underexplored pathway of phosphorus input into Lake Ohrid, namely the contribution of wildfire-derived $PM_{2.5}$ particles transported through the atmosphere. While phosphorus loading in Lake Ohrid has traditionally been attributed to river inflows and hydrological connections, the potential role of atmospheric particulate matter during intensive wildfire episodes has not been quantitatively assessed. The study integrates satellite observations from Copernicus and NASA platforms with a short term kinetic modeling framework adapted to oligotrophic lake conditions. Daily $PM_{2.5}$ concentrations, wildfire activity, aerosol optical depth, and chlorophyll-a data were combined with an extended phosphorus mass balance model to simulate short term ecosystem responses during the summer wildfire period of 2024. The findings represent an important assessment, as the phosphorus content of $PM_{2.5}$ was estimated indirectly and no in situ measurements of deposited particles were available. From an applied perspective, the proposed approach supports rapid screening and early warning assessments of wildfire related pressures on sensitive freshwater ecosystems. By linking $PM_{2.5}$ from wildfire deposition to phosphorus ecological responses, this study extends ecological engineering applications for the protection of oligotrophic transboundary lakes. This study aims to provide the first quantitative assessment of wildfire related atmospheric phosphorus inputs to Lake Ohrid and to evaluate their short term ecological relevance under summer wildfire conditions.

Keywords: wildfires, $PM_{2.5}$, Lake Ohrid, phosphorus deposition, remote sensing, air pollution, eutrophication, ecosystem impact.

INTRODUCTION

In the Mediterranean and Balkan regions, large scale wildfire events have become increasingly frequent and severe, with Greece, southern Italy, and the western Balkans repeatedly experiencing extreme fire seasons that generate dense smoke plumes affecting air quality over regional and transboundary scales (Evangeliou et al., 2019; Majdi et al., 2019; Masoom et al., 2023). Fine particulate matter ($PM_{2.5}$) emitted during wildfires contains chemically active components that can be transported over long distances and subsequently deposited into terrestrial and aquatic environments, where they may interact with local biogeochemical processes. Although the impacts of wildfire aerosols have been extensively documented in relation to air quality degradation and human health, their influence on nutrient dynamics in freshwater ecosystems remains comparatively underexplored.

Lake Ohrid constitutes a particularly vulnerable system in this context. As one of the oldest lakes in the world and is an established oligotrophic ecosystem, it is characterized by an exceptionally long hydraulic residence time and an extraordinary level of endemic biodiversity. These features imply a limited capacity to buffer sudden external nutrient inputs, even when such inputs occur over relatively short time scales. Episodic nutrient deposition may therefore trigger ecological responses that are not adequately captured by conventional assessments focused on long term phosphorus loading. Despite a substantial body of research addressing nutrient sources and eutrophication risks in Lake Ohrid, existing studies have focused predominantly on riverine inflows, groundwater exchanges with Lake Prespa, and internal nutrient cycling processes, while atmospheric deposition has largely been treated as a diffuse and secondary background source, without explicit consideration of episodic wildfire related $PM_{2.5}$ inputs (Matzinger et al., 2006, 2007). Recent studies in North America and other regions have demonstrated that wildfire smoke can mobilize phosphorus rich $PM_{2.5}$ and induce rapid biogeochemical responses in downwind aquatic ecosystems, including short term increases in dissolved phosphorus and primary productivity (Olson et al., 2023; Fernandez et al., 2024). However, comparable assessments are lacking for ancient oligotrophic lakes in the Balkan and Mediterranean regions, where ecosystem resilience is inherently low and nutrient perturbations may have disproportionate ecological consequences. This absence of region specific analysis represents a critical gap in current knowledge, particularly under conditions of increasing wildfire frequency associated with climate change.

The purpose of this study is to quantify the contribution to atmospheric phosphorus loading in Lake Ohrid and to assess its potential to trigger measurable ecological responses under summer wildfire conditions. The hypothesis is that episodic increases in $PM_{2.5}$ during wildfire events introduce a bioavailable phosphorus capable of accelerating eutrophication processes, even in a traditionally oligotrophic system. By integrating satellite observations with a kinetic modeling framework, this study aims to address an underexplored atmospheric pathway of nutrient input relevant for the protection of sensitive transboundary lake ecosystems.

MATERIALS AND METHODS

All methodological steps are described sequentially, and all data sources, temporal coverage, processing procedures, and modeling parameters are explicitly specified to ensure reproducibility,. The selected satellite datasets were chosen based on spatial resolution, temporal availability, and relevance for environmental assessment.

Study area

The study area includes the transboundary region of Lake Ohrid, extending between Albania and North Macedonia, an oligotrophic ecosystem of exceptional ecological importance and international protected status (UNESCO), also identified as a priority area for biodiversity conservation in conservation assessments (IUCN, 2016; IUCN, 2018). The analysis focused on the eastern and southeastern parts of the lake, areas that during the summer of 2024 were directly affected by atmospheric transport of wildfire smoke originating from surrounding territories (Figure 1).

Satellite data sources and processing

To assess air pollution dynamics and its impact on the aquatic ecosystem, satellite data from Copernicus and NASA sources were used. Identification and tracking of wildfires were carried out using the Fire Information for Resource Management System (FIRMS), based on MODIS and VIIRS sensors. The spatial distribution of active fire hotspots and their intensity were analyzed for the period from 1 July to 31 August 2024.

Active wildfire events and the associated atmospheric smoke plumes were visually confirmed using Copernicus Sentinel 2 optical imagery. Satellite images were examined to identify the spatial extent of smoke dispersion over the study region during peak fire activity, providing direct observational evidence of wildfire related aerosol transport (Figure 2).

Concentrations of $PM_{2.5}$ particles and black carbon were obtained from NASA's global MERRA 2 model, which provides daily data on atmospheric pollutants with suitable resolution for regional analyses. Values were processed for the area surrounding Lake Ohrid and were used as inputs for the modeling scenarios. Chlorophyll-a data were obtained from the MODIS Aqua sensor and analyzed to assess spatial and temporal

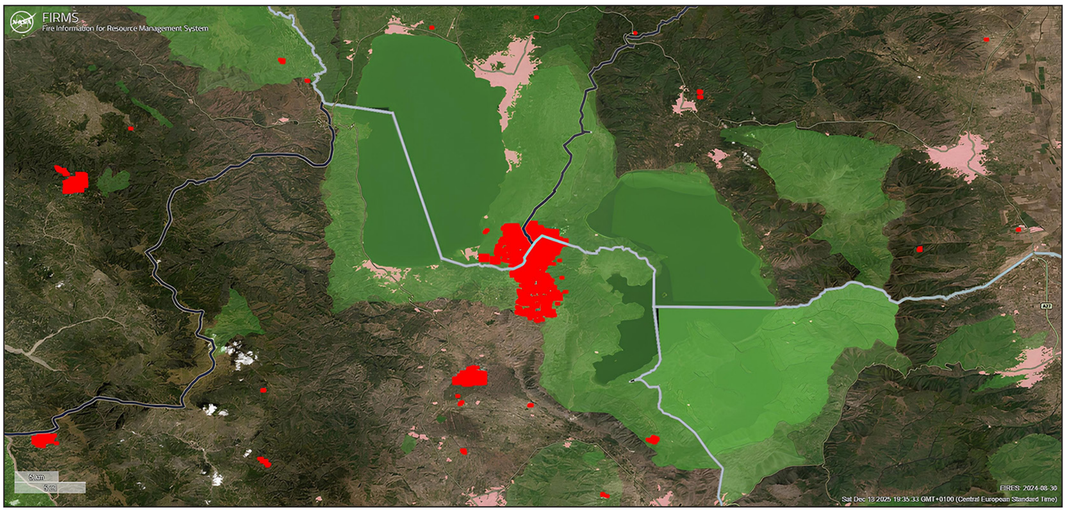

Figure 1. Study area and spatial distribution of wildfires (shown in red) on 30 August 2024, and forest cover in protected areas (shown in green). Source: FIRMS

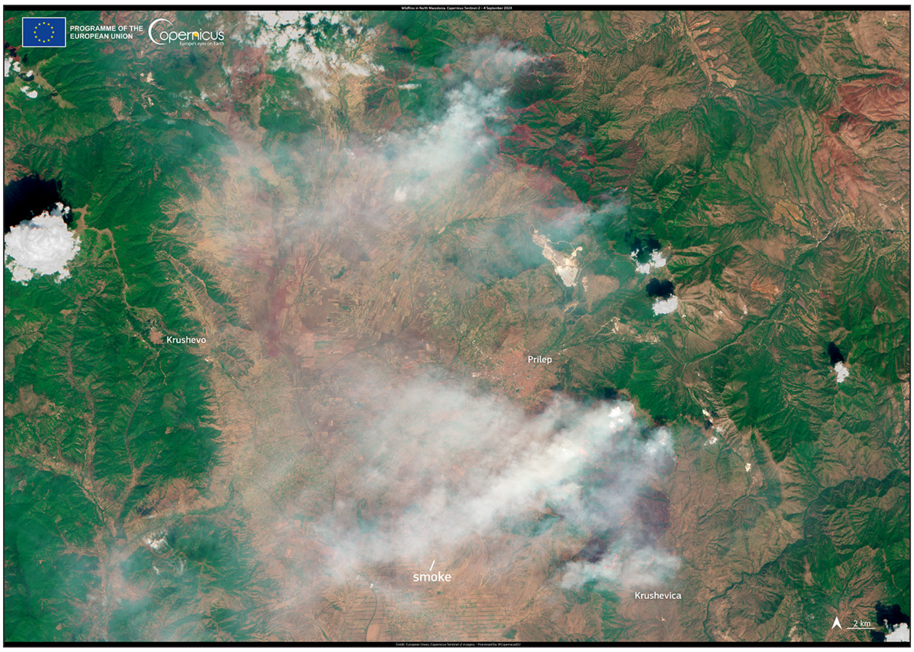

Figure 2. Copernicus Sentinel 2 optical imagery illustrating active wildfire smoke plumes over the study region during summer 2024. The image provides direct observational evidence of atmospheric smoke transport after regional wildfire activity

changes in primary productivity in the lake during the study period. Satellite data processing was performed using standard GIS tools and open analytical platforms.

Kinetic modeling of $PM_{2.5}$ impacts

The impact of wildfire pollution on the lake ecosystem was analyzed through an extended kinetic model specifically adapted for short-period dynamic conditions. This approach follows the methodology applied in previous studies that combine atmospheric and hydrological modeling to assess wildfire $PM_{2.5}$ impacts on nutrient transport and deposition (Olson et al., 2023; Emmerton et al., 2020; Brahney et al., 2015; Kaphle et al., 2025; Vicente et al., 2025). These works collectively demonstrate the robustness of coupling remote sensing datasets with kinetic mass balance formulations to evaluate phosphorus fluxes originating from wildfire aerosols. The model developed here includes an additional component representing the contribution of atmospheric $PM_{2.5}$ deposition during wildfire episodes. It is based on an extension of the classical total phosphorus (TP) mass balance model, originally developed by Vollenweider (1975, 1976) and successfully applied to Lake Ohrid by Matzinger et al. (2006, 2007).

The conventional Vollenweider approach typically considers phosphorus loading under steady-state conditions; however, in this study, it has been reformulated into a dynamic differential form to better represent short-term and transient changes, such as those arising from atmospheric deposition of $PM_{2.5}$ during wildfire events. This methodological adaptation is further supported by recent research demonstrating that wildfire smoke can mobilize substantial amounts of nutrients and transport them over long distances to aquatic ecosystems (Olson et al., 2023; Brahney et al., 2015). Additionally, Kaphle et al. (2025) reported that during the 2022 Hermit's Peak–Calf Canyon Fire, post-fire total phosphorus concentrations in the Gallinas–Pecos River and the Santa Rosa Lake system exceeded pre-fire medians by up to 615 times, confirming the rapid and intense nutrient mobilization – particularly phosphorus – resulting from wildfires.

Deposition into the lake can therefore be described through the following sequence:

> $PM_{2.5}$ (with P) → deposition (dry/wet) → leaching into water → increase in (TP) and eutrophication (increase in Chl-a, hypoxia).

These processes explain why phosphorus from wildfires is more bioavailable than that from other atmospheric sources (Brahney et al., 2015). The differential equation describing the evolution of total phosphorus concentration is:

$$\frac{d(TP)}{dt} = L_{baze} + L_{PM_{2.5}} - \sigma(TP) - \frac{(TP)}{\tau_w} \quad (1)$$

where: *TP* is the total phosphorus concentration in lake waters (expressed in mg/m³ or µg/L); L_{base} is the annual baseline phosphorus load from more stable sources (such as river inflows, hydrological connections with Lake Prespa, and typical atmospheric deposition), taken from estimates by Matzinger et al. (2007), approximately 47 tons/year for the bioavailable fraction under current conditions; $L_{PM_{2.5}}$ is the additional and more variable contribution from particulate deposition (calculated as $k \times PM_{2.5}$, where $k \approx 0.05\ d^{-1}$ is the deposition/leaching rate, estimated based on the general sensitivity of the lake to atmospheric inputs and data from similar wildfire episodes, according to Olson et al., 2023); σ is the net phosphorus sedimentation coefficient (approximately 0.18 yr^{-1}, converted to daily units for simulation, as calibrated by Matzinger et al., 2007); τ_w is the mean hydrological residence time of water in the lake (approximately 70 years for Lake Ohrid, according to Matzinger et al., 2006).

The numerical solution of this equation was performed using MATLAB for a simulation period of 60 days (July–August 2024), in order to capture precisely the peak wildfire episodes. Thanks to this extension, the model is able to describe effects that classical models such as the original Vollenweider model or its application by Matzinger cannot adequately capture, by directly integrating satellite $PM_{2.5}$ data from Copernicus and NASA services.

Phosphorus loading (P) is the key variable driving eutrophication, as well as phosphorus deposition and release processes. Specifically, phosphorus from $PM_{2.5}$ is deposited and converted into bioavailable forms, increasing primary production and reducing dissolved oxygen through organic matter decomposition. These effects are captured in our simulations, supporting satellite observations of local chlorophyll increases.

Model input data were derived from measurements during the period from 1 July to 31 August 2024, supported by sources such as Copernicus (Sentinel-2, EFFIS) and NASA (FIRMS), and include a daily average $PM_{2.5}$ concentration of 5.91 µg/m³, with peaks up to 13.71 µg/m³.

Through this model, a direct link is established between changes in air pollution and the ecological response of the aquatic system, making it particularly suitable for predictive simulations in oligotrophic ecosystems for short periods of time.

Simulations were performed for two scenarios: (i) a baseline scenario representing conditions without wildfire influence ($PM_{2.5}$ = 16.7 µg/m³), and (ii) a wildfire scenario representing intensive episodes during summer 2024 ($PM_{2.5}$ = 40 µg/m³). The simulation period was 60 days to capture the main wildfire activity peaks. Numerical solutions of the differential equations were obtained using standard numerical methods suitable for ecological simulations.

Data processing and reproducibility

All satellite datasets were processed using standard GIS environments and open access analytical platforms. Fire hotspot data from FIRMS were filtered by confidence level and aggregated on a daily basis. $PM_{2.5}$ and black carbon data from the MERRA-2 model were spatially averaged over the Lake Ohrid basin. Chlorophyll-a products were quality filtered to remove cloud contaminated pixels. The kinetic model was implemented in MATLAB R2020a using daily time steps. All parameter values were derived from published studies or calibrated within realistic ecological ranges. This structured, step by step workflow allows independent replication of the simulations using the same input datasets.

RESULTS AND DISCUSSION

$PM_{2.5}$ dynamics

One of the indicators measured by the NASA MERRA-2 satellite model that serves as a quantitative indicator of pollution is black carbon. Figure 3 shows high values of black carbon at the atmospheric surface over Albania and North Macedonia. It is precisely black carbon (BC) from wildfires that serves as the main carrier of nutrients such as phosphorus within $PM_{2.5}$ particles. During this period, the highest values are observed, reaching up to 50 μg/m³. These values are localized in the northeastern and eastern areas of Lake Ohrid, as well as in some regions in southern Albania.

Analysis of satellite data showed that during summer 2024, $PM_{2.5}$ concentrations in the area surrounding Lake Ohrid exhibited pronounced temporal variability. During periods without intense wildfire activity, values remained relatively low and represented the baseline state of the region. However, in mid July and throughout August, distinct episodes of increase were identified, with concentrations rising several times above the average level (Figure 4).

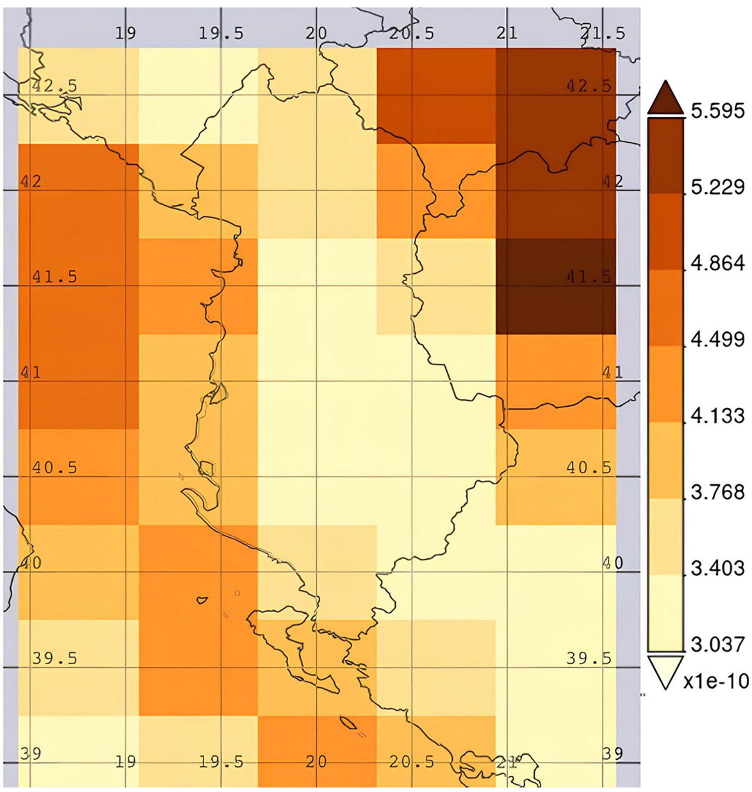

Figure 3. Spatial distribution of black carbon over Albania and North Macedonia during summer 2024, based on the MERRA-2 model

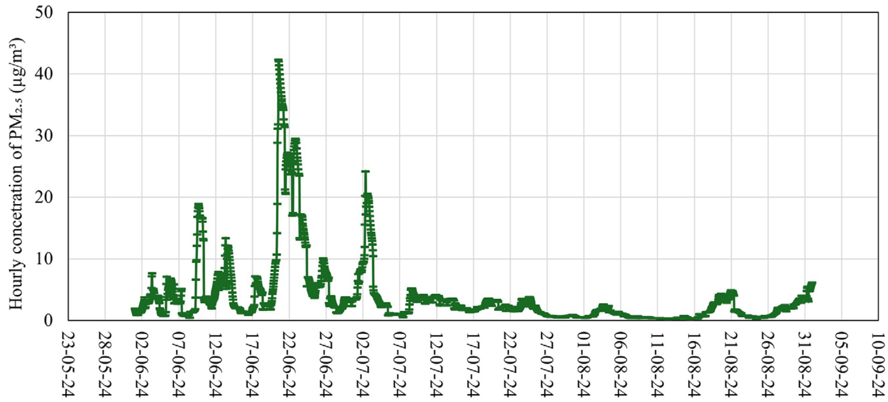

Figure 4. Time series of spatially averaged hourly $PM_{2.5}$ concentrations over the Lake Ohrid region for the period June–August 2024, based on MERRA-2 data

These peaks coincide temporally with the intensification of wildfires in Albania and North Macedonia, as shown in Figure 1, where active wildfire hotspots are identified on both sides of the lake. The temporal and spatial correspondence confirms that biomass burning smoke was the primary source of the increased fine particulate matter in the air (Figure 5).

The daily mean aerosol optical depth (AOD) over the Lake Ohrid region and surrounding areas fluctuated from 0.05 to high peaks of 0.44–0.45, especially in late July and August. These elevated values, which under typical summer conditions without wildfires do not exceed 0.15–0.20, coincide precisely with periods of intensive wildfires in North Macedonia and eastern Albania. This marked increase in aerosols confirms that wildfire smoke reached and covered the lake area throughout the summer of 2024 (Figure 6).

Changes in primary productivity (Chlorophyll-a)

The spatial distribution of chlorophyll-a, analyzed using MODIS-Aqua data, showed that the central part of the lake maintains low values, typical of an oligotrophic ecosystem. In contrast, during the July–August 2024 period, localized increases in concentrations were observed near the eastern and southern shorelines. These increases, shown in Figure 7, coincide with periods of intensive atmospheric particle deposition from wildfires and suggest an additional nutrient input in nearshore areas. The results are consistent with model outputs, indicating that wildfire atmospheric deposition can induce temporary changes in primary productivity, even in a lake traditionally characterized by low nutrient loads.

Similar wildfire impacts on water quality and increased primary productivity have also been

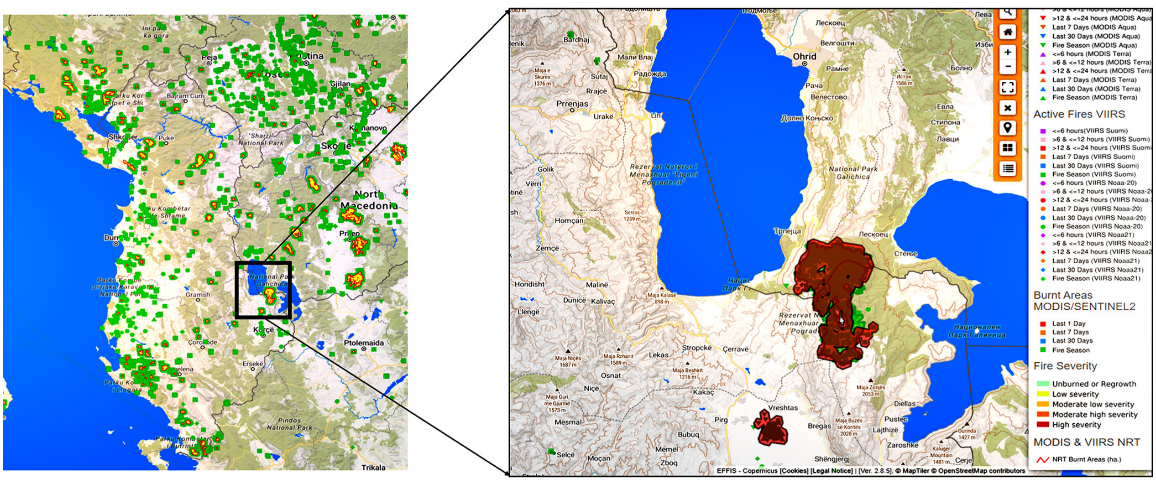

Figure 5. Spatial distribution of active wildfire hotspots in the Lake Ohrid region during summer 2024, based on FIRMS data

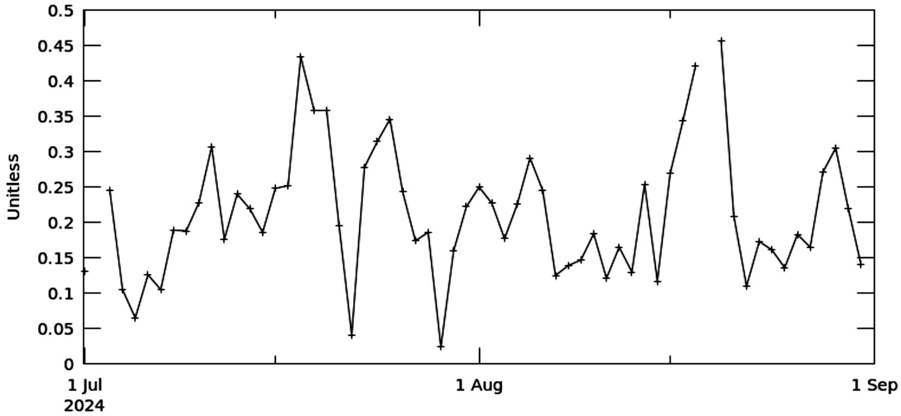

Figure 6. Daily mean aerosol optical depth (AOD) for the period 1 July–31 August 2024 over the region including Lake Ohrid and surrounding areas (coordinates: 20.3467°E–21.3849°E, 40.2848°N–41.1658°N). Source: MODIS (NASA Earthdata)

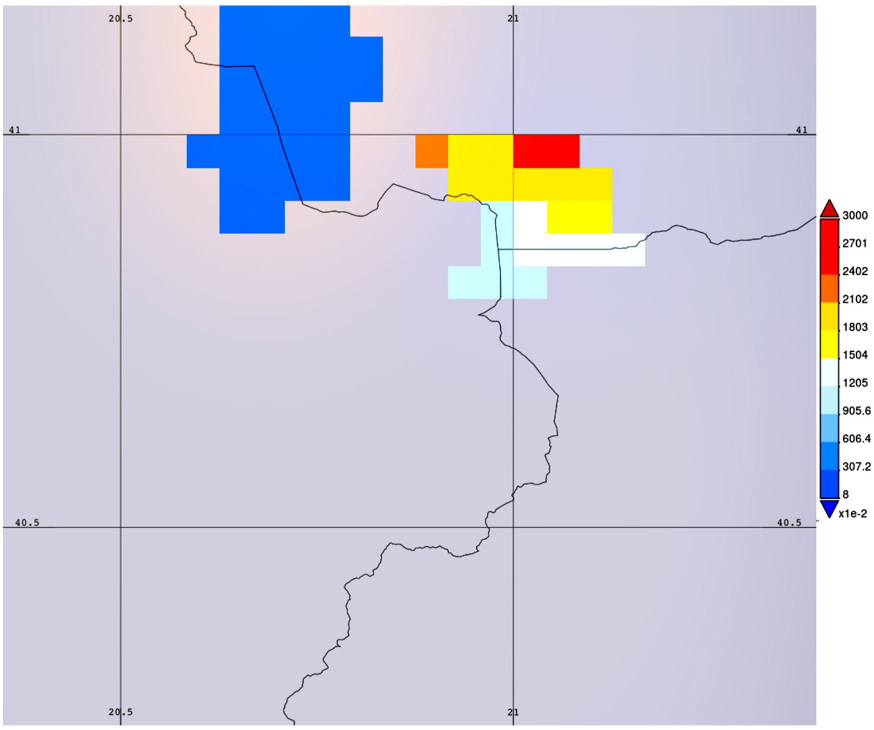

Figure 7. Spatial distribution of chlorophyll-a concentrations in Lake Ohrid during July and August 2024, based on MODIS-Aqua data

reported in large aquatic basins in Canada, where effects were observed even at regional scales (Emmerton et al., 2020).

Sensitivity analysis of the kinetic model

$PM_{2.5}$ concentration in atmospheric models is influenced by spatial resolution as coarser grids tend to smooth short lived pollution peaks and underestimate maximum values during intense episodes. Nevertheless, when applied at resolutions appropriate for regional analyses, chemical transport models have been demonstrated to reproduce temporal patterns and average $PM_{2.5}$ levels with sufficient accuracy for large scale environmental assessments (Fountoukis et al., 2013). To assess the robustness of the obtained results and to better understand the role of key parameters in system behavior, a sensitivity analysis of the applied kinetic model was conducted. The analysis focused primarily on the atmospheric deposition coefficient k, which represents the functional link between $PM_{2.5}$ concentrations in air and the additional input of bioavailable phosphorus into the aquatic ecosystem. The value of this parameter was varied within a realistic range (0.02–0.08 d^{-1}), while other model parameters were held constant.

The results showed that even relatively small changes in the coefficient k produce noticeable effects on the temporal evolution of total phosphorus and, consequently, on dissolved oxygen dynamics. In scenarios with higher k values, an acceleration of local eutrophication processes and increased oxygen consumption during organic matter decomposition were observed, bringing the system closer to hypoxic conditions. In contrast, variations in the sedimentation coefficient σ, even when altered by ±30% around its mean value, resulted in more moderate effects on dissolved oxygen and biodiversity indicators. This demonstrates that, under Lake Ohrid conditions, $PM_{2.5}$ associated atmospheric deposition represents the dominant mechanism driving short term ecological changes during intensive wildfire episodes.

Summary of modeling results

Figure 8 shows that total phosphorus is directly affected by short-term atmospheric deposition. In the baseline scenario, total phosphorus concentration increases slowly and reaches approximately 55 µg/L by the end of the simulation period. In the wildfire scenario, this increase is much stronger and nearly linear, reaching approximately 120 µg/L at the end of the period more than double the baseline value. Similar conclusions were reached by Fernandez et al. (2024) regarding Canadian wildfire smoke impacts on rivers in New York, where a 2–3 fold increase in dissolved phosphorus in river waters was observed during smoke-affected days.

Figure 9 (endemic biodiversity figure) shows that under baseline conditions, biodiversity declines gradually and reaches approximately 80% of its initial value by the end of the period, corresponding to a cumulative loss of 24.7%. This slow decline reflects natural ecological aging processes and minor changes in nutrient balance that occur even in an oligotrophic lake such as Ohrid, without extraordinary stress.

In the second, wildfire scenario, a rapid and pronounced reduction in biodiversity is observed, with only about 21% of the initial value remaining after 60 days. In this case, the cumulative loss reaches 70.5%. This rapid decline reflects a cascade of processes initiated by a sharp increase in bioavailable phosphorus → rapid local eutrophication → algal blooms → high oxygen consumption → hypoxia → massive loss of endemic species that are particularly sensitive to oxygen depletion.

Thus, the additional phosphorus deposition from wildfire $PM_{2.5}$ provides a rapid impulse to

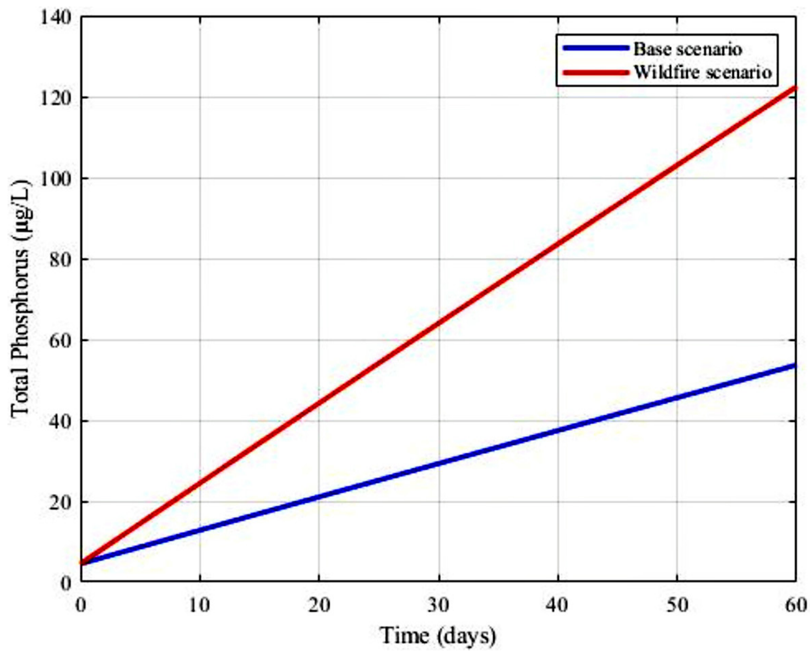

Figure 8. Graphical representation of model results for total phosphorus concentration under the two scenarios

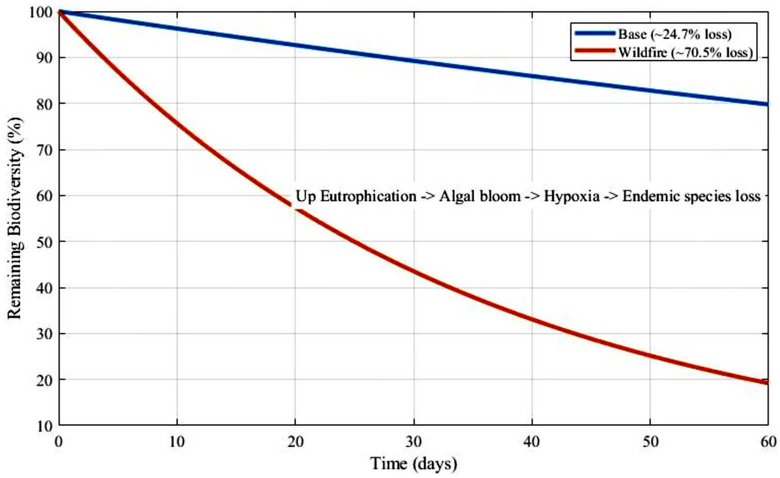

Figure 9. Predicted reduction of endemic biodiversity

short-term eutrophication processes, which in a lake with an extremely long residence time such as Lake Ohrid becomes a serious threat to endemic species. Such a substantial biodiversity loss within only two months is not merely a quantitative change but a clear indicator of the high sensitivity of this ancient ecosystem to wildfire-driven atmospheric inputs.

CONCLUSIONS

These findings demonstrate that wildfire-related atmospheric deposition represents a non-negligible and previously underappreciated phosphorus pathway for Lake Ohrid, with implications for future monitoring strategies under increasing regional wildfire pressureThe rise in $PM_{2.5}$ concentrations and their atmospheric deposition were reflected in a significant decrease in dissolved oxygen and a substantial increase in the risk of endemic biodiversity loss. Based on the performed simulations, Lake Ohrid appears to be particularly sensitive to atmospheric inputs associated with wildfire episodes.

The deposition of $PM_{2.5}$, enriched with ash and associated nutrients, can induce rapid changes in biogeochemical processes, directly affecting dissolved oxygen levels and the preservation of endemic biodiversity. From an environmental management perspective, the findings of this study suggest that protection measures for the lake must extend beyond the control of local aquatic pollution sources. Regional wildfire risk management, systematic monitoring of atmospheric pollution, and the use of real-time satellite data are key elements for preventing such impacts in the future.

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