



When less burning does not mean cleaner air: Decoupling of burned area, fire-related PM_{2.5} emissions, and population exposure in West Africa

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ABSTRACT

Fire activity plays a central role in West African ecosystems. However, substantial uncertainties remain in how changes in burned area (BA) are reflected in fire-related particulate emission estimates and, through their influence on air quality, in population exposure. This study provides a two-decade regional assessment of trends in BA, fire-related PM_{2.5} emissions, climate variables, and population exposure across West Africa from 2002 to 2023. BA declined significantly across most Sudanian and Sahelian savannas, with several countries experiencing reductions exceeding 50 %. In contrast, fire-related PM_{2.5} emissions showed weaker or non-significant declines and increased in parts of the coastal and forest–savanna mosaic, where agricultural and peri-urban open burning is common. These results indicate that BA alone is no longer a reliable proxy for open biomass-burning emissions in West Africa. A decoupling index was developed to identify locations where BA and fire-related PM_{2.5} emissions evolve independently. Approximately 7 % of the domain falls into strict or lenient decoupling categories, encompassing an estimated 551 000 residents. Decoupling is concentrated in agricultural mosaics and peri-urban landscapes, consistent with shifts in fire use, land-use practices, and fuel types associated with higher emissions per unit area burned. At the annual scale, fire-related PM_{2.5} emissions are positively associated with temperature in many countries and negatively associated with precipitation in semi-arid regions, suggesting that climate variability modulates emission patterns even where BA declines. Population exposure analyses reveal contrasting trends: the population-weighted PM_{2.5} indicator decreases over time (Theil-Sen slope of $-0.34 \text{ kt person}^{-1} \text{ yr}^{-1}$), while total exposure increases in most countries due to rapid population growth, often occurring alongside urban expansion and changing emission environments. Despite declining fire extent, total exposure increases significantly in 11 countries, highlighting emerging spatial inequalities in fire-related air pollution. Overall, the findings show that reductions in BA do not necessarily translate into proportional reductions in fire-related emissions or population exposure. Fire management and air-quality strategies in West Africa should therefore move beyond BA metrics alone and explicitly consider emission intensity and demographic dynamics.

Introduction

Landscapes fires are a central component of the terrestrial carbon cycle, atmospheric composition, and regional climate in the tropics (Bowman et al., 2020; Zhang et al., 2020). African savanna and grassland fires play a disproportionately large role in global fire-related emissions and atmospheric impacts. Satellite-based inventories indicate that Africa accounts for around 70 % of global burned area (BA) and roughly half of global fire carbon emissions (van der Werf et al., 2025; Giglio et al., 2018), making it the single largest regional source of biomass burning (BB) worldwide.

West Africa, like the rest of the continent, experiences widespread

fires across its biomes, particularly savannas during the dry season, thereby contributing substantially to the global fire regime. Several global and continental analyses have reported a decline in BA in African savannas, often attributed to fragmentation of fuel beds by agriculture and infrastructure and to changes in fire management practices (Andela et al., 2017; Zubkova et al., 2019). Yet these declines in BA do not necessarily imply proportional reductions in emissions (Zheng et al., 2021) or in human exposure to fire-related air pollution.

At the global scale, open BB contributes significantly to annual variability in trace gases and aerosols loaded into the atmosphere (Carter et al., 2020). Among these aerosols emitted from BB, fine particulate matter (PM_{2.5}) constitutes an important fraction, affecting both

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human health and climate through radiative forcing (Sangkham et al., 2024). The translation of landscape fire activity into health-relevant air pollution involves a sequence of coupled processes linking emissions, atmospheric transport and transformation, and surface-level air quality (Carter et al., 2020). BA emits a complex mixture of primary particles and gaseous precursors that contribute both directly and indirectly to ambient PM_{2.5} concentrations through secondary aerosol formation. The magnitude and spatial footprint of fire-related PM_{2.5} depend not only on BA and fuel characteristics, but also on meteorological conditions that control plume rise, transport, chemical processing, and removal. Climate variability and long-term climate change further modulate these processes by influencing fire weather, atmospheric stability, and the frequency of heat extremes, which can amplify surface PM_{2.5} concentrations and associated health risks. As a result, changes in fire activity do not translate linearly into changes in air quality or population exposure.

Fine particulate matter from landscape fires has well-documented health impacts. Exposure to PM_{2.5} is associated with increased risks of respiratory and cardiovascular disease, adverse pregnancy outcomes, and premature mortality (Grant and Runkle, 2022; Sangkham et al., 2024). Multi-decadal global assessments suggest that smoke from landscape fires contributes to tens of thousands of premature deaths annually (Pullabhotla et al., 2023). Populations in low- and middle-income tropical regions are often disproportionately affected because they experience both high background air pollution and limited capacity for air quality management (Grant and Runkle, 2022). West Africa exemplifies this combination of high vulnerability and rapid change. The population of the region has more than doubled since the early 1990s and continues to grow at some of the highest rates worldwide, particularly in coastal and inland urban corridors (Herrmann et al., 2020). This demographic expansion increases the number of people potentially exposed to fire-related smoke (Knippertz et al., 2015).

Building on these coupled processes, current evidence indicates that interactions between fire activity, emissions, atmospheric conditions, and exposure are increasingly shaped by climate variability and long-term climate change. Rising temperatures, altered rainfall regimes, and changing wind patterns influence fuel moisture, fuel availability, and fire weather, thereby modulating both the likelihood of ignition and the efficiency and completeness of combustion (Pienkosz et al., 2019). For fire emission estimates, differences among inventories largely stem from assumptions related to vegetation type, fuel load, and emission factors, while meteorological conditions govern plume rise, transport, and near-surface pollutant concentrations (Chen et al., 2021).

Understanding how fire activity, emissions, climate, and population dynamics interact in West Africa is therefore important for both scientific and policy reasons. From a physical perspective, fire behaviour and emissions are shaped by vegetation characteristics and meteorological conditions (Freeborn et al., 2022), both of which are sensitive to climate change (Ma et al., 2021). In parallel, land-use and land-cover changes, such as the conversion of savannas to cropland or plantations, modify fuel structure, landscape connectivity, and ignition patterns, thereby reshaping the spatial distribution of fires. From a societal perspective, agricultural practices, fire management policies, and air quality regulations influence both where and when fires occur and the degree to which smoke exposure is considered acceptable. Nationally Determined Contributions (NDCs) under the Paris Agreement increasingly reference fire management, deforestation control, and air pollution mitigation, yet quantitative evidence linking these policy domains to observed fire and emission trends in West Africa remains limited (Kiribou et al., 2025). Improving this evidence base is also essential for designing and implementing integrated fire management strategies that can adapt to ongoing and future changes in fire regimes while maximising benefits for both people and ecosystems (Menor et al., 2025).

Most existing remote sensing-based fire studies in West Africa can be grouped into three broad methodological approaches. A first group relies on global BA and fire radiative power products derived from satellite

sensors such as MODIS to characterise trends in fire occurrence and extent (Giglio et al., 2018; Chuvieco et al., 2018). These studies have documented widespread declines in BA across African savannas (Andela and van der Werf, 2014; Andela et al., 2017), but often do not include fire-related emissions or explicitly assess implications for ecosystem or population exposure. A second group uses global and regional fire emission inventories to quantify the contribution of African fires to atmospheric composition and chemistry (van der Werf et al., 2017, 2025), including several regional studies that provide detailed emission estimates for West Africa, but without extending the analysis to exposure or health impacts. These inventories are typically analysed at coarse spatial resolution and are only rarely combined with high-resolution population or ecosystem data to quantify exposure. A third group of studies focuses on the health burden attributable to fire-related PM_{2.5}, often at continental or global scales (Chen et al., 2021), and identifies substantial mortality impacts, but with limited spatial detail and regional specificity for West Africa. In the context of increasing heatwave occurrence across the region (He et al., 2025) and potential synergistic effects between heat stress and smoke exposure (Chen et al., 2024), a more spatially resolved characterisation of fire emissions and exposure is needed to better inform public health planning and policy in West Africa.

Several gaps emerge from the existing literature. First, relatively few studies have examined whether trends in BA and fire-related emissions evolve proportionally (Zheng et al., 2021), particularly within the dominant biomes of West Africa, or whether this relationship is spatially homogeneous across the region. More broadly, the concept of decoupling between activity and impact, which is widely applied in energy and carbon intensity assessments (Wang et al., 2024; Khan and Majeed, 2022), has not yet been systematically extended to fire emissions and population exposure in this context. Second, integrated regional analyses that link vegetation fires to emissions, atmospheric processing, exposure, and impacts remain scarce. Although PM_{2.5} is a key indicator of health-relevant air pollution, it reflects a mixture of primary combustion aerosols from biomass burning, fossil fuel use, and waste combustion, as well as secondary aerosols formed through atmospheric chemical processes. Existing studies in West Africa often focus on individual components such as fire occurrence (Naawa et al., 2025; Ouattara et al., 2025) or health outcomes (Li et al., 2023), rather than analysing how fire-driven emissions propagate through the atmosphere to shape exposure patterns. Third, most regional assessments operate at coarse administrative or global grid scales, without explicitly linking pixel-scale fire and emission dynamics to country-level indicators relevant for policy and public health decision-making. In this study, we quantify and interpret multi-decadal changes in fire activity, fire-related PM_{2.5} emissions, and population exposure across fifteen countries in West Africa for the period 2002 to 2023. BA is derived from MODIS MCD64A1 (Giglio et al., 2018) and aggregated to an annual 0.1° grid. Fire-related PM_{2.5} emissions are taken from FINNv2.5 (Wiedinmyer et al., 2023), converted from flux units to annual emissions per pixel, and harmonised to the same grid. Population counts are resampled from a global gridded population product (Sorichetta et al., 2015), and climate variables are obtained from ERA5 (Hersbach et al., 2023). Using this integrated dataset, we address three main questions: (1) How have BA, fire-related PM_{2.5} emissions, and a simple exposure proxy evolved in space and time across West Africa over the last two decades, at both pixel and country scales? (2) To what extent are trends in BA and emissions coupled or decoupled, and how does this decoupling relate to climatic drivers such as temperature and precipitation? (3) How does rapid population growth affect the evolution of exposure to fire-related PM_{2.5}, even in locations where BA is declining?

To answer these questions, we derive non-parametric trends using Theil-Sen estimators combined with Mann-Kendall tests and control for multiple testing using a false discovery rate approach. We then develop a decoupling index (DI) that classifies each grid cell and country according to the joint behaviour of BA and emissions, distinguishing between strict and lenient decoupling conditions. Finally, we analyse spatial patterns

of correlation between emissions and climate and quantify changes in population-weighted emissions as a proxy for exposure. The analysis provides a regionally consistent picture of how fire activity, emissions, and exposure in West Africa have evolved under a changing climate and rapid demographic expansion, and establishes a quantitative baseline to support air quality management and climate mitigation discussions in the region.

To clarify the use of the term decoupling in this study, we distinguish between two complementary levels of interpretation. Statistical decoupling refers to a divergence in observed long-term trends or correlations between BA and fire-related PM_{2.5} emissions, as diagnosed from satellite-based observations and emission inventories. Process-based decoupling, in contrast, refers to the physical and socio-environmental mechanisms (changes in fuel type, combustion efficiency, fire timing, land use, or climate modulation) that may cause emissions to evolve independently of area burned. The present analysis formally diagnoses statistical decoupling using trend-based metrics and interprets likely process-based drivers by comparison with established fire–emission relationships, without directly resolving these mechanisms.

Data and study area

Study area

The study encompasses fifteen West African countries covering roughly 6 million km² between 17.5° W–15.5° E and 4° N–18.5° N (Fig. 1). This region spans three major ecological belts that shape fuel availability and vegetation structure: the arid to semi-arid Sahelian zone in the north, the Sudanian savannas forming a broad central band, and the humid Guinean forest and forest–savanna mosaics along the Gulf of Guinea (CILSS, 2016). These gradients in precipitation, vegetation density, and land-use intensity create a diverse landscape in which fire activity varies markedly across latitude and ecological zone.

Climatic seasonality driven by the West African monsoon plays a central role in controlling fire occurrence (Bliefert et al. 2019). The Sahelian and Sudanian zones exhibit a unimodal rainfall regime with a short-wet season and an extended dry season when fuels cure and widespread burning takes place, aided by low humidity and recurring Harmattan winds. In contrast, the wetter Guinean zone experiences fewer large savanna fires; its fire activity is primarily tied to agricultural clearing, smallholder land management, and peri-urban burning (Laris et al., 2005; Dwomoh and Wimberly, 2017). Superimposed on these climate–fuel relationships are long-term warming trends, shifts in precipitation regimes, and strong interannual variability, all of which

influence fuel loads and fire timing across the region.

Fire characteristics and resulting emissions in West Africa reflect both the dominance of human-initiated burning and the structure of the landscape. Most ignitions are intentional and linked to agricultural calendars, grazing management, hunting practices, and residue removal (Amoako and Gambiza, 2020; Caillaud et al., 2020). A large share of fires is small and spatially fragmented, and these can be systematically under-represented in coarser observational products, leading to biases in regional estimates of BA, emissions, and radiative forcing (Ouattara et al., 2025; Gordon et al., 2023). Studies of local burning practices indicate relatively high combustion efficiency in West African savannas, which amplifies emissions of species such as NO_x, CO, and methane relative to other biomes in the region (Laris et al., 2021; Vernooij et al., 2023). These combined factors, including high fire frequency, the prevalence of small fires, and elevated combustion efficiency, reinforce West Africa’s substantial contribution to continental and global biomass-burning emissions.

Burned area data

BA was characterized using the MODIS MCD64A1 Collection 6.1 BA product at 500 m spatial resolution (Giglio et al., 2018). The MCD64A1 algorithm combines daily surface reflectance, active fire detections, and temporal change detection to identify burned pixels and to assign a burn date within each month. Relative to earlier MODIS products, Collection 6 improves detection in sparsely BA and reduces omission errors in fragmented landscapes (Giglio et al., 2018; Parrington et al., 2025).

Monthly MCD64A1 data were first extracted over West Africa for 2002–2023. For each year, we identified all 500 m pixels that burned at least once and converted them to annual BA at the native resolution. These annual 500 m layers were then aggregated to the 0.1° analysis grid by summing the burned 500 m pixels within each cell and multiplying by the pixel area to obtain total BA in km² per 0.1° cell and year. This yields a physically interpretable measure of fire activity that retains interannual variability in fire extent rather than only presence or absence. Annual country level BA was obtained by summing 0.1° cell values within each national boundary.

To focus the trend analysis on landscapes experiencing recurrent fire activity and to avoid spurious trends driven by isolated events, we excluded 0.1° grid cells that burned only once over the full 2002–2023 period when computing trend statistics. This temporal filtering step ensures that trend estimates reflect sustained fire activity rather than sporadic detections.

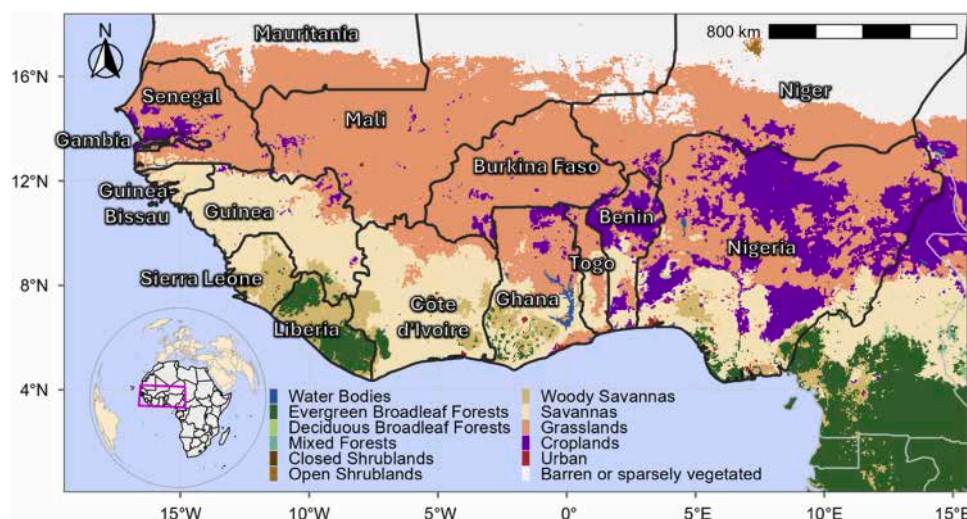


Fig. 1. Study area and major land-use and land-cover classes. Derived from the MODIS MCD12Q1 dataset (Friedl and Sulla-Menashe, 2022) for the year 2023.

Fire-related PM_{2.5} emissions

Fire emissions were derived from the Fire INventory from NCAR, version 2.5 (FINNV2.5) (Wiedinmyer et al., 2023). FINNV2.5 provides daily global emissions at 0.1° spatial resolution based on satellite fire detections, land cover, fuel loading, and emission factors for a range of gaseous and particulate species. The inventory is widely used for regional and global air quality and chemistry transport modelling (Ma et al., 2018; Liu et al., 2020; Jin et al., 2024).

We used the FINNV2.5 grid cell specific surface emissions of PM_{2.5} provided in units of molecules cm⁻² s⁻¹. We first extracted all daily fields for 2002–2023 over the West African domain, then converted the fluxes to annual emissions in tons PM_{2.5} per year for each 0.1° cell. The conversion involved multiplying the flux by the number of seconds per day, the number of days per year, the grid cell area, and the molecular mass of PM_{2.5}, and then converting from grams to tons. Annual country total PM_{2.5} emissions were computed by summing the cell level emissions within each country.

FINNV2.5 fire-related PM_{2.5} emission estimates are subject to several sources of uncertainty that are particularly relevant in West African contexts. Emissions are derived from satellite fire detections combined with global datasets of fuel type, fuel loading, combustion completeness, and emission factors, all of which may vary substantially across heterogeneous savanna, agricultural, and peri-urban landscapes (Liu et al., 2020; Wiedinmyer et al., 2023). In particular, agricultural residue burning, mixed anthropogenic fuels, and open waste burning are imperfectly characterised in global inventories and may therefore be under- or misrepresented. Uncertainty in emission factors and combustion completeness affects the absolute magnitude of estimated emissions and may influence trend strength, although it is less likely to generate spatially coherent divergence patterns on its own. In this study, FINNV2.5 is therefore used as a spatially and temporally consistent proxy for diagnosing long-term emission trends and contrasts, rather than as a precise quantification of true emissions.

Climate variables

Climate conditions were characterized using the ERA5 global reanalysis. ERA5 combines a large number of satellite and in situ observations with a modern numerical weather prediction model to produce physically consistent global fields of the atmosphere and land surface back to 1979 (Hersbach et al., 2023). We used single level ERA5 fields for temperature and total precipitation.

Hourly ERA5 data were accessed over the West African domain for 2002–2023 and aggregated to annual values on a 0.1° grid using Google Earth Engine (GEE) (Gorelick et al., 2017). We calculated annual means for near-surface air temperature and annual accumulated totals for precipitation, which together capture first-order climatic controls on fuel moisture, fire weather, and burning potential. While additional variables such as relative humidity or soil moisture are also relevant to fire behaviour, these are strongly correlated with temperature and precipitation at regional and annual scales and were therefore not considered separately in order to maintain a parsimonious and interpretable analysis. The native ERA5 grid has a resolution of approximately 0.25° and a reduced Gaussian structure. We therefore regridded the annual summary fields to the 0.1° analysis grid using bilinear interpolation for temperature and conservative remapping for precipitation, then cropped and masked them to the West African country mask.

Long term trends in these ERA5 variables have been shown to capture the main features of recent warming and changing rainfall regimes in the Sahel and adjacent regions, although uncertainties remain at local scale due to sparse in situ observations and model biases (Rauch et al., 2025). These limitations are taken into account in the interpretation of the climate–fire–emission relationships.

Population data

Population distribution was represented using the Global Gridded Population Dataset (GlobPOP) (Sorichetta et al., 2015), accessed via GEE. The product provides estimates of the number of inhabitants per grid cell for each year from 2002 to 2023. Population surfaces for each year were aggregated to the 0.1° grid by summing the population counts of all native pixels falling within each analysis cell. This step ensures that population is conserved during the resampling and that each 0.1° cell holds a physically meaningful integer or real-valued count of persons.

Methods

This study integrates satellite observations, emission inventories, climate reanalysis, and gridded population datasets. It applies a harmonised framework to detect long-term trends in fire activity, emissions, and exposure. The workflow combines preprocessing, trend estimation and a decoupling index to assess where BA and emissions evolve independently (Fig. 2).

Trend estimation and significance testing

The trend analysis is performed over the full 2002–2023 observational period, yielding a 22-year time series for each pixel and each variable. Temporal trends in BA, fire-related PM_{2.5} emissions, exposure proxy and climate variables were quantified using the Theil-Sen median slope estimator (Coen et al., 2020) and assessed with the non-parametric Mann-Kendall test (Zhang et al., 2019). The Theil-Sen method provides a robust slope estimate that is less sensitive to outliers than ordinary least squares, while the Mann-Kendall test evaluates the presence of a monotonic trend without assuming normality.

We retained all grid cells with at least five valid annual observations within the 2002–2023 period. Missing years were not imputed; the Theil-Sen estimator and Mann-Kendall test were applied directly to the available observations, consistent with their robustness to irregular temporal gaps.

For each pixel and each variable, we applied a function that: (1) removed non-finite values, (2) required at least five valid annual observations and at least three distinct values, (3) estimated the Theil-Sen slope, then (4) computed the Kendall tau (τ) statistic and its p-value (McLeod, 2022). The same procedure was applied to country level annual series, yielding country specific slopes, τ coefficients and p-values for BA, PM_{2.5}, the exposure proxy, temperature and precipitation.

To control for multiple testing across the large number of pixels and variables, we applied the Benjamini-Hochberg false discovery rate correction to the Mann-Kendall p-values for each variable (Benjamini and Hochberg, 1995). Adjusted p-values (p_{adj}) were derived both at the pixel level and at the country level. A trend was considered statistically significant when p_{adj} was less than 0.05 and the corresponding slope was non zero. Maps of significant trends show only pixels that satisfy this criterion; non-significant pixels are either shown in a neutral colour or omitted to avoid overstating weak or noisy trends.

Decoupling index (DI)

The core diagnostic of the study is a two-dimensional DI that compares the direction and significance of trends in BA and fire-related PM_{2.5} emissions at each pixel and for each country. The DI classifies each pixel according to whether BA and emissions evolve in the same direction, in opposite directions, or show no meaningful trend. The DI is computed using the Theil-Sen slope estimates for BA and emissions, together with the Mann-Kendall significance test (false discovery rate-corrected). The combination of slope direction (increasing, decreasing, or non-significant) and significance level provides an interpretable diagnostic of how fire activity and fire-related PM_{2.5} pollution change

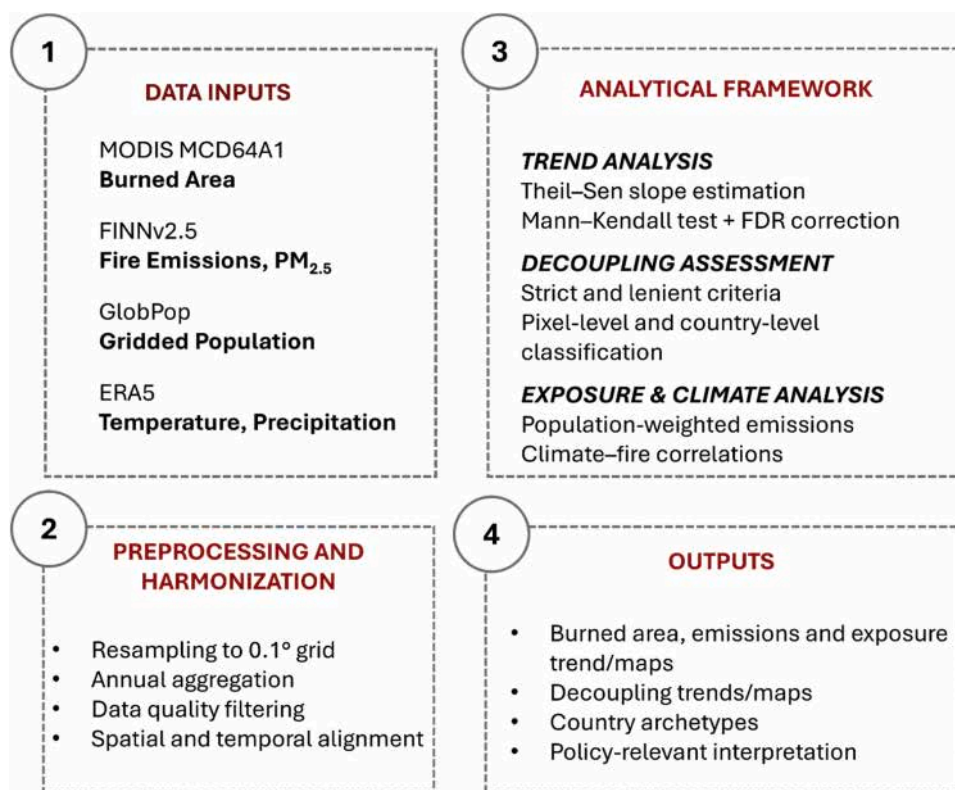


Fig. 2. Overview of the methodological workflow.

jointly over time.

Two levels of decoupling are distinguished. The strict DI identifies cases where BA decreases significantly while emissions increase significantly. These pixels represent the strongest form of decoupling, in which reductions in fire extent do not translate into expected improvements in air quality. The lenient DI captures intermediate cases where BA decreases significantly but emissions remain statistically stable or change only slightly. These cases still indicate a reduction of BA without proportional reductions in emitted particulate pollution.

The DI classification also includes categories where BA and emissions change in the same direction (either both increasing or both decreasing) as well as cases where one variable changes significantly while the other does not. Together, these categories allow for a systematic interpretation of how and why emissions diverge from, or align with, BA trends. The corresponding definitions used in the analysis, and their conceptual interpretation, are summarised in Table 1. This table clarifies how each DI category reflects different underlying fire-emissions dynamics, ranging from ideal improvements (both variables decreasing) to undesirable trajectories such as rising emissions without changes in BA.

The DI is designed as a statistical diagnostic of long-term trend divergence and does not attribute causality; interpretations of underlying mechanisms are therefore developed in the Discussion based on consistency with existing literature (Section 5.2).

Climate–emission correlation analysis

To assess the influence of meteorological conditions on fire-related emissions, we computed Pearson correlation coefficients between annual PM_{2.5} emissions and annual mean temperature and precipitation at the pixel level. In this analysis, temperature and precipitation are treated strictly as external climatic drivers that modulate fuel moisture, fire behaviour, and combustion efficiency, and hence influence emission magnitude. Correlations were calculated using detrended annual series when the objective was to quantify interannual co-variability

Table 1

Classification scheme of the Decoupling Index (DI) used to identify joint long-term trends in burned area and PM_{2.5} emissions.

Category	Burned Area (BA)	PM _{2.5} Emissions	Explanation
Strict DI – Strong	Significant ↓	Significant ↑	Fires go down a lot, pollution rises a lot.
Strict DI – Weak	Significant ↓	Slight ↑ (not significant)	Fires drop, pollution rises a bit.
Lenient DI – Stable Pollution	Significant ↓	No change (flat trend)	Less BA, but pollution not improving.
Lenient DI – Partial Improvement	Significant ↓	Slight ↓ (not significant)	Pollution decreases a little, but less than expected.
Uncoupled – Pollution-driven	No BA change	Significant ↑	Emissions increase without more fire activity.
Coupled – Both Improving	Significant ↓	Significant ↓	Fires drop, pollution drops: ideal case.
Coupled – Both Worsening	Significant ↑	Significant ↑	Fires increase, pollution increases.
Neutral / No Trend	No significant change	No significant change	Stable fire and pollution levels.

DI: decoupling index; ↑: increasing; ↓: decreasing; A trend is classified as significant when the p_{adj} is below 0.05.

independent of long-term trends. In contrast, raw (non-detrended) series were used to assess whether emissions and climatic variables exhibit similar long-term directional changes over time. All correlations are reported with associated p-values to distinguish statistically meaningful relationships from weak or non-significant associations. These climate–emission correlations complement the decoupling analysis by identifying whether persistent or increasing emissions are preferentially associated with long-term warming or drying conditions, without implying feedbacks from emissions to climate.

Exposure proxy and population-weighted indicators

To approximate population exposure to fire-related PM_{2.5}, we constructed an exposure proxy defined as

$$EXP_{i,t} = \left(\frac{PM_{2.5, i,t}}{10^6} \right) \times POP_{i,t} \tag{1}$$

for grid cell (i) and year (t), where PM_{2.5} is in kg yr⁻¹ per cell and POP is the number of inhabitants in that cell. Dividing by 10⁶ converts emissions from kilograms to kilotons, so EXP has units of kiloton persons per year and reflects the combined magnitude of emissions and the number of people potentially exposed. This metric was developed specifically for this study as a parsimonious proxy that combines the magnitude of emissions with the spatial distribution of population. This proxy does not represent ambient concentrations or inhaled dose, but it captures the spatial and temporal co-location of sources and population in a way that is suitable for trend analysis and comparative assessment across countries.

From the cell-level EXP values, we derived two complementary exposure metrics.

First, we mapped the time-averaged EXP over 2002–2023 to identify locations where high emissions coincide persistently with dense populations. To facilitate interpretation, the spatial distribution of EXP was

classified into five ordinal exposure classes using quantile-based intervals (Very Low, Low, Moderate, High, Very High), which divide the long term EXP distribution into equal frequency bins. These classes highlight persistent spatial contrasts in exposure intensity across ecological and demographic zones.

Second, we computed a population-weighted mean PM_{2.5} emission per person, defined as:

$$pwPM_{2.5, t} = \frac{\sum PM_{2.5, i, t} \times POP_{i, t}}{\sum POP_{i, t}} \tag{2}$$

This indicator was developed for this study as a synthetic measure of the average fire-related emission burden associated with an individual resident. It increases either when total emissions rise or when emissions remain stable while population grows, making it particularly useful for diagnosing the demographic amplification of fire-related exposure at regional and national scales. As with EXP, this metric does not represent ambient concentrations or individual dose, but provides a consistent basis for comparing temporal trends and spatial contrasts in population-weighted emissions.

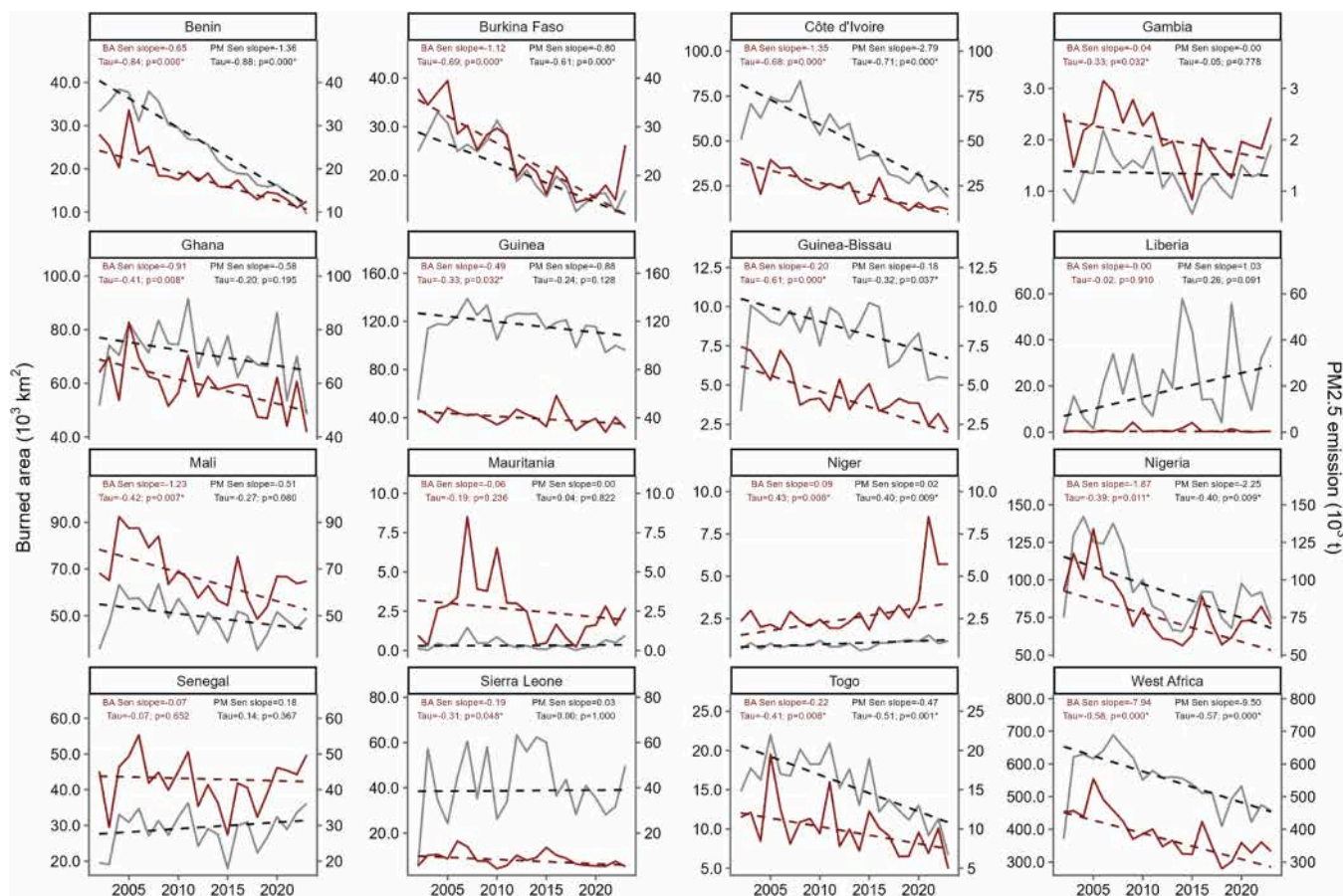


Fig. 3. Regional trends in burned area and PM_{2.5} emissions (2002–2023). Time series of standardized anomalies for total annual burned area (BA) and fire-sourced PM_{2.5} emissions across West Africa. The plot illustrates the significant decline in BA alongside the quasi-stable trend in emissions, with a notable divergence emerging post-2010. At the pixel-level, the spatial distribution of BA trends shows that the steepest declines are concentrated in the central Sudanian savanna and southern Sahel belt, corresponding largely to long-term savanna landscapes (Fig. 4a). In contrast, many coastal and Guinean forest–savanna mosaic zones display weak or non-significant BA trends. Using an unadjusted significance threshold of $p < 0.05$, approximately 29 % of the 0.1° grid cells exhibit a significant negative BA trend, whereas only about 5 % show significant increases. The remaining pixels, represented in neutral grey, do not show statistically detectable trends over the study period. These spatial contrasts are consistent with regions experiencing rapid land-use change, agricultural expansion, and increasing landscape fragmentation, which can disrupt fuel continuity and reduce fire spread in savanna systems. Conversely, forest-edge and mosaic zones may retain more persistent, though spatially heterogeneous, fire activity due to mixed land uses and localized ignition sources.

Results

Spatial and temporal dynamics of burned area and emission

Between 2002 and 2023, the aggregate BA across the fifteen West African countries shows a dominant downward trend, although the decline is neither spatially uniform nor strictly monotonic in all locations (Fig. 3). At the regional (pan-West African) scale, total annual BA decreased at a Theil-Sen median slope of about $-7.9 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ ($p_{\text{adj}} < 0.05$), which corresponds to an overall reduction of roughly 35–40 % relative to the 2002 baseline. Country-level analyses indicate significant BA declines in ten countries: Benin, Burkina Faso, Côte d'Ivoire, Ghana, Guinea, Guinea-Bissau, Mali, Nigeria, Sierra Leone and Togo. The strongest proportional reductions, exceeding about 60 % over the study period, occur in Côte d'Ivoire, Burkina Faso and Sierra Leone, followed by marked decreases of around 40–50 % in Benin, Nigeria, Togo and Mali. Ghana, Guinea and Gambia show more moderate declines, while Niger exhibits a significant increase in BA of the order of 80 %, and Senegal and Mauritania display only small or statistically non-significant changes.

Fire-related $\text{PM}_{2.5}$ emissions also decline at the regional scale, but less rapidly than BA. The West Africa time series has a significant negative Theil-Sen slope of approximately $-9.5 \times 10^3 \text{ t yr}^{-1}$ ($p_{\text{adj}} < 0.05$), implying an overall reduction in annual $\text{PM}_{2.5}$ emissions of about 50–55 % between 2002 and 2023, compared to the 35–40 % decrease in BA. At the national level, $\text{PM}_{2.5}$ emissions decrease significantly in Benin, Burkina Faso, Côte d'Ivoire, Guinea-Bissau, Nigeria and Togo, often with trend-based reductions of similar magnitude to the regional

value. Niger is the only country showing a significant increase in emissions, consistent with its rising BA, whereas most of the remaining countries exhibit statistically non-significant changes in emissions despite clear declines in BA. This difference in the strength and significance of BA and emission trends anticipates the decoupling patterns examined in subsequent sections.

The spatial pattern of $\text{PM}_{2.5}$ emission trends is more heterogeneous (Fig. 4b). Significant negative slopes are widespread across parts of the Sahelian and Sudanian zones, indicating decreasing emissions in many long-term savanna regions. In contrast, clusters of significant positive trends (red hues) occur primarily in coastal and forest–savanna mosaics, including peri-urban and agricultural areas. Only about 6 % of pixels show significant increases in $\text{PM}_{2.5}$ emissions, compared with roughly 24 % with significant decreases, but the positive trends are concentrated in areas where population density and land-use intensity are high. This contrast between widespread BA declines and localized emission increases in humid and mosaic regions anticipates the decoupling behaviour discussed in Section 5.

When emissions are normalised by BA to derive an emission intensity ($\text{PM}_{2.5}$ per km^2 burned), pixel-based trend analysis indicates a positive and statistically significant median slope ($p < 0.05$), meaning that, on average, fires that persist tend to emit more $\text{PM}_{2.5}$ per unit area burned over time. This pattern is consistent growing contribution of fire types associated with higher particulate emissions per unit area, such as agricultural and peri-urban burning, although fuel composition, combustion completeness, and fire behaviour are not directly observed in this analysis. While changes in biomass density could play a role, the present analysis does not allow this factor to be isolated from other co-

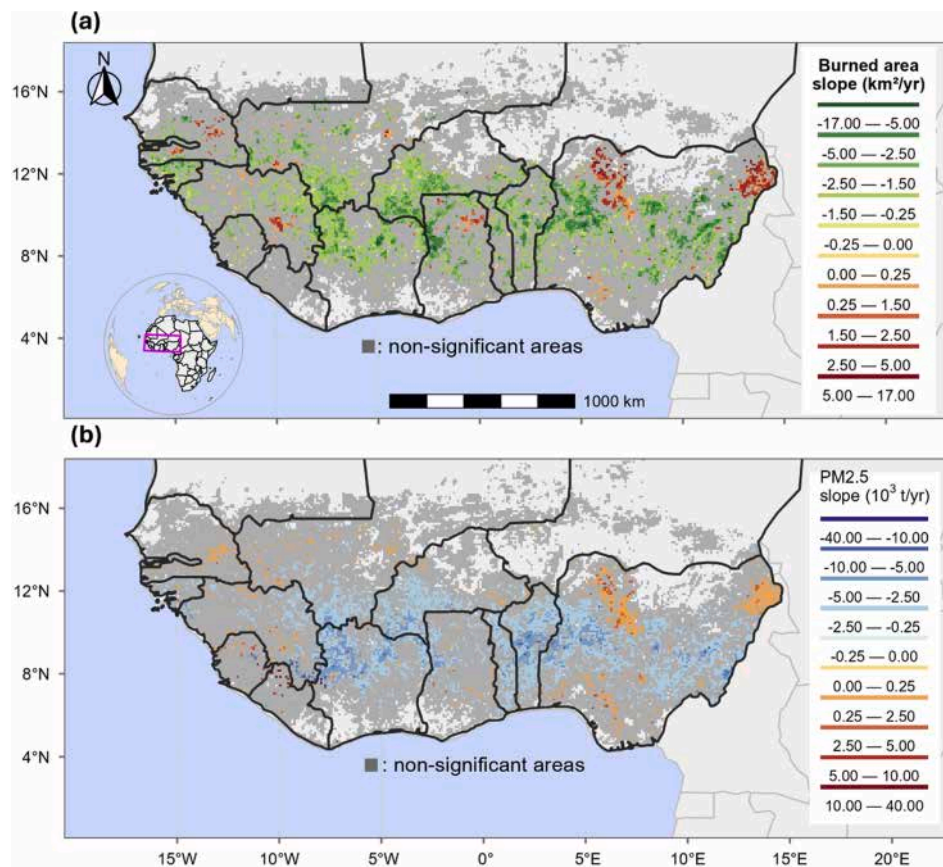


Fig. 4. Pixel-level trends in burned area and fire-related $\text{PM}_{2.5}$ emissions in West Africa for 2002–2023 at 0.1° resolution. Coloured pixels indicate statistically significant trends ($p < 0.05$). (a) Sen slope of annual burned area ($\text{km}^2 \text{ yr}^{-1}$). (b) Sen slope of annual $\text{PM}_{2.5}$ emissions (10^3 t yr^{-1}). The maps highlight widespread BA declines in Sudanian and Sahelian savannas, contrasted with more heterogeneous and locally increasing $\text{PM}_{2.5}$ emissions in coastal and forest–savanna mosaic regions.

occurring drivers.

For the maps in Fig. 4, significance is assessed using unadjusted p values ($p < 0.05$), rather than the false discovery rate -corrected values as in the country-level analyses. This choice reflects the different objectives of the two diagnostics: the maps are used to visualise broad spatial patterns and clusters of coherent trends, where a more conservative correction would remove much of the spatial structure, whereas the country-level statistics are used for formal inference and therefore apply multiple-testing correction.

Throughout this section, interpretations of emission behaviour are based on observed statistical patterns; fire intensity, combustion phase, and fuel characteristics are not directly observed and are therefore discussed in inferential terms.

Taken together, these results show that while BA has declined broadly across West African savannas, fire-related PM_{2.5} emissions

exhibit more heterogeneous and locally increasing trends, particularly in coastal and forest-savanna mosaic regions, highlighting an emerging divergence between fire extent and emission behaviour.

Decoupling of emissions from burned area

The previous section showed that long-term trends in BA and PM_{2.5} emissions are not consistently aligned. At the pixel level, annual BA and PM_{2.5} are generally positively associated, but the relationship is only moderate: the median Spearman correlation between the two-time series is around 0.5, with substantial spread across the domain. This indicates that BA alone is an incomplete descriptor of fire-related PM_{2.5} emission patterns, as emission estimates additionally reflect assumptions about fuel type, fuel load, and emission factors embedded in bottom-up inventories, as well as shifts in the spatial and temporal

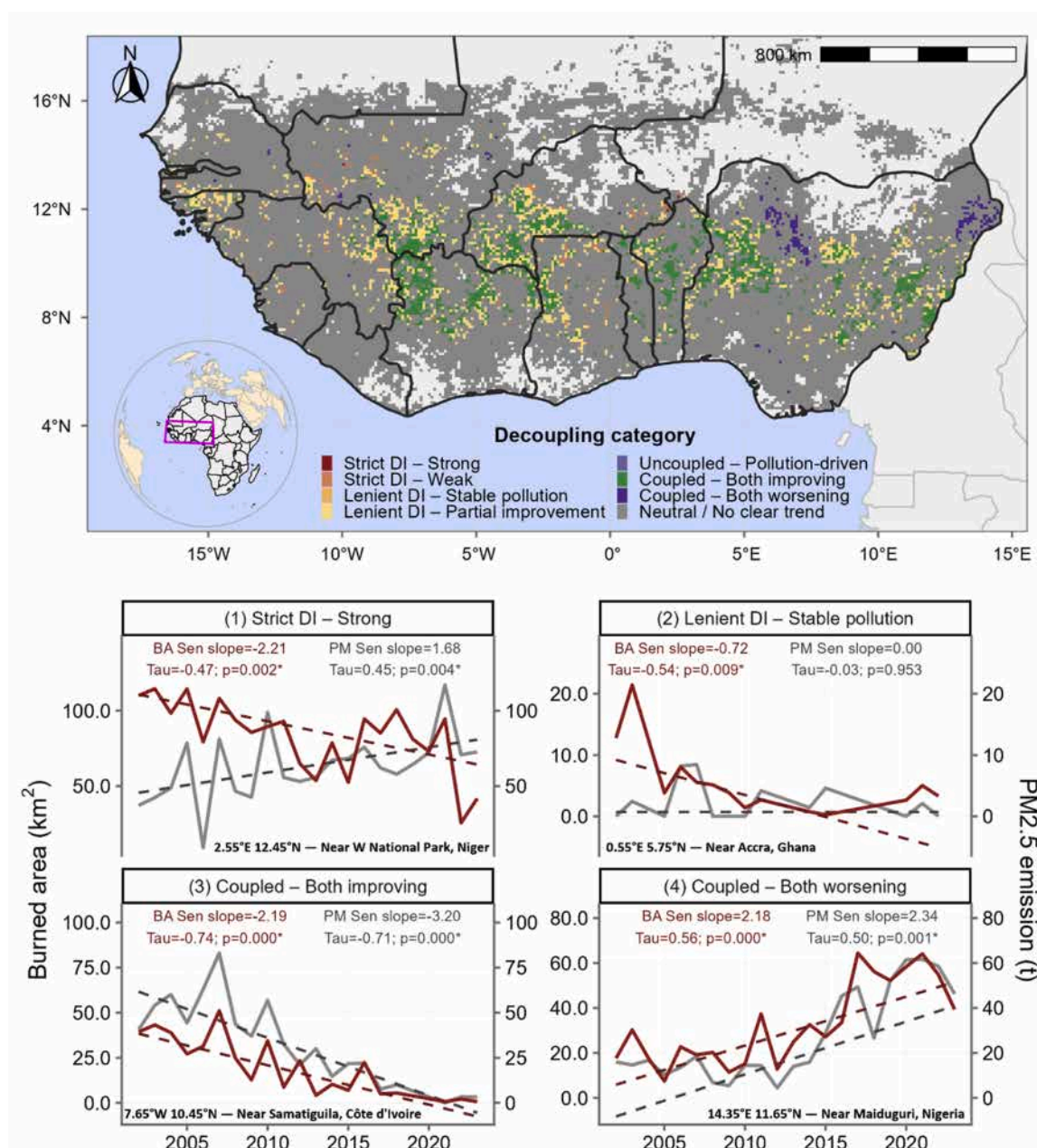


Fig. 5. Spatial distribution of the fire-emission Decoupling Index (DI) and examples of representative pixels. top: Map of DI categories at 0.1° resolution; Bottom: Time series of annual burned area (red) and PM_{2.5} emissions (grey) for four example pixels. Solid lines show the annual values and dashed lines the Theil-Sen trends, with corresponding Sen slopes, Kendall's τ and p values reported in each panel.

distribution of different fire types. Variations in combustion conditions, potentially influenced by fuel characteristics and meteorological setting, may therefore affect emission intensity, but these effects cannot be isolated with the present data.

To characterise this shift more systematically, we combined the Theil–Sen trends and their significance for BA and PM_{2.5} to define a set of DI categories at the pixel scale (Section 3.2). Across the full West Africa grid, the majority of pixels (about 85 %) fall into the neutral category, with no statistically detectable long-term trend in either BA or emissions (Fig. 5). Decoupling categories together account for approximately 7 % of all pixels: about 0.6 % satisfy the strict DI criteria and about 6.9 % the lenient DI criteria. These areas contain an estimated 551 000 people based on the 2015 to 2023 population average. This indicates that decoupling affects a non-negligible number of residents despite its limited spatial extent. When considering only pixels with a non-neutral DI classification, roughly half (51 %) are assigned to decoupling categories, while the other half are mostly classified as “coupled – both improving”, with a small fraction classified as “coupled – both worsening”. Spatially, decoupling pixels are concentrated in the Sudanian savanna, the southern Sahel and parts of the forest–savanna mosaic zone, especially in regions with long histories of shifting cultivation, grazing and fuelwood extraction.

The country-scale patterns mirror these spatial contrasts but are more heterogeneous. In several Sahelian and Sudanian countries, such as Burkina Faso, Guinea-Bissau, Ghana and Guinea, decoupling categories make up a relatively large fraction of the non-neutral pixels, whereas in others, such as Mauritania and Niger, most pixels remain neutral or fall into coupled categories. Coastal states with dense populations and intense land use, including Nigeria and Côte d’Ivoire, show mixtures of coupled and lenient decoupling patterns, with localised zones of “both worsening” near some urban and agricultural clusters. These results reinforce the conclusion that declines in BA do not automatically translate into proportional reductions in emissions and that local land-use and fire management practices strongly shape the emerging fire–emission regime.

Importantly, decoupling is spatially limited but demographically relevant: although affecting a minority of pixels, decoupling clusters in landscapes undergoing rapid land-use change and contains a non-negligible population, underscoring why BA alone is insufficient for evaluating fire-related air pollution impacts.

Climate associations and correlations with emissions

Over 2002–2023, the climate fields show a consistent but spatially heterogeneous warming signal across West Africa. Country-mean annual temperatures show positive trends in nearly all West African countries, with Theil–Sen slopes typically between about 0.05 and 0.30 °C per decade. The median warming rate across the fifteen countries is approximately 0.15 °C per decade, and warming is statistically significant ($p < 0.05$) in about half of them, including Benin, Côte d’Ivoire, Liberia, Senegal, Sierra Leone and Togo. In contrast, long-term trends in annual precipitation are weak: country-scale slopes are small in magnitude, with a regional median near -0.5 mm per decade, and none of the countries exhibits a robust monotonic trend at the 5 % significance level. Both temperature and precipitation are analysed at the annual scale to characterise broad climatic trends relevant to fire behaviour and emissions, without applying explicit temporal lags; lagged effects of rainfall on fuel dynamics are therefore not resolved within this framework.

At the country scale, correlations between annual fire-related PM_{2.5} emissions and climate variables are mixed rather than uniformly strong. Spearman correlations between PM_{2.5} and mean annual temperature are significant ($p < 0.05$) in five countries, with mostly negative associations in Benin, Côte d’Ivoire, Guinea and Guinea-Bissau, and a positive association in Liberia. Correlations between PM_{2.5} and annual precipitation are generally weaker and not statistically significant in any country,

indicating that country-integrated emissions respond to climate variability in a complex way once spatial heterogeneity is averaged out.

Pixel-wise correlation maps provide a more detailed picture of these relationships (Fig. 6). Strong positive correlations between PM_{2.5} and temperature ($\rho > 0.5$) occur mainly in parts of the eastern Sudanian belt and some coastal and peri-urban zones, whereas negative correlations ($\rho < -0.5$) are more frequent in humid and high-rainfall regions, particularly in western Guinea and along parts of the Guinean coast. For precipitation, negative correlations with PM_{2.5} dominate in the Sahelian and northern Sudanian zones, where years with below-average rainfall coincide with enhanced emissions, while weak positive or near-zero correlations prevail in more humid coastal areas. This spatial coherence is consistent with a climate-driven modulation of emission intensity, in which warmer conditions are associated with enhanced combustion potential in semi-arid and seasonal environments. While long-term trends in annual precipitation are weak, changes in the timing and intermittency of rainfall, which are not resolved by annual totals, may influence fuel drying and combustion conditions. Together, these processes can contribute to higher PM_{2.5} emissions per unit area burned and help sustain emissions even where BA is declining.

Overall, these correlations indicate that climate variability modulates emission intensity more strongly than it modulates BA, helping to sustain or amplify emissions even where fire extent declines.

Amplified human exposure driven by demographic growth

The combination of fire emissions and population density reveals how potential population exposure to fire-related particulate matter evolves across West Africa. The five exposure classes shown in Fig. 7a reveal strong spatial gradients shaped by both emission persistence and population concentration. Very High exposure is found along the coastal corridor and in major peri-urban regions of Nigeria and Ghana, as well as in humid savanna mosaics where emissions and population density remain simultaneously high. Moderate to High exposure dominates the southern Sudanian zone, while the Sahel is mostly classified as Very Low or Low. This pattern aligns with previous sections showing that BA has declined mainly in the Sahel and Sudanian regions, while emissions have stabilised or intensified in more densely inhabited southern landscapes. As a consequence, reduced BA does not directly imply reduced human exposure.

The regional time series of population weighted PM_{2.5} emissions (Fig. 7b) shows a clear and significant decrease from 2003 to 2023. The Theil–Sen slope is approximately -0.34 kt·yr⁻¹ per person per year (Kendall τ around 0.12, $p < 0.05$). This indicates that the average particulate burden associated with fires has declined at the regional scale. However, the effect of this decrease is moderated by rapid population growth. Total population in West Africa increased by about 62 % between 2002 and 2023, with the strongest expansion in peri-urban belts and forest savanna mosaics where emissions remain persistent.

This divergence between per capita and total exposure creates pronounced national level differences. Although the regional mean per capita exposure decreases, the total exposure increases in many countries because population growth amplifies even modest or stable emissions. Eleven of the fifteen countries show statistically significant increases in the total exposure proxy. The strongest rises occur in Nigeria and Ghana where demographic growth overlaps with areas of sustained fire activity. In Mali, Burkina Faso and Niger, exposure increases are more moderate because BA has declined sharply, although emissions per unit BA and population continue to rise.

These results show how the physical and ecological processes described in earlier sections translate into human risk. Population growth magnifies the impact of emissions trends. If emissions intensify or remain stable in populated regions, the overall exposure increases even when BA declines. The combined spatial and temporal patterns confirm that reductions in BA alone are not sufficient to reduce the health burden associated with fire-related particulate matter. Mitigation

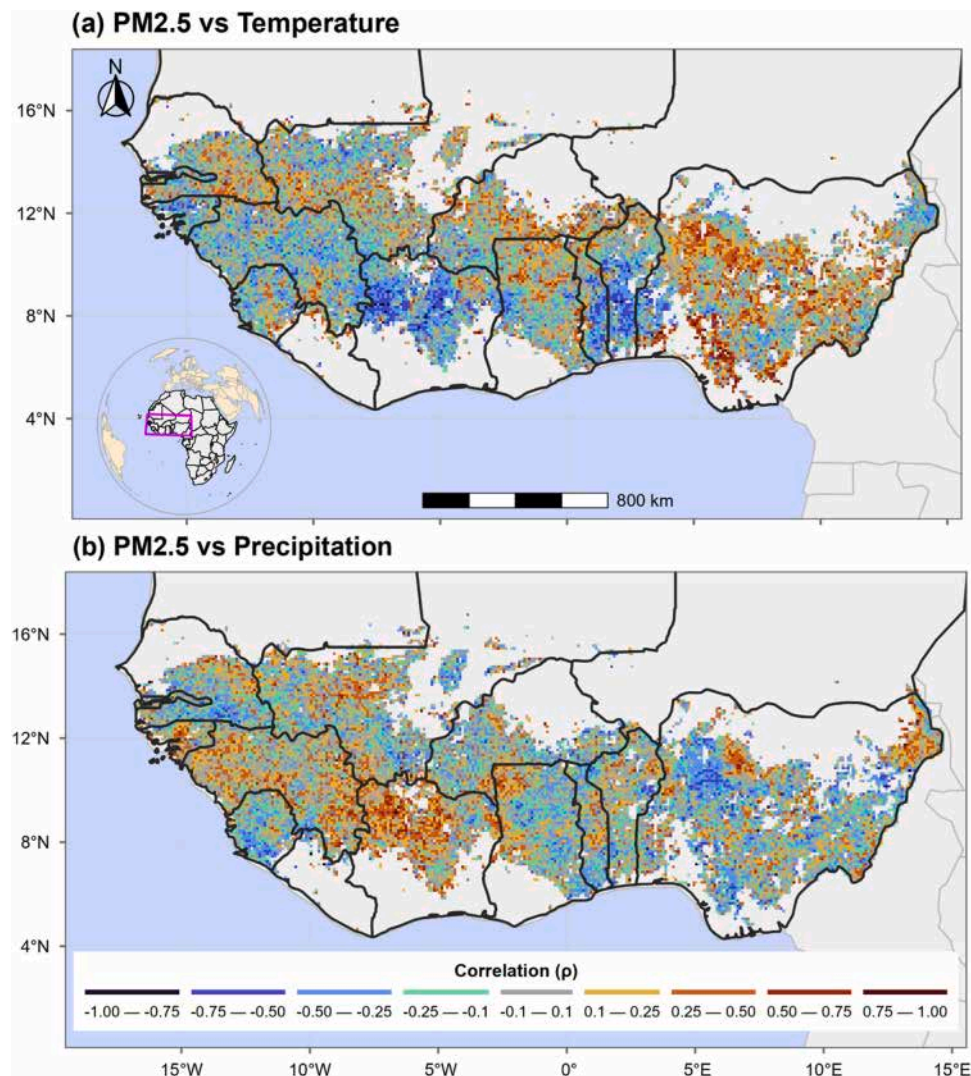


Fig. 6. Climate-Emission Correlation Maps. Pixel-wise Spearman correlation (ρ) between annual fire-related PM_{2.5} emissions and (a) mean annual temperature, and (b) annual precipitation over West Africa for 2002–2023.

strategies must therefore address emissions in densely populated regions and consider the influence of climate and land use change on future fire behaviour.

This contrast between declining per-capita exposure and increasing total exposure highlights the dominant role of demographic growth in shaping fire-related pollution burdens, particularly in regions where emissions persist near expanding population centres.

These results describe relative changes in a source-based exposure proxy and should not be interpreted as changes in ambient PM_{2.5} concentrations or individual health risk.

Discussion

Fire and emission trajectories in a global and regional context

The results indicate that West Africa is undergoing a transition in its fire regime. Because this study does not directly observe fire intensity, combustion phase, fuel loads, or sector-specific burning practices, the mechanisms discussed below are interpreted as plausible explanations consistent with the spatial-temporal patterns and prior literature, rather than as directly verified causal drivers. Over the last two decades, large parts of the region have experienced significant declines in BA, particularly across the Sudanian and Sahelian zones, while fire-related

particulate emissions have declined more slowly or have increased in several locations. This partial mismatch aligns with global analyses showing widespread reductions in BA across savanna and grassland biomes due to fragmentation, agricultural expansion, and landscape modification (Andela et al., 2017; Forkel et al., 2019). At the same time, global studies consistently report that reductions in BA do not necessarily lead to proportional reductions in emissions or fire radiative power because the characteristics of burning shift toward smaller but more intense, more complete, or more anthropogenic combustion events (Roteta et al., 2019; Van Der Werf et al., 2017).

At the country scale, strong declines in BA are most evident in the Sudano-Sahelian belt, whereas the Guinean and coastal zones show weaker or non-significant changes. This pattern is consistent with earlier work attributing reductions in BA in African savannas to land use change, fuel bed fragmentation, cropland expansion, and suppression of open rangeland fires (Archibald, 2016; Andela et al., 2017; Laris, 2021). However, the FINNv2.5 emission estimates used in this study reveal that emissions remain stable or increase in several of the same countries. This divergence shows that reductions in BA do not necessarily translate into proportional reductions in estimated emissions. The pattern is consistent with shifts in the spatial and temporal distribution of fire types and/or with the sensitivity of bottom-up inventories to fuel characterisation and emission-factor assumptions (Wiedinmyer et al., 2023). Similar

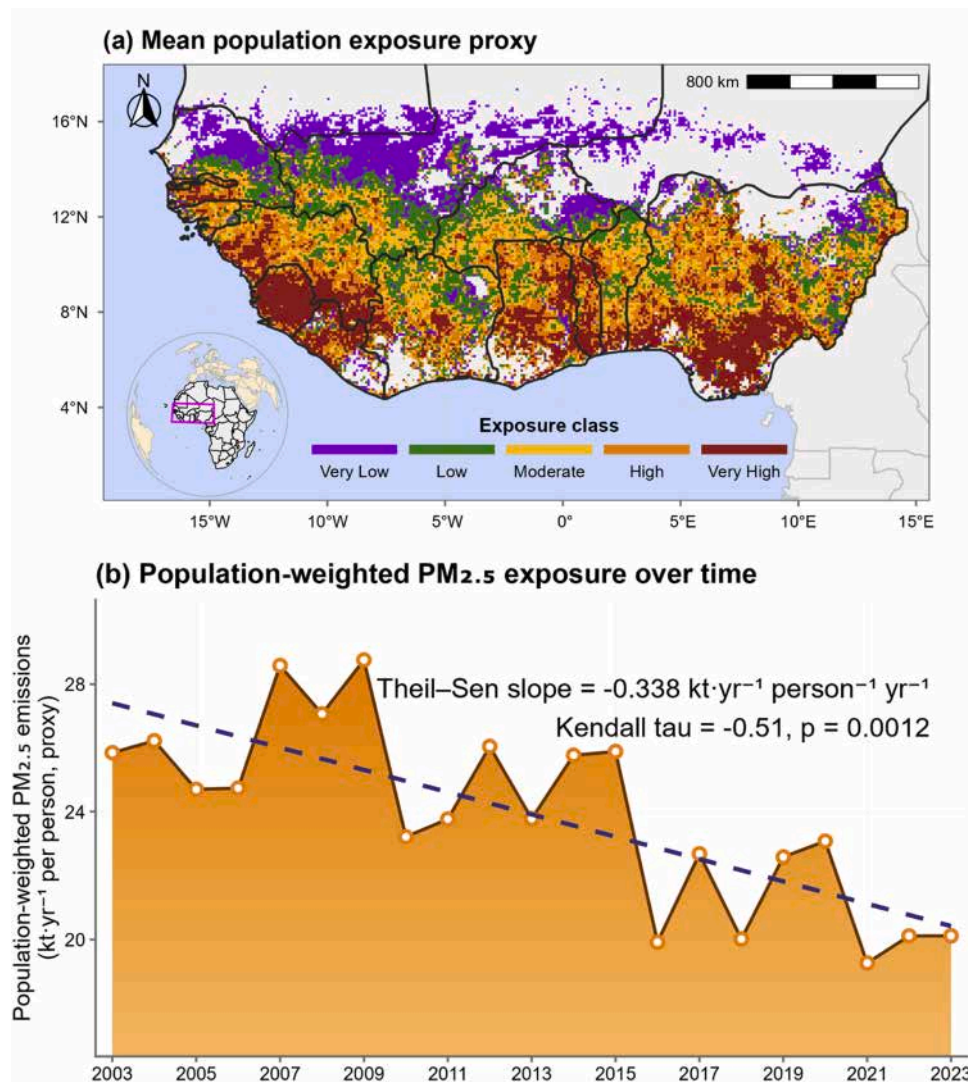


Fig. 7. Population exposure to fire-related PM_{2.5} emissions in West Africa. (a) Mean population exposure proxy for 2002–2023, showing hotspots where high population density overlaps with persistent fire-related PM_{2.5} emissions. (b) Time series of the population-weighted PM_{2.5} mean, showing a clear and significant decrease in the pollution burden experienced by the average resident.

discrepancies have been noted in global fire and Earth system models that rely on fixed emission factors per unit area burned and may therefore underestimate emissions in rapidly changing anthropogenic fire regimes (van der Werf et al., 2017). Such discrepancies also exist from atmospheric inversion carbon emissions (Zheng et al. 2021).

Pixel level trends and the DI distinguish three broad behaviours across West Africa. First, some regions show coherent declines in both BA and emissions, typically in sparsely populated savannas where extensive burning has diminished. Second, many pixels experience strong declines in BA but stable or rising emissions, especially in mosaics of cropland, fallow areas, and *peri* urban vegetation. This behaviour is consistent with a growing contribution of fire types associated with higher PM_{2.5} emission intensities per unit area burned, such as agricultural residue burning and mixed anthropogenic fuels in cropland, fallow, and *peri*-urban landscapes, as suggested by recent field and inventory studies showing strong dependence of particulate emissions on fuel type and combustion conditions (Yaro et al., 2024; Kapoor et al., 2025). Third, a smaller group of pixels shows limited change in BA but elevated emission intensity, pointing to changes in fuel composition, fire timing, or combustion conditions rather than in fire frequency. (Zheng et al., 2018). Rising emission intensity may reflect changes in fuel composition or combustion conditions, but could also be influenced by

longer-term shifts in biomass availability or structure, for example associated with land-use change or altered productivity. Disentangling these effects would require explicit fuel load or vegetation carbon data, which were beyond the scope of this study. These spatial patterns indicate that West Africa is moving away from a regime in which BA is a reliable proxy for emissions. Instead, fire emissions are increasingly shaped by human land management and climate controls, a trend consistent with findings from other fire prone regions undergoing rapid land use transformation (Archibald et al., 2013; Boer et al., 2020).

Drivers of decoupling between burned area and emissions

The decoupling analysis shows that BA and emissions are evolving independently in several parts of West Africa. Approximately seven percent of all pixels fall into strict or lenient decoupling categories, and these areas contain an estimated 551 000 people based on the average population from 2015 to 2023. Although this represents a minority of the total grid, it highlights a substantial number of residents living in landscapes where BA declines but emissions do not.

Several plausible processes, rather than directly verified mechanisms, may contribute to this pattern. Land-use change has altered both the spatial structure and the role of fire in many landscapes.

Fragmentation of savanna vegetation, expansion of cropland and fallow land, increased extraction of woody fuels, and suppression of extensive rangeland fires tend to reduce total BA, while increasing the relative contribution of fire types associated with higher emission intensities per unit area. These include agricultural residue burning, charcoal production, roadside vegetation clearing, and the open burning of household and municipal solid waste at formal or informal dumpsites. Such fire types are commonly associated with denser or more heterogeneous fuels and combustion conditions that yield higher particulate emissions per unit area, as documented in recent emission-factor and inventory studies (Wu et al., 2020; Wiedinmyer et al., 2023; Touré et al., 2025). Observed trends in this study are consistent with patterns reported in other regions undergoing agricultural intensification and rapid land-use change, including East Africa and parts of South America (Archibald, 2016; Bowring et al., 2024). A second mechanism relates to shifts in fire timing and fuel composition. Areas with declining BA but rising emissions often lie within forest savanna mosaics and *peri* urban landscapes where crop residues, woody debris and mixed fuels account for a larger share of burned material. These shifts modify combustion completeness and emission factors. Earth system models that rely on fixed emission factors generally assume a stable fuel composition and may therefore underestimate emissions in such settings (Wiedinmyer et al., 2023; Travis et al., 2023).

A third mechanism involves climate modulation. Warmer and drier years are associated with higher emissions in many semi-arid areas, even when BA declines. This relationship is consistent with more efficient and/or more emissive combustion conditions during warmer and drier years, which can amplify particulate production per unit BA, although combustion efficiency is not directly quantified here. The influence of temperature and precipitation on emission dynamics has been documented in other fire prone regions where climate variability affects both fire intensity and fuel dryness (Zheng et al., 2021; Senande-Rivera et al., 2022).

Taken together, these patterns suggest that decoupling may represent a structural feature of the evolving fire regime in West Africa. The observed spatial coherence is consistent with the influence of in land use change, fuel composition and climate modulation, although alternative explanations (inventory uncertainty and observational limitations) cannot be fully excluded. In such settings, BA is no longer a sufficient metric for characterising fire emissions or their impacts.

Although uncertainty in emission factors may affect the magnitude of estimated trends, it is unlikely to fully explain the spatial coherence of decoupling patterns observed across multiple countries and ecological zones.

Climatic controls and potential feedback

Climate conditions influence both fire occurrence and emission intensity. The analysis shows consistent warming across the region, with median trends around plus 0.15 °C per decade, while precipitation trends are weaker and spatially heterogeneous. This magnitude of warming is consistent with regional climate assessments for West Africa, which report comparable observed warming rates over recent decades and project continued temperature increases under future climate scenarios (Sylla et al., 2016). Despite these modest long-term changes, the correlation analysis reveals clear relationships between emissions and climate variability. PM_{2.5} emissions are positively associated with temperature in several countries and negatively associated with precipitation in semi-arid areas. This implies that year to year fluctuations in climate influence combustion conditions more strongly than they influence total BA.

Strong positive correlations between temperature and emissions occur in the eastern Sudanian zone and in parts of the coastal and peri-urban regions, whereas negative correlations between precipitation and emissions appear in the Sahel and northern Sudanian areas (Hantson et al., 2017). These spatial patterns are consistent with the

strong role of fire regimes and fire-season timing in West Africa, where most burning is anthropogenic and tightly linked to agricultural calendars and dry-season progression (Laris et al., 2021). In these regions, precipitation influences fire activity primarily through lagged and seasonal effects on fuel growth, curing, and the onset and duration of the dry season, rather than through contemporaneous annual totals.

Differences in the timing of burning within the dry season, for example early-season versus late-season fires, can substantially affect emission characteristics, as fuel moisture, fuel continuity, and fire behaviour evolve over the course of the season. Shifts in land use and agricultural practices, including the expansion of cash crops such as cashew, may further modify burning calendars by delaying or concentrating fire use to reduce risks to harvests. While warmer conditions are associated with higher emissions in several regions, the present analysis does not resolve changes in combustion efficiency or fire intensity directly. Instead, the observed climate–emission relationships likely reflect changes in fire timing, fuel condition, and fire regimes, which can sustain or enhance emissions even where BA declines. Assessing these mechanisms explicitly would require seasonal fire metrics and lagged climate analyses beyond the scope of this study.

Persistent fire emissions have important implications for regional air quality, particularly through atmospheric transport. In addition to local sources, aerosols from fires in Central and Southern Africa can be advected into West Africa, and dry-season circulation patterns such as the Harmattan further transport fire-related particulate matter toward densely populated coastal and urban areas (Akinyoola et al., 2019; Pante et al., 2021). As a result, fire emissions can contribute to elevated PM_{2.5} levels far from source regions, compounding air-quality challenges in rapidly growing cities.

Our source-oriented results are broadly consistent with studies based on atmospheric observations and chemical transport models. For example, atmospheric modelling and observational studies have demonstrated that smoke impacts on PM_{2.5} depend heavily on emission intensity, fuel characteristics, combustion conditions, long-range transport, and meteorological processes rather than on BA alone (Jaffe et al., 2020). Regional air-quality analyses have also shown that local and transported biomass burning emissions can be a dominant source of ambient PM_{2.5} and that their influence varies with atmospheric dynamics and secondary formation processes (Hu et al., 2024). While the present study does not simulate transport or atmospheric chemistry and therefore cannot be compared directly to concentration-based estimates, it complements these studies by diagnosing where and when the emission source term is becoming less coupled to BA, thereby helping to explain why air-quality outcomes may not track BA trends.

Population growth, exposure amplification, and environmental equity

The exposure analysis shows that population growth is a central mediator of changing fire-related particulate impacts (Seydi et al., 2025). Although regional mean per capita exposure has declined over time, total exposure has increased in most countries because rapid demographic expansion amplifies even modest or stable emissions. Recognizing the difference between per capita and total exposure is essential for understanding how fire-related risks evolve. While this proxy does not represent ambient concentrations, it is well suited for diagnosing how demographic growth amplifies the potential exposure burden associated with persistent fire emissions.

These trends raise important environmental equity concerns. Communities most affected by fire emissions often live in rapidly expanding peri-urban areas or agricultural mosaics where fire management capacity and air-quality monitoring are limited (Haslett et al., 2019; Deroubaix et al., 2019). From a public health and environmental justice perspective, the observed patterns are concerning. Populations living near or downwind of persistent fire sources, frequently in informal settlements or fast-growing peri-urban zones, experience elevated exposure without necessarily benefiting from the activities that drive

these burns. This exposure is mediated by atmospheric transport and accumulation of fire-related pollutants, which shape local and regional air quality and can extend impacts well beyond the immediate vicinity of emission sources. At the same time, national reporting that focuses on aggregate BA or total emissions can give the impression of progress and obscure the disproportionate exposure borne by low-income households and rural-to-urban migrants (Nakweya, 2022; Pisoni et al., 2022).

Together, these findings indicate that reductions in BA alone are insufficient to decrease the health burden of fire-related particulate matter. Effective mitigation requires interventions that address emission intensity, fire type and population distribution.

The country archetypes developed through the joint analysis of BA, emissions and exposure provide a practical framework for policy planning. Burkina Faso and Mali show strong reductions in BA but relatively persistent emissions and rising exposure, suggesting that climate change and demographic growth offset the benefits of reduced burning. Ghana and Nigeria combine stable or increasing BA with strong growth in emissions and exposure, particularly in densely populated regions, which highlights the need to regulate agricultural residue burning and open waste burning. Senegal illustrates a more moderate form of decoupling and may be more responsive to targeted interventions in specific sectors or locations. These archetypes can guide policymakers in determining where fire suppression is needed and where emission intensity and exposure require direct action.

Implications for fire and air quality governance

The decoupling between BA and emissions has direct implications for fire governance. Fire is an integral component of savanna ecosystems in West Africa and is essential for maintaining their structure, functioning, and biodiversity. Historical fire-suppression policies inherited from the colonial period have largely proven ineffective and, in some cases, counterproductive. More recent approaches increasingly recognise the role of managed burning and community-based fire use. At the same time, the results show that declining BA does not necessarily lead to proportional reductions in emissions, particularly where fire activity is increasingly dominated by agricultural and other anthropogenic ignitions. This reinforces conclusions from transport- and observation-based air-quality studies that effective mitigation depends on targeting emission-intensive burning practices and high-exposure corridors, not solely on reducing total BA.

Changes in land use and agricultural systems, including the expansion of cash crops such as cashew, have contributed to shifts in fire practices and, in some areas, to reductions in extensive savanna burning. Effective governance therefore requires moving beyond a sole focus on limiting BA toward strategies that differentiate between ecologically beneficial fires and emission-intensive fire types. This includes greater attention to emission intensity, fuel type, and the location and timing of burning, with particular emphasis on small-scale agricultural burning and open waste burning near settlements and transport corridors.

Institutional fragmentation further constrains effective action. Fire, air quality and climate mitigation are typically handled by separate agencies, and NDCs rarely include explicit or quantitative measures related to open burning or fire-related aerosols (Wright et al., 2023). Integrating climate trends and fire weather information into fire planning, including seasonal forecasts and fire danger ratings, would support decisions on prescribed burning and help avoid periods with high-intensity fire risk, thus contributing to better societal acceptance for implementation of integrated fire management strategies (Menor et al., 2025)

Air quality management frameworks also need to incorporate fire emissions more systematically. BB is often treated as a diffuse background source, yet the hotspots identified here show that fire-related PM_{2.5} is a major contributor to exposure in several densely populated areas (Mylonaki et al., 2024). Including these regions in air quality standards, monitoring networks and early warning systems would

improve public health responses.

From a climate policy perspective, the persistence of emissions despite declining BA indicates that inventories and mitigation scenarios cannot rely on area burned alone. The shift toward more emissive fire types must be accounted for. Global fire emission products offer spatially explicit information that, combined with land use and demographic data, can strengthen NDCs updates and long-term mitigation strategies (van der Werf et al., 2017; Wiedinmyer et al., 2011, 2023). Integrating these data streams can help identify co-benefits across climate mitigation, air quality improvement and health protection.

Limitations and future work

Several limitations should be considered when interpreting these results. BA estimates from the MCD64A1 product remain uncertain in fragmented landscapes, persistently cloudy humid zones and areas with small or understory fires (Giglio et al., 2018; Ramo et al., 2021; Ouattara et al., 2024). Aggregation to a 0.1° grid reduces noise but smooths fine scale variability, particularly near settlements. The annual temporal resolution also prevents assessment of shifts in fire seasonality.

Additional uncertainty arises from FINNV2.5 emission estimates, as discussed in Section 2.3, which rely on global fuel load datasets, emission factors and combustion completeness assumptions that do not fully capture West African vegetation and fuel use patterns (Wiedinmyer et al., 2023; Touré et al., 2025). Emissions from waste burning and other non-vegetation sources are imperfectly represented, which affects absolute values and trend estimates.

The exposure indicator used in this study is source-based and relies on gridded residential population counts, which do not capture short-term population movements, atmospheric transport of pollutants, or chemical transformation processes. In addition, the exposure proxy is source-based and does not account for atmospheric transport, chemical transformation, or deposition processes that redistribute fire-related pollutants and can expose populations far from emission sources. As a result, population exposure may be underestimated in regions affected by the transport of pollution plumes, particularly in downwind areas. The estimated exposure should therefore be interpreted as a first-order indicator of potential exposure rather than a direct measure of ambient concentrations or inhaled dose. Incorporating atmospheric transport modelling and dynamic population data would be required to better quantify downwind exposure and transient population vulnerability.

The statistical approach, based on Theil Sen slopes and Mann Kendall tests, is appropriate for detecting monotonic long-term trends but may not capture non-linear behaviour, step changes or short-lived anomalies linked to policy shifts or extreme events. The decoupling indices, defined from long term slopes, may therefore miss temporary recoupling or brief episodes of intensified emissions.

Finally, land cover change, policy histories and socio-economic indicators were not explicitly included, which limits causal attribution. Future work combining these datasets with the present framework would strengthen inference.

Incorporating fire radiative power and other fire intensity metrics would support a more detailed analysis of combustion conditions. Linking fire trends with land cover change and agricultural statistics would help identify specific practices that drive decoupling. Combining satellite-based emissions with chemical transport modelling (Hu et al., 2024; Mallia et al., 2025) and ground based or low cost PM_{2.5} monitoring (Grosvenor et al., 2024) would provide more direct estimates of exposure and health risk. As the temporal coverage of VIIRS BA and active fire products increases, their higher spatial resolution will enable improved detection of small fires in agricultural and *peri* urban mosaics, allowing more accurate trend assessments.

Conclusion

This study provides a comprehensive assessment of the changing relationship between BA, fire-related PM_{2.5} emissions, climate conditions and population exposure in West Africa from 2002 to 2023. The integration of satellite-based BA products, fire emission estimates, climate reanalysis data and gridded population datasets reveals a complex and evolving fire regime that cannot be characterised by BA alone. These findings reflect spatially heterogeneous and conditional responses across the region rather than a uniform outcome, shaped by differences in land use, climate modulation, and demographic dynamics.

BA has declined across much of the region, particularly in the Sudanian and Sahelian zones, yet emissions have not decreased at the same rate. In several countries and ecological zones, emissions remain stable or increase despite substantial reductions in BA. These findings are consistent with a transition from extensive savanna burning toward more localised agricultural and *peri* urban fires that produce higher particulate emissions per unit BA. This transition appears to be reinforced by climate conditions that are associated with higher emission intensities in warmer and drier years.

The DI confirms this transition by identifying pixels where BA and emissions no longer evolve together. Although decoupling affects about seven percent of the domain, these pixels contain more than 551 000 residents and are concentrated in landscapes undergoing rapid land use change. The climatic and land management factors driving decoupling reflect broader transformations in fire activity across fire prone regions globally. These interpretations are based on statistically diagnosed trend divergence and should be understood as plausible explanations consistent with prior literature, rather than as directly observed causal mechanisms.

Population exposure results show that demographic change strongly influences the environmental and health implications of fire emissions. While per capita exposure declines at the regional scale, total exposure increases in most countries due to rapid population growth in areas where emissions persist. These patterns highlight emerging inequalities in exposure and underscore the need for targeted management strategies.

Overall, the study demonstrates that reductions in BA are not sufficient to achieve proportional reductions in fire-related PM_{2.5} emissions or potential population exposure under current land-use, climatic, and demographic conditions in West Africa. Within the methodological scope of this study, which relies on satellite-derived BA, bottom-up emission inventories, and a source-based exposure proxy, these findings have direct implications for fire and air-quality governance. Effective fire and air quality governance must consider emission intensity, fire type, land use dynamics and the spatial distribution of populations. Incorporating satellite-based emissions, climate information and demographic trends into national fire and air quality strategies can support more realistic mitigation planning and accelerate progress toward climate and health objectives in West Africa.

CRedit authorship contribution statement

Boris Ouattara: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **N'Datchoh Touré:** Writing – review & editing, Writing – original draft, Conceptualization. **Jean Danumah:** Writing – review & editing, Writing – original draft, Visualization. **Tianjia Liu:** Writing – review & editing, Validation. **Florent Mouillot:** Writing – review & editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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