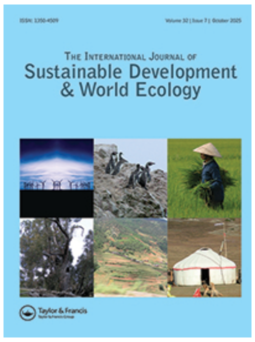

International Journal of Sustainable Development & World Ecology

ISSN: 1350-4509 (Print) 1745-2627 (Online) Journal homepage: www.tandfonline.com/journals/tsdw20

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To cite this article: Md. Emran Hossain, Shamsa Kanwal, Sana Fatima, Abdullah Önden, Mohd Ziaur Rehman & Mohammed Alnour (2025) Monitoring the spatial spillover effects of wildfire carbon emissions and urban settlements on biodiversity loss in sub-Saharan Africa, International Journal of Sustainable Development & World Ecology, 32:7, 757-774, DOI: 10.1080/13504509.2025.2557199

To link to this article: https://doi.org/10.1080/13504509.2025.2557199

INTERNATIONAL JOURNAL OF SUSTAINABLE DEVELOPMENT & WORLD ECOLOGY
2025, VOL. 32, NO. 7, 757–774
https://doi.org/10.1080/13504509.2025.2557199

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Monitoring the spatial spillover effects of wildfire carbon emissions and urban settlements on biodiversity loss in sub-Saharan Africa

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ABSTRACT

Wildfires in Sub-Saharan African (SSA) drylands are major drivers of deforestation, forest degradation, and biodiversity loss, with consequences that often extend beyond national borders. However, the spatial impacts of wildfire-related carbon emissions, burned areas, and urban expansion on biodiversity remain understudied. This research addresses this gap by applying the Spatial Durbin Model (SDM) to annual data from 40 SSA countries spanning 2003–2020. The results indicate significant negative spatial dependence among countries. Domestic carbon emissions from wildfires and the total land area burned both show a strong positive effect on biodiversity loss, though their spillover effects on neighboring countries are negligible. Urban expansion is also found to significantly intensify biodiversity decline. Conversely, non-forested ecosystems exert influence primarily through cross-border spillovers. These findings emphasize that biodiversity threats in SSA are shaped largely by domestic drivers, particularly wildfires and urbanization, while spillover effects play a smaller but selective role. Accordingly, the study recommends prioritizing national conservation strategies that directly address wildfire management and sustainable urban growth to safeguard biodiversity across the region.

ARTICLE HISTORY
Received 24 April 2025
Accepted 1 September 2025

KEYWORDS
Wildfire management; biodiversity conservation; wildfire carbon emissions; African ecosystem; Sub-Saharan Africa

1. Introduction

Wildfires are caused by spontaneous ignition sources, including lightning, volcanic activity, or anthropogenic actions, across diverse ecosystems such as forests, grasslands, and shrublands. The rise in global temperatures and the increase in the frequency and intensity of droughts in recent decades have led to the emergence of favorable circumstances for wildfires (Jolly et al. 2015). In addition, the woodlands have seen recent climate warming and drying, which has caused an escalation in the occurrence, magnitude, strength, and intensity of wildfires (Pausas and Keeley 2021). Over the past several years, Brazil, Australia, and California have had severe wildfire incidents Boer et al. (2020), which have once again captured public and research interest. Wildfires are significant factors in worldwide forest degradation (Huy et al. 2024), making them crucial contributors to both global warming and biodiversity loss (Kelly and Brotons 2017). Therefore, it is crucial to prioritize research efforts in investigating the correlation between wildfires and biodiversity decline.

The primary consequence of wildfires is an increase in carbon emissions from burning organic soil (Walker et al. 2018). However, wildfires also have an indirect impact on biodiversity through their carbon emissions. Studies have not shown the direct impact of carbon emissions from wildfires on biodiversity loss, but rather indirectly address the climatic changes triggered by emissions that lead to devastating impacts on soil biomass (Vestergård et al. 2015). The forest peatland fire damages the biodiversity as the area becomes staggeringly high in pH, humic acid, hydrophobicity, organic matter, etc., due to accumulated ashes. These areas have low water-holding capacity and emit huge amounts of greenhouse gas (GHG), severely affecting biodiversity (Agus et al. 2018). Conversely, carbon emissions resulting from wildfires in one country can have a significant impact on the biodiversity and environment of a neighboring country if they share a border and have forested areas in common. Therefore, it is crucial to analyze the regional spillover effects of carbon emissions caused by wildfires on biodiversity.

Moreover, the burned area is of utmost significance in addressing global mandates aimed at reducing fire emissions, such as the Kyoto Protocol, the Paris Agreement, the United Nations Sendai Framework on Disaster Risk Reduction 2015–2030, and the Sustainable Development Goals (SDGs) (Kganyago

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and Shikwambana 2019). Conversely, the extent of non-forested ecosystems (i.e. terrain devoid of natural or cultivated tree stands that reach a minimum height of five meters, regardless of their productivity, and do not include tree stands inside agricultural production systems) is also associated with biodiversity, as forests are home to a wide variety of species. Non-forested ecosystems primarily occur because of deforestation, which can subsequently lead to a significant decline in biodiversity. For example, Amazon deforestation leads to a decline in biodiversity (Paiva et al. 2020).

Africa, a continent rich in biodiversity, is experiencing rapid urbanization. The urban population is projected to grow more than threefold over 40 years – from 395 million in 2010 to approximately 1.339 billion by 2050—representing about 21% of the world's projected urban population (United Nations 2014). While urbanization offers new economic opportunities, it also imposes significant environmental challenges, including pollution, deforestation, climate change, and the expansion of informal settlements – all of which pose varying degrees of risk to biodiversity (Simkin et al. 2022). Although several in-depth case studies have explored the relationship between urbanization and environmental change, urbanization has generally received limited attention from conservationists as a major driver of biodiversity loss, with a few notable exceptions (Garschagen and Romero-Lankao 2015; Han et al. 2018; Humbal et al. 2023). Considering this, the present study seeks to examine the spatial spillover effects of urbanization on biodiversity loss in the context of SSA.

Wildfires cause substantial ecological and economic damage in countries worldwide, with particularly severe impacts on arid ecosystems. The dryland regions of SSA are no exception. For instance, forest fires, a specific category of wildfires, are accountable for 90% of the continent's deforestation and contribute to 50% of the global carbon emissions caused by fires (van Lierop et al. 2015). The occurrence of fires can be attributed to natural factors such as seasonal changes and high temperatures in arid regions, and it accounts for around 70% of the global burned area (Giglio et al. 2013); however, wildfires in SSA are mostly caused by economic activities (Machete and Dintwe 2023; Oloruntoba et al. 2025). In addition, Africa is responsible for roughly half of the worldwide annual vegetation burned (Machete and Dintwe 2023). Wildfires may temporarily enhance species' richness; however, these species are frequently introduced and non-endemic. Nonetheless, wildfires diminish the quantity and diversity of indigenous species, hence impeding biodiversity. Thus, this study seeks to evaluate the relationship between carbon emissions caused by wildfires and the decline of biodiversity in the SSA region, controlling for other factors such as total area burned, urbanization, and non-forested ecosystems. From the above debate, we derive the following research questions:

(1) How do carbon emissions from wildfires exert spatial spillover effects on biodiversity loss in SSA?
(2) How do urban settlements, land areas burned, and non-forested ecosystems exert spillover impact on biodiversity in SSA?

This work contributes to the current corpus of literature in the following ways: First, this work is the first to examine the spatial spillover impact of carbon emissions from wildfires on biodiversity in the SSA regions, as far as the authors are aware. Second, this study specifically chose the 40 SSA countries that share borders, which is a significant factor in potential spillover effects. Additionally, this region is highly vulnerable to forest fires or wildfires. On the other hand, this region also boasts a diverse range of ecosystems and biodiversity, with various species. Thus, investing in this region would enable policymakers to develop an effective policy to combat wildfires and, consequently, preserve biodiversity. Third, there is a lack of previous research investigating the relationship between urbanization and biodiversity, as well as the relationship between land areas burned and biodiversity. This study aims to fill this research vacuum by examining these relationships in the context of the SSA region. Fourth, certain case studies examine the extent of deforestation in a specific area as a means of assessing biodiversity in a particular ecosystem. In contrast, this study evaluates the spatial spillover impact using suitable economic and spatial spillover modeling, specifically analyzing the direct and indirect effects of all explanatory variables on biodiversity. Finally, we incorporated the Red List Index (RLI) to quantify biodiversity decline, a measure not previously applied in studies of biodiversity loss within the SSA context. The RLI is particularly suitable for quantifying biodiversity loss as it measures trends in the aggregate extinction risk across species groups, based on genuine changes in IUCN Red List categories rather than shifts due to improved knowledge or taxonomy, offering a standardized, sensitive indicator that reflects the impacts of threats like habitat loss and climate change. Its application has been well-established in past studies (Henriques et al. 2020), including global assessments by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Convention on Biological Diversity (CBD) to track progress toward biodiversity targets, as well as national-scale monitoring in countries such as Australia and Finland (IUCN 2025).

2. Literature review

2.1. Theoretical underpinnings

Climate change is a danger to biodiversity worldwide; it can cause extinctions, upset ecological systems, and modify the geographical distribution and quantity of species. Theoretically, the Ecological Resilience Theory highlights the borderline beyond which ecosystems experience irreversible changes attributable to wildfire carbon emissions that contribute to biodiversity loss. The dissemination, prevalence, and interaction of species are directly impacted by drastic shifts in climate, while the composition and functioning of ecological systems are indirectly impacted. These alterations may therefore result in a decline in the diversity of genes within a population, which would lessen such communities' resistance to ecological shocks (Dias 2023). In addition, the Intermediate Disturbance Hypothesis suggests that wildfires can enhance the diversity of species by avoiding the dominance of some specific species that promote habitat heterogeneity (Furnas et al. 2022). Contrarily, habitat destruction by wildfires degrades the adaptive capacity of any ecosystem, destroys habitat, and enhances biodiversity loss (Lagerstrom et al. 2022). While wildfire is found to threaten biodiversity and ecosystems, some studies highlighted different mechanisms through which the land area burned by wildfire can increase biodiversity. According to Puig-Gironès et al. (2023), wildfires can form a mosaic of a variety of habitats, attracting species that develop in post-fire environments, thus increasing habitat heterogeneity and conserving biodiversity.

Moreover, wildfires can limit invasive species that outcompete native ones and allow native flora and fauna to flourish and recover (Carmona-Yáñez et al. 2023). In addition, controlled wildfires reduce the danger of pests affecting the ecosystem, facilitating nutrient cycling by releasing blocked vegetation in soil and creating a nutrient-rich environment for plants and animals (Santos et al. 2023). Furthermore, Ecological Succession Theory states that post-fire environments open up habitat for early successional species that include invasive species that rapidly take over the disturbed areas (Ogwayo 2023). Some species, such as r-selected organisms, thrive in disturbed areas due to their ability to adapt to available resources (Edwards et al. 2021; Peng et al. 2022). Thus, wildfires can increase species richness temporarily, yet they can lead to a negative impact on ecology in the long term (Harrison et al. 2021; Walesiak et al. 2022).

Ecological systems are also destroyed and fragmented because of the conversion of natural habitats into farms, cities, and infrastructure as human populations grow. It also alters population structure, connections, and species distribution, which frequently leads to localized extinction and a decline in species worldwide. The survival of species with wide distributions, tiny populations, and particular habitat needs is negatively impacted by fragments (Carmona-Yáñez et al. 2023; Ogunbode et al. 2024). Therefore, within the postulation of the Ecological Resilience Theory, this study examines the geographical spillover effect of climate change caused by wildfire on biodiversity loss for 40 countries across SSA.

Despite the contrasting theoretical perspectives, there remains an evident lack of consensus in the literature regarding the uniformity of biodiversity responses to wildfire-induced carbon emissions across different ecological contexts and spatial scales. While small-scale or short-term studies often suggest temporary gains in species richness following disturbances, broader-scale or long-term analyses tend to demonstrate an overall decline in biodiversity, particularly within ecologically fragmented landscapes. This inconsistency indicates a significant gap in comparative and integrative assessments across diverse geographic regions and ecosystem types.

2.2. Literature on biodiversity loss and CO_2 emissions from wildfires

There is a scarcity of studies that have been undertaken to investigate the carbon emissions from wildfires and the resulting loss of biodiversity. According to Jerrett et al. (2022), wildfires were the second most important contributor to CO_2 emissions in 2020. However, forests are the hub of carbon storage (Gupta 2019) but are becoming vulnerable due to forest fires, leading to habitat loss, land degradation, and overall biodiversity loss (IPBES, W. 2019). As large forest areas continue to burn globally every year, a compounding amount of GHG is emitted into the atmosphere, leading to an increase in global warming and climate change issues (Dong et al. 2022). In Africa, savanna burning accounts for up to 25% of total carbon emissions from agricultural land combustion and annually contributes up to 40% of carbon dioxide emissions, particularly in West Africa (Bougma et al. 2023). The wild species are not able to adapt to the frequently changing conditions, which result in their habitat loss as well as their increasing proximity towards extinction. Thus, forest fires contribute significantly to environmental degradation and biodiversity loss.

While studies increasingly recognize the link between wildfire-driven carbon emissions and biodiversity loss, they remain geographically fragmented and analytically disconnected. In SSA, savanna burning is widely identified as a major source of CO_2 emissions and biodiversity decline, whereas research on Southeast Asia highlights peatland fires as emitting far greater CO_2 per hectare, posing severe risks to endemic species and fragile ecosystems (Omar et al. 2022). Yet, these contrasting fire regimes and emission intensities have rarely been examined through systematic comparative analysis, leaving spatial variations in their ecological impacts insufficiently explored.

2.3. Literature on biodiversity loss and total land area burned by wildfire

One of the key factors of wildfires due to land-use pressure is a global change that has been single-handedly contributing to major landscape changes around the globe. For example, Zubkova et al. (2019) found that between the years 2002–2016, Africa lost 18.5% of land to burning due to terrestrial moisture increase impacting agricultural practices. In Northern Central Africa, the fire frequency has reduced with a decrease of 2.7–3.2 million hectares between the years 2003–2017 (Jiang et al. 2020). In the Horn of Africa and Madagascar, 1–15% area is burnt every year. However, Guineo-Congolian, Malagasy East, Kalahari-Highveld, Karoo-Namib, and Sahel are the least burnt-protected areas, with less than 1% area burnt every year, which affects the biodiversity (Grégoire et al. 2012).

Regarding the other parts of the world, in the case of Central Chile, which is one of the biodiversity hotspots, commercial pine and eucalyptus are affected due to regular changes in the environmental dynamic coerced by wildfires. The land-use changes tend to destroy the environmental integrity and lead to severe habitat loss. The fragmentation of local plant species is mediated by the joint effects of wildfire and land-use changes, where nearly 39% of the total burnt area has been covered between 1985 and 2020. This gradual and unrestricted burning threatens the last remaining native forest species in Central Chile (Braun et al. 2021). Similarly, in the Latin American forests, the frequency of wildfires and post-fire trajectories was analyzed between the years 2001–2018. It was found that nearly 1.1% of the forests were burnt in 2002–2003, which reached 40.1% in 2018. This caused irreversible forest loss, and ecosystems have become increasingly vulnerable to more devastation (Armenteras et al. 2021).

The reviewed regional studies collectively accentuate the spatial heterogeneity in fire regimes and their ecological consequences. However, a notable limitation across the literature is the insufficient critical analysis of how spatial scale and land-use designation mediate the impacts of fire on biodiversity outcomes. Such dimensions are particularly relevant in the SSA context, where conservation governance and land management practices vary widely. Thus, this study seeks to fill this gap by offering a spatially nuanced assessment of biodiversity loss across SSA, considering wildfire-burned areas.

2.4. Literature on biodiversity loss and urbanization

Urbanization is one of the important reasons for biodiversity loss and habitat degradation. This is one of the reasons why the biodiverse coastal areas have been a prime target of urban expansions over any other ecosystems (Elmqvist et al. 2013). Globally, urbanization is projected to drive significant biodiversity loss between 2015 and 2050 (Simkin et al. 2022). An estimated 30,393 terrestrial vertebrate species could be affected by a 25% reduction in habitat, while up to 855 species – representing 2–3% of those assessed – may face heightened risk with just a 10% loss of habitat. The protected areas are also under threat due to urbanization in tropical regions of SSA. The man-made interference in wildlife has been reflected in the loss of species richness in Africa. It is hence estimated that biodiversity degradation will bring about a 50% loss of birds and mammals in Africa by 2100 (Chapman et al. 2022). The relationship between urbanization and biodiversity levels is not linear, and the studies on the temporal effects of urbanization on biodiversity are sparse (Van Nuland and Whitlow 2014).

It is important to note that the relationship between urban expansion and biodiversity loss is further mediated by the spatial configuration of urban growth. Emerging empirical evidence suggests that low-density, sprawling peri-urban development tends to produce more severe habitat fragmentation compared to compact, high-density urban forms (Ayeni et al. 2025). However, this distinction has not been sufficiently explored in biodiversity literature within the SSA region. This study seeks to contribute to this limited area of inquiry by investigating how urbanization influences adjacent ecological zones and biodiversity outcomes at multiple spatial scales.

2.5. Literature on biodiversity loss and non-forested ecosystems

With the rise in population, the demand for cashew, rubber, cacao, rubber, and coffee has resulted in 7% forest loss in Africa (Masolele et al. 2024). With the rising forest cover loss, the Ivory Coast of Africa has been estimated to have lost 232 animal species, including antelopes, pygmy hippopotamus (4 species), forest bird species (7 species), and crocodile (3 species). Further, the International Union for Conservation of Nature (IUCN) has mentioned 59 endangered species that are under threat in Africa (Singh et al. 2022).

Tropical deforestation has severe impacts on the globally high-profile species that are threatened. Symes et al. (2018) studied the impact of deforestation and wildfire on biodiversity loss in Southeast Asia with 308 forest-dependent bird species. It was found that around 89% of them had already faced 16% of habitat loss, while the extinction rate of regionally endemic species doubled. Similarly, Negret et al. (2021) conducted a study in Colombia to study the impact of deforestation on 550 forest-dependent bird species. It was found that all of them had lost their habitat, while 18% had lost half of their habitat by 2015. Further, it was projected that if these trends in forest loss continue, the loss index will shoot up to 43 by 2040. The threat assessment on the endemic species suggested that 30% of the species will face habitat loss by 2040. Nonetheless, these species are not classified as threatened by IUCN, indicating that several unlisted species are experiencing habitat loss and extinction risks, hence negatively affecting the tropical ecosystem (Singh et al. 2022).

Although non-forested ecosystems such as savannas, wetlands, and grasslands are ecologically valuable – especially in biodiversity-rich regions like SSA – they remain underrepresented in research on fire-induced biodiversity loss. The dominant focus on forests has overlooked the conservation needs and dynamics of these equally vulnerable landscapes. By including non-forested ecosystems in its framework, this study broadens the literature and provides a more comprehensive view of spatial spillover effects on biodiversity.

3. Methodology and data

3.1. Cross-sectional dependence test

Cross-sectional dependence (CSD hereafter) is an issue of panel data. Hao et al. (2021) stated that CSD arises due to shocks and unobserved components in data. Hence, globalization and integration among economies are the reasons for CSD. Therefore, it is crucial to address CSD to avoid biased and inconsistent outcomes. Pesaran (2015) verified the existence of CSD, and the test statistics are defined as:

$$CSD_t = \left[\frac{TN(N-1)}{2}\right]^{1/2} \mathrm{P}_N \tag{1}$$

where 'T' and 'N' show the time period and number of cross-sections, respectively. While ' P_N' is the parameter of pairwise correlation. This study uses second-generation panel data tests such as CSD and Westerlund cointegration, which allow for slope heterogeneity given by Kapetanios et al. (2011). Therefore, the Pesaran CSD method gives unbiased findings. The Levin-Lin-Chu test is used to test the stationarity of panel data. The framework of this test for the unit is as under:

$$\Delta \mathrm{y}_{\mathrm{it}} = (\rho_{\mathrm{i}} - 1)\gamma \mathrm{y}_{\mathrm{it}-1} + \sum_{\mathrm{j}=1}^{\mathrm{P}_{\mathrm{i}}} \gamma_{\mathrm{ij}} \Delta \mathrm{y}_{\mathrm{it}-\mathrm{j}} + \theta_{\mathrm{mi}} \mathrm{c}_{\mathrm{mt}} + \mu_{\mathrm{it}}, \mathrm{m} = 1, 2, 3 \tag{2}$$

Here, c_{mt} is a deterministic component, $\rho = 0$ is composed of a unit root. If $\rho < 0$, then the deterministic term/component, which is 'y', is stationary. Therefore, the null hypothesis of the Levin-Lin-Chu test is indicated as H0: y = 0, while the alternative hypothesis is H1: y < 0. Hence, the Levin-Lin-Chu test permits heterogeneous interceptions across the panels and suggests that all cross-sectional units are homogeneous. Compared to other heterogeneity tests, these tests outperform by ignoring long-term data and small cross-sections.

3.2. Westerlund cointegration

Traditional panel data methods, such as fixed effects, random effects, and instrumental variable estimators, fail to address the CSD issue and instead offer skewed conclusions. So, this study applies Westerlund's (2007) cointegration approach to check the linkages between biodiversity loss and regressors in 40 SSA countries. This test pits the alternative hypothesis – that the variables are cointegrated – against the null hypothesis – that they are not. Kapetanios et al. (2011) claimed that this test gives more reliable outcomes when error terms have CSD. The Westerlund cointegration equation is as under:

$$\alpha i(L)\Delta \mathrm{y}_{\mathrm{it}} = \gamma 1_{\mathrm{it}} + \gamma 2_{\mathrm{it}} + \beta_{\mathrm{i}}\left(\mathrm{y}_{\mathrm{it}} - 1 - \acute{\mathrm{a}}_{\mathrm{i}}\mathrm{x}_{\mathrm{it}}\right) + \gamma_{\mathrm{i}}(\mathrm{L})^{\prime}\mathrm{v}_{\mathrm{it}} + \eta_{\mathrm{i}} \tag{3}$$

where $\delta 1i = \beta i(1)\hat{\vartheta}_{2i} - \beta_i\lambda_{1i} + \beta_i\hat{\vartheta}_{2i}$ and $\gamma_{2i} = -\beta_i\lambda_{2i}$

Now the test statistics are written below:

$$G_t = \frac{1}{N}\sum_{i=1}^{N}\frac{\acute{a}i}{SE(\acute{a}i)} \tag{4}$$

$$G_a = \frac{1}{N}\sum_{i=1}^{N}\frac{T\acute{a}i}{\acute{a}i(1)} \tag{5}$$

$$P_T = \frac{\acute{a}}{SE(\acute{a})} \tag{6}$$

$$P_a = T\acute{a} \tag{7}$$

In Equation 4, $\acute{a}i$ is the cointegration-associated vector between the dependent and independent variables. Ga and Gt denote group means, while Pa and Pt are panel statistics. This test checks the hypothesis of 'no integration' and 'cointegration' among the variables of the study.

3.3. Spatial Durbin model (SDM)

To test the spillover effects, this study employs the partial differential overture to the direct and indirect impacts, which are the most beneficial and unique advantages of spatial analysis (Abban et al. 2023).

The total effect of a variable is the summation of direct and indirect effects. The endogenous variable (dependent variable) is impacted by variations in the explanatory factors, as indicated by the direct impact. Conversely, the indirect impact shows how variations in the external variables of the bordering area affect the socioeconomic outcomes of the focus countries.

Initially, it is vital to specify the spatial weight matrix before any examination for spatial regression. It is an exogenous parameter that measures the degree of spatial dependency among the states *′i′* and *′j′* in the study samples. This study adopts the widely used contiguity spatial weight matrix by assigning weights of 1 to the contiguous units and weights of 0 to non-contiguous units (Wong 2021). For the normal design of the proximity matrix, Queen contiguity is used. It defines neighbors as the units that share a common border or a single common point. W is an adjacent order matrix with n × nspaces.

$$W_{ij} = \begin{cases} 1, \textit{countries } i \wedge \text{j are neighboring countries} \\ 0, \textit{countries } i \wedge \text{j are not neighboring countries} \end{cases} \tag{8}$$

To reflect spatial interactions among the underlying variables, the spatial Durbin model (SDM) is employed. The SDM can be specified as follows:

$$z_{it} = \alpha + \lambda \Sigma_{\mathrm{j}=1} W z_{jt} + \Sigma_{\mathrm{k}} x_{it}^{(k)} \delta_k + \Sigma_{\mathrm{j}=1} W x_{jt}^{(k)} \theta_k + \mu_i + \vartheta_t + \eta_{it}, \tag{9}$$

where θ is a k × 1 vector of parameters to be estimated. η_{it} is the disturbance term.

In the spatial analysis, the spatial autoregressive (SAR) model accounts for the influence of the dependent variable in neighboring countries on the dependent variable of a given unit, whereas the spatial error model (SEM) captures spatial dependence through correlations among the disturbance terms across the units under analysis. In contrast, the SDM offers a more comprehensive specification, incorporating spatial interactions in both dependent and independent variables (Alnour and Kocak 2025; Guo et al. 2025). Furthermore, Kassouri (2021) and Kuşkaya et al. (2025) highlighted that SDM can be robustly estimated using maximum likelihood estimation (MLE) or quasi-maximum likelihood estimation (QMLE), which are particularly effective in addressing estimation inconsistencies arising from the joint presence of spatial interactions, as well as conventional fixed and random effects. Thus, this study utilizes maximum likelihood estimation, which is more widely used in spatial analysis (Kassouri 2021).

3.4. Model specification and data description

This study selected 40 SSA nations based on the data availability spanning from 2003 to 2020. The information regarding the sampled countries can be found in Appendix. To examine the spatial spillover effect of wildfire-based carbon emissions and the land area burned by wildfire (ha) on biodiversity loss, this study constructs the following model:

$$\mathrm{BLS}_{\mathrm{jt}} = \alpha_0 + \alpha_1 \mathrm{NFE}_{\mathrm{jt}} + \alpha_2 \mathrm{WCO}_{2\mathrm{jt}} + \alpha_3 \mathrm{TBW}_{\mathrm{jt}} + \alpha_4 \mathrm{URB}_{\mathrm{jt}} + \varepsilon_{\mathrm{jt}}, \tag{10}$$

Where the corresponding BLS_{jt} is biodiversity loss, $\mathrm{NFE}_{jt}$is non-forested ecosystems, WCO_{2jt} is wildfire carbon emissions, TBW_{jt} is the area burned by wildfire, and URB_{jt} is urbanization in country *′j′* at time *′t′*. α_1, α_2 α_3 α_4 are the parameters to be estimated while ε_{jt} indicates the stochastic error term. Following Henriques et al. (2020), this study uses the Red List Index (RLI) as a proxy for biodiversity loss. RLI is a quantifiable measure used for the extinction of the risk of a species. RLI shows patterns in the total survival risk for species groupings and serves as a surrogate for the loss of biodiversity. It is an index ranging from 0 to 1. Where 1 depicts that none of the species involved are now at risk of extinction. Conversely, a score of 0 would indicate the extinction of every species listed. The extinction risk estimates for mammals, birds, cycads, amphibians, and corals are used to calculate the RLI. It is computed by weighting the fraction of each species' distribution occurring within them.

Non-forested ecosystem is another critical factor in determining biodiversity loss, as forests are the most biodiverse ecosystems (Wani and Sahoo 2021). If forest cover is reduced due to logging or deforestation, it directly affects the species living there, which is their habitat. Hence, this loss leads to habitat defragmentation and reduces the size of the ecosystem where diverse species thrive (Mackey et al. 2020).

Wildfire carbon emissions and areas burned by wildfires have complex impacts on forest ecology, such as changes in vegetation, climate change, and loss of biodiversity (Gajendiran et al. 2024). Wildfires change climate patterns and contribute to global warming by destroying vast portions of forests (Ansari et al. 2024). On the contrary, wildfires can increase seed production and positively influence ecological communities and species. Fires can destroy animals' food, jeopardizing the food chain of herbivores (Gajendiran et al. 2024). Hence, many species migrate or penetrate human living areas to fulfill their food needs and act as a major hazard to human lives (Singh 2022). Figure 1 further plots the spatial ranking of sampled countries in wildfire carbon emissions.

Urbanization is a major driver of biodiversity loss (Ayeni et al. 2023). Urbanization (URB) is a spatial and demographic process that involves land use for shelter, industrialization, and commercial purposes. These processes are dependent on certain push and

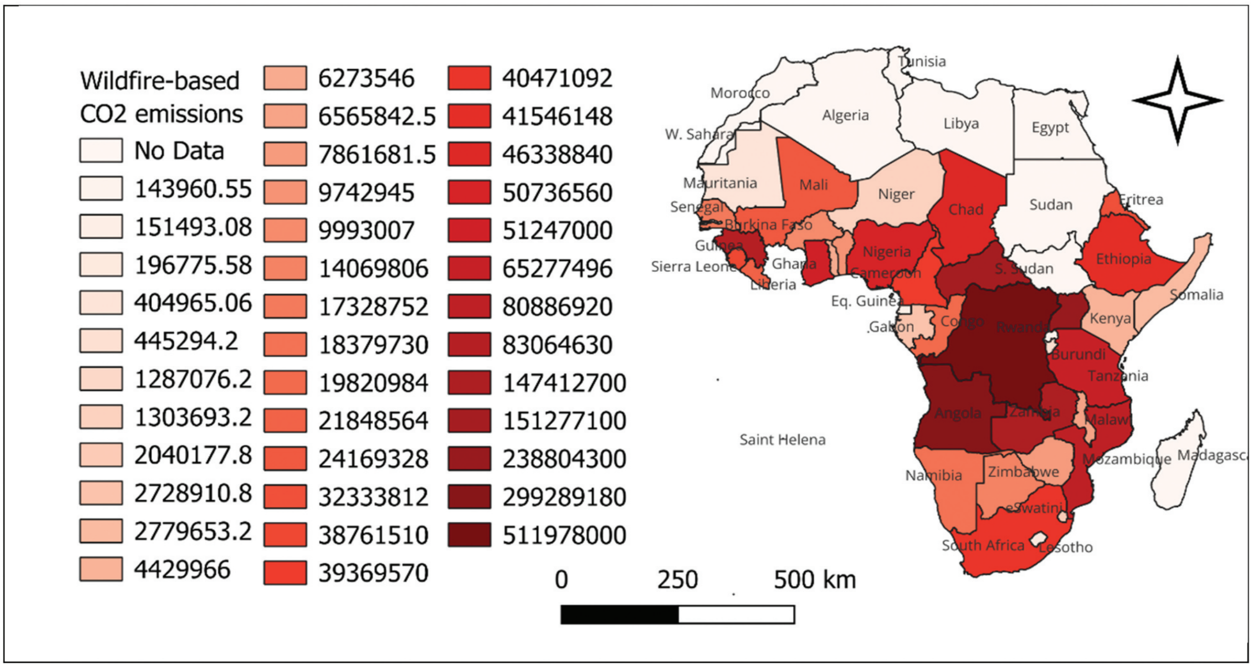

Figure 1. A choropleth map with a gradient color scheme showing the ranking of countries based on carbon emissions from wildfires (in tons).

Table 1. Data description.

Variables	Definition	Sources
Biodiversity loss (BLS)	Red List Index (Biodiversity loss). It shows trends in overall extinction risk for groups of species. It is an index between 0 and 1. A value of 1 indicates that there is no current extinction risk to any of the included species. A value of 0 would mean that all included species are extinct. Note: Extinction risk estimates for mammals, birds, cycads, amphibians, and corals are used to calculate the Red List Index.	BirdLife International and IUCN – processed by Our World in Data. Retrieved from https://unstats.un.org/sdgs/dataportal/database.
Non-forested ecosystems (NFE)	Share of land area which has no forest coverage (%).	UN Food and Agriculture Organization (FAO). Forest Resources Assessment 2020. Retrieved from https://fra-data.fao.org/.
CO_2 from wildfire (WCO_2)	Carbon dioxide released by wildfires in tonnes.	Global Wildfire Information System (2024). Retrieved from https://ourworldindata.org/wildfires.
area burnt under wildfire (TBW)	Total area of forests, savannas, shrublands/grasslands, croplands, and other land that have been burned as a result of wildfires each year. (ha).	Global Wildfire Information System (2024). Retrieved from https://ourworldindata.org/wildfires.
Urbanization (URB)	Share of population living in urban areas (%)	The World Bank (World Development Indicators)

pull factors (benefits) such as resource abundance, social benefits, educational facilities, changes in living standards, and psychological factors. Hence, these benefits are associated with significant environmental costs and biodiversity loss (Li et al. 2022, 2024; Ogunbode et al. 2024). Therefore, following Ayeni et al. (2023) and Li et al. (2024), this study uses URB as a determining factor of biodiversity loss. Table 1 provides the definitions, measurements, and data sources for all variables. The data are freely accessible and require no preprocessing; however, in this research, all variables have been transformed into natural logarithms to ensure consistency in measurement units.

4. Results and discussion

4.1. Main results

Initially, we set off the analysis by highlighting some important descriptive statistics. Table 2 reports dispersion and central tendency measures. Accordingly, the total land area burned by wildfire (ha) demonstrates the highest average of 5,693,662 (ha) with a standard deviation of 9,059,372 during the period 2003–2020. In the same period, the share of non-forested ecosystems (%) has shown a considerable increase, with an average of 67.78 and a standard deviation of 25.16. The biodiversity index demonstrated a relatively slight change from 0.69 to 0.99 with an average of 0.89 and a standard deviation

Table 2. Descriptive statistics.

Variable	Obs.	Mean	Std. Dev.	Min.	Max.
Biodiversity loss (BLS)	720	0.8886	0.067048	0.69	0.99
Non-forested ecosystems (NFE)	720	67.780	25.16248	7.646	99.75
CO_2 from wildfire (WCO_2)	720	6.46e+08	1.20e+08	5388	7.23e+08
Area burnt under wildfire (TBW)	720	569366	9059372	0.000	4.08e+06
Urbanization (URB)	720	40.369	17.55704	8.908	90.09

Table 3. Levin-Lin-Chu unit root test with CSD.

	Level		1st Difference	
Variables	Statistic	p-value	Statistic	p-value
Biodiversity loss (BLS)	−1.1871	0.9994	−17.9412*	0.0000
Non-forested ecosystems (NFE)	−0.0821	0.4644	−7.4816*	0.0122
CO_2 from wildfire (WCO_2)	−8.9832*	0.0213	−29.9750*	0.0000
Area burnt under wildfire (TBW)	−12.1400*	0.0001	−29.6260*	0.0000
Urbanization (URB)	−9.2087*	0.0000	10.5759*	0.0021

under the null hypothesis of no stationarity, *, indicates a 1% level of significance.

of 0.07. Similarly, wildfire carbon emissions (WCO_2) have shown little change, opposite to urban expansion, which increased from 8.91% to 90.09% during the study period. As an important prerequisite, this study utilized the Levin-Lin-Chu unit root test with cross-sectional dependence (CSD) to test for the stationarity of the proposed variables. Table 3 reveals a mixed output since some variables are stationary at the level, while others are stationary at the first difference. To unveil the long-run relationship among the underlying variables, this study used the Westerlund cointegration test. Table 4 indicates that there is strong evidence of cointegration among the variables of interest in the long term at a 1% level of significance.

The Spatial Durbin regression (SDM) model results are divided into spatial direct, indirect effects, and total effects. The total effect is the sum of direct and indirect effects, while the direct effect is the effect of the focused variable on the outcome variable in a certain area or region. Whereas the indirect effect gives the impact of the independent variables of nearby areas on the outcome variable in the local area (spillover effect). Figures A1–A5 in the appendix show the spatial distribution of the underlying variables using the latest cross-section data for 2020.

From Table 5 (main results), we find a heterogeneous effect of carbon dioxide emissions from wildfires (WCO_2) and land area burned by wildfire (TBW) on biodiversity loss (BLS). WCO_2 emissions exert a negative impact on the Red List Index (increasing biodiversity loss), while TBW decreases BLS. For every 1% rise in $WCO_{2,}$ there is a rise in BLS, highlighting the detrimental effects of changes in species construction, habitat destruction, and climate change (Senande-Rivera et al. 2022). These findings align with the ecological resilience theory that highlights the borderline beyond which ecosystems experience irreversible changes attributable to WCO_2 emissions that contribute to BLS (Dias 2023). On the contrary, the empirical results reveal that TBW declines BLS.

Table 4. Westerlund cointegration test.

Statistic	Value	Z-value	P-value
Gt	−2.889	5.599	0.000*
Ga	−0.349	8.476	1.000
Pt	−3.245	5.51	1.000
Pa	−0.363	4.975	1.000

In addition, we find spatial rho, which describes the geographical spillover effects of BLS. The results indicate a substantial adverse geographical correlation among the SSA countries that were sampled (Spatial rho = −0.404***) (Table 5). It captures the degree of spatial autocorrelation present in the dependent variable. In essence, it measures how much the value of the dependent variable in one location is influenced by the values of the same variable in neighboring locations. Our rho result demonstrates that the decline in biodiversity in neighboring SSA nations has an adverse effect on the biodiversity of the home nation, emphasizing a significant spillover impact. One possible explanation for the spatial spillover effect of BLS is migration among SSA countries. Any form of migration, either cross-border or internal, from the areas with biodiversity crises will aggravate resource insecurities in neighboring nations due to increased demand for depleted resources and poor environmental standards in SSA countries. Baltagi et al. (2016) argue that the coefficients of the SDM model cannot give marginal effects of independent variables adequately. Hence, to examine the spatial spillover effect, direct and indirect effects need to be estimated.

Results of the direct effect for WCO_2 and TBW are consistent with the main findings. Wildfire and its emissions have a substantial influence on African biodiversity loss. The results show that local carbon emissions from wildfires have a significant negative impact on the Red List Index (increase in biodiversity loss). For every one percent increase in domestic carbon, caused by wildfire, leads to a decline in biodiversity by 3.88E−11%. The spillover has no reliable impact on biodiversity loss. The minimal elasticity may reflect the temporal scope of the data, which extends only to 2020, before the extreme heatwaves and prolonged droughts that have recently intensified wildfire severity. In much of SSA, particularly in savanna-dominated ecosystems such as Namibia and Botswana, pre-2020 wildfires were largely seasonal and tied to management practices like periodic burning (Nieman et al. 2021). These fires were typically lower in intensity and spatially contained, resulting in less impact on biodiversity loss compared to the megafires observed in subsequent years.

Table 5. Results of the spatial Durbin regression analysis.

Red List Index (Biodiversity loss (BLS))	Coef.	Std. Err.	z	P>z	[95% Conf.	Interval]
Main						
Non-forested ecosystems (NFE)	1.82E–05	0.000233	0.08	0.938	–0.00044	0.000475
CO_2 from wildfire (WCO_2)	–3.42E–11	1.73E–11	–1.98	0.048**	–6.81E–11	–3.39E–13
Area burnt under wildfire (TBW)	5.19E–10	2.25E–10	2.31	0.021**	7.84E–11	9.59E–10
Urbanization (URB)	–0.00016	0.000122	–1.35	0.178	–0.0004	7.45E–05
_cons	1.197837	0.056264	21.29	0.000*	1.087562	1.308112
W(x)						
W(Non-forested ecosystems) (NFE)	0.002262	0.000402	5.63	0.000*	0.001474	0.003049
W(CO_2 from wildfire) (WCO_2)	2.66E–11	3.04E–11	0.88	0.381	–3.29E–11	8.62E–11
W(Area burnt under wildfire) (TBW)	5.38E–11	4.06E–10	0.13	0.895	–7.41E–10	8.49E–10
W(Urbanization) (URB)	–0.00229	0.000209	–10.98	0.000*	–0.0027	–0.00188
Spatial rho	–0.40404	0.055973	–7.22	0.000*	–0.51374	–0.29433
Variance						
lgt_theta	–4.18516	0.133242	–31.41	0.000*	–4.44631	–3.92402
sigma^{2}_e	3.41E–05	1.92E–06	17.82	0.000*	3.04E–05	3.79E–05
Direct effect						
Non-forested ecosystems (NFE)	–0.00019	0.000249	–0.77	0.438	–0.00068	0.000296
CO_2 from wildfire (WCO_2)	–3.88E–11	1.79E–11	–2.17	0.03**	–7.39E–11	–3.74E–12
Area burnt under wildfire (TBW)	5.60E–10	2.32E–10	2.41	0.016*	1.05E–10	1.02E–09
Urbanization (URB)	5.24E–05	0.000137	0.38	0.702	–0.00022	0.000321
Indirect effect (spillover effect)						
Non-forested ecosystems (NFE)	0.001834	0.000337	5.44	0.000*	0.001173	0.002495
CO_2 from wildfire (WCO_2)	3.31E–11	2.65E–11	1.25	0.211	–1.88E–11	8.49E–11
Area burnt under wildfire (TBW)	–1.45E–10	3.21E–10	–0.45	0.652	–7.74E–10	4.84E–10
Urbanization (URB)	–0.0018	0.000177	–10.21	0.000*	–0.00215	–0.00146
Total effect						
Non-forested ecosystems (NFE)	0.001641	0.000317	5.18	0.000*	0.00102	0.002261
CO_2 from wildfire (WCO_2)	–5.76E–12	2.39E–11	–0.24	0.81	–5.27E–11	4.12E–11
Area burnt under wildfire (TBW)	4.16E–10	2.93E–10	1.42	0.157	–1.60E–10	9.91E–10
Urbanization (URB)	–0.00175	0.000128	–13.68	0.000*	–0.002	–0.0015

The results further indicate that total land areas burned by wildfire (ha) at home have a significant positive impact on biodiversity. On the contrary, results of indirect effects report that a non-forested ecosystem (NFE) significantly reduces biodiversity loss (positive effect on the Red List Index). Every 1% increase in NFE leads to a 0.00164% upsurge in the Red List Index (decline in biodiversity loss). However, the increasing effect of non-forested ecosystems on biodiversity comes only from the neighboring countries. A 1% increase in the spillover effect of NFE upsurges biodiversity domestically by 0.001834%. Results indicate that an increase in the share of the population living in urban areas significantly increases biodiversity loss. Expanding urbanization (URB) by 1% leads to a 0.00175% increase in biodiversity loss. Only the spillover effect of urbanization on neighboring countries has a significant negative impact on biodiversity (−0.0018%). The local urban expansion has no power to explain the variation in biodiversity loss. This implies that domestic urbanization is not a significant driver of biodiversity loss.

As a robustness check, we employed a pooled OLS estimator to validate the consistency of our findings (Table 6). The results show that the direction of the coefficients is consistent with the total effects identified in the spatial models, reinforcing the reliability of our primary estimations. Although pooled OLS does not account for spatial dependence and may overlook country-specific heterogeneity, the alignment in coefficient signs provides additional confidence that our main results are not model-specific but remain stable across alternative estimation techniques.

5. Discussion

Biodiversity loss (BLS) is a major global threat, and Africa is no exception to it. Although Africa is rich in biodiversity, African countries are now facing insurmountable problems with biodiversity these days (Sintayehu 2018). This study covers many factors affecting BLS in SSA countries to have an in-depth understanding, in contrast to existing studies in this area (Symes et al. 2018; Jerrett et al. 2022). Therefore, understanding the spatial impact of wildfire carbon emissions, urbanization, and wildfire area burnt on

Table 6. Pooled OLS estimator.

Red List Index (Biodiversity loss (BLS))	Coef.	Std. Err.	t	P > t	[95% Conf.	Interval]
Non-forested ecosystems (NFE)	0.00060	0.000114	5.35	0.000	0.000385	0.00083
CO_2 from wildfire (WCO_2)	−1.83E−11	5.92E−11	−0.31	0.757	−1.35E−10	9.79E−11
Area burnt under wildfire (TBW)	3.50E−10	7.87E−10	0.45	0.656	−1.20E−09	1.90E−09
Urbanization (URB)	0.00107	0.000155	6.93	0.000	0.000772	0.001382
Constant	0.80321	0.012672	63.38	0.000	0.77833	0.82809

BLS in SSA countries is a vast area of research that seeks sustainable methods to manage its ecological system.

Results demonstrate that the non-forested ecosystem (NFE) has a significant positive indirect and total spillover effect on BLS. So, evidence displays a strong effect of neighboring spillover effects, suggesting that the neighboring country's NFE leads to biodiversity conservation in the local country that impacts adjacent ecosystems in the local nation of Africa. Ecologically, due to the transboundary nature of species habitat, and non-forested ecosystems often extend across borders in SSA, for example, the Serengeti-Mara ecosystem is shared by Tanzania and Kenya. Similarly, these ecosystems provide critical habitat for migrating wild animals and bird species that have to migrate. When these habitats degrade in one country through overgrazing, land conservation, and resource extraction, the ecological consequences migrate to neighboring nations, which fragments wildlife corridors and reduces genetic diversity. Furthermore, if one country maintains and preserves its NFE, it creates a contiguous habitat that benefits wildlife in neighboring units, promoting BLS stability. Arroyo-Rodríguez et al. (2020) argue that forests are beneficial for biological communities and are positively related to attracting different taxa of species. Furthermore, forests mitigate the negative effects of disasters and buffer climate change, help regulate water cycles, and avoid soil erosion, which affects cross-border BLS (Piczak et al. 2023; Tari et al. 2024).

Wildfires are often unplanned and similarly uncontrolled. Contingent on severity, wildfires have a significant impact on ecosystems and biodiversity (Mastachi-Loza et al. 2024). Findings of land area burned by wildfire (TBW) demonstrate a positive direct spillover impact on BLS. The ecosystems prone to natural wildfires play a vital role in maintaining savannas (Cassidy et al. 2022). TBW also creates varied habitats in boreal forests that provide sustenance to several species that thrive after fires. So, the particular pyro diversity is strongly predicted to influence spatial patterns of biodiversity in such areas (Puig-Gironès et al. 2023). Some SSA ecosystems, such as savannas, grasslands, and certain woodland mosaics, are fire-adapted and have evolved under frequent yet low-intensity burning. Hence, periodic fires in these landscapes prevent woody plant encroachment, maintain open habitat, and promote a mosaic of vegetation patches at succession stages that support higher diversity of plant and animal species (Huntley 2023). For instance, the Okavango Delta in Botswana and the savanna in Namibia maintain grazing quality and sustained herbivore population through these periodic fires that indirectly support predator species and overall ecosystem function (Grobler 2023). Therefore, in such ecosystems, increased fire-burning areas help reduce the accumulation of combustible material and lower the risk of catastrophic high-intensity fires that cause extensive habitat loss and wildlife mortality, as observed in some areas of Zambia and Tanzania. Pausas and Keeley (2019) confirm the notion by stating that wildfires are natural processes that are beneficial for humans and biodiversity conservation. On the contrary, these wildfires are greatly connected with extreme pollution by releasing carbon emissions into the atmosphere (Singh 2022). This causes a change in the habitat of species and reduces their survival, which increases the risk of BLS (Driscoll et al. 2021).

Results of carbon dioxide emissions from wildfires (WCO_2) establish a negative direct spillover impact on BLS. It shows that WCO_2 primarily affects BLS through local ecological stress rather than regional spillovers. Wildfires release a significant amount of carbon dioxide, contributing to increased greenhouse gas emissions and accelerating climatic changes by altering temperature from low to high, changing precipitation patterns, and prolonged droughts (Pausas and Keeley 2021). Hence, these changes directly impair the psychological resilience of species and their reproductive capacity, particularly in non-forested sensitive ecosystems (savannas and shrublands).

Results demonstrate a positive spillover effect of urbanization on biodiversity loss (negative Red List Index). We find a significant indirect effect of URB on BLS in Africa and a significantly negative total effect on BLS. The indirect effect demonstrates that living around highly urbanized nations increases the local BLS (Simkin et al. 2022). However, the spillover effect of URB in all neighboring nations is greater than the direct spillover effects, as they show no impact on BLS. This implies that the local URB might not be a driver of BLS. In the SSA region, most urban expansion is concentrated in a few economic hubs such as Nairobi, Lagos, etc., rather than an even distribution across the region (Forget et al. 2021). Therefore, the direct effect of URB does not exert any strong pressure on BLS, especially when urban development occurs in already degraded areas. Moreover, evidence shows a strong effect of neighboring spillover effects, suggesting that URB leads to habitat loss and deforestation that impacts adjacent ecosystems (Kassouri 2021; Ortiz et al. 2021). Similarly, migration to urban areas puts pressure on natural resources in adjacent areas, leading to their biodiversity loss. Besides, pollution and emissions from neighboring countries can easily cross borders, damaging habitats and disturbing wildlife (McDonald et al. 2020; Ayeni et al. 2023; Ren et al. 2023). Intuitively, the cross-border spillover effect is mainly due to land-use decisions in neighboring countries, habitat fragmentation, transboundary resource extraction, and pollution in shared water bodies. Urban growth in one country can indirectly affect land-use decisions in borderland ecosystems such as

Guinean forests, Zambezian woodlands (Assede et al. 2023). Similarly, expansion in urban infrastructure fragments contiguous habitat across borders that disrupts wildlife corridors and increases species vulnerability (Ayeni et al. 2023). Additionally, cross-border wildlife trade and transboundary resource extraction to meet demand for timber, fuelwood, and agricultural commodities deplete local resources with increasing pressure on forests, wetlands, and savannas, which accelerates BLS. This argument is in line with Rathod et al. (2024), stating that transboundary pollutants are a major cause of environmental contamination.

6. Conclusion and policy recommendations

6.1. Conclusion

Due to the vast expanse of drylands in the SSA regions, wildfires pose a significant threat to biodiversity protection in this area. In this work, we investigate the spatial spillover effect of carbon emissions from wildfires, the area burned by wildfires, urbanization, and the non-forested ecosystem on biodiversity loss in countries in SSA countries from 2003 to 2020 using the spatial Durbin model.

The findings indicated that the CO_2 emissions from wildfires have a detrimental effect on biodiversity, leading to an increase in biodiversity loss. Remarkably, the total land area burned resulted in a reduction in biodiversity decline. Nevertheless, the findings revealed a significant negative geographical correlation among the countries in the SSA region. Therefore, it is crucial to investigate the spatial impact in this area. This analysis demonstrated that the decrease in biodiversity in neighboring SSA countries has a detrimental effect on the biodiversity of the home country. Regarding the direct and indirect (spillover) impact, this study discovered varying results. The findings indicated that local carbon emissions resulting from wildfires have a substantial adverse effect on the rise in biodiversity loss. The spillover has no reliable impact on biodiversity loss. The findings additionally demonstrated that the extent of land area affected by wildfire (measured in hectares) in the home country had a notable and favorable influence on biodiversity. On the contrary, results of indirect effects report that non-forested ecosystem significantly declines in biodiversity loss. However, the increasing effect of non-forested ecosystems on biodiversity comes only from the neighboring countries. Ultimately, the findings demonstrated that a rise in the proportion of individuals residing in urban areas has a substantial impact on the loss of biodiversity. The only significant detrimental impact on biodiversity resulting from urbanization is the spillover effect on adjacent countries. The local urban expansion has no power to explain the variation in biodiversity loss.

6.2. Policy implications

The spatial spillover effects of wildfire carbon emissions and urban settlement expansion on biodiversity loss in SSA highlight the need for integrated, regionally coordinated policy responses. These impacts are not confined within national borders and therefore require cross-boundary solutions that reflect ecological interconnections and governance realities across the region.

First, carbon sequestration should be embedded within national climate mitigation strategies and supported through regional cooperation, particularly in ecologically sensitive and transboundary ecosystems such as the Congo Basin. Regional institutions like the Central Africa Forests Commission (COMIFAC) must play a leading role in coordinating forest conservation, carbon capture, and biodiversity protection efforts (Jaureguiberry et al. 2022). Initiatives such as REDD+ should be spatially tailored to account for the cross-border movement of emissions and the ecological impacts of wildfire activity.

Second, wildfire management must be improved through a comprehensive approach that includes prevention, early detection, rapid response, and the development of long-term ecological and societal resilience. National policies should integrate firebreaks, buffer zones, and community-based fire prevention into local land-use planning, especially in high-risk and peri-urban zones (Marshall et al. 2024). Moreover, the implementation of satellite images and remote sensing technology to promptly detect and monitor wildfires in real time is necessary. At the regional level, platforms such as the ISDR Regional Sub-Saharan Wildland Fire Network can facilitate shared wildfire monitoring systems, satellite-based early detection, and coordinated emergency responses (Chuvieco et al. 2020).

Third, unregulated urban expansion into biodiversity-rich areas should be addressed through the adoption of ecological zoning, biodiversity impact assessments, and urban growth boundaries. Planning frameworks should mandate the integration of green infrastructure, including ecological corridors and urban biodiversity reserves, to reduce habitat fragmentation and maintain species connectivity. Regional policy alignment under frameworks like the African Union's Agenda 2063 can help guide sustainable urbanization across national borders.

Thus, effective biodiversity conservation in SSA requires spatially informed, multi-level governance approaches that integrate environmental, urban, and climate policies. Through coordinated regional strategies, the spatial spillover effects of wildfires and urban growth can be managed in a way that ensures long-term biodiversity protection.

Acknowledgments

The authors acknowledge and appreciate the Ongoing Research Funding Program (ORF-2025-1038), King Saud University, Riyadh, Saudi Arabia.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was supported by the Ongoing Research Funding Program [ORF-2025-1038] King Saud University, Riyadh, Saudi Arabia.

Data availability statement

Data will be made available on reasonable request.

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Appendix

Table A1. List of countries with a schematic diagram of adjacent space weight matrix.

1	Botswana	8	25	33	37	0	0	0	0
2	Dem. Rep. Congo	6	8	11	12	13	14	31	35
3	Chad	6	9	23	40	0	0	0	0
4	Sierra Leone	5	34	0	0	0	0	0	0
5	Guinea	4	19	20	34	36	0	0	0
6	Central African	2	3	23	31	0	0	0	0
7	Djibouti	15	32	0	0	0	0	0	0
8	Zambia	1	2	13	25	29	30	35	37
9	Nigeria	3	10	23	40	0	0	0	0
10	Benin	9	27	28	40	0	0	0	0
11	Rwanda	2	12	13	14	0	0	0	0
12	Uganda	2	11	13	22	0	0	0	0
13	Tanzania	2	8	11	12	14	22	29	30
14	Burundi	2	11	13	0	0	0	0	0
15	Ethiopia	7	21	22	32	0	0	0	0
16	Gabon	23	24	31	0	0	0	0	0
17	Ghana	27	28	0	0	0	0	0	0
18	Mauritania	19	36	0	0	0	0	0	0
19	Senegal	5	18	20	26	36	0	0	0
20	Guinea-Bissau	5	19	0	0	0	0	0	0
21	Somalia	15	22	0	0	0	0	0	0
22	Kenya	12	13	15	21	0	0	0	0
23	Cameroon	3	6	9	16	24	31	0	0
24	Eq. Guinea	16	23	0	0	0	0	0	0
25	Namibia	1	8	33	35	37	0	0	0
26	Gambia	19	0	0	0	0	0	0	0
27	Togo	10	17	28	0	0	0	0	0
28	Burkina Faso	10	17	27	36	40	0	0	0
29	Malawi	8	13	30	0	0	0	0	0
30	Mozambique	8	13	29	33	37	38	0	0
31	Congo	2	6	16	23	35	0	0	0
32	Eritrea	7	15	0	0	0	0	0	0
33	South Africa	1	25	30	37	38	39	0	0
34	Liberia	4	5	0	0	0	0	0	0
35	Angola	2	8	25	31	0	0	0	0
36	Mali	5	18	19	28	40	0	0	0
37	Zimbabwe	1	8	25	30	33	0	0	0
38	eSwatini	30	33	0	0	0	0	0	0
39	Lesotho	33	0	0	0	0	0	0	0
40	Niger	3	9	10	28	36	0	0	0

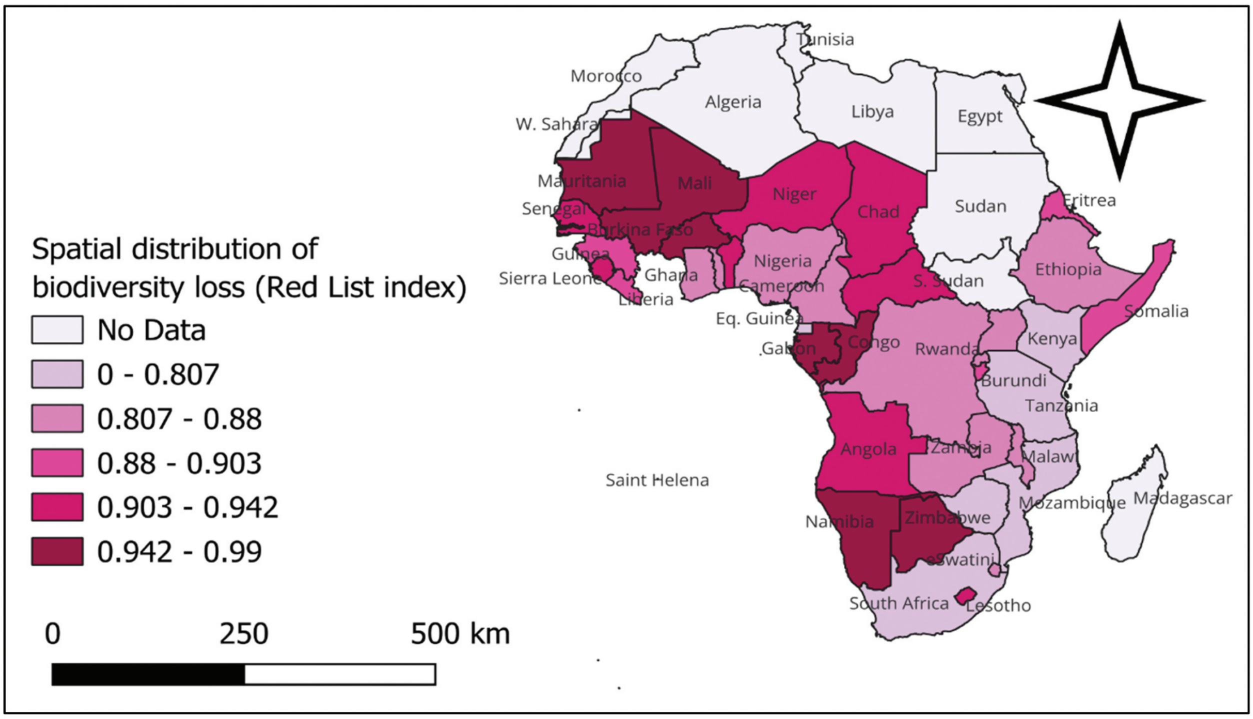

Figure A1. Spatial distribution of biodiversity loss (red list index). The red list index represents the accounting unit for biodiversity loss, showing the overall extinction risk for groups of species. A data-driven classification of the red list index is used to depict the countries with the largest biodiversity loss (lighter) and the lowest countries with biodiversity loss (in dark maroon).

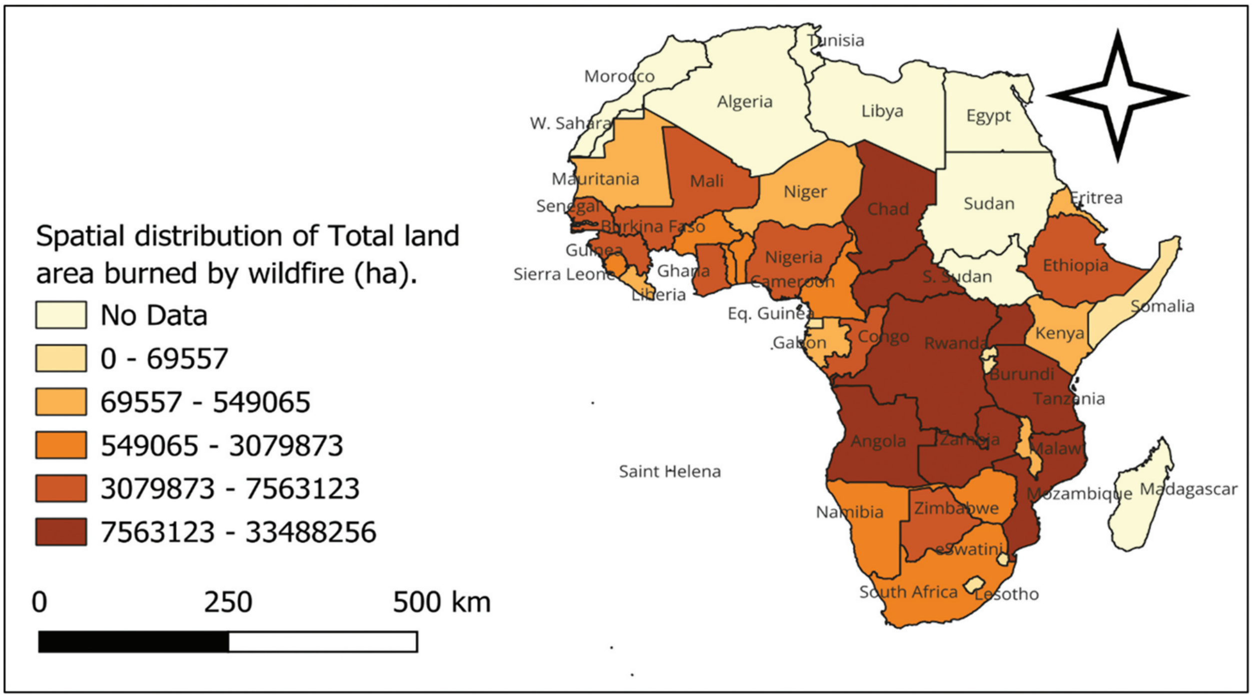

Figure A2. Spatial distribution of total land area burned by wildfire; ha indicates the accounting unit for area burned by wildfires in hectares. The data-driven classification of this unit is used to show the countries that experienced the largest hectares burned by wildfire (in dark yellow).

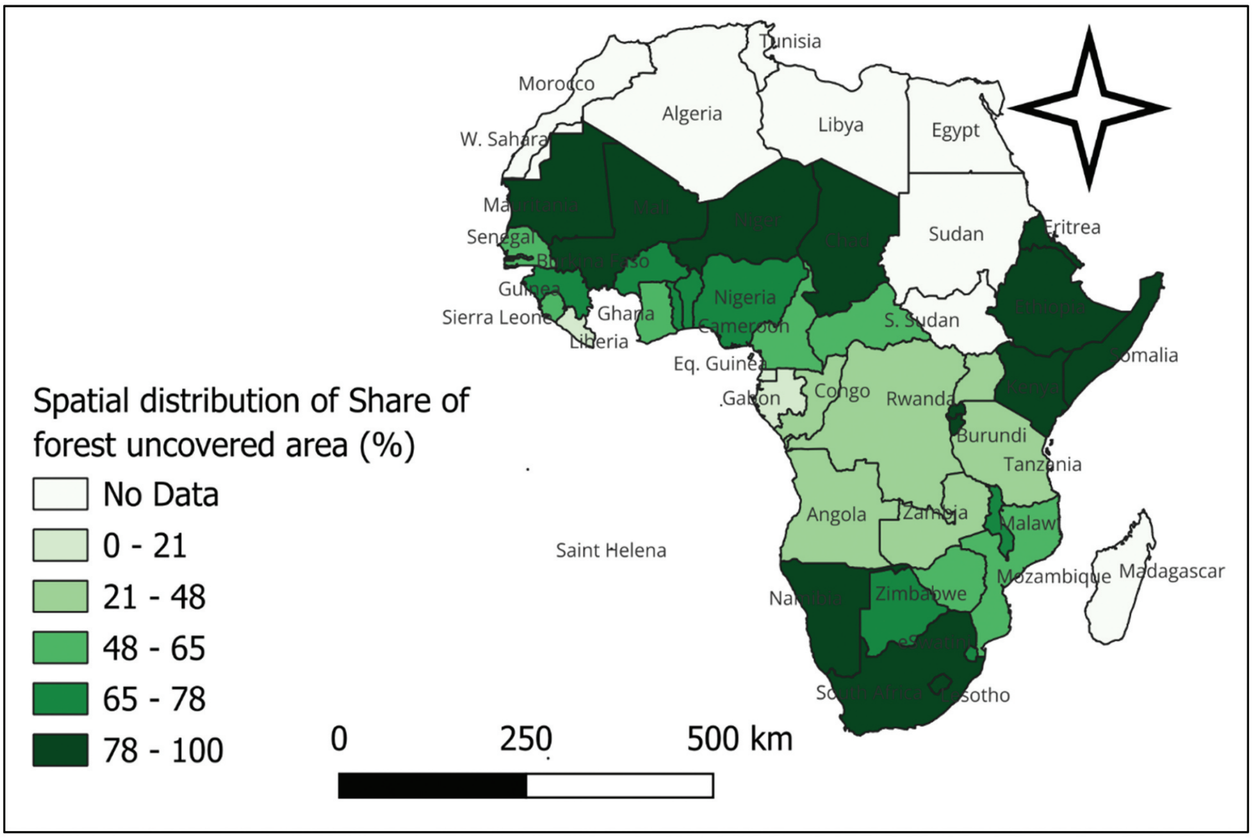

Figure A3. Spatial distribution of the share of forest non-forested ecosystems, the % of total land is accounting unit for the land area that has no forest coverage. The highest share of non-forested areas is depicted by the dark green.

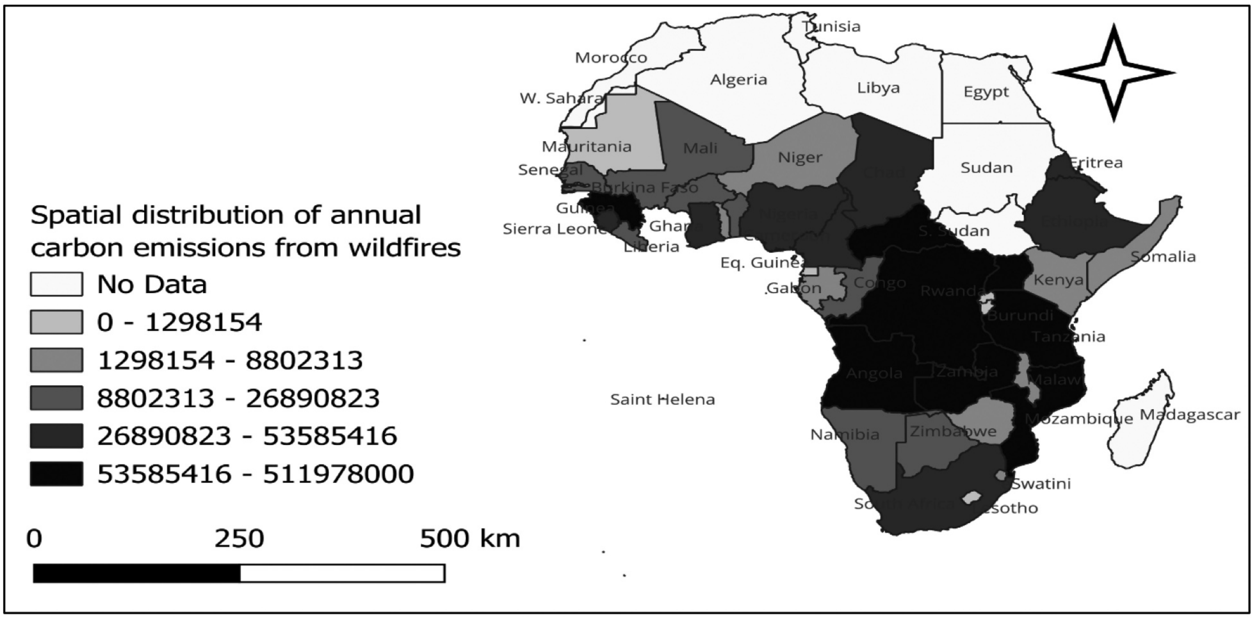

Figure A4. Spatial distribution of annual carbon emissions from wildfire (in tons), tons represent the accounting unit for wildfire-induced carbon emissions. The data-driven classification for annual carbon dioxide emissions from wildfires shows the countries with higher (WCO_2) emissions stemming from wildfires (in dark gray).

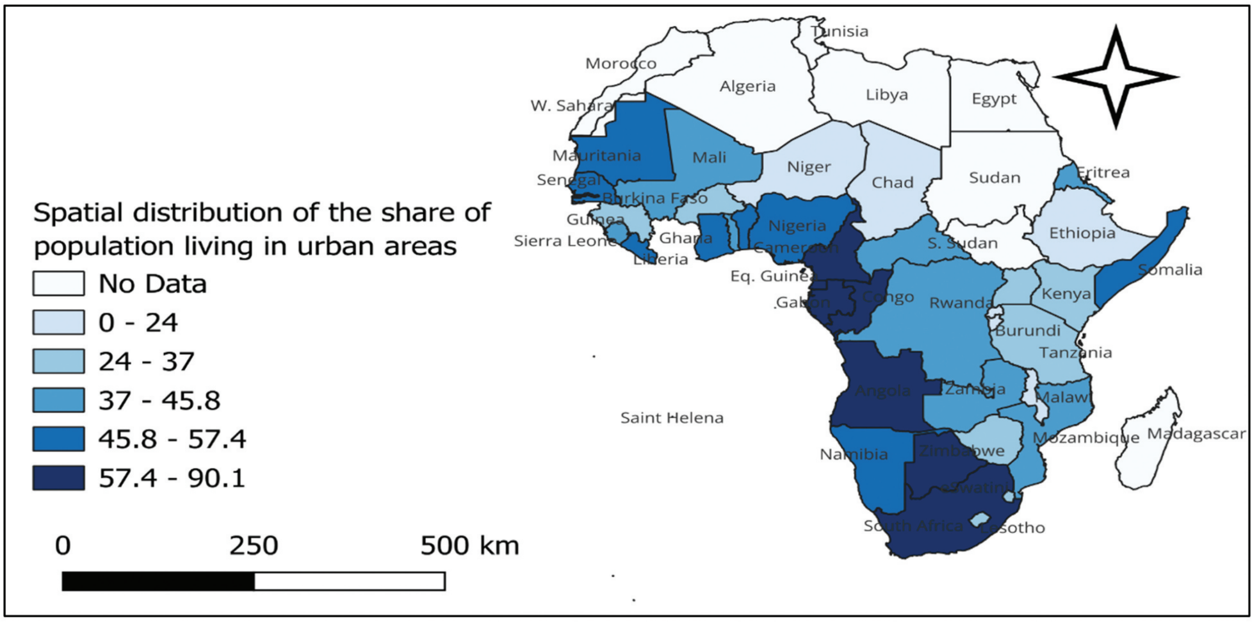

Figure A5. Spatial distribution of the share of population living in urban areas, % of the total population, is used as the accounting unit to show the countries with higher rates of urban population (in dark blue).