**Estimating population exposure to multiple environmental burdens in sub-Saharan Africa: A pixelated study over last two decades (2000-2019)**

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**Theoretical background**

Environmental uncertainties have increased across the world. Unprecedented episodes of heat waves, droughts and floods have been striking different regions in the last decades (Calvin et al., 2023), making climate change a tangible reality for all. Half of the global population is exposed to increasing fine particulate matter (PM2.5) air pollution (Shaddick et al., 2020). The devastating toll on forests is also evident, with an estimated loss of approximately 420 million hectares of forest due to conversions to other land uses since 1990 (UNEP & FAO, 2020). However, these challenges are far from uniform, varying significantly in magnitude and impact due to complex interplays of factors such as population densities, urbanization levels, socio-economic conditions, political regulation and geography on international, national, and subnational scales. Sub-Saharan Africa remains at higher risks due to intensifying environmental burden. The adversities aggregate due to much of its population lives under the poverty line and are marked by large inequalities and little social protection (Fosu, 2015). Moreover, lack of enough and timely environmental monitoring at ground is another issue. In light of these limitations, the role of remotely sensed data is immense.

**Research motivation**

It is imperative to recognize that different environmental challenges often coexist in the same geographical location, compounding risks for the populations residing there. In the context of this study, 'environmental burden' refers to the threatening state of four key environmental parameters presenting multifaceted risks to human health and well-being globally. Specifically, we focus on hazardous levels of PM2.5 (air pollution factor), temperature increase and prolonged drought severity (extreme event factor), and green deficit (land use change factor). Further, we report simultaneous presence of more than one of these challenges as multiple environmental burdens (MEB). We quantify the population exposed to each of these key environmental risks and to MEB in sub-Saharan Africa at the finest spatial resolution (1Km grid), for the years 2000 and 2019, and analyze the changes in exposure over this period. We also ask: what is the contribution of population change, environmental change and its interaction in the change in exposure to specific environmental risk factors and MEB? The findings are then aggregated at national, regional, and subcontinental levels, providing a comprehensive understanding of the population exposed to environmental burden in Sub-Saharan Africa.

**Data**

To derive population and environmental indicators we employed publicly available raster data. These data were spatially processed (clipped, reprojected, rescaled, and aggregated using zonal statistics) under QGIS software. The years 2000 and 2019 were selected to capture tong term changes and to avoid the temporary impact of COVID-19 restrictions on environmental parameters. Population data was derived from the WroldPop project(Stevens et al., 2015). Temperature and Palmer Drought Severity Index data were derived from the Terraclimate dataset (Abatzoglou et al., 2018). The annual average of particulate matter (PM2.5) concentrations were estimated by the Atmospheric Composition Analysis Group (Van Donkelaar et al., 2021). Data on the Fraction of Vegetation Cover (FCover) was downloaded from the Copernicus Global Land Service(Camacho et al., 2013). Administrative boundaries were downloaded from the Natural Earth Data platform (https://www.naturalearthdata.com/).

**Methods**

We set indicator-specific thresholds to define the environmental burden by considering as a factor of risk the following levels:

a) Hazardous PM2.5 levels: pixels with values above 20 $\mu g/m^3$ (annual).

(b) Extreme temperature increase: pixels with greater than 1 °C increase in average annual temperature compared to the reference year (twenty years before).

(c) Prolonged severe drought: pixels with PSDI ≤ -3 for at least four months during the year and/or in the previous year.

(d) Green deficit: pixels with a FCover value of less than 0.3 for average of the last two years

These four rasters of environmental risk factors were superimposed to create new rasters of MEB. We identified three new successive rasters representing the exposure to at least two (2MEB), three (3MEB), or four (4MEB) above-mentioned risks for 2000 and 2019.

After creating these criteria-specific spatial data, we multiplied them separately with population in each pixel following the methods described by (Jones et al., 2015).

Following previous studies (Chen et al., 2020; Iyakaremye et al., 2021; Jones et al., 2015), we decompose the total change in exposure (total effect) into three components by (i) allowing the area under environmental burden to change over time but keeping population fixed at the base year (environment effect), (ii) allowing population to change over time and keeping the area under environment burden fixed at base year (population effect), and (iii) subtracting the sum of population and environment effects from total exposure (interaction effect).

**Results (partial results without main figures and table due to page limit)**

Population exposure to hazardous PM2.5 levels

In sub-Saharan Africa, the population exposed to hazardous PM2.5 levels rose from approximately 438 million (69%) in 2000 to about 898 million (80%) in 2019. The escalation is particularly significant in densely populated areas and regions experiencing notable population growth. These observed spatial patterns in population and PM2.5 levels are substantiated by country-level aggregated statistics, presented (in %) as in Table 1. Notably, the Central African region exhibits the highest percentage of exposed population (98.5%) compared to other regions.

Population exposure to extreme temperature increase

In our analysis, we focused on populations residing in areas where temperature increase exceeds 1°C, considering them exposed to extreme temperature rise. Table 1 provides country-level aggregated statistics of exposed population for 2000 and 2019. In sub-Saharan Africa, the population exposed to extreme temperature increase rose from approximately 30,000 (0.01%) in 2000 to around 16 million (1.4%) in 2019. At regional levels, Southern Africa accounted for the largest share of exposed population (2.6%) compared to other regions. A noticeable heterogeneity in exposure levels is evident at the country level. Remarkably, during 2019, countries with high population exposure included Ethiopia (~2.24 million), DR Congo (~1.93 million), South Africa (~1.74 million), and Angola (~1.15 million), among others. Conversely, countries with the lowest population exposure (almost zero) during 2019 included Guinea-Bissau, Gambia, and Burundi.

Population exposure to prolonged severe drought

The population exposed to prolonged severe drought has increased substantially, rising from approximately 9.35 million (1.5%) in 2000 to about 22.68 million (2%) in 2019 (see Table 1). East Africa exhibits a relatively higher share of population exposure, accounting for 2% in 2000 and 2.5% in 2019, in comparison to other regions. During 2019, countries with high population exposure include the highly populated nations such as DR Congo (~3.6 million or 3.3%), Ethiopia (~2.3 million or 2.3%), Kenya (~1.8 million or 3.5%), South Africa (~1.7 million or 2.9%), and Nigeria (1.2 million or 0.6%), among others. Notably, the changes in exposure also differ among these countries. For instance, South Africa experienced a substantial increase in exposure (1.6 million), whereas Nigeria witnessed only a marginal rise (48 thousand) from 2000 to 2019. Conversely, some countries, including Madagascar (-371 thousand), Sierra Leone (-90 thousand), and Zambia (-80 thousand), experienced a decline in exposure over this period. These variances in exposure and change are influenced by the interplay of both population size and the varying severity of droughts over space and time.

Population exposure to green deficit

The population exposed to green deficit increased from approximately 291 million (45.6%) in 2000 to about 537 million (48%) in 2019 (see Table 1). Regionally, West and East Africa bore the maximum burden of population exposure, accounting for 68.3% and 62.4% in 2019, respectively, compared to other regions. Highly populated countries exhibited significantly elevated exposure levels and notable changes over time, including Nigeria [from ~71 million (61%) to ~140 million (67%)], Ethiopia [from ~53 million (87%) to ~72 million (71%)], Sudan [from ~25 million (99%) to ~40 million (97%)], Kenya [from ~15 million (52%) to ~23 million (45%)], and Niger [from ~11 million (100%) to ~23 million (100%)], among others. Remarkably, despite higher exposure levels in 2019, the percentage of the population exposed to green deficit decreased for many of these countries. Rapid increases in both absolute and percentage of the population exposed were observed in several countries, such as South Africa, Angola, and Ghana, among others. A negative change in exposure was observed only in Lesotho, where the population remained stable from 2000-2019, contributing to an improvement in FCover values.

Population exposure to Multiple Environmental Burden (MEB)

Figures 1(a) and 2(b) illustrate the spatial distribution of Multiple Environmental Burden (MEB), represented in shades of light to dark blue, alongside populated areas marked in black, for the years 2000 and 2019, respectively. The analysis identifies areas characterized by at least two (2MEB), three (3MEB), or four (4MEB) environmental burdens, as detailed methods. A noticeable expansion in the regions burdened by MEB is evident over time. In 2000, the majority of the subcontinental area exhibited 2MEB. However, by 2019, there was a significant increase in areas with 3MEB, and patches characterized by all four environmental burdens (4MEB) became apparent. At the subcontinental level, the population exposed to MEB experienced a remarkable increase over the study period. Specifically, there was an increase in population exposure from approximately 300 million to about 465 million for 2MEB, from around 47 million to approximately 292 million for 3MEB, and from none to approximately 92 million for 4MEB.

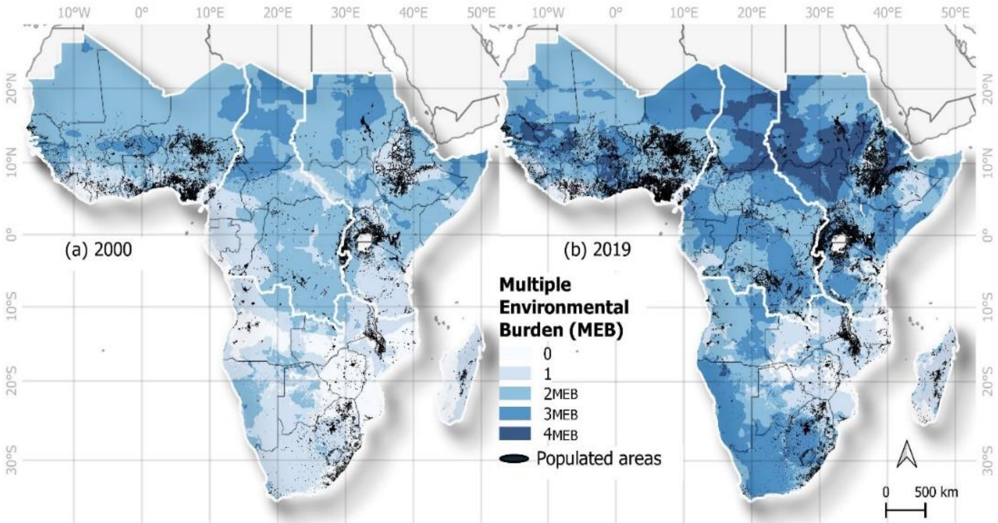


*Figure 1 Multiple Environmental Burden (MEB) and population exposure. (a) spatial patterns of MEB and populated areas during 2000; (b) spatial patterns of MEB and populated areas during 2019.*

*Table 1 Country-level population exposure (in million) to different environmental burdens during 2000 and 2019.*

| | Total Population (in million) | | Exposure (%) to hazardous PM2.5 | | Exposure (%) to temp. increase | | Exposure (%) to prolonged severe drought | | Exposure (%) to green deficit | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2000 | 2019 | 2000 | 2019 | 2000 | 2019 | 2000 | 2019 | 2000 | 2019 |
| **Central Africa** | **85.8** | **175.4** | **93.3** | **98.5** | **0.0** | **1.9** | **1.7** | **2.2** | **21.3** | **25.7** |
| Burundi | 6.7 | 11.1 | 99.5 | 99.3 | 0.0 | 0.0 | 4.0 | 4.0 | 1.1 | 3.4 |
| Cameroon | 15.0 | 27.1 | 99.7 | 99.6 | 0.0 | 1.7 | 0.6 | 1.8 | 38.2 | 44.4 |
| CAR | 3.6 | 5.2 | 100.0 | 100.0 | 0.0 | 0.8 | 3.0 | 3.5 | 15.4 | 24.4 |
| Chad | 8.0 | 16.0 | 100.0 | 100.0 | 0.0 | 1.5 | 2.6 | 2.2 | 97.8 | 99.3 |
| Congo | 4.5 | 3.8 | 71.5 | 99.4 | 0.0 | 2.5 | 0.1 | 1.6 | 12.4 | 21.3 |
| DR Congo | 45.7 | 108.3 | 96.1 | 99.9 | 0.0 | 1.8 | 2.9 | 3.3 | 4.0 | 6.4 |
| Eq. Guinea | 0.9 | 1.2 | 98.7 | 98.6 | 0.0 | 2.9 | 0.0 | 0.0 | 0.1 | 1.6 |
| Gabon | 1.3 | 2.8 | 81.0 | 91.4 | 0.0 | 3.7 | 0.0 | 1.4 | 1.8 | 4.7 |
| **East Africa** | **195.6** | **335.9** | **69.2** | **78.4** | **0.0** | **1.6** | **2.0** | **2.5** | **64.8** | **62.4** |
| Djibouti | 0.6 | 1.1 | 99.5 | 99.6 | 0.0 | 0.7 | 0.0 | 0.1 | 91.8 | 93.2 |
| Eritrea | 3.2 | 4.2 | 96.8 | 99.9 | 0.0 | 0.5 | 1.8 | 0.7 | 97.4 | 97.9 |
| Ethiopia | 61.3 | 101.0 | 22.1 | 59.9 | 0.0 | 2.2 | 1.2 | 2.3 | 87.4 | 71.0 |
| Kenya | 29.3 | 52.8 | 30.8 | 57.7 | 0.0 | 1.7 | 3.0 | 3.5 | 52.2 | 44.7 |
| Rwanda | 7.8 | 13.2 | 99.6 | 99.7 | 0.0 | 0.6 | 4.0 | 3.9 | 1.4 | 3.1 |
| S. Sudan | 6.1 | 15.5 | 93.9 | 80.5 | 0.0 | 2.3 | 0.8 | 3.8 | 83.6 | 81.2 |
| Somalia | 6.6 | 11.0 | 34.2 | 33.3 | 0.0 | 2.4 | 2.7 | 1.5 | 97.6 | 97.0 |
| Sudan | 25.2 | 41.5 | 99.1 | 99.8 | 0.0 | 2.3 | 1.3 | 3.3 | 99.3 | 97.1 |
| Tanzania | 32.5 | 54.6 | 23.2 | 56.5 | 0.0 | 1.5 | 3.4 | 2.3 | 8.3 | 11.8 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Uganda | 23.1 | 41.1 | 92.4 | 96.6 | 0.0 | 1.6 | 1.4 | 4.0 | 29.1 | 27.4 |
| **Southern Africa** | **133.7** | **206.1** | **30.1** | **46.8** | **0.0** | **2.6** | **0.9** | **1.4** | **16.7** | **19.8** |
| Angola | 20.2 | 33.3 | 47.3 | 72.5 | 0.0 | 3.4 | 0.4 | 1.5 | 8.9 | 41.8 |
| Botswana | 1.6 | 2.3 | 9.1 | 5.3 | 0.1 | 3.7 | 0.1 | 2.0 | 38.9 | 34.0 |
| Eswatini | 1.0 | 1.1 | 59.4 | 38.7 | 0.0 | 4.1 | 0.0 | 0.4 | 0.0 | 0.2 |
| Lesotho | 1.9 | 1.9 | 94.7 | 99.2 | 0.0 | 4.0 | 0.0 | 3.9 | 27.6 | 14.2 |
| Madagascar | 15.3 | 26.7 | 0.0 | 10.9 | 0.0 | 3.4 | 3.1 | 0.4 | 1.0 | 3.4 |
| Malawi | 10.5 | 18.1 | 6.2 | 89.7 | 0.0 | 0.3 | 1.3 | 0.4 | 0.2 | 1.2 |
| Mozambique | 16.4 | 29.6 | 9.6 | 42.4 | 0.0 | 0.3 | 0.4 | 0.2 | 0.7 | 3.3 |
| Namibia | 1.8 | 2.4 | 17.0 | 12.8 | 0.2 | 3.7 | 2.7 | 2.9 | 74.7 | 76.2 |
| South Africa | 44.0 | 58.8 | 54.5 | 59.1 | 0.0 | 3.0 | 0.3 | 2.9 | 29.6 | 34.6 |
| Zambia | 9.6 | 17.9 | 32.4 | 66.1 | 0.2 | 1.0 | 1.8 | 0.5 | 1.2 | 6.9 |
| Zimbabwe | 11.3 | 14.1 | 1.4 | 17.7 | 0.0 | 1.7 | 0.0 | 0.1 | 0.5 | 1.8 |
| **West Africa** | **223.2** | **400.8** | **94.9** | **92.0** | **0.0** | **0.7** | **1.1** | **2.0** | **62.8** | **68.3** |
| Benin | 6.4 | 12.6 | 100.0 | 100.0 | 0.0 | 0.4 | 1.7 | 2.9 | 50.0 | 57.2 |
| Burkina Faso | 11.6 | 22.0 | 100.0 | 100.0 | 0.0 | 0.3 | 2.4 | 3.0 | 100.0 | 99.3 |
| Gambia | 1.2 | 2.3 | 97.7 | 98.0 | 0.0 | 0.0 | 0.5 | 2.9 | 87.3 | 89.8 |
| Ghana | 18.8 | 31.9 | 99.9 | 86.8 | 0.0 | 2.9 | 0.6 | 2.0 | 39.3 | 51.5 |
| Guinea | 7.7 | 12.0 | 98.6 | 99.3 | 0.0 | 0.6 | 2.4 | 2.0 | 46.8 | 59.2 |
| Guinea-Bissau | 1.1 | 1.8 | 99.5 | 99.5 | 0.0 | 0.0 | 3.6 | 3.7 | 65.8 | 56.0 |
| Ivory Coast | 15.6 | 25.3 | 78.4 | 43.7 | 0.0 | 0.3 | 0.2 | 2.3 | 21.2 | 29.8 |
| Liberia | 2.8 | 4.2 | 52.7 | 56.4 | 0.0 | 0.7 | 0.0 | 0.1 | 4.9 | 22.5 |
| Mali | 10.4 | 22.3 | 100.0 | 100.0 | 0.0 | 1.8 | 0.5 | 1.2 | 99.6 | 99.3 |
| Mauritania | 2.5 | 4.3 | 99.9 | 99.8 | 0.0 | 0.3 | 0.0 | 1.9 | 98.5 | 98.4 |
| Niger | 10.6 | 22.9 | 100.0 | 100.0 | 0.0 | 0.5 | 0.4 | 0.3 | 99.9 | 99.8 |
| Nigeria | 116.2 | 208.8 | 99.5 | 98.9 | 0.0 | 0.0 | 1.0 | 0.6 | 61.4 | 67.3 |
| Senegal | 9.2 | 15.8 | 98.6 | 98.6 | 0.0 | 0.3 | 0.2 | 3.4 | 96.2 | 95.3 |
| Sierra Leone | 4.4 | 6.4 | 99.2 | 99.1 | 0.0 | 1.5 | 2.1 | 0.1 | 8.4 | 27.5 |
| Togo | 4.6 | 8.4 | 100.0 | 99.9 | 0.0 | 1.3 | 1.2 | 3.5 | 62.5 | 71.8 |
| **Sub-Saharan Africa** | | | | | | | | | | |
| All countries | **638.3** | **1118.2** | **68.6** | **80.3** | **0.0** | **1.4** | **1.5** | **2.0** | **45.6** | **48.0** |

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