Urban Sprawl and Traffic-Related Air Pollution in Greater Gaborone: A Spatial Analysis of the Land Use–Transport–Environment Relationship

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Abstract

Rapid urban sprawl in many Sub-Saharan African cities has significantly reshaped urban mobility patterns, resulting in longer commuting distances, increased private vehicle dependence, and growing pressure on major transport corridors. These trends have important implications for environmental quality, urban sustainability, and climate resilience. This paper investigates the spatial relationship between urban sprawl and traffic-related air pollution (TRAP) in Greater Gaborone, Botswana, using Geographic Information Systems (GIS) and remote sensing techniques. Landsat imagery from the United States Geological Survey (USGS), accessed via Google Earth Engine, is used to map land use and land cover change between 2006 and 2026, and Sentinel-5P TROPOMI tropospheric NO_2 data are used to map TRAP hotspots for 2026 using the Getis-Ord Gi* statistic. Built-up land area in Greater Gaborone grew by 79.6% over the study period, spreading outward from the historic core in multiple directions. TRAP hotspots are concentrated in this core and extend along the city's major roads into nearby growth areas, while more distant peripheral growth remains in the coldspot zone. This suggests that pollution has not spread uniformly with the built-up footprint, and that Greater Gaborone's transport corridors may play a role in shaping which growth areas experience elevated pollution and which do not. These findings offer evidence-based insights for land use planning and air quality management within Botswana's urban development framework, and highlight that Greater Gaborone spans multiple local government jurisdictions with no single authority responsible for the metropolitan area as a whole.

Keywords: *Urban Sprawl, Traffic-Related Air Pollution, GIS, Remote Sensing, Urban Mobility, Greater Gaborone*

1. Introduction

Africa is urbanising faster than any other region in the world, and its cities are expanding outward far more quickly than their populations are growing inward (Jiang et al., 2021; UN-Habitat, 2022). This outward expansion – commonly termed urban sprawl – is typically characterised by low-density, fragmented, and often unplanned peripheral development that outpaces the provision of infrastructure and services (Shao et al., 2021; Tumwesigye et al., 2023). In Sub-Saharan Africa, this pattern has been linked to disconnected road networks, longer commuting distances, and a growing reliance on private motorised transport, since public transit and non-motorised infrastructure rarely keep pace with the spatial extent of new development (Kolowa et al., 2024).

Botswana's capital, Gaborone, exemplifies this trajectory. The Greater Gaborone area has grown from a population of just over 72,000 in 1981 to more than 429,000 by 2022 (Statistics Botswana, 1981, 2022), and this growth has been accompanied by substantial conversion of shrubland and agricultural land to built-up use, particularly along the city's periphery and in adjoining villages such as Tlokweng, Mogoditshane, and Gabane (Matlhodi et al., 2019). As the built-up footprint has expanded outward, commuting patterns have become increasingly corridor-dependent, concentrating traffic volumes on a small number of arterial routes connecting peripheral residential areas to the central business district and major employment nodes – a dynamic documented in comparably structured West African cities, where large-scale road corridor investment and peripheral sprawl have been shown to reinforce one another (Amedzro et al., 2024).

Traffic-related air pollution (TRAP) is among the most extensively studied categories of ambient air pollution worldwide. A systematic review and meta-analysis of more than 350 studies conducted for the Health Effects Institute found consistent associations between long-term TRAP exposure and increased risks of mortality, cardiovascular and respiratory disease, and adverse birth outcomes (Boogaard et al., 2022; Health Effects Institute, 2022b). Road traffic is also widely identified as a leading and growing source of ambient air pollution in fast-growing cities globally, and this pattern is increasingly well documented in Sub-Saharan Africa specifically, where fine-grained monitoring in Accra, Ghana, has linked traffic density directly to elevated nitrogen oxide concentrations and significant socioeconomic inequality in exposure (Wang et al., 2024).

This sprawl–mobility relationship has an environmental consequence that has received comparatively little empirical attention; traffic-related air pollution (TRAP). Globally, extensive research has established that urban sprawl increases vehicle kilometers traveled (VKT), driving up emissions of fine particulate matter ($PM_{2.5}$), nitrogen oxides (NOx), and carbon monoxide (CO) along major transport networks (Cappelli et al., 2021; Ewing & Cervero, 2010; Tao et al., 2021). While vehicle emissions are a major and growing contributor to urban air pollution across Sub-Saharan Africa, the region's air quality monitoring infrastructure remains sparse (Health Effects Institute, 2022a; United Nations Environment Programme, 2021). Consequently, satellite-based and GIS-driven approaches are especially valuable for characterising pollution patterns where ground-based sensor networks are limited or absent. Recent satellite-based evidence from East African cities has shown that TRAP does not necessarily track distance from the city centre in the way older, monocentric models of urban air pollution would predict. Rather, pollution levels have been found to be higher in suburban and peripheral areas than in city centres, where combustion-related commuter activity concentrates (Chua et al., 2025). Understanding where TRAP concentrates, and whether that concentration coincides with the transport corridors serving sprawling peripheral growth, is therefore essential for integrating land use, transport, and air quality management in rapidly urbanising cities such as Gaborone.

This paper addresses that gap by examining the spatial relationship between urban sprawl and TRAP hotspots in Greater Gaborone over the period 2006–2026. The specific objectives are to: (i) quantify the extent and pattern of urban expansion in Greater Gaborone over the study period; (ii) map the spatial distribution of TRAP and identify statistically significant pollution hotspots; and (iii) qualitatively compare the resulting sprawl and TRAP hotspot patterns against each other and against Greater Gaborone's major transport corridors. The paper is organised as follows: Section 2 reviews relevant literature; Section 3 describes the study area; Section 4 details the data and methods; Section 5 presents the results; Section 6 discusses the findings; and Section 7 concludes with policy implications and recommendations.

2. Literature Review

2.1 Urban Sprawl and Land Use Change in African Cities

A growing body of remote sensing and GIS research has documented land use and land cover (LULC) change across Sub-Saharan African cities, generally finding rapid conversion of natural and agricultural land to built-up use driven by rural-to-urban migration and weak enforcement of planning regulations (Afuye et al., 2024; Alemu & Kombe, 2025). Within Botswana specifically, several studies have used multi-temporal Landsat and Sentinel-2 imagery to track this process. Matlhodi et al. (2019) documented substantial built-up area growth in the Gaborone Dam catchment between 1984 and 2015, with the fastest rates of change occurring in the 1995–2005 and 2005–2015 periods. Suh et al. (2023) found continued conversion of shrubland to built-up land across the Greater Gaborone area between 1988 and 2022, tracking closely with population growth in peripheral villages. Moyo et al. (2025) extended this line of work by linking Gaborone's land cover dynamics and land surface temperature using the Getis-Ord Gi* statistic to identify surface urban heat island hotspots, demonstrating the applicability of hotspot analysis to urban environmental questions in this specific study area – an approach this paper adapts for pollution rather than temperature. Earlier peri-urban case studies of villages such as Gabane and Tlokweng similarly found land use conflict and rapid conversion of agricultural land at the urban fringe, underscoring that Gaborone's sprawl has a long and well-documented trajectory (Mpofu et al., 2017; Nkambwe & Totolo, 2005).

More broadly across the region, a systematic literature review of urban sprawl research across five Anglophone Sub-Saharan African countries found that most existing studies address the causes and environmental effects of sprawl in isolation from one another (Yiran et al., 2020). Within this literature, air pollution is repeatedly identified as a significant effect, attributed specifically to increased vehicular traffic from commuting between sprawling outskirts and city centres. However, comparatively little attention has been paid to sprawl's interaction with transport infrastructure as an integrated system. To address this gap, recent scholarship advocates for more comprehensive remote sensing and GIS-based methodologies capable of capturing such urban complexity (Seto et al., 2012; Yiran et al., 2020).

2.2 Transport Corridors and Land Use–Transport Interaction

The land use–transport interaction (LUTI) framework holds that urban form and transport systems co-evolve: sprawling, low-density development increases trip lengths and private vehicle dependence, while the resulting road investment in turn shapes where further development occurs (Wegener & Fürst, 1999). In the Greater Accra Metropolitan Area, Ghana, Amedzro et al. (2024) show that large-scale road corridor investments, while intended primarily to serve trade and economic connectivity, have themselves become a driver of continued peripheral sprawl in the absence of integrated land use planning controls. This finding illustrates the two-way nature of the land use–transport interaction relationship in a Sub-Saharan African city structurally similar to Gaborone. Complementing this, Kolowa et al. (2024) find that informal, unplanned peripheral settlements across seven Tanzanian secondary cities exhibit measurably (approximately 12.8%) lower street network connectivity than planned areas, reinforcing the expectation that sprawling growth concentrates traffic onto a limited number of corridors rather than distributing it across a well-connected grid. This bidirectional dynamic is particularly relevant for Greater Gaborone, where a small number of arterial corridors (e.g., the Tlokweng, Molepolole, Kanye, and Lobatse roads) carry a disproportionate share of commuter traffic between peripheral residential areas and the city core area.

2.3 Traffic-Related Air Pollution in Sub-Saharan African Cities

Vehicle emissions are increasingly recognised as a leading source of urban air pollution across Sub-Saharan Africa, driven by ageing vehicle fleets, traffic congestion, and limited use of emissions controls (Ajayi et al., 2023; Oviedo et al., 2025; Schwela, 2012). In the Greater Accra Metropolitan Area, Wang et al. (2024) combined ground-based sensor networks with spatio-temporal mixed-effects modelling to characterise nitrogen oxide concentrations at fine spatial (50 m) and temporal (weekly) resolution, finding that road traffic was the dominant explanatory factor for both NO_2 and NO concentrations. Comparable satellite-based work by Chua et al. (2025) in Kampala, Nairobi, and Dar es Salaam mapped particulate matter ($PM_{2.5}$) concentrations at 1 km resolution using low-cost sensors integrated with satellite data, and found, counter-intuitively, that pollution levels were not highest in city centres, but were elevated in suburban and peripheral areas where combustion-related activity concentrated. This finding is directly relevant to a sprawl-focused study such as this one, since it suggests that TRAP hotspots in a sprawling city may not simply track distance from the city centre but may instead track the specific transport corridors that carry peripheral commuter traffic.

Despite this growing evidence base, very few studies have explicitly linked sprawl metrics, transport corridor classification, and TRAP hotspot mapping within a single spatial framework for an African city, and none, to the authors' knowledge, have done so for Gaborone. This paper addresses that specific gap.

3. Study Area

Greater Gaborone comprises the city of Gaborone and its surrounding peri-urban villages and settlements, including Tlokweng, Mogoditshane, Mmopane, and Gabane, located in South Eastern Botswana within the Notwane and Metsimotlhabe river catchments. The metropolitan area has grown from a planned colonial-era administrative capital of under 4 km² at independence in 1966 to a sprawling metropolitan region of several hundred square kilometres today, with a semi-arid climate, summer rainfall of approximately 450–550 mm per annum, and population growth driven predominantly by rural-to-urban migration.

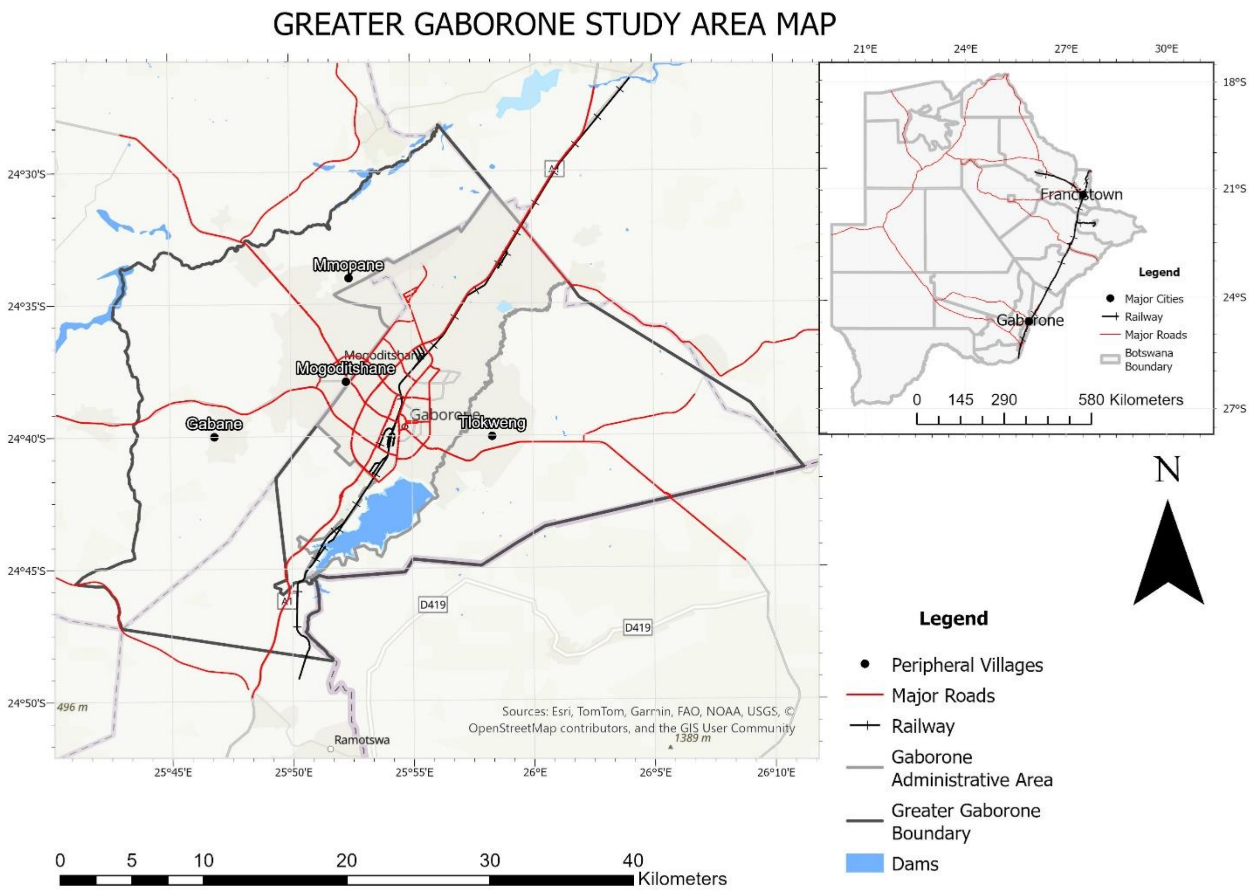

Figure 1. Greater Gaborone study area, showing the administrative boundary, peripheral villages, major road and rail network, and Gaborone Dam. Basemap: Esri, TomTom, Garmin, FAO, NOAA, USGS, and OpenStreetMap contributors.

Figure 1 situates Greater Gaborone's peripheral villages relative to the city's formal administrative boundary and its wider functional footprint. The Gaborone Administrative Area – the city's official municipal boundary – encloses only the historic urban core, while the broader Greater Gaborone Boundary used in this study extends well beyond it to incorporate Mmopane, Mogoditshane, Gabane, and Tlokweng, illustrating that the metropolitan area's lived and commuted extent has already outgrown its formal administrative limits. Two transport backbones structure movement through this extended area: the A1 trunk road and the parallel railway, both running broadly north-northeast to south-southwest through the urban core, connecting Greater Gaborone to the South African border to the south and to Francistown and the rest of Botswana to the north. Within the urbanised core itself, a denser mesh of arterial and collector roads links the peripheral villages to the central city core; this road network is referenced throughout the study, including in the TRAP hotspot comparison in Section 5.2. The Gaborone Dam, visible immediately south of the urban core, is a further constraint on the city's expansion, channelling peripheral growth toward the west and northeast rather than allowing uniform radial sprawl in all directions.

4. Materials and Methods

4.1 Data Sources

- Landsat imagery (USGS Earth Explorer, accessed via Google Earth Engine) for the 2006 and 2026 reference years, selected for low cloud cover (<10%) and dry-season acquisition to minimise vegetation phenology effects on classification. Landsat's sensor lineage spans this period – the 2006 scene is expected to come from the Landsat 5 TM archive and the 2026 scene from Landsat 8/9 OLI, since Landsat 5 was the operational US sensor in 2006 – but the exact platform, sensor, and acquisition date used for each date should be confirmed and stated explicitly in the final draft, since the two sensors differ slightly in spectral bands and radiometric calibration. As 2026 is still in progress, the most recent available cloud-free Landsat acquisition (most recent dry-season window) is used as the practical endpoint. A two-date bookend design (2006 vs. 2026) is used rather than a three-date series, to establish that sprawl occurred over the study period within the available timeline while keeping the classification workload feasible.
- Road network data extracted from OpenStreetMap, classified by road hierarchy (primary, secondary, tertiary, and local/residential) to identify major commuting corridors. This reflects the current (2026) network only – comprehensive historical OSM coverage for Botswana does not extend back to 2006 – and is treated as the cumulative outcome of two decades of corridor development in response to sprawl, not as a time series in its own right (see Section 4.3).
- Population and administrative boundary data from Statistics Botswana, used to contextualise built-up growth against demographic change.
- Sentinel-5P TROPOMI tropospheric NO_2 column data (ESA Copernicus programme, via Google Earth Engine), used as the TRAP proxy (see Section 4.4).

4.2 Urban Sprawl Measurement

Land use and land cover classification is performed in Google Earth Engine using a supervised classification approach (Random Forest, consistent with prior Gaborone-focused LULC studies), producing built-up, vegetated, bare land, and water body classes for the 2006 and 2026 reference years (Figure 2). Built-up area growth, overall and annualised growth rate, and sprawl intensity are then calculated through post-classification change detection between the two dates. Directional urban expansion is assessed using a sector-based analysis (e.g., concentric buffer rings and radial sectors from the central business district) to identify which parts of the metropolitan periphery have sprawled fastest, and standard landscape metrics, such as edge density and the largest patch index, computed for each date and compared, are calculated in a GIS environment to characterise the compactness versus fragmentation of new development. In addition to these summary statistics, the two classified surfaces are combined into a single binary sprawl-age layer that labels each 2026 built-up pixel as either pre-2006 core (built-up in both dates) or 2006–2026 growth (built-up only in 2026); this layer is the basis for relating the longitudinal sprawl process to the cross-sectional pollution surface in Section 4.5. A two-date bookend design is used; it establishes that sprawl occurred and where it occurred. Due to a timeline feasibility limitation, the current study does not seek to distinguish which sub-period within 2006–2026 grew fastest (a limitation noted in Section 6.1).

The initial 2006 classification substantially under-represented several peri-urban villages, including Tlokweng and Gabane, as built-up. This is consistent with the documented tendency of standard classifiers to misclassify low-density, traditional settlement patterns, whose spectral signature differs from the dense, high-reflectance built form of central Gaborone (Kolowa et al., 2024). The 2006 classification was therefore revised: training samples were augmented with village-area examples and the classification rerun. The revised 2006 map, used throughout this paper, is shown in Figure 2.

Classification accuracy for each date is assessed via a confusion matrix comparing classified output against independently interpreted reference points (n = 113 for 2006, n = 100 for 2026). Ground-truth class labels are assigned by visual interpretation of historical Google Earth imagery for the 2006 points and the ArcGIS Pro World Imagery basemap for the 2026 points. This assessment reports overall accuracy and the Kappa coefficient (Landis & Koch, 1977).

4.3 Transport Corridor Reference Layer

The current (2026) OpenStreetMap road network for Greater Gaborone, focusing on major arterial roads, is used as a qualitative reference layer. It is displayed alongside the TRAP hotspot surface (Section 4.4) to visually assess whether pollution concentrations correspond to the city's major transport corridors, rather than through a formal road classification or statistical overlay.

4.4 Traffic-Related Air Pollution Mapping

Traffic-related air pollution (TRAP) is proxied in this study using tropospheric NO_2 column density from the Sentinel-5P TROPOMI instrument, accessed as an image collection in Google Earth Engine. NO_2 is used as a single-pollutant proxy for TRAP rather than a composite of multiple traffic-linked pollutants (e.g., $PM_{2.5}$, CO, black carbon); this scope decision reflects both data availability and NO_2's suitability as a traffic marker specifically. Among the pollutants retrievable from TROPOMI, NO_2 is the most directly attributable to road traffic in urban areas, whereas SO_2 and CH_4 are dominated by industrial and agricultural sources respectively (Goldberg et al., 2021; Yu et al., 2023). Aerosol-index-based $PM_{2.5}$ estimation would require additional surface-calibration modelling not feasible within the project resources. NO_2's short atmospheric lifetime (on the order of hours) further means its spatial distribution remains closely tied to nearby emission sources, making it well suited to corridor-level hotspot mapping, in contrast to longer-lived combustion products such as CO whose spatial signal is smeared across the wider region. This single-pollutant scope is stated explicitly as a study limitation in Section 6.1, alongside the temporal constraints already discussed.

TROPOMI has been in operation since May 2018, which does not permit a historical pollution surface matching the 2006 land cover reference year; the TRAP layer is therefore treated as a current outcome surface rather than a second longitudinal time point, consistent with the sprawl-age design described in Section 4.2.

Two features of the sensor shape the compositing approach. First, TROPOMI has a single daily overpass, crossing Gaborone at approximately 13:30 local solar time; it cannot capture morning or evening commute-hour emissions directly, and the resulting surface reflects early-afternoon conditions rather than peak-hour concentrations – a limitation stated explicitly in Section 6.1. Second, day-to-day NO_2 columns vary substantially with meteorology (wind, boundary-layer height, temperature inversion) independent of underlying emissions, so a single image is not usable on its own. The image collection is therefore filtered to weekdays only and to pixels meeting the standard NO_2 retrieval quality threshold (qa_value > 0.75), to isolate the traffic-related signal and exclude cloud-affected scenes, and a median composite is computed from dry-season (May–July) overpasses pooled across 2025 and 2026, chosen to align with the Section 4.1 optical imagery and to maximise the number of valid, cloud-free retrievals.

Once the composite pollution surface is generated, spatial hotspot analysis is conducted using the Getis-Ord Gi* statistic in ArcGIS Pro to identify statistically significant clusters of high pollution concentration (hotspots) and low concentration (coldspots) at a 95% and 99% confidence level, following the same hotspot methodology validated for Gaborone's urban heat island analysis by Moyo et al. (2025).

5. Results

5.1 Urban Sprawl Pattern

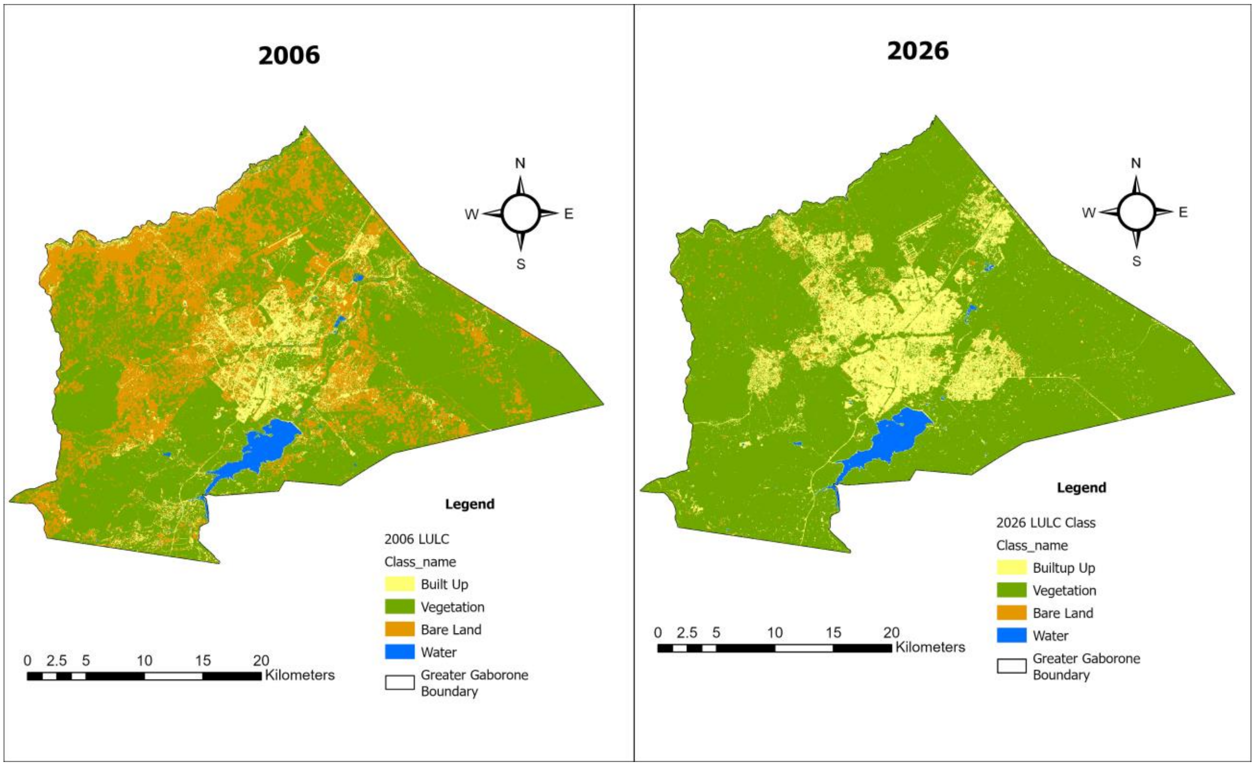

Figure 2. Land use/land cover classification for Greater Gaborone, 2006 (revised) and 2026 (Random Forest classification, Google Earth Engine).

The Random Forest classification achieved an overall accuracy of 84.96% (Kappa = 0.76, n = 113 reference points) for 2006 and 88.0% (Kappa = 0.77, n = 100 reference points) for 2026, both corresponding to substantial-to-almost-perfect agreement (Landis & Koch, 1977), supporting the reliability of the change-detection results reported below.

Built-up land area in Greater Gaborone increased from 85.37 km² (8.88% of the study area) in 2006 to 153.32 km² (15.95%) in 2026 – an increase of 67.95 km², or 79.6%, corresponding to an annualised compound growth rate of 2.93% per year (Puyravaud, 2003). Table 1 summarises area and share by land cover class for both dates, using the revised 2006 classification described in Section 4.2.

Table 1. Land cover class area and share, Greater Gaborone, 2006 and 2026

Class	2006 (km²)	2006 (%)	2026 (km²)	2026 (%)
Built-up	85.37	8.88	153.32	15.95
Vegetation	586.02	60.96	770.67	80.17
Bare land	271.76	28.27	18.57	1.93
Water	18.14	1.89	18.73	1.95
Total	961.29	100.00	961.29	100.00

Cross-tabulating the revised 2006 classification against 2026 (Table 2) shows that of the 153.32 km² built-up in 2026, 55.06 km² (35.9%) was already built-up in 2006 – the pre-2006 core – while

98.26 km² (64.1%) represents new 2006–2026 growth, consistent with the sprawl-age layer described in Section 4.2. This new growth was sourced predominantly from land classified as bare in 2006 (61.85 km², 62.9% of new growth) and from vegetated land (35.70 km², 36.3%), with a negligible contribution from open water (0.71 km², 0.7%).

Table 2. Land cover transition matrix, 2006–2026 (km²)

2006 ↓ / 2026 →	Built-up	Vegetation	Bare land	Water	Total 2006
Built-up	55.06	28.64	0.67	1.00	85.37
Vegetation	35.70	543.90	5.66	0.76	586.02
Bare land	61.85	197.54	12.24	0.14	271.76
Water	0.71	0.60	0.00	16.83	18.14
Total 2026	153.32	770.67	18.57	18.73	961.29

The pre-2006 core itself was less stable than expected: only 64.5% of 2006's built-up area remained classified as built-up in 2026, with 33.5% reclassified as vegetation, 1.2% as water, and 0.8% as bare land. This is a lower persistence rate than typically expected for established urban land, and is most plausibly linked to the 2006 revision itself: because that revision specifically added detection of low-density, village-style development (Section 4.2), the newly-captured pixels are likely more spectrally ambiguous, and therefore more prone to reclassification across dates, than the well-established urban core of central Gaborone. This is noted as an additional consideration in Section 6.1.

The bare land and vegetation classes remain unstable between dates even after the 2006 revision. Bare land fell from 271.76 km² (28.27%) to 18.57 km² (1.93%) – a 253.20 km² decline, still nearly 3.7 times larger than the 67.95 km² built-up growth signal – while vegetation rose by a corresponding 184.65 km² (31.5%). This most plausibly reflects differing antecedent rainfall or vegetation greenness, or the change in Landsat sensor (5 TM in 2006 vs. 8/9 OLI in 2026), between acquisition dates, rather than genuine 20-year ecological change of this magnitude. The built-up class is treated as the reliable signal in this study, since built environment is spectrally far more distinct and stable across dates than the bare-soil/senesced-grass boundary separating the other two classes. This vegetation/bare-land instability is stated explicitly as a limitation in Section 6.1.

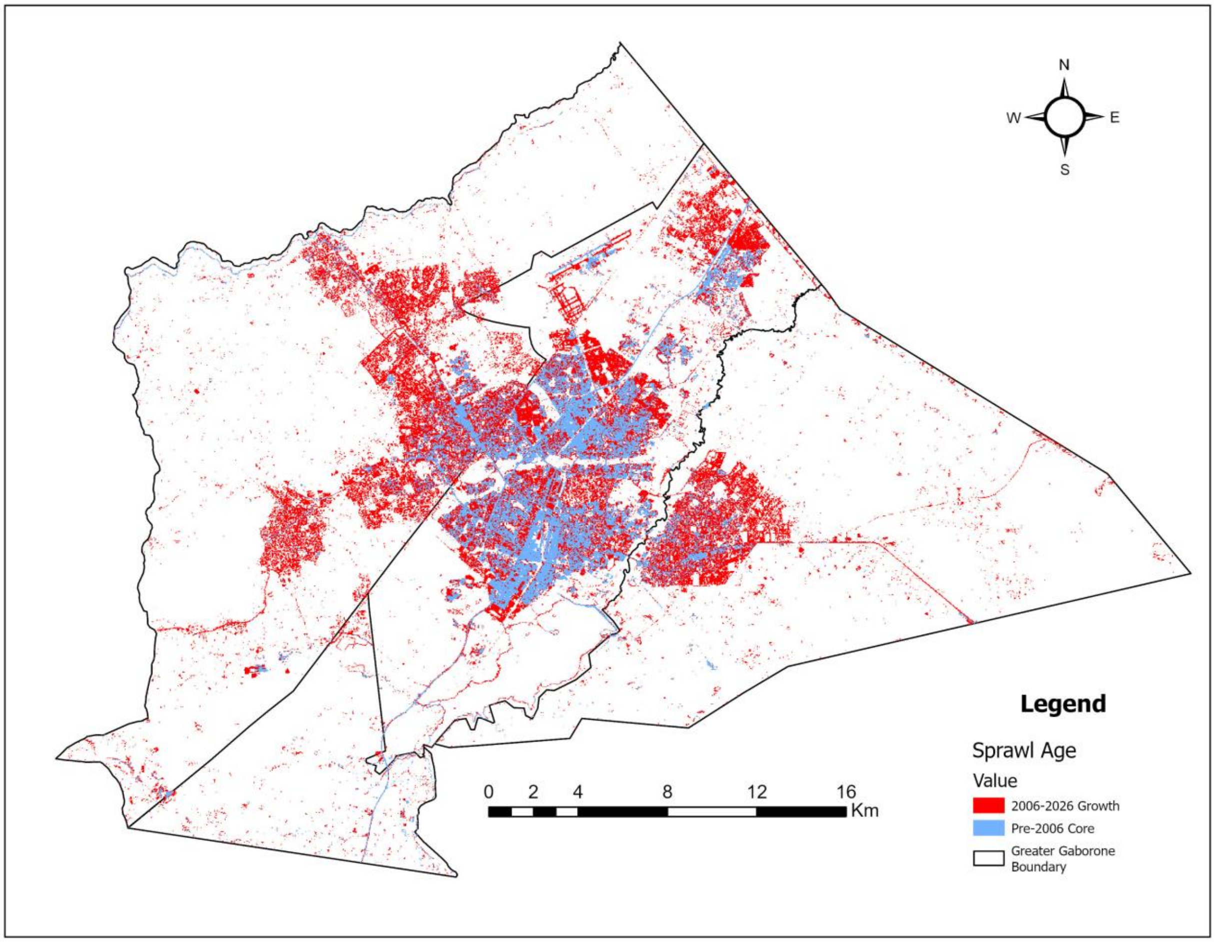

Figure 3. Sprawl-age classification for Greater Gaborone: pre-2006 core (blue, 55.06 km²) versus 2006–2026 growth (red, 98.26 km²).

The spatial pattern in Figure 3 shows that growth was not confined to a single direction. Substantial new development surrounds the pre-2006 core on most sides, with three large, semi-detached growth clusters visible to the west, north, and east of the core, consistent with the westward, northward, and eastward peri-urban villages (Section 3) coalescing towards central Gaborone. This suggests that sprawl in Greater Gaborone has proceeded along multiple fronts simultaneously, rather than in a single dominant direction.

5.2 TRAP Hotspot Pattern

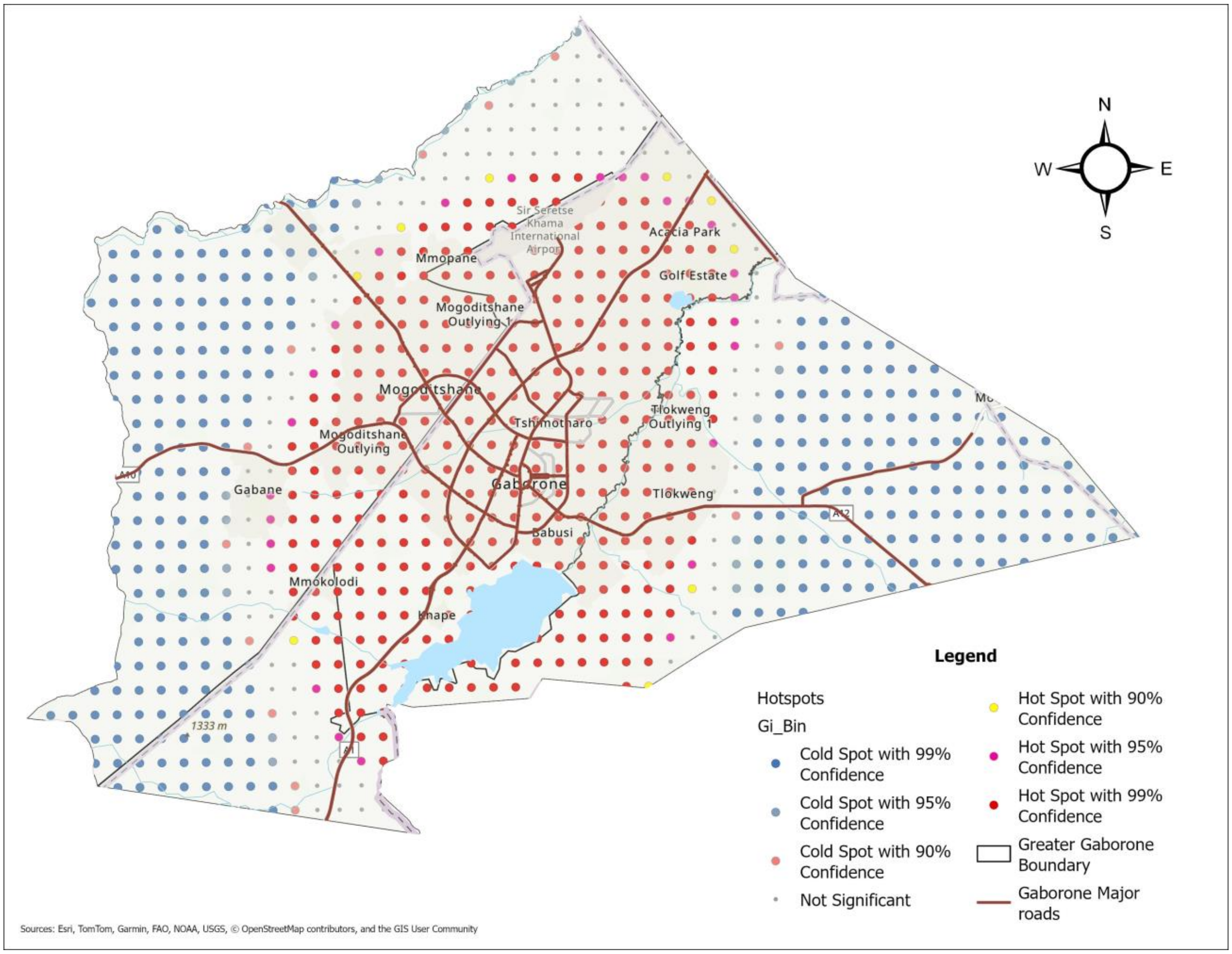

Figure 4. Getis-Ord Gi hot spot analysis (fixed-distance spatial weights, FDR correction) of the 2026 dry-season NO_2 composite, Greater Gaborone, with major roads shown for reference. Red = statistically significant hotspot (90–99% confidence); blue = statistically significant coldspot; grey = not significant.*

With major roads now shown for reference, the hotspot pattern is not a simple circle: it extends further south along the A1, past the dam, and further east along the A12 towards Tlokweng, than it does in other directions. Statistically significant hotspots, mostly at the 99% confidence level, cover the central urban core and these two extensions. Statistically significant coldspots dominate the remaining periphery, including areas west of Gabane and north of Mmopane, with no buffer zone of meaningful width between hot and cold.

This elongation along major roads is consistent with either a genuine corridor effect or simple radial decay, since Gaborone's principal roads radiate outward from the core along broadly the same axes as the city's recent growth (Section 5.1). At a pixel size of approximately 3.5–5.5 km, TROPOMI cannot resolve emissions from an individual road corridor separately from the surrounding land use, so the two explanations cannot be fully distinguished with this dataset. This resolution constraint is discussed further in Section 6.

6. Discussion

The land use–transport–environment framework applied here anticipated that Greater Gaborone's TRAP hotspots would align closely with the areas and corridors that sprawled between 2006 and 2026. This is consistent with the East African finding that suburban and peripheral zones can carry pollution burdens comparable to, or exceeding, those of city centres where combustion-related commuter traffic concentrates (Chua et al., 2025). The hotspot pattern found in Section 5.2 partly supports this. TRAP is concentrated in the pre-existing urban core, but the hotspot zone also extends into Mmopane and Tlokweng, both areas of substantial 2006–2026 growth. Coldspots dominate the remaining periphery, including areas further from the core such as Gabane and Modipane.

This pattern is best explained by the spatial resolution of the TROPOMI sensor, not by an absence of a corridor effect. Each NO_2 pixel spans approximately 3.5–5.5 km. Individual road corridors cannot be resolved at this scale, so the composite necessarily reflects city-wide activity density concentrated around the city core rather than corridor-specific emissions. Sprawl has clearly redistributed Gaborone's built-up footprint towards the periphery (Section 5.1), but TRAP has largely redistributed with it uniformly. Mmopane and Tlokweng, both areas of substantial 2006–2026 growth, fall largely within the hotspot zone. This suggests that TRAP has genuinely extended into these villages alongside the sprawl that produced them, rather than the hotspot classification simply spilling over from the core. The smaller portions of these villages that fall outside the hotspot zone are more likely a function of the sensor's coarse resolution than of genuinely lower pollution: at a pixel size of 3.5–5.5 km, fine-grained variation within a village cannot be resolved, so some sub-areas may be under-classified as not significant rather than being truly unpolluted. More distant parts of the periphery, further from the core than Mmopane and Tlokweng, remain in the coldspot zone, suggesting that the sprawl-TRAP relationship may hold most clearly for growth areas near enough to the core to be captured within this effect.

These findings also carry a jurisdictional implication worth noting. The Greater Gaborone boundary used in this study is an analytical construct. It was assembled to capture the metropolitan area's functional extent, not a single formally constituted administrative unit. In practice, the villages and areas that make up this functional area fall under several different district and city or town council jurisdictions, and none of these has planning authority over the region as a whole. The TRAP hotspot pattern identified in this study extends beyond the urban core into surrounding villages. It is, in effect, a metropolitan-scale problem without a metropolitan-scale authority to address it. Any land use or transport intervention motivated by these findings would require coordination across multiple local authorities, or a national-level instrument capable of covering the functional urban area regardless of administrative boundaries. The absence of such a single authority is itself a planning challenge that merits attention.

6.1 Limitations

Two constraints stem from the study's spatial data design rather than the TRAP proxy itself. First, the sprawl analysis uses a two-date bookend (2006 vs. 2026) rather than a multi-point time series;

this establishes that sprawl occurred and identifies where, but cannot distinguish which sub-period within 2006–2026 grew fastest or whether growth was continuous or episodic – a three- or four-date series (e.g., adding 2016) would strengthen this if time permitted in a follow-up study. Second, the bare land and vegetation classes showed substantial cross-date instability, even after the 2006 classification was revised to correct for village undercounting (Section 4.2) – a 253.20 km² decline in bare land against a corresponding rise in vegetation, still nearly 3.7 times larger than the 67.95 km² built-up growth signal (Section 5.1) – most plausibly reflecting differing antecedent rainfall/greenness or the change in Landsat sensor (5 TM in 2006 vs. 8/9 OLI in 2026) between acquisition dates rather than genuine land cover change. The built-up class, this study's primary interest, is comparatively more stable, with 64.5% of 2006's built-up area still classified as built-up in 2026 (Section 5.1); this is markedly higher persistence than bare land's 4.5%, though still lower than expected for well-established urban land, plausibly because the 2006 revision added detection of spectrally ambiguous village-style pixels that are more prone to reclassification than the historic urban core.

Five further constraints follow from the TRAP proxy itself. First, TROPOMI's operational record begins in May 2018, so the TRAP layer necessarily represents current conditions rather than a second point in the 2006–2026 longitudinal series; the study therefore tests whether accumulated sprawl explains present-day pollution, not how pollution itself has changed over two decades. Second, the pollution composite is built from dry-season (May–July) weekday overpasses pooled across 2025 and 2026, chosen to align with the Section 4.1 optical imagery and to maximise retrieval quality; this characterises dry-season TRAP conditions specifically, and results may not generalise to the wet season, when rainfall scavenging and different boundary-layer dynamics could alter both pollutant concentrations and their spatial distribution. Third, NO_2 is used as a single-pollutant proxy for TRAP rather than a multi-pollutant composite (e.g., $PM_{2.5}$, CO, black carbon); NO_2 was selected as the most traffic-attributable pollutant retrievable from TROPOMI, with a short enough atmospheric lifetime to preserve corridor-level spatial detail, but the resulting hotspot map reflects NO_2 patterns specifically and may not fully represent the broader TRAP pollutant mix. Fourth, TROPOMI's single daily overpass occurs at approximately 13:30 local solar time, so the pollution surface reflects early-afternoon conditions and cannot directly capture morning or evening peak-hour emissions, which likely understates the sharpest corridor-level concentrations at rush hour, though it still reflects the broader spatial pattern of where traffic-related emissions concentrate, since Gaborone's corridors carry elevated traffic through much of the day, not only at the two rush-hour peaks. Fifth, TROPOMI's pixel size (~3.5–5.5 km) is far coarser than the width of any individual road corridor, so the hotspot surface reported in Section 5.2 reflects city-wide activity density rather than corridor-specific emissions; any correspondence observed between hotspots and major roads should therefore be treated as suggestive rather than a formally tested corridor effect.

Ground-truthing the TROPOMI-derived hotspots against low-cost sensor or traffic-count data, and extending the pollution composite to the wet season for comparison, are further directions for follow-up work.

7. Conclusion and Recommendations

This study examined the relationship between urban sprawl, transport corridors, and traffic-related air pollution (TRAP) in Greater Gaborone, using a two-date land cover comparison (2006–2026) and a 2026 TRAP hotspot surface derived from Sentinel-5P TROPOMI NO_2 data. Built-up land area grew from 85.37 km² to 153.32 km², an increase of 79.6% over the study period. This growth was not confined to one part of the city. It occurred to the west, north, and east of the pre-2006 core, consistent with peri-urban villages coalescing towards central Gaborone.

The TRAP hotspot pattern is concentrated in this core and extends along two of the city's major roads, the A1 to the south and the A12 to the east, reaching as far as Mmopane and Tlokweng, both areas of substantial recent growth. Coldspots dominate elsewhere on the periphery, including areas that have also sprawled but sit farther from these corridors. TROPOMI's coarse spatial resolution means this study cannot fully distinguish a genuine transport-corridor effect from simple radial decay away from the core; both remain consistent with the evidence presented here. What is clear is that pollution has not spread uniformly with the built-up footprint: some growth areas already show elevated TRAP, while others, at least for now, do not.

This has two practical implications for Greater Gaborone. First, air quality and transport interventions are best targeted at the core and its road-based extensions, and at growth villages already showing elevated pollution, rather than assumed to be needed uniformly across all peripheral growth. Second, any such intervention faces a structural obstacle. Greater Gaborone, as delineated in this study, is a functional urban area assembled for analysis rather than a single administrative unit, and it falls under multiple separate local authorities. Addressing a metropolitan-scale pollution problem will require coordination across these authorities, or a national-level instrument, since no single one has planning jurisdiction over the area as a whole.

Ground-truthing the TROPOMI-derived hotspots against independent sensor or traffic-count data, and extending the pollution composite to the wet season, are further directions for future work. Extending this combined sprawl–TRAP analytical approach to Botswana's other secondary cities would also test how well these findings generalise beyond Gaborone.

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