

Spatial Analysis of Urban Settlement Distribution and Social Distancing Challenges in Ghana Using GRID3 Geospatial Data

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Abstract

Ghana's urban settlement patterns show strong spatial clustering, which has important ramifications for service delivery, urban planning, and public health. This study used the GRID3 Social Distancing dataset to examine the density and dispersion of urban settlements throughout Ghana. To find settlement hotspots, measure geographical compactness, and evaluate multi-scale clustering, spatial analytical methods such as Kernel Density Estimation (KDE), nearest-neighbor distance analysis, and Ripley's K and L functions were used. The findings show that settlements are strongly concentrated southward, with the Ashanti and Greater Accra regions having the largest densities and the northern savannah zones having more dispersed settlement patterns. While northern towns showed more isolation, creating logistical issues for service delivery, nearest-neighbor distances verified compactness in southern urban centers, emphasizing difficulties for social distancing and public health interventions. The existence of clustering across several spatial scales was statistically confirmed by Ripley's K and L functions. The results emphasize the necessity for distinct regional policies that strike a balance between infrastructure provision, urban expansion, and public health readiness, as well as the use of high-resolution geospatial databases like GRID3 for evidence-based planning. In order to promote focused service delivery, sustainable urban growth, and increased resilience in Ghanaian cities, this study offers vital insights.

1.0 Introduction

Urban settlement patterns across sub-Saharan Africa have been undergoing rapid transformation due to population growth, continuous urban expansion, and the spatial reorganization of human activity. Ghana reflects this trend clearly, with its urban population rising from 28.4% in 1984 to more than 56% by 2021 (GSS, 2021). This rapid expansion has resulted in densely clustered settlements, increased mobility, and mounting pressure on infrastructure and social services. These spatial dynamics strongly influence public health planning, disaster preparedness, social service delivery, and national development. The COVID-19 pandemic further exposed vulnerabilities in densely settled environments, where compact spatial arrangements significantly accelerated transmission and complicated containment strategies. Studies show that spatial compactness and clustering of human settlements heighten contact rates and increase the speed at which diseases spread (Rocklý & Sjödin, 2020; Hamidi, Sabouri & Ewing, 2020). Yet, across many African nations, the absence of high-resolution geospatial data has severely limited the capacity of planners and health authorities to assess social-distancing feasibility, identify high-risk settlement clusters, or design targeted interventions (Buchanan, Fifield & Riley, 2021). The GRID3 (Geo-Referenced Infrastructure and Demographic Data for Development) program developed through collaboration among the Global Partnership for Sustainable Development Data, UNFPA, Flowminder, and CIESIN was created to address such data and planning gaps. GRID3 provides harmonized spatial datasets, including population estimates, health facility locations, administrative boundaries, and detailed settlement layers, to support evidence-based planning in low- and middle-income countries (Bondarenko et al., 2022). Among these, the GRID3 Ghana Social Distancing Layer offers high-resolution data on the location, size, and dispersion of settlements derived from satellite imagery and remote-sensing methods (WorldPop, 2020). Each settlement centroid in the dataset includes attributes such as

settlement name, geographic coordinates, and urban extent identifiers. As the spatial determinants of health, mobility, and social well-being grow more evident, a nationwide analysis of settlement distribution, clustering patterns, and proximity relationships has become increasingly necessary. Such analysis provides critical insights into potential constraints on social-distancing measures, emergency response operations, population movement patterns, and regional variations in settlement structure.

Despite the availability of census data and administrative boundary maps in Ghana, the country lacks harmonized, high-resolution settlement datasets suitable for rigorous spatial analysis of clustering and public-health-related concerns such as social-distancing feasibility. Traditional datasets often aggregate information at broad administrative levels, masking local variations essential for understanding exposure risk and planning infrastructure effectively (UN-Habitat, 2020). During the COVID-19 pandemic, these limitations became particularly evident, as public health officials struggled to pinpoint high-density settlement clusters, identify communities with limited open space, or anticipate locations where settlement proximity could accelerate transmission (Agyeman, 2021). Beyond pandemic response, understanding settlement clustering is vital for planning health-facility locations, allocating emergency response resources, and monitoring urban expansion. National-scale spatial analysis of settlement patterns in Ghana remains limited due to the absence of tools to assess social-distancing feasibility using geospatial data, the lack of standardized datasets suitable for GIS-based analysis, limited integration of remote-sensing products into public health and development planning, and a general scarcity of studies that quantify nationwide clustering and proximity relationships among settlements. This study addresses these gaps by applying advanced geospatial analytical methods including kernel density estimation (KDE), nearest-neighbor distance (NND) analysis, and spatial clustering techniques to the GRID3 Social Distancing dataset to generate high-resolution, evidence-based insights into Ghana's settlement patterns.

The study maps and visualizes the spatial distribution of urban settlements in Ghana, analyzes clustering and density through KDE, computes nearest-neighbor distances to evaluate settlement compactness and potential social-distancing challenges, identifies hotspot regions with high settlement density, and provides spatial statistics relevant to public health, emergency response, and development planning. Through these contributions, the study enhances national capacity for geographically informed decision-making and strengthens the foundation for using geospatial intelligence in public health and sustainable development.

2.0 Materials and Methods

This section describes the study area, datasets, software, and analytical methods used in the study.

2.1 Study Area

Ghana is surrounded by Côte d'Ivoire, Burkina Faso, Togo, and the Gulf of Guinea. It is situated in West Africa between latitudes 4.5°N and 11.5°N and longitudes 3°W to 1°E. There is significant ecological and

settlement diversity among its sixteen administrative regions. With sparser settlement patterns in the northern savannah zones, urban centers are concentrated in the southern sector, especially in Greater Accra, Ashanti, Western, and Eastern Regions (GSS, 2021). Ghana is a perfect case study for national-scale spatial settlement analysis because of its diversity.

2.2 Data Sources

The GRID3 Ghana Social Distancing Layer (2020), which offers high-resolution geographic data on settlement dispersion throughout Ghana, served as the main dataset for this investigation. Feature identification numbers (FID), geographic coordinates (latitude and longitude), settlement names (urb_NAME), and distinct urban extent identification codes (uext_ID) are among the comprehensive spatial attributes included in this GeoJSON-formatted dataset. The GRID3 program has mapped and categorized each record to reflect a settlement centroid. The United Nations Population Fund (UNFPA), WorldPop at the University of Southampton, Flowminder Foundation, the Global Partnership for Sustainable Development Data, and the Center for International Earth Science Information Network (CIESIN) worked together to create the dataset. Its main goal is to offer accurate spatial data on the locations and sizes of settlements so that assessments pertaining to public health planning, social distancing viability, and settlement structure evaluation can be supported. When needed, additional spatial data on Ghana's administrative borders were added to the GRID3 dataset to improve the study. Regional or district-level shapefiles from reliable national and international sources were included in these boundaries. The United Nations Office for the Coordination of Humanitarian Affairs (OCHA) provided globally harmonized boundary files, although the Ghana Statistical Service (GSS) was the primary national repository for administrative boundary records. These layers made it possible for administrative units to compile settlement data for comparative analyses and summaries at the regional level.

Because of its strong capabilities in managing spatial datasets and using cutting-edge geospatial analysis techniques, the R statistical computing environment was used as the primary analytical platform in the study. To make the analysis easier, a number of R spatial libraries were used. Spatial files were read, managed, and altered using the sf package. Cartographic visualization was enabled by the tmap package, making it possible to create both static and interactive maps. The spatstat software was used for point pattern analysis, which included kernel density estimation and spatial pattern evaluation. Additional necessary libraries included dbscan for clustering analysis and tidyverse for data cleaning and processing. Together, these instruments offered a thorough spatial analytical framework appropriate for assessing Ghanaian settlement trends.

$$NND = \min_{j \neq 1} d(i, j)$$

1

Where;

NND = nearest-neighbor distance for settlement i

$d(i, j)$ = Euclidean distance between settlement i and another settlement j

The formula identifies the closest settlement to each point.

Equation (1) illustrates how the Euclidean distance between every pair of settlements was used to determine the nearest-neighbor distance for every settlement. A measure of spatial compactness is provided by the minimum distance, which shows how close each town is to its closest neighbor.

$$\hat{f}(x) = \frac{1}{nh^2} \sum_{i=1}^n K\left(\frac{x - x_i}{h}\right)$$

2

Where;

$\hat{f}(x)$ = estimated density at location x

n = number of settlement points

h = bandwidth (smoothing parameter)

K = kernel function (usually Gaussian)

x_i = coordinates of each settlement point

Settlement hotspots were found using Kernel Density Estimation. The estimator uses a kernel function to weight neighboring points in order to smooth the point pattern. The KDE formulation used to determine the density surface is shown in Eq. (2).

$$N_{\epsilon}(p) = \{q \in D \mid \text{dist}(p, q) \leq \epsilon\}$$

3

$$\lceil N_{\epsilon}(p) \rceil \geq \text{minpts}$$

Where;

$N_{\epsilon}(p)$ = neighborhood of point p within distance ϵ

$\lceil N_{\epsilon}(p) \rceil$ = number of points in that neighborhood

A cluster forms when enough points meet this density requirement. Based on density, the DBSCAN algorithm finds clusters. If the number of surrounding points within a given radius (ϵ) equals or

surpasses the minimal number of points needed to establish a dense region (*minpts*), the point is considered a core point. Equations (3a) and (3b) provide a mathematical expression for this.

2.3 Analytical Methods

The GRID3 dataset was cleaned, prepared, and projected to start the analytical process. The `st_read()` function from the `sf` package was used to import the GeoJSON file into the R environment. The dataset was converted from the default WGS84 coordinate system (EPSG:4326) to the Universal Transverse Mercator (UTM) Zone 30N projection (EPSG:32630), which is suitable for Ghana, because precise distance-based analyses need a projected coordinate reference system rather than a geographic one. This projection improved analytical precision by ensuring that spatial quantities like densities and distances were calculated in meters rather than degrees. The spatial distribution of settlements throughout the nation was investigated after projection. A first visual representation of the spatial arrangement of settlements in Ghana was created by mapping settlement sites using the `tmap` software. By assisting in the identification of broad trends like clustering tendencies or sparsely inhabited areas, this exploratory visualization provided a basis for further investigations.

Calculating nearest-neighbor distances (NND) to measure the proximity of towns to one another was the next step in the investigation. The `st_distance()` function and the `ngeo` package's nearest-neighbor search feature were combined to accomplish this. The measured distances made it possible to evaluate the compactness of settlements and shed light on regions with densely populated areas, which is crucial information for comprehending the viability of social distancing and potential public health issues. Using methods from the `spatstat` package, Kernel Density Estimation (KDE) was used to find regions where settlements form substantial clusters. KDE highlights spatial hotspots with exceptionally high settlement concentrations by converting the point pattern into a continuous density surface. Hotspot zones were identified by interpreting the density surface to find locations that were within high-density percentiles, usually the top 10–20%. These areas offer vital data for public health monitoring and urban planning.

The study used the DBSCAN clustering technique as an optional but complementary investigation to find settlement groupings that show density-based spatial clustering that goes beyond what KDE captures. DBSCAN provides a detailed understanding of settlement groups that may not be readily apparent from density surfaces alone. It is especially helpful in differentiating between core clusters, border points, and noise. In order to facilitate regional summaries, administrative boundary layers were finally incorporated into the analysis. The study measured the number and distribution of settlements inside each administrative unit by spatially connecting the settlement dataset with Ghana's regional or district boundaries. By connecting the findings with governmental administrative systems, this improved their policy relevance and made cross-regional comparisons easier.

3.0 Results and Discussions

Figure 1 shows the spatial distribution of Ghanaian urban settlements based on the GRID3 geospatial dataset. The locations of major cities and mapped urban communities are superimposed on the national

boundaries. To help explain the country's settlement patterns, the major cities Accra, Kumasi, Tamale, Takoradi, Cape Coast, Ho, Sunyani, Koforidua, Bolgatanga, and Wa are shown as reference points. The distribution of urban settlements is non-uniform and spatially clustered, according to the findings. The southern region exhibits a notable concentration of settlements, especially in the vicinity of Accra, Kumasi, Takoradi, and Cape Coast. These regions, which represent long-standing population concentration and economic activity along the coast and in the forest zone, make up Ghana's main urban belt.

The Upper East, Upper West, and Northern Region, on the other hand, show fewer but more scattered urban centers, which correspond to lower population densities and more expansive rural settlement patterns. However, metropolitan nodes like Bolgatanga, Wa, and Tamale serve as important regional hubs. Overall, the map's spatial arrangement emphasizes Ghana's urbanization's southward tilt, which has significant ramifications for disease transmission modeling, urban planning, and service delivery. For the ensuing investigations on clustering, density estimates, nearest-neighbor relationships, and hotspot detection, the visualization offers a fundamental insight.

The kernel density estimation (KDE) of urban settlement locations obtained from the GRID3 dataset is shown in Fig. 2. KDE shows regions where settlements are dense or geographically clustered by providing a smoothed, continuous surface. Finding underlying spatial features that might not be apparent when looking at individual points is made easier with the help of this technique. Ghana's density surface has significant spatial variability. The country's southern region, especially the vicinity of Accra, Kumasi, Cape Coast, Takoradi, and the surrounding peri-urban zones, is home to the higher-density areas, which are represented by warmer colors (yellow to green). These areas, which have historically seen rapid urbanization and population growth, serve as Ghana's main economic and metropolitan centers. Central and transitional zones, such as those surrounding Sunyani, Koforidua, and Ho, also have moderate densities. These patterns show secondary city development and rising urban growth, albeit at a lower intensity than in the southern metropolitan corridor.

Settlement densities are lower and more dispersed in the northern areas, such as Tamale, Wa, and Bolgatanga. Due to its regional significance, Tamale exhibits a localized density spike, although the overall density surface validates the difference in urban concentration between the north and south. This is consistent with more general demographic trends related to migrant flows, infrastructure accessibility, and economic prospects. Overall, the KDE results show that Ghana's urban settlements are heavily concentrated rather than dispersed randomly, with a significant concentration in the country's south and along important metropolitan corridors. Regional planning, service delivery, and public health initiatives are all impacted by this spatial pattern, particularly when it comes to identifying places where population density may increase the risk of disease transmission or make social distancing more difficult.

Table 1
Summary statistics of Nearest Neighbor Distance

Min	1st Qu.	Median	Mean	3rd Qu.	Max
0	4129	5606	7597	8675	45723
<i>Source: GRID3</i>					

The nearest-neighbor (NN) distances calculated for the GRID3 urban settlement locations are summarized in Table 1. Compactness or dispersal in the national settlement pattern is directly indicated by the NN metric, which measures the degree of proximity between communities. The findings show that settlement spacing varies greatly throughout the nation. The presence of settlements mapped very close to one another likely dense urban clusters or nearby built-up polygons captured in the dataset is suggested by the minimum NN distance of 0 m. For at least half of all communities, the closest neighboring settlement is located between around 4 and 6 km distant, according to the first quartile (4,129 m) and median (5,606 m). The influence of more dispersed settlements is shown in the mean NN distance of 7,597 m, especially in Ghana's rural and northern regions, where settlements are often farther apart. The third quartile (8,675 m), which indicates that 25% of settlements have neighbors more than 8.6 km distant, lends greater credence to this. Extreme occurrences of isolation are highlighted by the greatest NN distance of 45,723 m, which probably corresponds to remote villages or thinly populated areas.

Overall, the NN statistics show a mixed pattern of dispersal and compactness, which is consistent with Ghana's split settlement system, which consists of widely separated villages in the northern savannah region and dense urban agglomerations in the south. Planning for public health is significantly impacted by these trends, particularly when social alienation is involved. While significantly separated northern communities present difficulties for service delivery and emergency response logistics, areas with very short NN distances may have increased exposure hazards due to closely packed population centers.

The spatial distribution of nearest-neighbor distances among GRID3 urban communities throughout Ghana is shown in Fig. 3, which highlights notable regional differences in settlement spacing. Darker colors on the chart indicate shorter nearest-neighbor distances in the southern region of the country, especially in Accra, Kumasi, Cape Coast, Takoradi, and Ho. The existence of dense, closely spaced urban settlements that create continuous or semi-continuous built-up zones is reflected in this. The northern regions, on the other hand, have substantially greater nearest-neighbor distances and more scattered and isolated towns, which result in lighter color patterns on the map. The low-density settlement structure typical of northern Ghana is highlighted by the existence of isolated locations with extremely long nearest-neighbor distances. Overall, the map shows a distinct north-south gradient in settlement compactness, which has consequences for service delivery, spatial planning, and the possible spread of infectious illnesses.

Using the GRID3 settlement dataset, the KDE hotspot map shows the geographical distribution of Ghana's densest human settlements. The map emphasizes the regions with the strongest settlement clustering intensity because the technique only finds the top five percent of density values obtained from kernel density estimation. The most important nodes of human habitation in the nation are found in these zones, which are places where settlement points are densely packed within comparatively limited radii. Ghana's urban hierarchy, urban corridors, and regional patterns of settlement concentration may all be clearly visualized using this technique. The Greater Accra Metropolitan Area, where Accra and Tema comprise the largest and continuous high-density cluster in the dataset, is where the geographical distribution of hotspots shows a strong concentration. This area represents the largest and fastest growing urban environment in the nation and has the strongest and longest-lasting peak values. In the Ashanti Region, Kumasi comprises a wide, polycentric zone of intensive settlement clustering that stretches outward into neighboring municipalities, creating a comparable but more centrally placed hotspot. The linear urbanization that follows the coastal highway corridor is reflected in the concentrated band of settlement along the coast formed by Takoradi–Sekondi and Cape Coast. In the middle belt, Sunyani and Techiman exhibit moderate but clear hotspot signals, while in northern Ghana, Tamale forms the most prominent urban core, accompanied by smaller but notable hotspots around Wa and Bolgatanga. The map shows density levels ranging from peak intensities close to $1.6e-09$ in major urban centers to around $8.0e-10$ at the lower hotspot threshold. The most geographically compact settlement clusters in the underlying GRID3 point data are represented by these values. Geographically speaking, the hotspots together make up between three and five percent of Ghana's total land area; however, this can be exactly estimated if the shapefile or raster is available. Urban growth and population size have a significant impact on the regional distribution of hotspots; Greater Accra and Ashanti together account for around half of all high-density settlement zones, with the remaining portion coming from coastal areas and the northern urban triangle. These hotspots' forms and spatial organization provide more information about Ghana's patterns of settlement. Due to transportation-driven growth and urban sprawl, hotspots in the south, especially those surrounding Accra and Kumasi, are often lengthy and occasionally polycentric. Northern clusters, like Tamale or Bolgatanga, on the other hand, are more compact and conform to the region's traditional nucleated settlement formations. Since the hotspot zones show the locations most likely to see sustained growth, increased infrastructure demand, and higher degrees of human–environment interaction, these patterns have important ramifications for population management, infrastructure provision, and spatial planning.

All things considered, Ghana's most densely populated areas are clearly and data-driven represented by the KDE hotspot layer. It facilitates decision-making in the areas of service delivery, urban planning, demographic modeling, and catastrophe management. I can produce accurate area calculations, regional summaries, and other spatial data appropriate for technical reports or scholarly publications if you have the underlying KDE raster or hotspot polygons.

The results from Ripley's K and L functions provide a statistical confirmation of the clustering tendencies observed in the settlement distribution across Ghana. The K function curve rises consistently above the theoretical Poisson curve across nearly all distance bands, indicating that settlement points are more

aggregated than would be expected under a completely random spatial process. As distance increases, the divergence between the empirical $\widehat{K}_{iso}(r)$ and the theoretical $K_{pois}(r)$ becomes more pronounced, which reflects the presence of increasingly large clusters or urban agglomerations. The empirical curve maintains a noticeably higher trajectory than the random expectation beyond about twenty kilometers, indicating that settlements tend to form geographically dependent clusters rather than being independently distributed.

The L function, which is a variance-stabilized transformation of the K function, shows a similar pattern. The empirical $\widehat{L}_{iso}(r)$ lies consistently above the expected Poisson curve across the entire distance range, reinforcing the interpretation that the settlement pattern exhibits significant clustering. The upward deviation offers a more lucid and easily comprehensible visual representation of clustering intensity since the L function linearizes the K function. The empirical curve starts above the theoretical line at smaller distances, indicating that local-scale clustering is present even at short radii, which is in accord with the dense settlement patches observed in large cities. The presence of mesoscale and regional-scale clustering associated with Ghana's urban corridors and hierarchical settlement pattern is confirmed by the L function's continued rise and divergence from the Poisson reference as the distance grows. When combined, the K and L function results provide compelling statistical evidence that settlement locations show significant geographical dependence caused by urban expansion, transportation networks, and regional development trends rather than being distributed randomly. By demonstrating that clustering exists at various geographical scales, from small neighborhoods to vast metropolitan areas, these functions enhance the KDE hotspot mapping. The observed concentration of settlements near Accra, Kumasi, Tamale, and other important cities, as well as the extended settlement structures along inland and coastal transportation corridors, are consistent with this multi-scale clustering pattern.

4.0 Conclusion and Recommendation

The spatial analysis of Ghana's settlement patterns using GRID3 data shows a clear and persistent clustering structure shaped by historical development, economic opportunity, and ecological differences. Urban settlements are heavily concentrated in the south, especially around Accra, Kumasi, Cape Coast, and Takoradi, where kernel density maps and hotspot analyses reveal intense settlement clusters linked to long-standing investment patterns and migration flows. Secondary hotspots in Sunyani, Techiman, Ho, Tamale, Wa, and Bolgatanga highlight the emergence of secondary cities and expanding regional urban systems. Nearest-neighbor distance results indicate that southern settlements are compact and closely spaced, heightening contact rates and complicating disease-control measures, a concern reinforced during the COVID-19 pandemic. Conversely, northern settlements are widely dispersed, which reduces transmission risks but creates challenges for infrastructure provision, emergency response, and service delivery. Ripley's K and L functions confirm that clustering occurs across multiple spatial scales, reflecting a hierarchical settlement network anchored by major metropolitan centers. These patterns illustrate two contrasting spatial realities: dense, interconnected settlements in the south with potential

public health vulnerabilities, and dispersed settlements in the north with significant logistical constraints. Together, the findings demonstrate the need for regionally differentiated planning and underscore the importance of high-resolution spatial datasets like GRID3 for targeted, evidence-based decision-making. Strengthening infrastructure and essential services in high-density southern zones while expanding amenities and economic opportunities in low-density northern areas is essential for balanced national development. Effective land-use planning is needed to guide future settlement growth and prevent unplanned sprawl, and continuous geospatial monitoring will support adaptive, evidence-driven planning across sectors.

Declarations

Author Contribution

R.E. and E.A. conceived the study and designed the research framework. F.A.-M. and R.E. processed and analyzed the GRID3 geospatial dataset. R.E. performed the spatial statistical analyses and prepared Figures 1–3. R.E. and F.B.K.T. contributed to the kernel density estimation and clustering analyses and prepared Figures 4–6. R.E. and E.A. wrote the main manuscript text. I.A. and R.K.A. contributed to the discussion and conclusion. All authors reviewed, edited, and approved the final manuscript.

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Figures

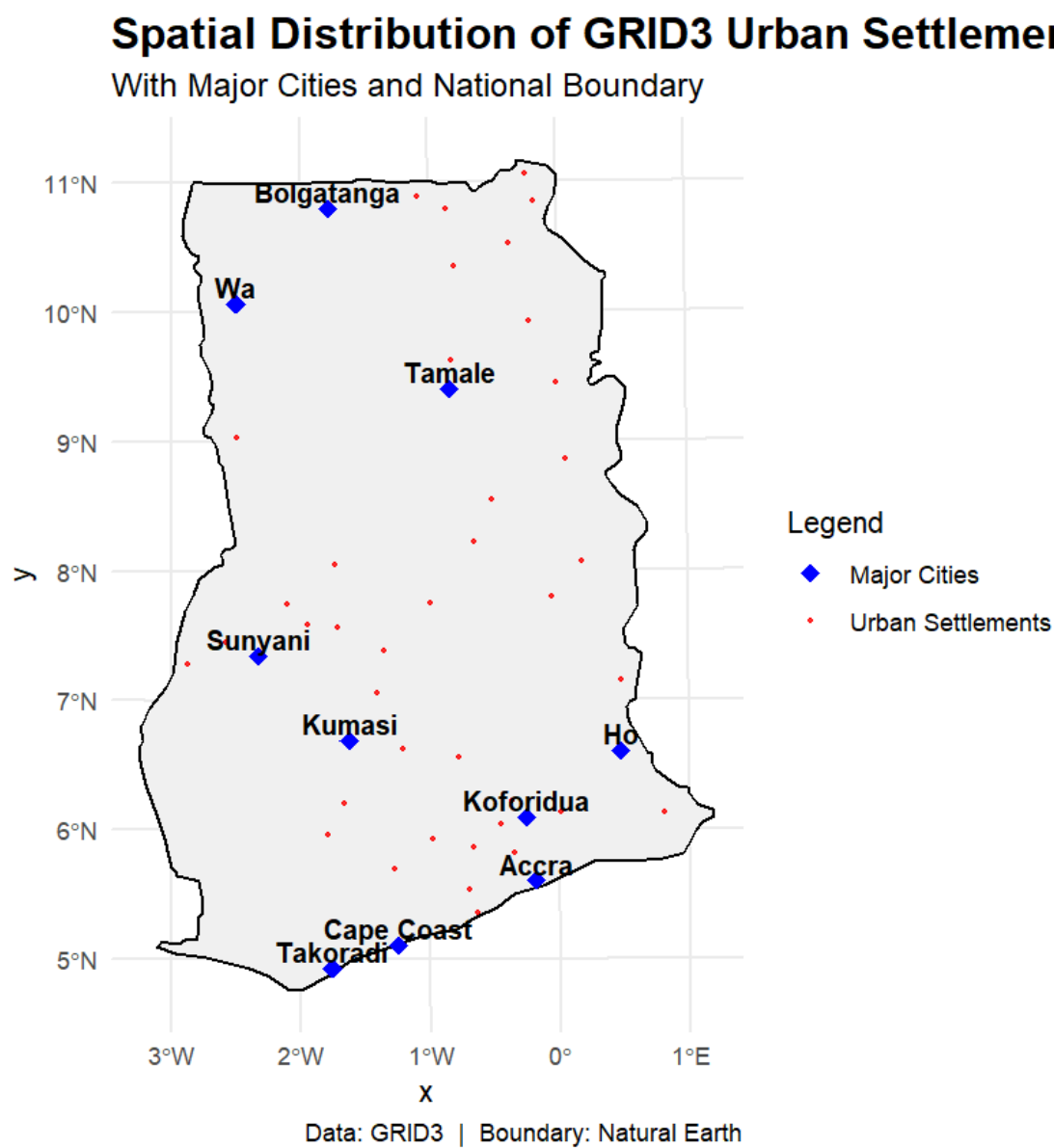


Figure 1

Distribution of Urban Settlements in Ghana

Source: GRID3

KDE of Settlement Density in Ghana

GRID3 Settlement Kernel Density Estimate

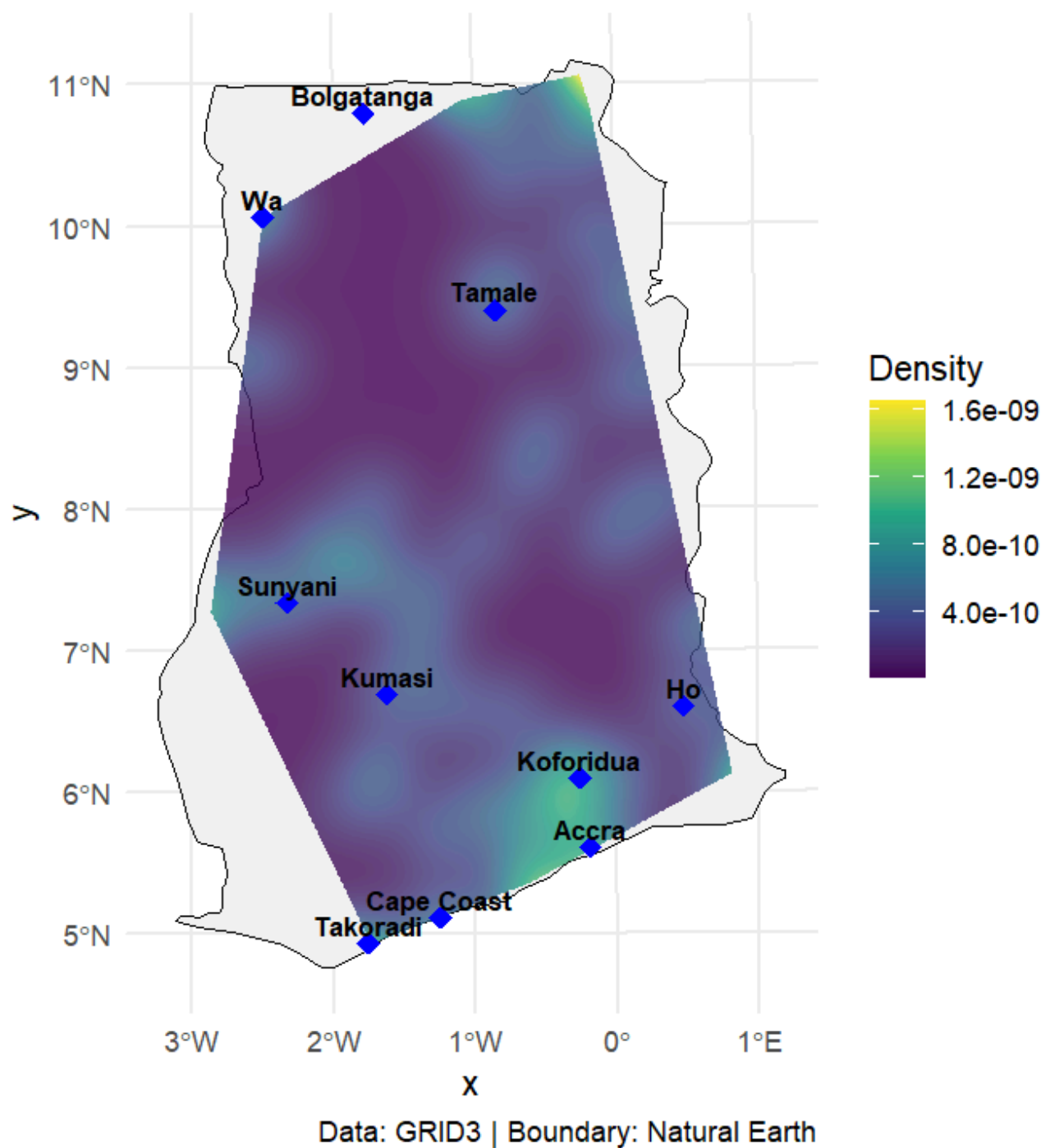


Figure 2

Spatial clustering and density of settlements using KDE

Source: GRID3

Nearest-Neighbor Distances Between Settlements

GRID3 Settlement Proximity

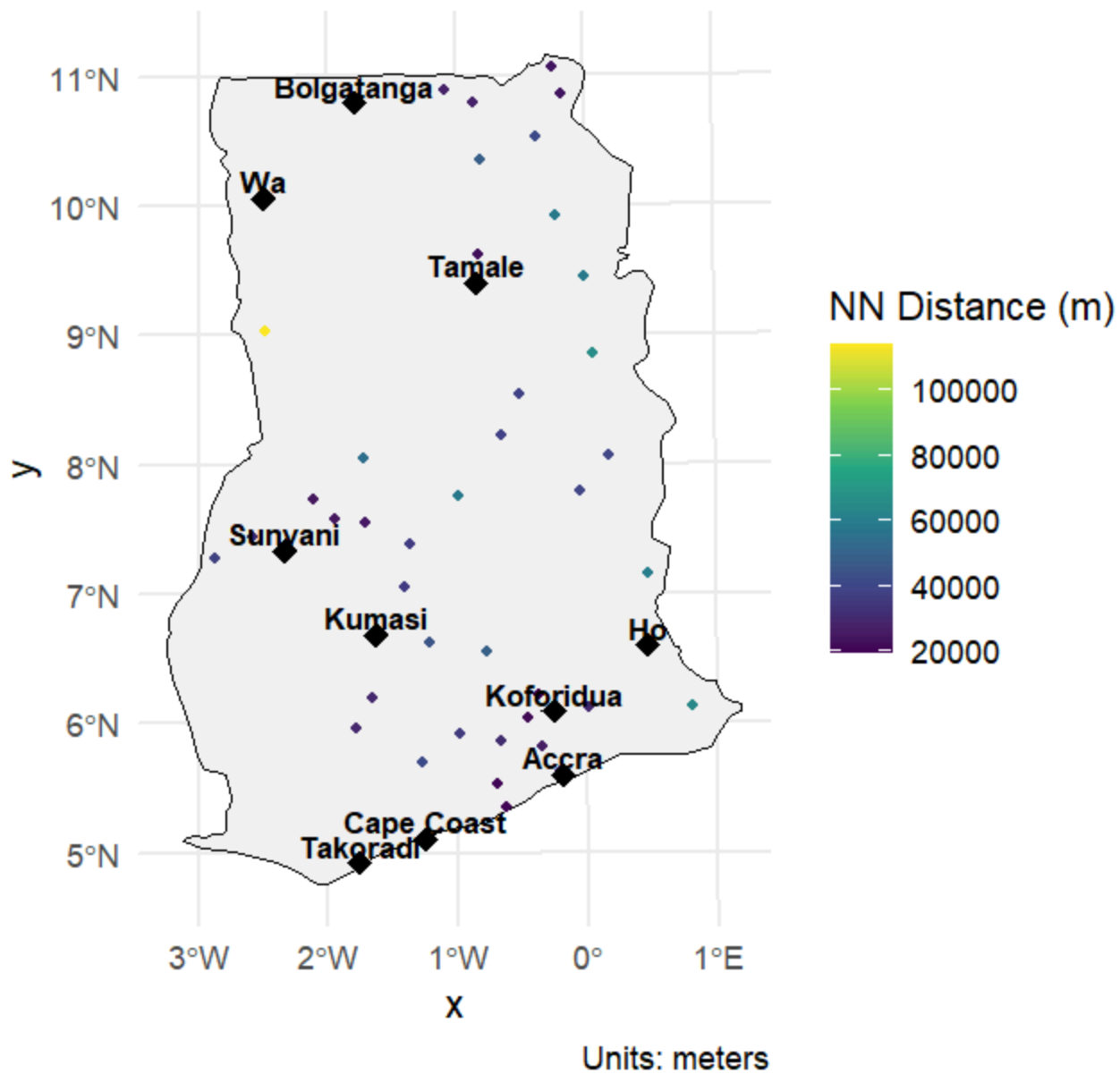


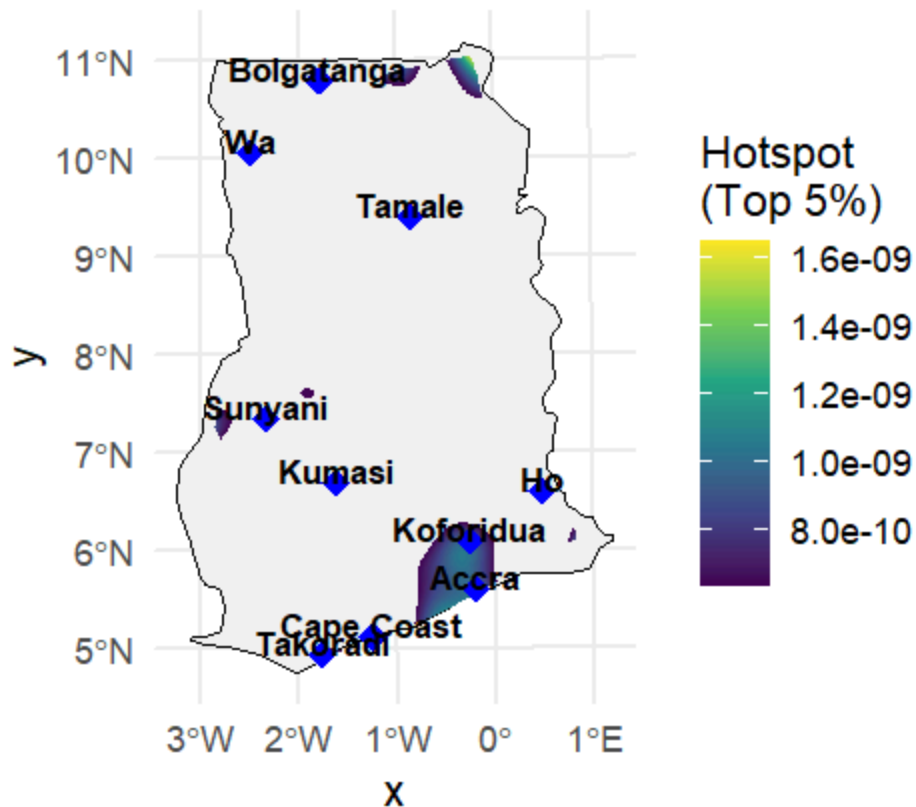
Figure 3

Nearest Neighbor Distances between Settlement

Source: GRID3

KDE Hotspot Map (Top 5% Density)

GRID3 Settlement Density Hotspots



Hotspots = areas with highest settlement concentration

Figure 4

Cities with high Settlement Density

Source: GRID3

Ripley's K Function for Settlement Clustering

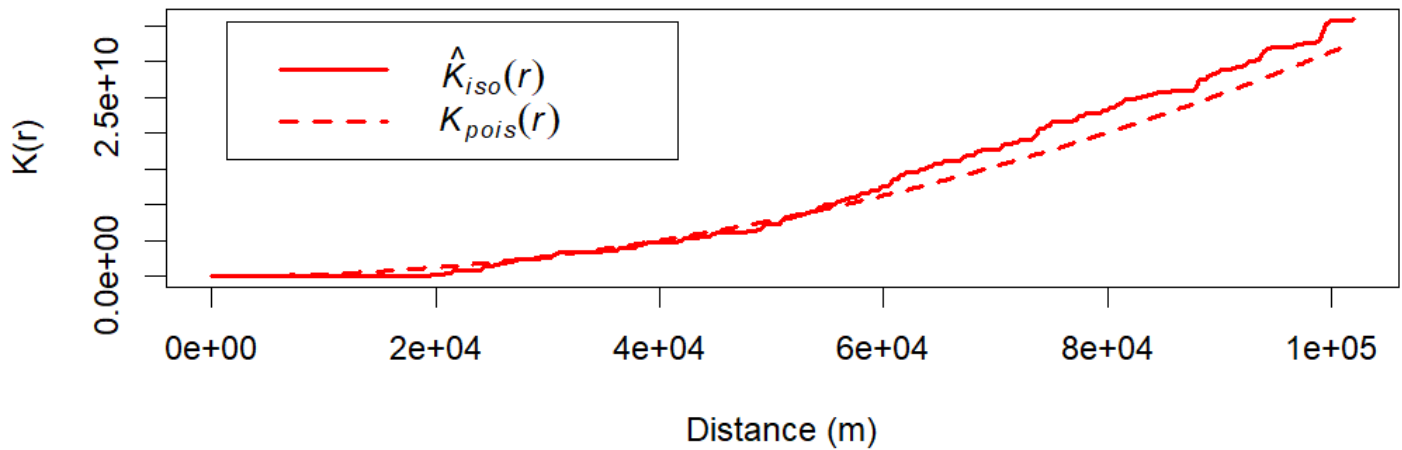


Figure 5

Ripley's K Function for Settlement Clustering

Source: GRID3

Ripley's L Function for Settlement Clustering

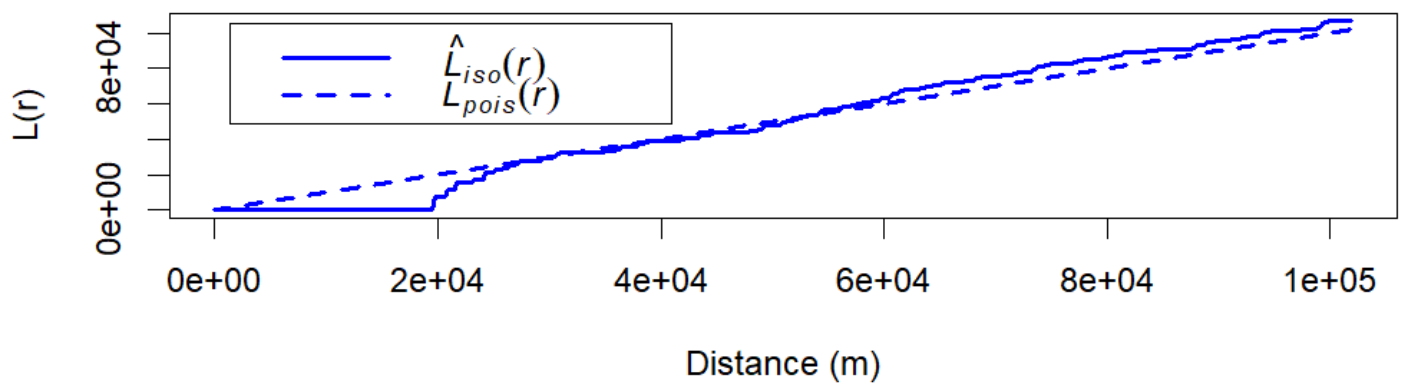


Figure 6

Ripley's L Function for Settlement Clustering

Source: GRID3

Supplementary Files

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