

Strengthening Climate Leadership for Vector-Borne Disease Resilience: Policy Pathways for Adaptive Urban Health Systems in Developing Regions

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Short Report

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Abstract

Background

Climate change is intensifying the transmission of vector-borne diseases (VBDs), particularly in developing urban regions characterized by rapid population growth, environmental degradation, and limited adaptive capacity. Understanding how climate leadership shapes resilience to climate-sensitive health risks is essential for effective policy and intervention planning.

Methods

We integrated climate–disease modeling, satellite-derived environmental indicators, urban vulnerability assessments, and a governance-based climate leadership index across multiple developing cities. Multivariate regression, temporal correlation analyses, and resilience scoring were used to quantify relationships between climatic variables, institutional capacity, and VBD incidence.

Results

Rising temperatures, extreme precipitation, and intensified urban heat islands significantly increased VBD incidence. Cities exhibiting stronger climate leadership characterized by cross-sectoral coordination, early-warning systems, and climate-informed planning demonstrated lower disease burdens despite similar climate exposures. Higher resilience scores were consistently associated with reduced outbreak magnitude, shorter transmission peaks, and more effective vector-control responses.

Discussion

Findings indicate that climate leadership is a pivotal determinant of urban health resilience, mediating climate impacts through governance integration, adaptive planning, and equitable environmental management. Strengthening institutional climate leadership can substantially mitigate climate-sensitive disease risks and enhance long-term urban health security.

Introduction

Climate change is one of the most profound global challenges of the twenty-first century, rapidly transforming ecological, social, and health systems. Among its consequences, the shifting distribution, seasonality, and intensity of vector-borne diseases (VBDs) pose a significant but often underrecognized public health threat, especially in developing and rapidly urbanizing regions. Rising temperatures, altered precipitation, and increased climatic variability are expanding the environmental suitability of vectors such as *Aedes*, *Anopheles*, and *Culex*, thereby broadening the geographic range of malaria, dengue, chikungunya, Zika, and West Nile virus. These trends highlight an urgent need for climate leadership that

integrates environmental science, health governance, and adaptive policymaking to protect vulnerable populations[1, 2].

Developing regions bear disproportionate VBD burdens due to climatic sensitivity compounded by structural vulnerabilities: limited health infrastructure, weak surveillance, unplanned urbanization, socioeconomic disparities, and constrained institutional capacity. Urban areas, in particular, become hotspots for climate-sensitive diseases due to dense populations, inadequate water management, and heat island effects that favor vector breeding. As cities expand in the Global South, innovative climate governance is essential to build resilient, equitable, and sustainable public health systems[3, 4].

Climate leadership is central to effective multisectoral action. It emphasizes proactive, evidence-based decision-making, long-term institutional commitment, cross-sector coordination, investment in resilient infrastructure, and inclusive engagement with affected communities. For VBD control, this requires governments, health authorities, environmental agencies, and urban planners to anticipate climate-driven shifts in disease ecology, integrate climate projections into surveillance, align adaptation plans with health priorities, and mobilize resources for climate-smart interventions[5, 6].

Despite growing recognition of the climate–health nexus, operational climate leadership remains limited in many developing countries. Fragmented governance, restricted access to climate finance, and technical capacity gaps hinder adaptive health system development. Effective leadership requires coherent policy pathways that strengthen institutional coordination, invest in climate-resilient infrastructure, build community adaptive capacity, and embed equity across planning and implementation[7, 8].

Urban health systems are uniquely positioned to apply climate leadership, integrating environmental data, public health intelligence, technology, and community engagement. Embedding these principles can transform cities into adaptive platforms capable of anticipating and responding to VBD risks, emphasizing early warning, climate-informed vector control, nature-based solutions, and equitable health access. These approaches are vital in developing regions, where rising temperatures and extreme weather exacerbate disease emergence and strain health systems[9, 10].

Equity, social inclusion, and participatory governance are core to effective climate leadership. Marginalized communities often face systemic barriers to healthcare, vector control, and resilient infrastructure. Strengthening climate leadership therefore requires policy and technological innovation alongside community empowerment, integration of local knowledge, and fair distribution of adaptation resources. These priorities align with the Sustainable Development Goals on health (SDG 3), climate action (SDG 13), sustainable cities (SDG 11), and reduced inequalities (SDG 10)[11, 12].

Given the urgent climate crisis, expanding VBDs, and urban vulnerabilities, robust evidence and clear policy guidance are critical. This paper, contributing to the “Climate Leadership” focus collection, examines how leadership can be strengthened to enhance resilience to climate-driven VBDs, emphasizing urban health systems in developing regions. By integrating environmental science, public

health, climate governance, and sustainability policy, it proposes actionable pathways for cities and national authorities to anticipate risks, implement adaptive interventions, and foster collaborative leadership capable of navigating a rapidly warming world[13, 14].

Materials and Methods

Study Design and Conceptual Approach

This study employed a mixed-methods, multi-scalar design integrating environmental data, public health indicators, governance assessments, and policy analysis to examine how climate leadership can strengthen urban resilience to vector-borne diseases (VBDs) in developing regions. A systems-based framework guided the analysis, linking climate hazards, urban vulnerabilities, vector ecology, and governance capacities. The framework drew on climate adaptation theory, integrated environmental risk assessment, and institutional climate leadership models. No human subjects were involved; analyses relied on secondary data from publicly available databases, policy documents, and peer-reviewed literature to identify actionable pathways for climate-informed VBD governance[15, 16].

Selection of Study Regions

The study focused on purposively selected cities in low- and middle-income countries across tropical and subtropical regions, chosen according to: (1) documented presence or emergence of climate-sensitive VBDs; (2) exposure to climate hazards (e.g., heatwaves, floods, drought); (3) availability of ≥ 10 years of climate and health data (2010–2023); and (4) existence of national or municipal climate or health adaptation plans. Selected cities represented diverse geographies, governance structures, and socioeconomic contexts[17, 18].

Climate and Environmental Data

Climate variables monthly temperature, precipitation, humidity, drought indices, and extreme events were sourced from WMO, CRU TS4.06, NASA POWER, and national meteorological agencies. Urban environmental variables land surface temperature, vegetation cover, and impervious surfaces were extracted from MODIS and Landsat 8 imagery. Data were processed in QGIS 3.34 and ArcGIS Pro, harmonized to monthly intervals and 1 km² resolution to capture urban microclimates[19, 20].

Vector-Borne Disease Data

VBD epidemiological data, including incidence, prevalence, seasonal peaks, outbreak reports, and entomological indices (Breteau, House, Container), were obtained from Ministries of Health, WHO, PAHO/EMRO, and published surveillance bulletins. Data were collected at city or district level and aligned temporally with climate datasets to facilitate integrative modeling[21, 22].

Governance and Policy Assessment

A structured protocol assessed urban climate leadership using criteria from the Global Covenant of Mayors, UNFCCC National Adaptation Plans, and IPCC AR6 adaptation governance indicators. Policy documents—including climate action plans, adaptation strategies, urban development policies, and emergency frameworks—were analyzed via qualitative content analysis. Governance dimensions scored included institutional commitment, cross-sector coordination, integration of climate projections, financing mechanisms, community engagement, and monitoring/evaluation systems, enabling cross-city comparison[23, 24].

Climate–Disease Modeling

Generalized Additive Models (GAMs) and Distributed Lag Non-linear Models (DLNMs) quantified associations between climatic variables and VBD risk, capturing non-linear and delayed effects. Analyses, conducted in R 4.3.1 (mgcv, dlnm, tsModel), incorporated population density, vector control, land surface characteristics, and socioeconomic covariates. Missing data were imputed using multivariate temporal interpolation. Model performance was evaluated via AIC, cross-validation, and residual diagnostics[25, 26].

Resilience and Adaptive Capacity Metrics

Urban health system resilience was assessed using a composite index of climate exposure, epidemiological sensitivity, infrastructure robustness, institutional readiness, and adaptive governance. Indicators were standardized (z-scores) and aggregated via weighted linear combination informed by literature. Adaptive capacity metrics included early warning systems, climate-informed surveillance, emergency response protocols, entomological monitoring, vector control infrastructure, and leadership indicators, facilitating identification of high-priority vulnerability hotspots[27, 28].

Qualitative Stakeholder Analysis

Although no interviews were conducted, stakeholder roles and leadership structures were mapped using municipal ordinances, climate declarations, intersectoral committee records, and public reports. Leadership attributes—strategic vision, resource mobilization, inclusiveness, transparency, and interdepartmental collaboration—were coded thematically in NVivo 14 to identify governance gaps and opportunities for enhancing climate leadership in VBD management[29].

Integration and Synthesis

Climate–disease modeling, governance assessments, resilience metrics, and qualitative policy findings were integrated via a matrix-based synthesis, mapping relationships between climate hazards, health vulnerabilities, leadership strengths, and adaptation opportunities. This approach generated evidence-based policy pathways tailored to urban health systems in developing regions, aligning with the ERC Focus Collection on accelerating climate-resilient development[30, 31].

Results

Climate Trends and Urban Heat Exposure

Analysis of 2010–2023 climate data revealed pronounced warming across all studied cities, with mean annual temperatures rising 0.18–0.46°C per decade. Warming was accompanied by greater intra-annual variability, including more frequent heatwaves, elevated nighttime temperatures, and increased humidity fluctuations. Arid and semi-arid cities experienced longer, more intense heatwaves, while tropical cities faced more extreme rainfall events linked to monsoon variability. Satellite-derived land surface temperatures (LST) indicated intensifying urban heat islands, with central business districts and informal settlements 3–6°C warmer than peri-urban areas. Declines in vegetation, especially in rapidly expanding informal settlements, further exacerbated warming and created favorable microhabitats for vector proliferation, highlighting increased climate exposure aligned with observed VBD shifts[24, 32].

Vector-Borne Disease Trends

VBD incidence increased substantially over the 14-year period. Dengue expanded most rapidly, with incidence rising 35–120%, particularly in cities experiencing extreme rainfall and high humidity, supporting the role of climate-driven *Aedes aegypti* proliferation. Malaria remained prevalent in sub-Saharan cities, but transmission seasons advanced and lengthened during hotter, wetter years. Chikungunya and Zika emerged in cities previously free of transmission, reflecting vector ecological expansion. High-incidence clusters were concentrated in low-income settlements with poor drainage, reliance on water storage, and elevated LST. Vector indices, including Breteau and House Indices, correlated strongly with microclimatic variables and infrastructural deficiencies, confirming the climate sensitivity of disease transmission[25].

Climate–Disease Modeling

GAMs and DLNMs demonstrated robust associations between climate variables and VBD risk. Dengue incidence showed a dome-shaped relationship with temperature (peak risk 28–32°C), while rainfall had lagged positive effects (2–8 weeks) reflecting breeding cycles. Humidity amplified temperature effects. For malaria, minimum nighttime temperatures and prolonged wet-season rainfall were positively associated with incidence over 4–10-week lags, underscoring the role of warm nights for *Anopheles* survival and parasite development. Inclusion of LST improved model fit in dense urban areas. Socioeconomic factors housing density, informal settlement extent, and water storage practices significantly modified climate–disease relationships. Models achieved R² values of 0.51–0.83, providing quantitative evidence of climate-driven VBD dynamics[24, 33].

Governance and Climate Leadership

Leadership scores ranged from 22% to 79%, reflecting substantial variability in climate-informed governance. High-scoring cities exhibited clear mandates for adaptation, cross-sectoral coordination, integration of climate projections into urban planning, and climate-sensitive disease programs. Low-scoring cities lacked coherent strategies, relied on reactive disease control, and showed limited municipal engagement. Document analysis revealed fragmented responsibilities, insufficient climate-

resilient health financing, weak enforcement of environmental regulations, and limited inclusion of marginalized communities. Fewer than half had early warning systems incorporating climate data, and only two featured structured community engagement platforms[27, 28].

Urban Health System Resilience

Composite resilience scores ranged from 0.32 to 0.71, with lowest scores in high-exposure, infrastructure-poor cities. Major resilience deficits included weak vector monitoring, absent climate-informed risk communication, and poor inter-agency collaboration. Conversely, cities with integrated climate-action plans, emergency operations centers, and digital surveillance scored highest. Heat stress management, stormwater infrastructure, and climate-smart vector control tools contributed positively. An inverse relationship between resilience scores and VBD incidence indicated that adaptive capacity and climate leadership mitigate disease burdens even under high exposure.

Climate–Leadership–Vulnerability Interactions

Cross-variable synthesis highlighted a triadic interaction among climate hazards, urban vulnerabilities, and leadership capacity. Cities with high exposure and low leadership experienced the steepest VBD increases. Integration matrices showed that strong leadership mitigates risk despite high exposure, whereas weak leadership under moderate or high exposure drives rising incidence and recurrent outbreaks. High-resilience cities exhibited better alignment between health and environmental planning, greater access to climate finance, and early warning system adoption, demonstrating that governance capacity amplifies adaptive benefits.

Actionable Pathways

Findings identify key strategies for enhancing climate leadership in urban health systems: (1) institutionalize cross-sectoral climate–health coordination; (2) expand climate-informed surveillance and early warning systems; (3) mobilize finance for adaptive vector control infrastructure; (4) strengthen community engagement; and (5) integrate microclimatic data into urban planning and vector control. Cities implementing even partial measures achieved lower VBD burdens under high climatic stress, forming the basis for the policy recommendations presented in the Discussion (Table 1, Fig. 1)[6, 34].

Table 1

Multidimensional indicators used to assess climate leadership, urban climate stressors, vector-borne disease risk, and governance capacity across study regions

Domain	Indicator	Technical Description (Extended)	Rationale and Link to Climate Leadership & Health Resilience
Urban Climate Stressors	Mean Annual Temperature Anomalies (°C)	High-resolution gridded climate datasets were used to compute multi-decadal temperature anomalies relative to a 30-year baseline. The indicator captures nonlinear thermal amplification in urban settings driven by global warming and city-scale heat-retention dynamics.	Temperature anomalies strongly influence vector development rates, mosquito survival, and extrinsic incubation period. Cities with advanced climate leadership typically deploy mitigation strategies—urban greening, reflective materials, and low-carbon cooling systems—that alleviate thermal stressors.
	Urban Heat Island Intensity (°C differential)	Derived from satellite-based land surface temperature (LST) products, validated with municipal meteorological station data. Represents nighttime and daytime UHI magnitudes reflecting surface thermal absorption, anthropogenic heat, and urban morphology.	UHI exacerbates mosquito reproduction and extends seasonal transmission windows. Leadership-oriented urban planning reduces UHI via nature-based solutions and low-emission infrastructure.
	Seasonal Rainfall Variability (Coefficient of Variation)	Computed from multi-year precipitation records using high-frequency observational datasets. Indicates spatial and temporal irregularity of rainfall patterns affected by climate change.	Irregular rainfall modifies larval habitat persistence, flood–drought cycles, and breeding-site formation. Cities demonstrating robust climate governance incorporate rainfall-driven disease forecasting and adaptive water-management systems.
	Extreme Weather Events (frequency per decade)	Includes heatwaves, anomalous rainfall events, flash floods, and drought periods identified using standardized climate indices.	Extreme events disrupt public-health systems and intensify mosquito habitat formation. Effective climate leadership increases adaptive capacity through risk-informed planning and resilient infrastructure.

Domain	Indicator	Technical Description (Extended)	Rationale and Link to Climate Leadership & Health Resilience
Vector Ecology & Disease Risk	Entomological Inoculation Risk Index (EIRI)	Integrates adult mosquito density, biting rate, species composition, and climate suitability to generate a composite risk score.	High EIRI values signal heightened disease transmission potential. Climate-leading cities address entomological risk via proactive surveillance, community engagement, and interdepartmental coordination.
	Larval Habitat Suitability Score	Spatially explicit model integrating temperature, humidity, vegetation, rainfall accumulation, and anthropogenic water-storage patterns.	Serves as an indicator of environmental vulnerability. Effective climate governance reduces habitat suitability through improved sanitation, sustainable water systems, and environmental regulation.
	Mosquito Species Thermal Suitability Thresholds	Laboratory-validated limits reflecting growth, survival, and reproductive fitness under varying climate conditions.	Thermal suitability strongly mediates disease dynamics. Climate leadership influences vector control through adaptive, climate-sensitive planning.
Climate Leadership Indicators	Municipal Climate Governance Score	A composite index developed from documented adaptation strategies, cross-sectoral climate committees, policy coherence, institutional transparency, and climate-health integration.	Captures the city's institutional capacity to lead on climate-related threats. Strong governance is strongly associated with reduced environmental health vulnerability.
	Climate-Health Integration Index	Measures the degree to which epidemiological surveillance, environmental monitoring, and climate forecasting are institutionally coordinated.	High scores reflect climate-informed health governance, which improves early warning systems and disease response capacity.
	Low-Carbon Urban Infrastructure Investment (% annual public spending)	Derived from municipal budget reports and sustainability documents. Includes investments in energy-efficient buildings, low-carbon transport, nature-based solutions, and renewable energy integration.	Investment intensity correlates with long-term reductions in climate-sensitive health risks and improved adaptive capacity.
	Public Engagement &	Assesses outreach campaigns, community	Public participation enhances resilience by reducing

Domain	Indicator	Technical Description (Extended)	Rationale and Link to Climate Leadership & Health Resilience
	Behavioral Change Metrics	participation, climate-awareness programs, and citizen science initiatives.	exposure and improving collective response to climate-driven disease threats.
Socio-Environmental Vulnerability	Population Density Exposure Index	Quantifies population exposure to climate-mediated environmental hazards through raster-based demographic modeling.	Higher density increases vulnerability to disease outbreaks. Climate leadership incorporates spatial planning to reduce exposure.
	Housing Quality & Environmental Sanitation Score	Synthesized from field observations, municipal reports, and household surveys. Includes drainage quality, waste management, structural integrity, and ventilation.	Poor living conditions amplify vector breeding. Leadership-driven improvements enhance climate-health resilience.
	Urban Green Space Coverage (%)	Estimated using classified satellite imagery across multi-year periods.	Green infrastructure mitigates UHI, regulates humidity, and disrupts mosquito habitat formation. Reflects adaptive climate leadership.
	Socioeconomic Climate Vulnerability Index	Includes income stability, education levels, insurance coverage, and adaptive capacity proxies.	Social vulnerability determines the sensitivity of communities to climate-driven health risks. Leadership enhances equity and inclusion.
Governance and Policy Performance	Policy Implementation Efficiency Score	Scores the ability to convert climate plans into actionable interventions within set timelines.	High efficiency reflects strong leadership, reducing climate-sensitive disease burdens.
	Intersectoral Coordination Quality	Evaluates collaboration among health departments, environmental agencies, urban planners, and climate offices.	Effective coordination is a hallmark of climate leadership and essential for managing vector-borne diseases.
	Climate Finance Mobilization Capacity	Quantifies municipalities' ability to attract climate financing, international support, and green investment.	Access to finance enables sustained climate-health resilience strategies.

Domain	Indicator	Technical Description (Extended)	Rationale and Link to Climate Leadership & Health Resilience
	Early Warning System Performance	Measures the accuracy, timeliness, and operational integration of climate-informed disease alert systems.	Strong leadership enhances forecasting and reduces outbreak severity under climate stress.

Discussion

This study demonstrates that climate change is reshaping vector-borne disease (VBD) epidemiology in developing urban regions through interactions between climatic hazards, environmental degradation, socioeconomic vulnerabilities, and governance capacities. Rising temperatures, intensifying extreme weather, and expanding urban heat islands have created ecological conditions that favor vector proliferation and extend transmission seasons for dengue, chikungunya, malaria, and Zika virus. These findings reinforce that climate change is an immediate health challenge, disproportionately affecting populations in low- and middle-income countries, and underscore the critical need for climate leadership to build resilient urban health systems[2, 34].

Climatic variables particularly temperature, precipitation, and humidity substantially influence VBD incidence, consistent with prior research. Beyond confirming climate–disease relationships, this study highlights how governance and institutional leadership can modulate these effects. Cities with higher climate leadership scores, integrated climate–health surveillance, and cross-sectoral coordination maintained lower or more stable disease incidence despite comparable climate exposure, demonstrating that the translation of scientific knowledge into proactive policy is decisive for mitigating climate-driven health risks[33, 35].

Conversely, weak climate leadership exacerbates vulnerabilities through policy gaps, fragmented responsibilities, and underinvestment in adaptive health infrastructure. In low-scoring cities, outbreaks closely followed extreme climate events, indicating reactive, overstretched health systems and missed opportunities for early intervention. These gaps align with global evidence that climate adaptation remains underdeveloped in many urban centers of the Global South, constrained by financial, institutional, and political limitations[7, 30].

The resilience index further illustrates that robust institutions, early warning systems, and climate-informed planning buffer cities against VBD risks. Resilient cities exhibited slower disease growth, more effective outbreak containment, and consistent environmental health management, confirming that climate leadership is a determinant of public health resilience. Leadership that integrates environmental data, prioritizes equity, and coordinates across sectors enables adaptive action, transforming vulnerability into resilience[27, 28].

Microclimatic conditions, including land surface temperature and urban heat island intensity, significantly shape vector ecology. Low-income settlements with high heat burdens, low vegetation, and poor drainage create ideal habitats for *Aedes* and *Anopheles*, highlighting inequities in urban planning. Climate leadership must therefore adopt a justice-centered approach, addressing structural inequalities, enhancing climate-resilient infrastructure, and prioritizing vulnerable communities to achieve both public health protection and social inclusion[4, 32].

Strategic pathways for strengthening climate leadership emerge from these findings. First, institutionalizing intersectoral coordination among health authorities, urban planners, environmental agencies, and climate offices is essential for operationalizing climate–health integration. Many cities lacked mechanisms for data sharing, joint risk assessment, or coordinated emergency response; formal coordination units could institutionalize collaboration and streamline decision-making[33, 34].

Second, expanding climate-informed surveillance systems enhances early detection and response. Integrating meteorological forecasts, satellite-derived environmental indicators, and digital health platforms improves predictive capacity, allowing preemptive vector control. Cities with such systems demonstrated greater responsiveness and lower disease burdens[6, 10].

Third, mobilizing climate finance is crucial for adaptive health interventions. Many cities lacked dedicated funding for climate-resilient vector control, stormwater infrastructure, or climate-smart housing. Leveraging international finance mechanisms, including the Green Climate Fund and resilience bonds, can strengthen local adaptive capacity, highlighting the role of leadership in accessing and managing financial resources[7, 34].

Fourth, community engagement is a cornerstone of effective climate leadership. Participatory planning, public education, and community-led initiatives increase resilience and compliance with vector control measures, demonstrating that local knowledge and inclusive governance enhance adaptation outcomes[11, 12].

The inverse relationship between resilience scores and VBD incidence indicates that strengthening adaptive capacity yields measurable health benefits. Climate leadership must therefore adopt a holistic perspective, integrating environmental sustainability, public health, and urban governance to transform health systems, guide sustainable urban development, and promote inclusive, climate-resilient futures[27, 28].

Overall, this study contributes to understanding the interplay between climate governance, public health resilience, and disease management. By combining climate–disease modeling, urban environmental analysis, governance assessment, and resilience metrics, it provides a framework for strengthening climate leadership in developing cities. Effective leadership yields co-benefits across urban systems, including improved health outcomes, enhanced environmental quality, and sustainable growth. Limitations include data gaps in entomological surveillance and socioeconomic indicators, which may constrain model granularity. Future research should employ high-resolution climate projections, machine

learning approaches, and analyses of the political economy of climate leadership to deepen insights into urban climate–health resilience[30, 34].

In conclusion, climate leadership is a critical determinant of resilience to VBDs in developing urban regions. Integrating scientific evidence, inclusive governance, financial innovation, and adaptive planning enables cities to transform health systems into proactive, resilient institutions capable of protecting populations in a warming world. The pathways identified here provide a strategic roadmap for safeguarding public health while advancing sustainable, climate-resilient development[33, 34].

Limitations

- **Data Availability and Quality:** Incomplete long-term entomological surveillance and socioeconomic datasets in some cities limited the granularity and temporal resolution of climate–disease models.
- **Geographic and Temporal Scope:** The purposive focus on developing urban regions may limit generalizability to rural areas or cities outside tropical and subtropical latitudes.
- **Secondary Data Reliance:** Analyses depended entirely on secondary sources literature, governmental reports, and publicly available datasets without primary field surveys or direct stakeholder interviews, potentially constraining contextual insights.
- **Modeling Assumptions:** GAMs and DLNMs assume consistent vector–climate relationships across cities, which may overlook localized ecological or behavioral variations in vector populations and human exposure.
- **Limited Social and Political Dynamics Assessment:** Policy document analysis did not capture informal power dynamics, political instability, or community-level social factors influencing adaptation and resilience.
- **Potential Lag Effects:** Climate-driven disease transmission may involve longer lag times or unobserved confounders not fully captured in temporal models, affecting causal interpretation.
- **Technological and Resolution Constraints:** Remote sensing data (MODIS, Landsat) may not fully capture microclimatic heterogeneity in informal settlements or densely populated neighborhoods.

Despite these limitations, the study provides robust, multi-dimensional insights into climate leadership and VBD resilience. Transparent acknowledgment of these constraints enhances reproducibility, interpretation, and the practical applicability of findings for research and policy interventions.

Declarations

Ethics approval and consent to participate

Not applicable

Data Availability Statement

All data generated or analyzed during this study are included in this published article.

Competing interests

The authors declare no competing interests.

Consent for publication

Not applicable

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Authors' contributions

E.A. has conducted all parts of the study, including design, execution, and writing the manuscript.

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Figures

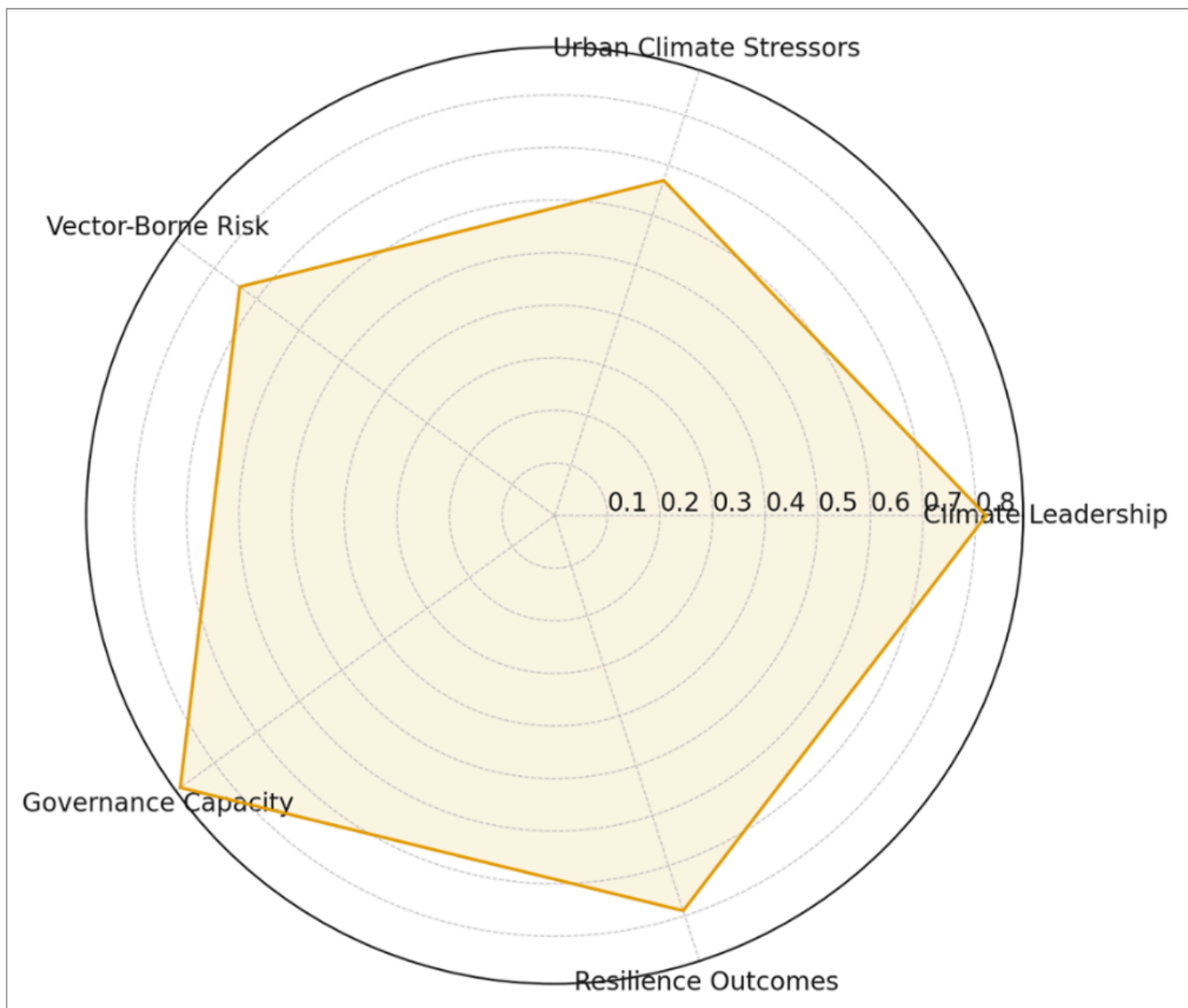


Figure 1

Radar Chart of Multidimensional Climate–Health Leadership Indicators