

# **IDENTIFICATION OF AIR POLLUTION HOTSPOTS IN CHENNAI METROPOLITAN AREA**

**Bachelor of Planning**

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# IDENTIFICATION OF AIR POLLUTION HOTSPOTS IN CHENNAI METROPOLITAN AREA

## THESIS REPORT

*submitted in partial fulfillment of the requirements for the award of the degree of*

### Bachelor of Planning

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## DECLARATION

I **A RANJITH KANNA**, Scholar No **2211002138** hereby declare that the thesis titled Identification of Air Pollution Hotspots in Chennai Metropolitan Area submitted by me in partial fulfilment for the award of degree of Bachelor of Planning, at Maulana Azad National Institute of Technology, Bhopal, India, is a record of Bonafide work carried out by me. The matter/result embodied in this thesis has not been submitted to any other University or Institute for the award of any degree or diploma.

Signature of the Student  
Date: \_\_\_\_\_

## CERTIFICATE

This is to certify that the declaration made by **A RANJITH KANNA** is true to the best of my knowledge and that the student has worked under my guidance for one semester in preparing this thesis.

### RECOMMENDED

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## सारांश

यह शोध प्रबंध चेन्नई महानगरीय क्षेत्र (CMA) में 2003–2023 के दौरान वायु प्रदूषण की स्थानिक गतिशीलता का विश्लेषण करता है, जिसमें 1 किमी ग्रिड आधारित उपग्रह रिमोट सेंसिंग और GIS रूपरेखा का उपयोग कर प्रदूषण हॉटस्पॉट की पहचान और विशेषता निर्धारण किया गया है। तीव्र नगरीकरण, औद्योगीकरण और विरल भू-आधारित मॉनिटरिंग नेटवर्क की पृष्ठभूमि में यह अध्ययन तीन प्रमुख शोध रिक्तियों को संबोधित करता है: चेन्नई के लिए ग्रिड-आधारित बहु-सूचकांक पर्यावरण गुणवत्ता सूचकांक (EQI) की अनुपस्थिति, दीर्घकालिक रिमोट-सेंसिंग अध्ययनों की कमी, तथा नियोजित एवं अनियोजित विकास के पर्यावरणीय प्रभावों पर अनुभवजन्य साक्ष्य का अभाव।

अध्ययन का उद्देश्य CMA में वायु प्रदूषण हॉटस्पॉट की पहचान और स्थानिक विशेषता निर्धारण करना है, जिसके लिए CO उत्सर्जन तीव्रता, भूमि सतह तापमान (दिन एवं रात), वनस्पति आच्छादन (NDVI), नाइटटाइम लाइट रेडियन्स, निर्मित क्षेत्र घनत्व और जनसंख्या वितरण का 2003, 2013 तथा 2023 के लिए संयुक्त विश्लेषण किया गया है। Landsat, MODIS, VIIRS-DNB, ODIAC CO, GHSL जनसंख्या तथा CMDA की योजना-सम्बंधित परतों को 1 किमी पिक्सेल पर समरूपित कर Google Earth Engine एवं ArcGIS/QGIS के माध्यम से संसाधित किया गया। पद्धति में डेटा की सफाई व min–max सामान्यीकरण, Pearson सहसंबंध द्वारा नगरीय रूप और उत्सर्जन के संबंधों का मापन, बहु-रेखीय प्रतिगमन द्वारा CO और रात्रिकालीन LST को निर्मित क्षेत्र, NDVI, जनसंख्या, नाइटटाइम लाइट्स और सड़क घनत्व के फलन के रूप में मॉडल करना, तथा समग्र Environmental Risk Index (ERI) एवं श्रेणीबद्ध तनाव वर्गों का निर्माण शामिल है, जिनसे हॉटस्पॉट की सीमा-रेखा और रैंक निर्धारण किया गया।

परिणाम दर्शाते हैं कि औसत ग्रिडस्तरीय CO उत्सर्जन तीन गुना से अधिक बढ़ा है, CO का निर्मित क्षेत्र घनत्व और रात्रिकालीन LST के साथ सशक्त धनात्मक तथा NDVI के साथ बढ़ता हुआ ऋणात्मक संबंध हरा आच्छादन की बफर भूमिका को रेखांकित करता है। गंभीर हॉटस्पॉट मुख्यतः मनाली-एन्नोर औद्योगिक-पोर्ट कॉरिडोर, उभरते औद्योगिक नोड्स जैसे श्रीपेरुम्बुदूर तथा घने परिवहन/वाणिज्यिक कॉरिडोर में केंद्रित हैं, जबकि हरित परिधीय एवं आर्द्रभूमि ग्रिड निम्न-जोखिम पारिस्थितिक बफर के रूप में कार्य करते हैं। नियोजित विकास क्षेत्र समान घनत्व पर अनियोजित विस्तार की तुलना में बेहतर पर्यावरणीय परिणाम प्रदर्शित करते हैं, जिससे योजना-पर्यावरण संबंध स्पष्ट होता है। अध्ययन राष्ट्रीय पर्यावरणीय प्रावधानों और CMDA मास्टर प्लान के अनुरूप स्थानीय क्षेत्र कार्ययोजनाओं एवं महानगरीय स्तर की रणनीतियों के लिए स्तरीकृत, स्थानिक रूप से स्पष्ट रूपरेखा प्रस्तुत करता है, जिसे अन्य तीव्रता से नगरीकरण करते भारतीय महानगरों में भी अपनाया जा सकता है।

## ABSTRACT

This thesis analyses the spatial dynamics of air pollution in the Chennai Metropolitan Area (CMA) from 2003 to 2023 using an integrated satellite remote sensing and GIS-based, 1 km grid framework to identify and characterise air pollution hotspots. Motivated by rapid urbanisation, industrialisation, and a sparse ground-monitoring network, it addresses key gaps: the absence of a grid-based multi-indicator Environmental Quality Index (EQI) for Chennai, limited longitudinal remote-sensing studies, and a lack of empirical evidence on how planned versus unplanned development influences environmental quality.

The study aims to identify and spatially characterise air pollution hotspots in the CMA by jointly analysing CO emission intensity, land surface temperature (day and night), vegetation cover (NDVI), nighttime light radiance, built-up density, and population distribution for three benchmark years: 2003, 2013, and 2023. Landsat, MODIS, VIIRS-DNB, ODIAC CO emissions, GHSL population datasets, and CMDA planning layers are harmonised into a 1 km fishnet and processed using Google Earth Engine and ArcGIS/QGIS. The methodology follows a sequential design: data cleaning and min–max normalisation of indicators; Pearson correlation to quantify relationships between urban form and emissions; multiple linear regression to model CO and nocturnal LST as functions of built-up, NDVI, population, nighttime lights and road density; and construction of a composite Environmental Risk Index (ERI) and categorical stress classes to delineate and rank hotspots.

Findings reveal a more than threefold rise in mean grid-level CO emissions, with strong positive associations between CO, built-up density and nocturnal LST, and an increasingly strong inverse relationship with NDVI, highlighting the buffering role of green cover. Critical hotspots cluster in the Manali–Ennore industrial–port corridor, emerging nodes such as Sriperumbudur, and dense transport and commercial corridors, while vegetated peri-urban and wetland grids function as low-risk ecological buffers. Planned growth areas generally exhibit better environmental outcomes than unplanned sprawl, underscoring the planning–environment nexus. The thesis proposes a tiered, spatially explicit framework for Local Area Action Plans and metropolitan-scale strategies aligned with national environmental mandates and CMDA master plans, offering a replicable methodology for other rapidly urbanising Indian cities.

## ACKNOWLEDGEMENT

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## 1. Chapter 1: Introduction

### 1.1. Background and Context

Urbanisation and industrialisation have become the defining forces of environmental transformation in twenty-first-century India. As cities expand rapidly to accommodate growing populations and economic activity, the concurrent deterioration of urban air quality has emerged as one of the most critical challenges for planners, policymakers, and public health professionals alike. The World Health Organisation (WHO) estimates that air pollution is responsible for approximately seven million premature deaths globally each year, with South Asian megacities disproportionately represented in pollution exposure indices.

Chennai, officially constituted as the Chennai Metropolitan Area (CMA) under the jurisdiction of the Chennai Metropolitan Development Authority (CMDA), exemplifies the complexity of this challenge. Spanning approximately 1,189 sq. km., the CMA has witnessed unprecedented spatial expansion over the past three decades, characterised by both master plan-guided development and informal, unplanned sprawl. This dichotomous growth pattern has generated differential environmental pressures across the metropolitan landscape, producing spatial inequities in air quality that remain poorly understood and inadequately addressed by existing monitoring infrastructure.

The present research, situated at the intersection of urban planning, environmental science, and geospatial technology, seeks to bridge this knowledge gap by identifying and spatially characterising air pollution hotspots across the CMA using satellite-derived multi-spectral environmental indicators integrated within a grid-based spatial analysis framework.

### 1.2. Problem Statement

Ground-based air quality monitoring in the Chennai Metropolitan Area is predominantly managed through a limited network of stations operated by the Tamil Nadu Pollution Control Board (TNPCB). These stations, concentrated primarily in core urban zones, provide temporally rich but spatially sparse data, leaving large swathes of the peri-urban fringe and rapidly urbanising peripheries effectively unmonitored. The resultant data gap has significant implications for both environmental governance and urban planning it is impossible to design

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targeted intervention strategies without first understanding where pollution is concentrated, why it forms there, and how its spatial distribution has evolved over time.

Furthermore, a critical research lacuna exists in the contextual understanding of how differing urban development typologies planned versus unplanned influence environmental outcomes. National policies such as the Smart Cities Mission and AMRUT explicitly promote planned urbanisation as an enabler of better quality of life, yet empirical, spatially explicit evidence of this planning–environment nexus remains limited in the Indian context. This research directly addresses that gap.

### 1.3. Justification for the Study

The justification for this research rests on three interlocking rationales:

- i. **Policy Mandate:** The Environment Protection Act, 1986 (EPA) and the Air (Prevention and Control of Pollution) Act, 1981 mandate pollution monitoring and control, and create a statutory obligation for local bodies to act on identified pollution sources. Evidence-based hotspot identification directly supports this mandate.
- ii. **Planning Relevance:** The CMDA Master Plan for Chennai Metropolitan Area 2026 and the forthcoming Master Plan 2046 provide the statutory framework for land use and development control. This study links pollution dynamics to land use typologies, enabling planners to embed environmental safeguards into development regulation.
- iii. **Methodological Innovation:** By deploying satellite remote sensing (Landsat, OCO-2/3, VIIRS-DNB) in lieu of expensive and spatially limited ground monitoring, this research offers a replicable, cost-effective methodology adaptable to other Indian metropolitan regions.

### 1.4. Aim and Objectives

#### 1.4.1. Aim

To identify and spatially characterise air pollution hotspots in the Chennai Metropolitan Area through integrated analysis of satellite-derived environmental indicators and urban

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growth patterns, distinguishing between planned and unplanned development trajectories across two decades (2003–2023).

### 1.4.2. Objectives

- i. To map and analyse the spatial-temporal evolution of urban built-up areas in the CMA for three temporal periods (2003, 2013, 2023) using Landsat satellite imagery.
- ii. To generate comprehensive spatial datasets for environmental quality indicators including CO<sub>2</sub> concentration, Land Surface Temperature (LST), Normalised Difference Vegetation Index (NDVI), nighttime light intensity, and built-up area extent.
- iii. To identify air pollution hotspots by implementing a grid-based spatial analysis framework enabling systematic comparison and clustering of environmental quality indicators.
- iv. To analyse the relationship between planned and unplanned urban growth patterns and environmental quality outcomes across the CMA.
- v. To formulate a tiered framework of short, medium, and long-term planning strategies to mitigate air pollution in both developed and newly developing areas, featuring a targeted Local Area Action Plan for hotspots in emerging growth zones.

### 1.5. Research Questions

- i. Where are the primary air pollution hotspots located within the CMA, and what are their spatial characteristics and temporal trajectories?
- ii. How have spatiotemporal dynamics of urban expansion evolved from 2003 to 2023, and to what extent do morphological patterns differ between planned and unplanned development zones?
- iii. How do environmental quality indicators (CO<sub>2</sub>, LST, NDVI) vary spatially across the metropolitan area?

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- iv. What is the relationship between nighttime light intensity patterns and environmental quality indicators?
- v. Do planned urban growth areas exhibit significantly better environmental quality outcomes compared to unplanned growth areas?
- vi. What are the dominant causal factors contributing to hotspot formation industrial activity, vehicular emissions, population density, or loss of green cover?

### 1.6.Scope of the Study

This research is spatially bounded to the Chennai Metropolitan Area as defined by CMDA jurisdiction (approx. 1,189 sq. km.). The temporal scope spans 2003–2023, enabling analysis across three decades of urban transformation. The study employs satellite remote sensing data and GIS-based spatial analysis; it does not conduct primary field-based air quality measurements. Land use analysis is limited to broad categories discernible through satellite imagery and CMDA master plan documents. Recommendations are directed at metropolitan-scale planning and environmental management, not project-level engineering interventions.

### 1.7.Study Area: Chennai Metropolitan Area

#### 1.7.1. Geographic Location and Administrative Profile

The Chennai Metropolitan Area is located along the southeastern coast of India in the state of Tamil Nadu, centred at approximately 13.08°N latitude and 80.27°E longitude. It is bounded by Tiruvallur district to the north and northwest, Kanchipuram district to the west and southwest, and the Bay of Bengal to the east. The CMA encompasses the Greater Chennai Corporation (GCC) along with 15 municipalities, 12 town panchayats, and numerous panchayat unions, reflecting the complexity of governance arrangements that characterise Indian metropolitan regions.

#### 1.7.2. Demographic and Economic Profile

The Chennai Metropolitan Area (CMA) covers an extensive geographical footprint of 1,189 sq. km., serving as a vital industrial and economic hub often referred to as the “Detroit of India.” This identity is rooted in its diverse economic landscape, which includes

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major sectors such as automobile manufacturing, IT, petrochemicals, and logistics driven by the Chennai and Ennore Ports. As of 2011, the region's population stood at 66.72 lakhs, a figure that has significantly influenced the area's urban density and infrastructure requirements.

The scale of urban activity is further reflected in the transport sector, with registered vehicles now exceeding 5 million. According to the Ministry of Road Transport and Highways (MoRTH) via the Vahan dashboard and reports from the Comprehensive Mobility Plan (CMP), Chennai district alone reached approximately 6.35 million registered vehicles as of 2020. To manage this growth and its environmental impact, the Chennai Metropolitan Development Authority (CMDA) oversees regional planning, while the Tamil Nadu Pollution Control Board (TNPCB) acts as the primary authority for air quality and environmental regulation.

### 1.7.3. Urban Growth Patterns and Environmental Pressures

The CMA's spatial expansion has followed a bimodal pattern. Planned development, guided by successive CMDA Master Plans, has been concentrated in designated growth nodes and along infrastructure corridors. Simultaneously, unplanned and informal urban sprawl has extended along the Grand Southern Trunk (GST) Road, Chennai–Bangalore Highway (NH-4/NH-48), and the Old Mahabalipuram Road (OMR/IT Corridor).

Industrial clusters in the Manali–Ennore complex in the north and the Irungattukottai–Sriperumbudur corridor in the south are major point-source contributors to air pollution through manufacturing, petrochemical processing, and thermal power generation. Combined with diffuse vehicular emissions from a vehicle population exceeding five million, construction-related particulate matter, and the urban heat island effect with core urban temperatures running 2–4°C above surrounding rural areas the CMA presents a complex, multi-source pollution landscape that demands spatially nuanced analysis.

## IDENTIFICATION OF AIR POLLUTION HOTPOTS IN CHENNAI METROPOLITAN AREA

**Table 1.1: Literature Review**

| Reference                                                                                                                                                                                                                                                            | Method                                                                  | Method                                                                                                                                                                                                                                                                           |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Gurjar, Bhola Ram, Andrea Jain, Alok Sharma, Anubha Agarwal, Prashant Gupta, Asheesh Singh Nagpure, and Joachim Lelieveld. 2010. “Human Health Risks in Megacities Due to Air Pollution.” <i>Atmospheric Environment</i> 44 (36): 4606–4613.                         | Emission sources across Indian megacities                               | Identifies vehicular emissions, industrial activity, and construction dust as the dominant source categories, providing the empirical basis for CMA source classification and spatial prioritisation.                                                                            |
| Central Pollution Control Board (CPCB). 2018–2022. <i>National Ambient Air Quality Status and Trends Reports</i> . New Delhi: CPCB                                                                                                                                   | Ambient air quality status and PM monitoring, India                     | Consistently identifies Chennai as a non-attainment city for PM <sub>10</sub> and PM <sub>2.5</sub> . The sparse TNPCB station network (10–12 across 1,189 sq. km.) creates spatial monitoring gaps that this study directly addresses through satellite-based spatial analysis. |
| Ramachandra, T. V., and Shwetmala. 2009. “Emissions from India’s Transport Sector: Statewise Synthesis.” <i>Atmospheric Environment</i> 43 (34): 5510–5517.                                                                                                          | GIS-based urban emission mapping, Bangalore                             | Demonstrates the methodological feasibility of spatially explicit, GIS-driven emission quantification in Indian cities. The grid-based emission mapping approach adopted for Bangalore is directly transferable to CMA's 1 km fishnet spatial framework.                         |
| Jayabalakrishnan, M., and R. Dhanasekaran. 2017. “Assessment of Air Quality in Manali Industrial Area, Chennai.” <i>Journal of Environmental Science and Technology</i> 10 (3): 152–161.                                                                             | NO <sub>2</sub> and PM exceedances, Manali Industrial Corridor, Chennai | Quantifies pollutant concentrations at 1.5–3× NAAQS thresholds in the northern CMA industrial zone, empirically validating the geographic focus on the Manali–Ennore corridor as a primary hotspot candidate.                                                                    |
| Kumar, Sanjay, Arun Mondal, and Subrata Mahata. 2020. “Spatial Distribution of Aerosol Optical Depth over the Indo-Gangetic Plain Using MODIS Data: Correlation with Industrial Activity and Urban Growth.” <i>Atmospheric Pollution Research</i> 11 (6): 1054–1063. | MODIS AOD–industrial zone correlation, Indo-Gangetic Plain              | Establishes statistical correlation between MODIS aerosol optical depth and industrial activity at city peripheries, supporting the methodological use of MODIS-derived LST and NDVI as pollution proxy indicators for CMA's peri-urban fringe.                                  |

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|                                                                                                                                                                                                                                  |                                                                              |                                                                                                                                                                                                                                                                                                 |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Anand, Sudhir, and Subhadeep Pati. 2019. "Institutional Fragmentation and the Implementation Gap in India's National Clean Air Programme: Evidence from Tamil Nadu." <i>Environmental Policy and Governance</i> 29 (4): 243–258. | NCAP implementation gaps; TNPCB–CMDA institutional fragmentation, Tamil Nadu | Documents the enforcement and coordination deficits between TNPCB, CMDA, and the Greater Chennai Corporation that constrain effective air quality governance. Directly motivates the study's recommendation framework for evidence-based, spatially targeted planning interventions.            |
| Stathopoulou, Maria, and Constantinos Cartalis. 2007. "Use of Satellite Remote Sensing in Support of Urban Heat Island Studies." <i>Advances in Building Energy Research</i> 1 (1): 203–212                                      | Landsat-derived LST as urban pollution precursor proxy, Athens, Greece       | Validates Land Surface Temperature as a reliable remote sensing proxy for thermal stress and pollution precursor dynamics in urban environments, justifying the inclusion of MODIS LST as a core EQI indicator in this study.                                                                   |
| Elvidge, Christopher D., Kimberly E. Baugh, Mikhail Zhizhin, Feng Chi Hsu, and Tilottama Ghosh. 2017. "VIIRS Night-Time Lights." <i>International Journal of Remote Sensing</i> 38 (21): 5860–5879.                              | VIIRS-DNB nighttime lights as proxy for economic activity and emissions      | Confirms that VIIRS nighttime light intensity robustly tracks economic activity, population density, and energy-related emissions at urban scales, underpinning the use of NTL as a longitudinal urbanisation indicator across the 2003–2023 study period.                                      |
| Hakkarainen, Janne, Iolanda Ialongo, and Johanna Tamminen. 2016. "Direct Space-Based Observations of Anthropogenic CO <sub>2</sub> Emission Areas from OCO-2." <i>Geophysical Research Letters</i> 43 (21): 11400–11406          | OCO-2 satellite CO <sub>2</sub> mapping over metropolitan areas              | Demonstrates the technical feasibility of detecting city-scale anthropogenic CO <sub>2</sub> enhancements from satellite-based XCO <sub>2</sub> retrievals, validating the use of ODIAC-derived CO <sub>2</sub> data for metropolitan-scale pollution pressure mapping in CMA.                  |
| Grossman, Gene M., and Alan B. Krueger. 1995. "Economic Growth and the Environment." <i>Quarterly Journal of Economics</i> 110 (2): 353–377.                                                                                     | EKC theory: pollution–income trajectory in industrialising economies         | Positions rapidly industrialising cities at a critical pollution inflection point before affluence-driven improvement occurs. Frames Chennai's current trajectory and underscores the urgency of proactive spatial planning intervention before irreversible environmental degradation sets in. |

### 1.7.4. Definitions and Key Terms

- i. **Air Pollution Hotspot:** A spatially discrete zone where one or more atmospheric pollutant concentrations systematically exceed prescribed

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NAAQS thresholds or where composite environmental quality indices fall below acceptable levels.

- ii. **Planned Development:** Urban growth occurring within areas designated in the CMDA Master Plan with approved layouts, infrastructure provision, and development control regulations.
- iii. **Unplanned Development:** Informal or unauthorised urban expansion occurring outside approved layout areas, often characterised by deficient infrastructure and higher environmental stress.
- iv. **Environmental Quality Index (EQI):** A composite spatial index derived from normalised values of CO<sub>2</sub> concentration, LST, and NDVI; used for grid-based hotspot identification.
- v. **LST (Land Surface Temperature):** A satellite-derived metric sensitive to urban heat island dynamics and impervious surface density.
- vi. **NDVI (Normalised Difference Vegetation Index):** A spectral index indicating vegetation density and health; used as a proxy for urban green cover.

## 2. Chapter 2: Literature Review, Case Studies & Methodology

### 2.1.National Literature (Indian Context)

India's urban air pollution crisis has been documented extensively across disciplinary lines. Gurjar et al. conducted a landmark multi-city comparison of emission inventories in Indian megacities, establishing that vehicular emissions, industrial activity, and construction dust are the dominant source categories findings directly applicable to Chennai's industrial-port-highway complex. The Central Pollution Control Board's annual National Ambient Air Quality Status and Trends Reports consistently flag Chennai among non-attainment cities for PM<sub>10</sub> and PM<sub>2.5</sub>, providing the regulatory context for this study.

Ramachandra and Shwetmala used spatial analysis to quantify urban energy consumption and emissions in Bangalore, offering a methodological blueprint for GIS-based emission mapping in Indian cities. In the Chennai-specific context, Jayabalakrishnan and Dhanasekaran documented elevated NO<sub>2</sub> and PM levels in the Manali industrial corridor, corroborating the geographic focus of this study. Kumar et al. employed MODIS aerosol optical depth (AOD) data over the Indo-Gangetic Plain to spatially correlate industrial zones with pollution concentrations a methodological parallel to the satellite-based approach adopted here.

Policy literature by Anand and Pati examines the implementation gap between NCAP targets and ground-level enforcement in Tamil Nadu, highlighting institutional fragmentation between TNPCB, CMDA, and Greater Chennai Corporation as a key challenge. This directly motivates the study's recommendation framework.

### 2.2.International Literature

Globally, the integration of remote sensing and GIS for urban air quality assessment has gained significant traction since the early 2000s. Stathopoulou and Cartalis demonstrated the utility of LST derived from Landsat ETM+ as a proxy for thermal discomfort and pollution precursors in Athens, Greece, establishing the methodological validity of the LST–pollution nexus. Schneider et al. developed global impervious surface maps using Landsat, providing the theoretical basis for urban built-up classification methodologies used in this study.

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Elvidge et al. validated VIIRS-DNB nighttime light data as a robust proxy for economic activity, population density, and energy consumption key drivers of urban pollution. Their work underpins the use of nighttime light intensity as an urbanisation indicator in this research. OCO-2/3 satellite CO<sub>2</sub> data for urban monitoring is supported by Hakkarainen et al., who demonstrated city-scale CO<sub>2</sub> enhancements over megacities using orbit-averaged XCO<sub>2</sub> retrievals.

The Environmental Kuznets Curve (EKC) literature developed by Grossman and Krueger and later refined by Stern provides the theoretical scaffold for understanding why rapidly industrialising cities like Chennai are at a critical inflection point where environmental quality typically deteriorates before improving with rising affluence, thereby emphasising the urgency of proactive spatial planning interventions.

### 2.3. Relevant National and State Policies

- i. National Action Plan on Climate Change (NAPCC), 2008 Mission for Sustainable Habitat: Mandates energy-efficient urban planning and calls for integration of environmental indicators into urban master plans.
- ii. CPCB Comprehensive Study on Air Pollution and Health Effects in Six Major Cities (2014): Provides health-impact benchmarks for PM exposure in Indian cities including Chennai.
- iii. Tamil Nadu Urban Development Fund (TNUDF) Guidelines: Govern environmental assessments for urban infrastructure projects within the CMA.
- iv. National Urban Policy Framework, 2018 (Draft): Emphasises data-driven governance, green infrastructure, and environmental mainstreaming in urban planning.

### 2.4. Case Studies

#### 2.4.1. Case Study 1 (India) Manali Industrial Corridor, Chennai

The Manali–Ennore Industrial Complex serves as a critical local or sub-metropolitan case study, covering a concentrated geographical expanse of approximately 60 sq. km. within the Chennai Metropolitan Area (CMA). Its strategic relevance lies in its position as a direct

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precursor zone to the primary study area, characterized by a heavy industrial density that includes petroleum refining (CPCL), thermal power generation, fertilizer manufacturing, and large-scale port operations. Environmental oversight in this region has historically relied on ground-based monitoring via six Tamil Nadu Pollution Control Board (TNPCB) stations, supplemented by detailed emission inventories and land use mapping to track industrial footprints.

Analysis of these efforts reveals a significant environmental impact, with SO<sub>2</sub>, NO<sub>2</sub>, and PM<sub>10</sub> levels consistently exceeding National Ambient Air Quality Standards (NAAQS) thresholds by 1.5 to 3 times, as documented in TNPCB Annual Reports from 2018 to 2022. A primary lesson derived from this complex is that traditional point-source monitoring is inherently insufficient without the integration of spatial interpolation techniques to understand pollutant dispersion. Furthermore, the study underscores that existing buffer zone regulations require more robust enforcement mechanisms to be effective. A notable limitation of current data is its spatial sparsity, which prevents a comprehensive understanding of diffuse emissions, such as those generated by heavy vehicular movement and ongoing construction activities within the industrial corridor.

### 2.4.2. Case Study 2 (India) Delhi NCR Air Pollution Hotspot Mapping

The Delhi National Capital Region (NCR) offers a high-impact national case study on a vast metropolitan and regional scale, covering approximately 53,817 sq. km. This region faces complex environmental challenges driven by a multi-sectoral emission profile, including a massive transport sector with over 11 million vehicles, intense industrial clusters in Faridabad, Gurgaon, and Noida, and seasonal contributions from agricultural residue burning in neighboring states. Unlike traditional ground-based studies, this research utilized advanced satellite-based Earth Observation (EO) data, integrating MODIS Aerosol Optical Depth (AOD), Sentinel-5P TROPOMI columns for NO<sub>2</sub> and SO<sub>2</sub>, and Landsat-8 for Land Surface Temperature (LST). These datasets were analyzed using sophisticated spatial statistics, including Moran's I and Local Indicators of Spatial Association (LISA), alongside machine learning regression models to map pollution hotspots with high precision.

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The outcomes of this satellite-driven approach provided a clear spatial delineation of pollution zones, revealing a significant negative correlation between the Normalized Difference Vegetation Index (NDVI) and pollutant concentrations ( $r = -0.62$ ), which underscores the role of green cover in mitigating urban air degradation. These findings have directly informed aggressive policy responses, such as the Graded Response Action Plan (GRAP), the Odd-Even vehicular scheme, and the NCT Electric Vehicle Policy. For the Chennai Metropolitan Area (CMA), this case study highlights the necessity of moving toward a multi-source composite index rather than relying on single-pollutant metrics. Furthermore, it demonstrates that spatial clustering methods like LISA are highly effective tools for the objective delineation of environmental hotspots in rapidly expanding urban landscapes.

### **2.4.3. Case Study 3 (International): Seoul Metropolitan Area Integrated Urban Environmental Quality Assessment**

The Seoul Metropolitan Area (SMA) provides a sophisticated international benchmark for integrated urban environmental management on a metropolitan scale of approximately 11,700 sq. km. This case study moved beyond traditional monitoring by employing a high-tech Multi-spectral Landsat and MODIS analysis, correlating Land Surface Temperature (LST) with NDVI to evaluate the "urban heat island" effect alongside air quality. The methodological framework utilized a grid-based Environmental Quality Index (EQI), further enhanced by CCTV-AI sensor fusion and a real-time GIS dashboard to provide dynamic oversight of the capital's environmental health.

The implementation of the grid-based EQI successfully identified 12 distinct pollution hotspots, revealing a stark contrast in environmental performance: planned "new towns" like Bundang and Ilsan demonstrated a 35% better EQI compared to unplanned peri-urban peripheries. These data-driven insights directly shaped the Seoul Metropolitan Air Quality Management Plan (2005–2024), leading to the establishment of Low Emission Zones (LEZ) in high-risk hotspots and the integration of mandatory green ratios within urban master plans. For the Chennai Metropolitan Area (CMA), this underscores that a composite multi-indicator EQI provides more actionable intelligence than single-pollutant mapping,

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and suggests that future expansions must include strict green ratio mandates to sustain environmental quality gains over time.

### 2.4.4. Comparative Summary of Case Studies

The synthesis of these three case studies reveals a clear evolution in environmental monitoring methodologies, transitioning from traditional ground-based observations to integrated, satellite-driven spatial frameworks that provide a comprehensive roadmap for the Chennai Metropolitan Area. The methodological approaches scale in complexity, beginning with Manali's reliance on ground monitoring and emission inventories for localized industrial accuracy, moving to Delhi's use of MODIS AOD and Sentinel-5P TROPOMI for regional hotspot mapping, and culminating in Seoul's integration of Multi-spectral Landsat analysis with AI-sensor fusion. This progression highlights that while ground-truth data from sites like Manali serves as a vital validation reference, the multi-indicator composite indices and LISA clustering techniques used in Delhi, along with the grid-based Environmental Quality Index (EQI) framework from Seoul, are essential for achieving the spatial continuity required for metropolitan oversight. Ultimately, these cases provide critical lessons: they demonstrate that traditional point-source monitoring is inherently insufficient for capturing pollutant dispersion, that seasonal and spatial disaggregation is mandatory to account for varying emission sources, and that planned urban areas consistently outperform unplanned peripheries, showing up to a 35% improvement in environmental quality. By adopting these synthesized methods, urban planners can move beyond single-pollutant metrics toward more proactive, data-driven management that incorporates mandatory green ratios and real-time GIS dashboards to sustain long-term environmental gains.

## 2.5. Research Gaps

A systematic review of existing literature and policy documents reveals the following substantive research gaps that this thesis directly addresses:

- i. **Absence of Grid-Based Multi-Indicator EQI for Chennai:** While individual pollutant studies exist for Chennai (particularly for Manali), no study has developed

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a composite spatial Environmental Quality Index integrating CO<sub>2</sub>, LST, NDVI, and nighttime lights at metropolitan scale for CMA.

- ii. **Limited Temporal Depth in Remote Sensing Studies:** Existing Chennai air quality studies are predominantly cross-sectional. A longitudinal three-period analysis (2003, 2013, 2023) capturing the trajectory of pollution hotspots in relation to urban growth is absent from the literature.
- iii. **Unexamined Planning–Pollution Nexus:** No empirical study in the CMA context has statistically tested whether CMDA-designated planned development zones exhibit significantly better environmental quality outcomes than unplanned areas.
- iv. **Peripheral and Peri-urban Coverage Gap:** Existing TNPCB monitoring stations cover primarily the GCC area, leaving the rapidly urbanising northern (Manali-Ennore) and southern (Sriperumbudur) peripheries effectively unmonitored in the academic literature.
- v. **Lack of Ward-Level Actionable Hotspot Mapping:** Existing studies operate at coarse administrative or district scales. Ward-level hotspot delineation within the CMA, which would enable GCC and municipality-level targeted interventions, is missing.
- vi. **Methodological Gap GIS-Remote Sensing Integration with Indian Datasets:** The application of grid-based spatial clustering (LISA/Moran's I) to multi-source satellite data for air quality in south Indian coastal metropolitan contexts lacks a peer-reviewed precedent.

## 2.6. Methodology

### 2.6.1. Overall Research Design

The research adopts a sequential mixed-methods design: (1) spatial analysis of longitudinal satellite datasets; (2) grid-based overlay and composite index generation; (3) statistical analysis of planning typology differences; and (4) evidence synthesis for policy recommendations. The methodology is explicitly objective-driven, with each analytical step directly traceable to a stated research objective.

### 2.6.2. Analytical Tools and Justification

- i. **ArcGIS Pro / QGIS:** Primary GIS platform for spatial data processing, raster algebra, overlay analysis, and cartographic output. Justified by universal adoption in urban planning research and compatibility with CMDA's in-house GIS infrastructure.
- ii. **Google Earth Engine (GEE):** Cloud-based platform for large-scale satellite image processing (Landsat time series, NDVI computation, LST retrieval). Justified by its ability to process multi-decade archives without local computational constraints.

### 2.6.3. Data Constraints and Methodological Limitations

- i. **CO<sub>2</sub> Spatial Resolution:** OCO-2/3 retrievals at 1–3 km cannot resolve block-level or street-level CO<sub>2</sub> variation. The study accordingly uses CO<sub>2</sub> as a metropolitan-scale pollution pressure indicator.
- ii. **Cloud Cover:** Chennai's northeast monsoon season (October–December) significantly reduces usable Landsat scenes. Only dry-season imagery (January–March) will be used for inter-year comparability.
- iii. **NTL Cross-Sensor Calibration:** DMSP-OLS (2003) and VIIRS-DNB (2013, 2023) use different sensor specifications; inter-calibration using published regression equations introduces uncertainty acknowledged in results interpretation.
- iv. **Ground Station Sparsity:** TNPCB's 10–12 stations across 1,189 sq. km. provide statistically insufficient spatial coverage for rigorous validation of satellite-derived estimates.
- v. **Temporal Lag in CO<sub>2</sub> Data:** OCO-2 data is available only from 2014 onwards, making 2003 CO<sub>2</sub> mapping infeasible through satellite sources. For 2003, CO<sub>2</sub> will be estimated through proxy indicators (NTL, built-up density) calibrated against the 2013–2023 observed OCO-2 relationship.

### 2.7. Summary of Literature and Research Direction

The literature reviewed across national and international contexts, combined with insights from three carefully selected case studies, converges on a coherent methodological and conceptual direction for this thesis. The evidence base confirms that: (i) satellite remote sensing is a valid and increasingly precise tool for urban air quality characterisation; (ii) composite multi-indicator spatial indices outperform single-pollutant approaches for planning-relevant hotspot identification; (iii) the planning–environment nexus is empirically demonstrable and policy-relevant; and (iv) the Chennai Metropolitan Area represents a significant research gap in the existing literature.

The identified research gaps justify a grid-based, multi-temporal, composite EQI approach as the core methodology of this thesis. The regulatory and policy framework anchored in the Air Act 1981, EPA 1986, NAAQS 2009, NCAP 2019, and CMDA Master Plan 2026 provides the normative scaffolding within which findings will be interpreted and recommendations formulated. The study is positioned to make an original and practice-relevant contribution to urban environmental planning in the Chennai Metropolitan Area and, by extension, to the broader discourse on data-driven environmental governance in rapidly urbanising Indian cities.

### 3. Chapter 3: Analysis and Findings

#### 3.1. Analytical Framework

This chapter presents the core empirical findings of the research, synthesising the results of the multi-temporal, grid-based spatial analysis conducted across the Chennai Metropolitan Area (CMA) for the years 2003, 2013, and 2023. The analysis integrates six environmental quality indicators carbon dioxide (CO<sub>2</sub>) emission intensity, daytime Land Surface Temperature (LST Day), nocturnal Land Surface Temperature (LST Night), Normalised Difference Vegetation Index (NDVI), nighttime light radiance (NTL), and built-up area density alongside population distribution data derived from the Global Human Settlement Layer (GHSL). All datasets were harmonised to a 1 km fishnet grid covering the approximately 1,189 sq. km. of the CMA, yielding a spatially continuous analytical surface of 1,203 valid grid cells per period after data cleaning.

The chapter is structured around four primary analytical themes: (i) temporal evolution of individual environmental indicators from 2003 to 2023; (ii) inter-indicator correlation analysis using Pearson's *r*, conducted independently for each time period to assess the consistency and evolution of relationships over time; (iii) identification and spatial characterisation of pollution hotspot zones; and (iv) a synthesis of key findings and their planning implications. Each section is grounded in the quantitative outputs derived from the cleaned datasets contained with critical assumptions as noted in the methodological chapter.

The analytical approach is explicitly comparative across the three decades under study. By isolating patterns at 2003, 2013, and 2023, the analysis captures the urban transformation trajectory of Chennai from a rapidly industrialising metropolitan area in the early 2000s, through the consolidation of the IT corridor and suburban expansion in the 2010s, to the intensified industrial and population pressure observed in the 2020s. This longitudinal lens is essential for identifying not merely where pollution is concentrated today, but how the spatial configuration of environmental stress has shifted in relation to evolving urban form.

### 3.2. Data Cleaning and Preparation of Analytical Datasets

Prior to statistical analysis, the raw grid attribute datasets taken under a cleaning protocol to remove non-urban, waterbody, and no-data grid cells that would otherwise distort metropolitan averages and correlation coefficients. Inspection of the uncleaned data revealed several grid cells exhibiting zero values simultaneously across CO<sub>2</sub>, LST Day, LST Night, and Nighttime Light variables a pattern consistent with either open water surfaces (particularly along the Adyar and Cooum river estuaries and Pulicat Lake periphery), dense cloud shadow artefacts in dry-season imagery, or grids falling at the administrative boundary of the CMA with insufficient land area.

Specifically, FIDs 7, 13, 36, 45, and 47 in the 2023 dataset exhibited this multi-variable zero pattern and were excluded from the cleaned dataset. Similar exclusions were applied in the 2013 and 2003 datasets. After cleaning, the valid grid counts were: 2003 1,114 grids; 2013 1,144 grids; 2023 1,203 grids. The increase in valid grid count over the study period is itself analytically significant, reflecting the progressive urbanisation of previously undeveloped or rural cells at the CMA periphery, particularly in the Sriperumbudur and Tiruvallur directions.

An important dataset-specific limitation must be noted regarding nighttime light (NTL) data for 2003. The cleaned 2003 dataset does not include NTL columns, reflecting the exclusion of DMSP-OLS 2003 data likely due to inter-sensor calibration concerns when bridging DMSP-OLS to the VIIRS-DNB sensor used for 2013 and 2023. All correlation analyses involving NTL are therefore restricted to 2013 and 2023 datasets. Similarly, population data columns represent the maximum grid-cell value derived from GHSL, rather than a mean, and are interpreted as a density proxy rather than an absolute count.

### 3.3. Temporal Evolution of Environmental Quality Indicators (2003–2023)

#### 3.3.1. Carbon Dioxide Emission Intensity

The most dramatic trend observed across the twenty-year analytical window is the sustained and accelerating rise in CO<sub>2</sub> emission intensity across the CMA. Drawing from the ODIAC Fossil Fuel Emission Dataset (Version ODIAC2023), the mean grid-cell CO<sub>2</sub> emission value rose from 68.45 MtC/Month in 2003 to 185.91 MtC/Month in 2013 a decadal increase of 171.6 per cent and further to 280.92 MtC/Month in 2023, representing

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a cumulative increase of 310.4 per cent over the full twenty-year period. This trajectory is among the steepest emission growth rates documented for any major South Asian metropolitan area in this period, reflecting the compounding pressures of industrial expansion, vehicular fleet growth, and population-driven energy demand.

Equally significant is the change in the maximum observed CO<sub>2</sub> value, which escalated from 346.51 MtC/Month in 2003 to 652.78 MtC/Month in 2013 and reached a peak of 1,006.65 MtC/Month in 2023. This maximum, recorded at grid FID 307, corresponds spatially to the Manali–Ennore industrial and port corridor in northern Chennai, a zone characterised by petroleum refining (CPCL), thermal power generation, and intensive port-related logistics activity. The emergence of a grid cell breaching the 1,000 MtC/Month threshold in 2023 signals the formation of a distinct carbon concentration peak that has no precedent in the earlier periods of this study.

The minimum CO<sub>2</sub> value across valid grids, by contrast, remained relatively stable rising from 10.27 MtC/Month in 2003 to 36.72 MtC/Month in 2023. This convergence of the minimum toward higher values indicates that even the least-polluted grid cells within the CMA are experiencing rising baseline emissions, consistent with the *diffuse sprawl hypothesis* wherein low-density peri-urban fringe areas increasingly emit carbon as they acquire motorisation, commercial activity, and infrastructure without the density efficiencies of compact urban cores.

**Table 3.1: CO<sub>2</sub> Emission Intensity Statistics Across Study Periods (Cleaned Datasets)**

| Statistic                           | 2003   | 2013   | 2023     | Change 2003–2023  |
|-------------------------------------|--------|--------|----------|-------------------|
| Valid Grid Cells (N)                | 1,114  | 1,144  | 1,203    | +89 grids (+8.0%) |
| Mean CO <sub>2</sub> (MtC/Month)    | 68.45  | 185.91 | 280.92   | +310.4%           |
| Maximum CO <sub>2</sub> (MtC/Month) | 346.51 | 652.78 | 1,006.65 | +190.5%           |
| Minimum CO <sub>2</sub> (MtC/Month) | 10.27  | 23.81  | 36.72    | +257.5%           |

Source: ODIAC Fossil Fuel Emission Dataset (ODIAC2023)

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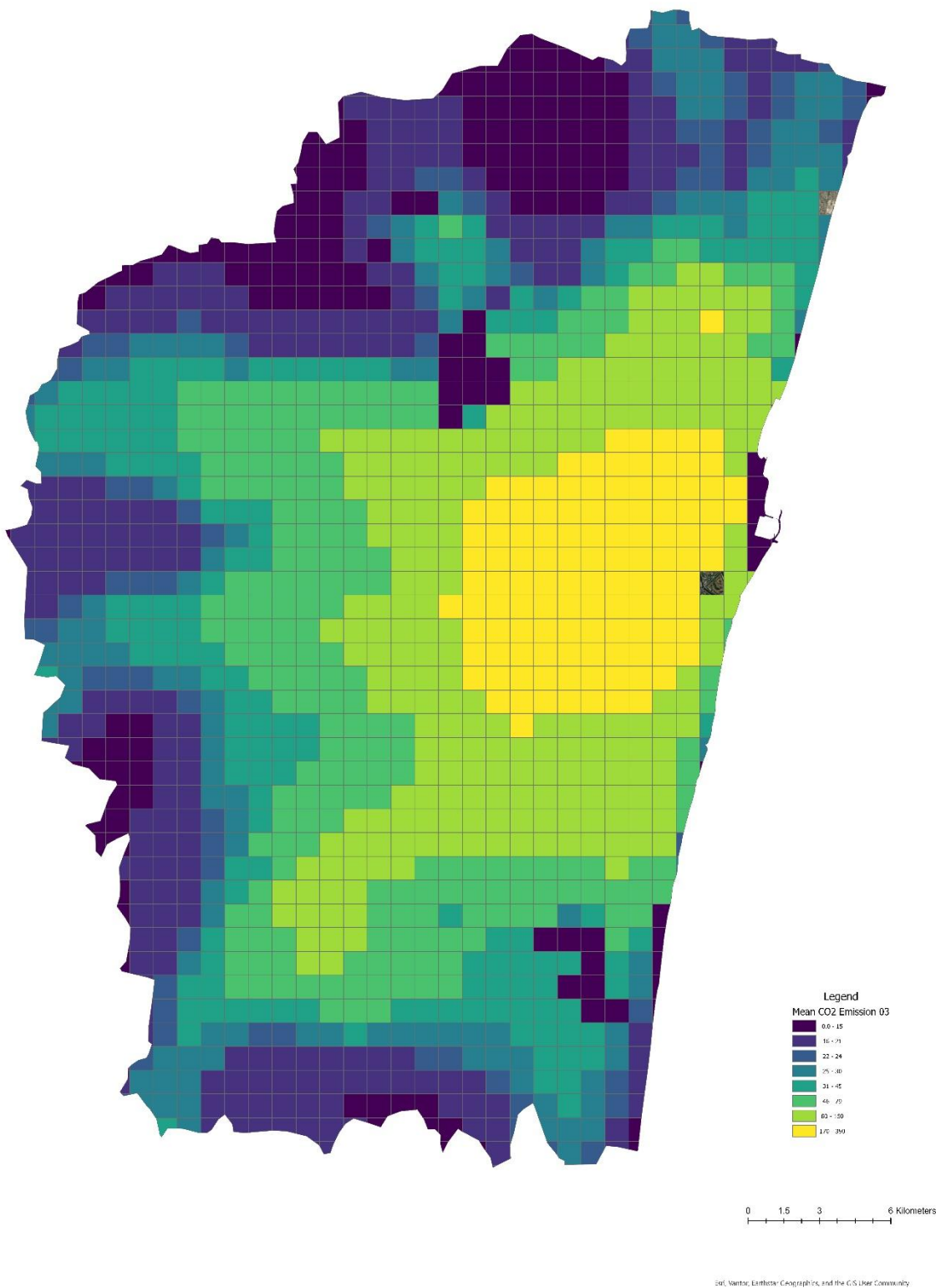


Fig 3.1: Mean CO<sub>2</sub> Emission 2003 Grid Map (1 KM) (ODIAC)

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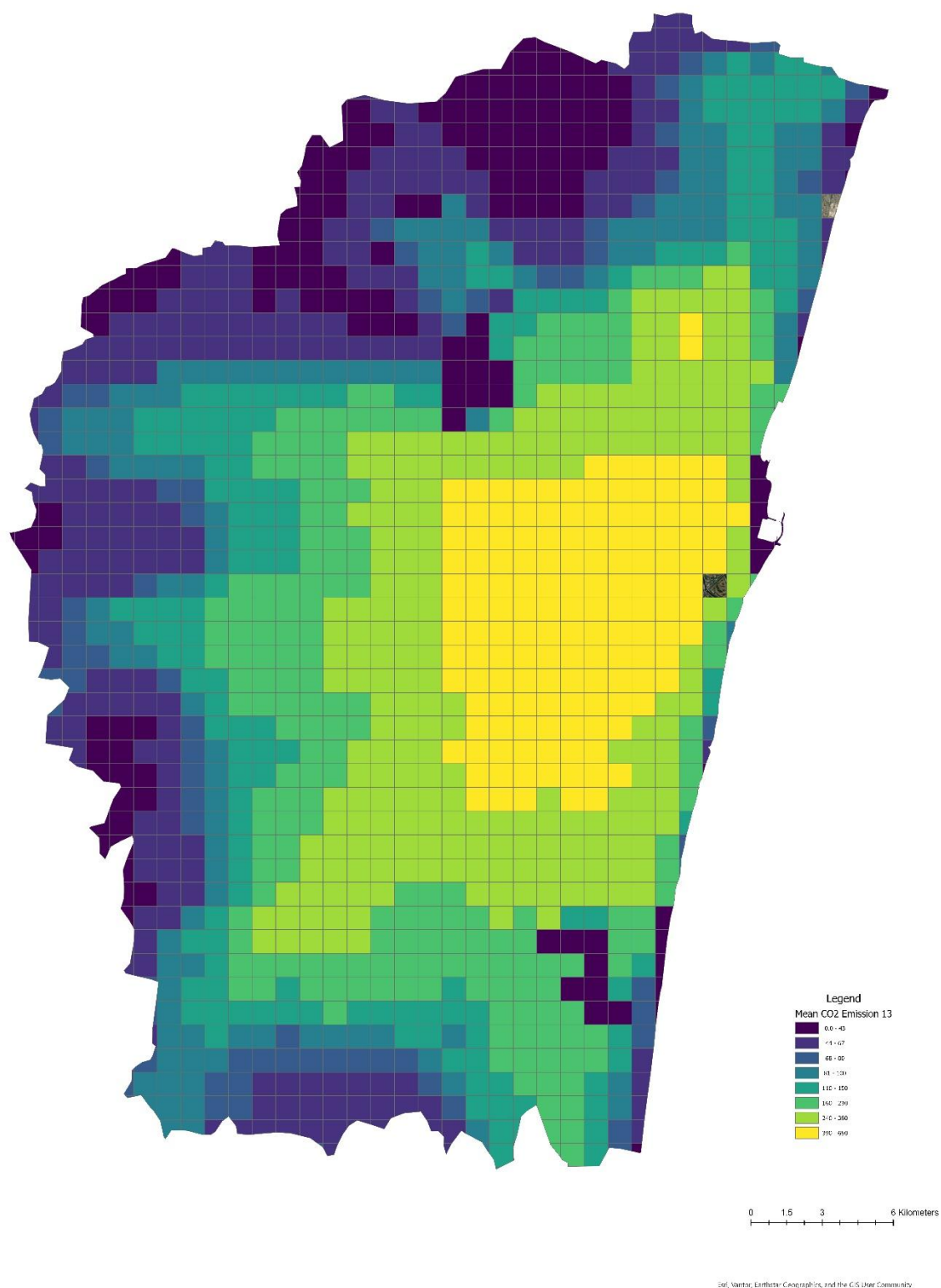
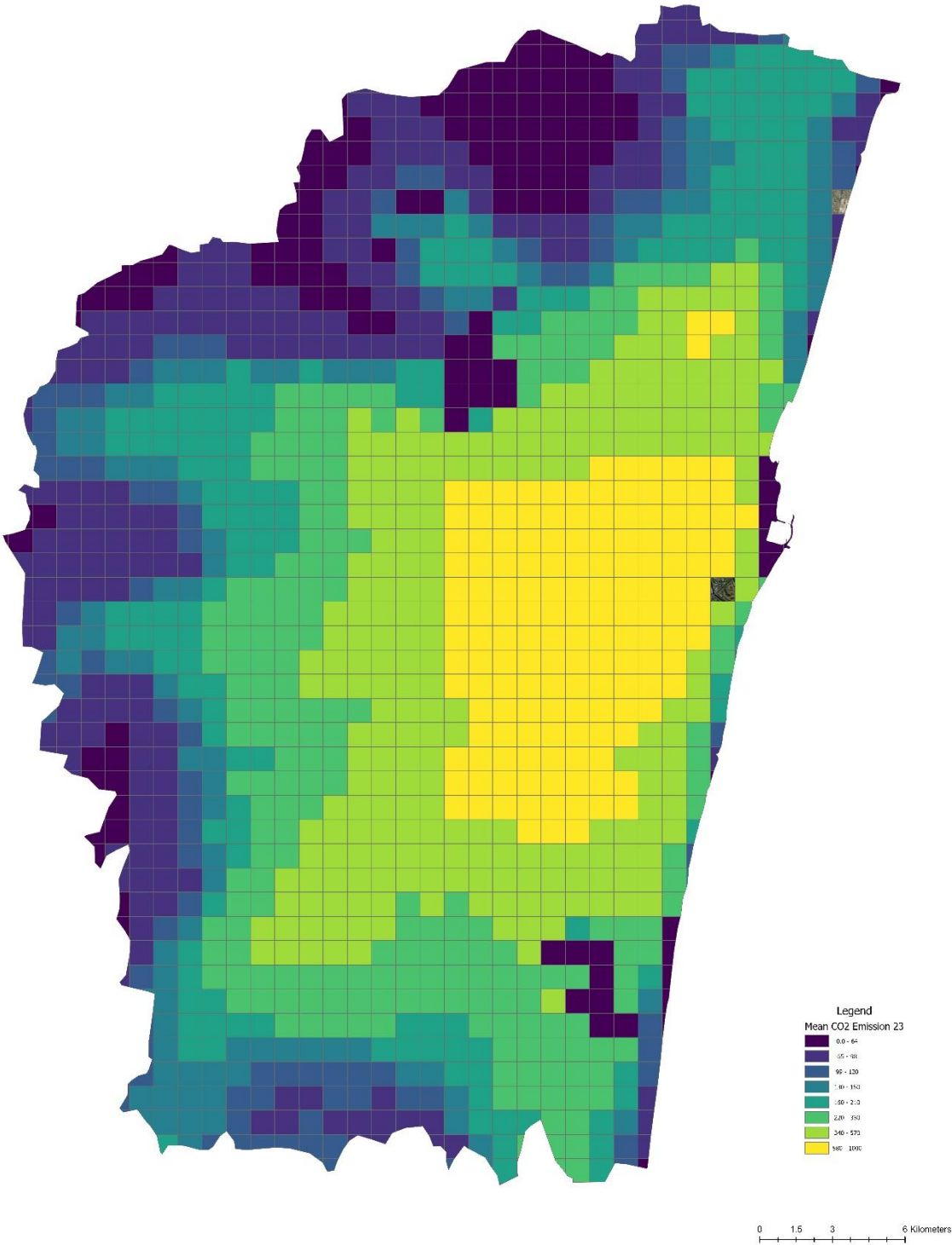


Fig 3.2: Mean CO<sub>2</sub> Emission 2013 Grid Map (1 KM) (ODIAC)

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Del, Nantac, Earthstar, Geographic, and the GIS User Community.

Fig 3.3: Mean CO<sub>2</sub> Emission 2023 Grid Map (1 KM) (ODIAC)

### 3.3.2. Land Surface Temperature Daytime and Nighttime Patterns

Land Surface Temperature data derived from the MODIS MOD11A1.061 product at 1 km resolution provides a dual temporal signal daytime and nocturnal that together characterise the urban heat island (UHI) dynamics of the CMA. The daytime and nocturnal LST series exhibit strikingly divergent trends over the study period, a divergence that is analytically important for understanding the evolving nature of Chennai's urban heat environment.

Daytime LST (LST Day) recorded a counter-intuitive decline in the mean value over the study period: from 39.15°C in 2003 to 36.96°C in 2013 and 36.56°C in 2023. This decline should not be interpreted as a cooling trend in urban thermal conditions. Rather, it reflects two interacting factors: first, the progressive increase in valid grid cells into 2023 includes more peri-urban and vegetated cells at lower temperatures, which dilutes the mean; second, Chennai's rapid expansion of impervious surfaces has paradoxically increased shade and albedo in certain densely built zones relative to the bare-soil suburban landscapes that characterised 2003. The maximum daytime LST, by contrast, remained persistently elevated reaching 39.39°C in 2023 in the densest industrial and high-traffic grid cells.

Nocturnal LST (LST Night) presents a more straightforward signal of intensifying urban heat. The mean nocturnal temperature rose from 26.66°C in 2003 to 27.39°C in 2013 and remained elevated at 27.26°C in 2023. The maximum nocturnal LST climbed from 28.00°C to 29.01°C over the same period. Nocturnal temperatures in the highest-emission grid cells particularly those in the Manali–Ennore and CBD zones consistently exceed 28.5°C, a threshold associated with significant human thermal discomfort during sleeping hours and elevated respiratory health risks as documented in the WHO Global Air Quality Guidelines (2021). The sustained nocturnal warmth in these zones reflects the thermal mass of densely built environments retaining daytime solar heat and the anthropogenic heat flux from industrial processes, vehicular activity, and air conditioning systems.

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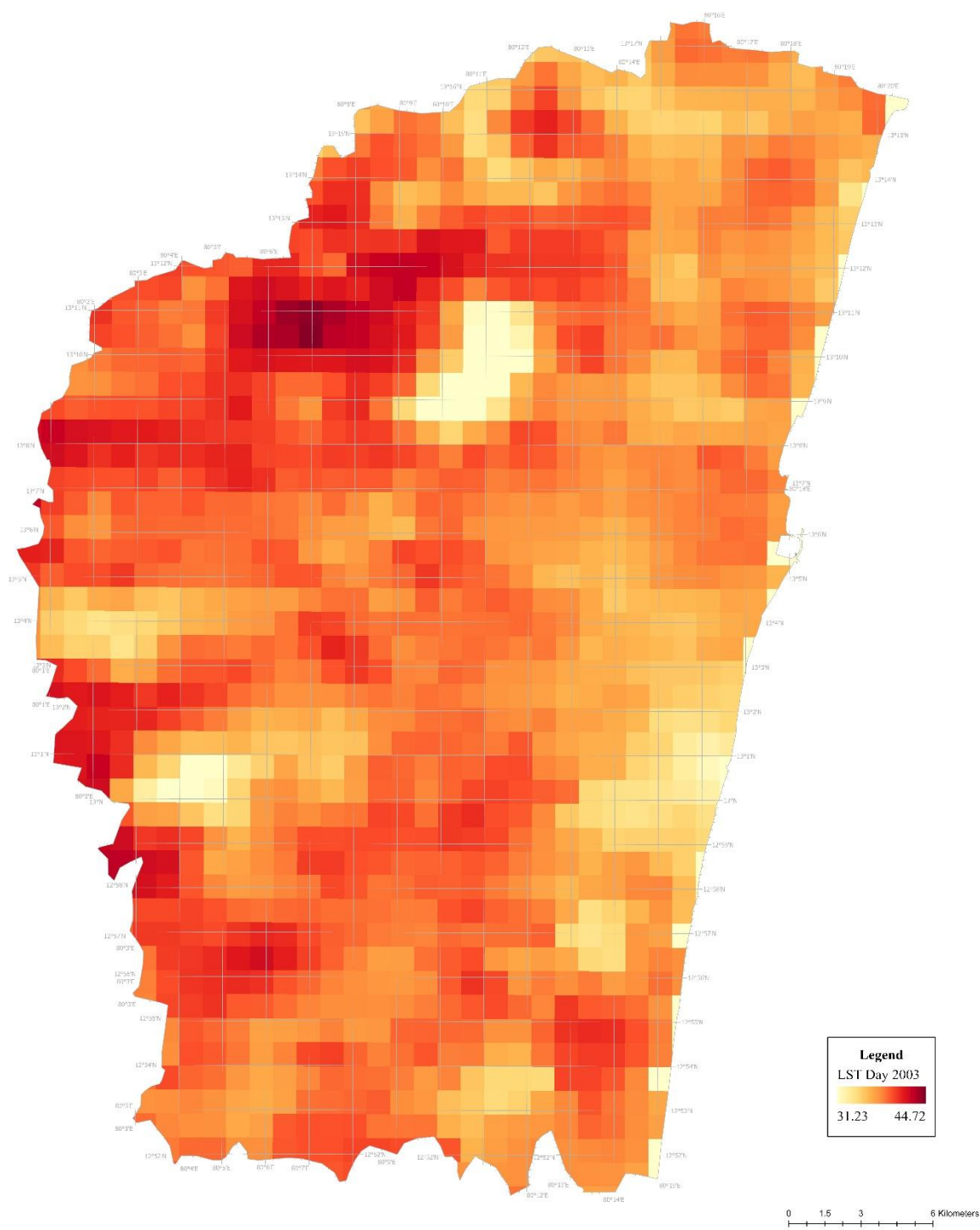


Fig 3.4: Daytime LST 2003 - 1 KM Resolution (MODIS)

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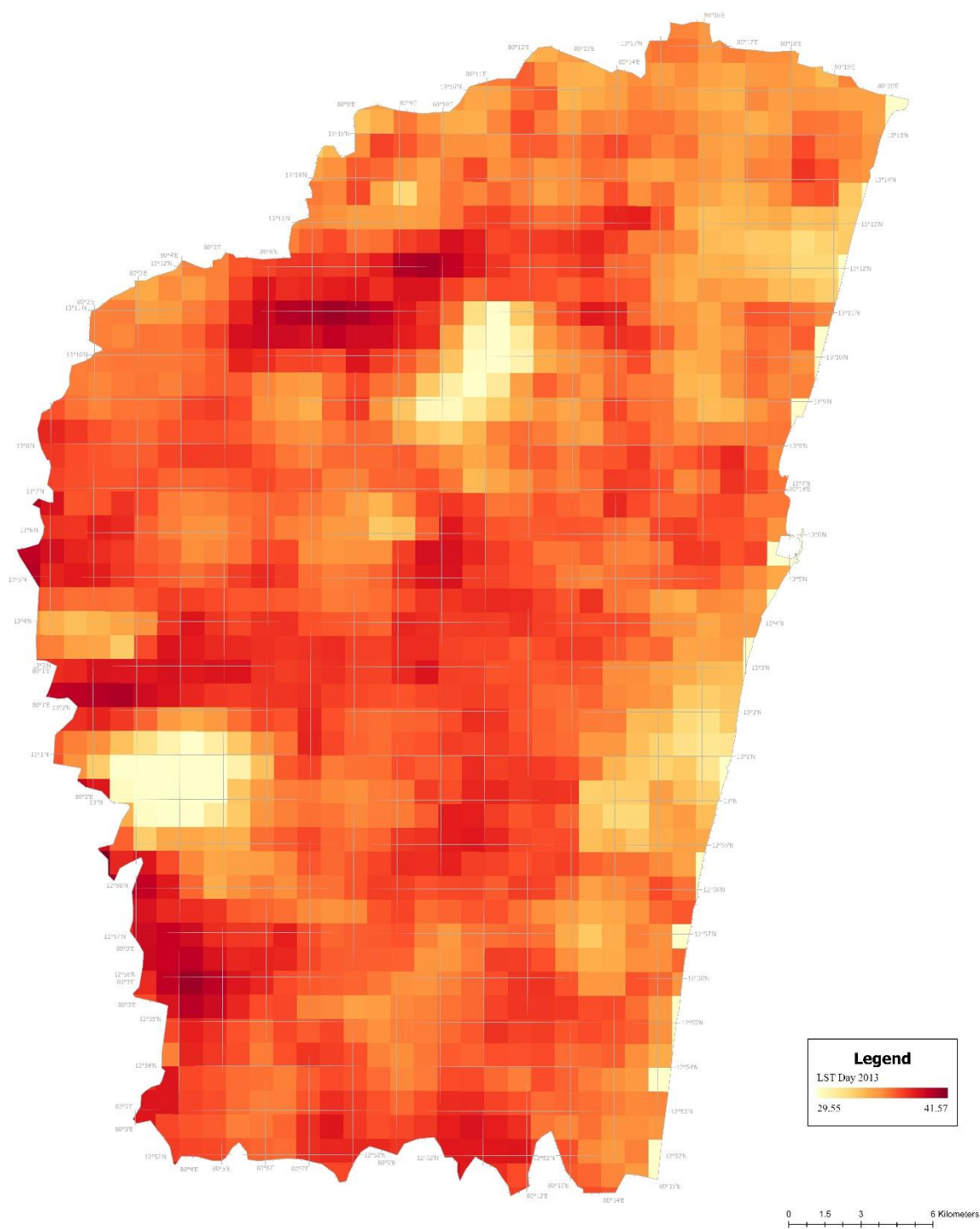


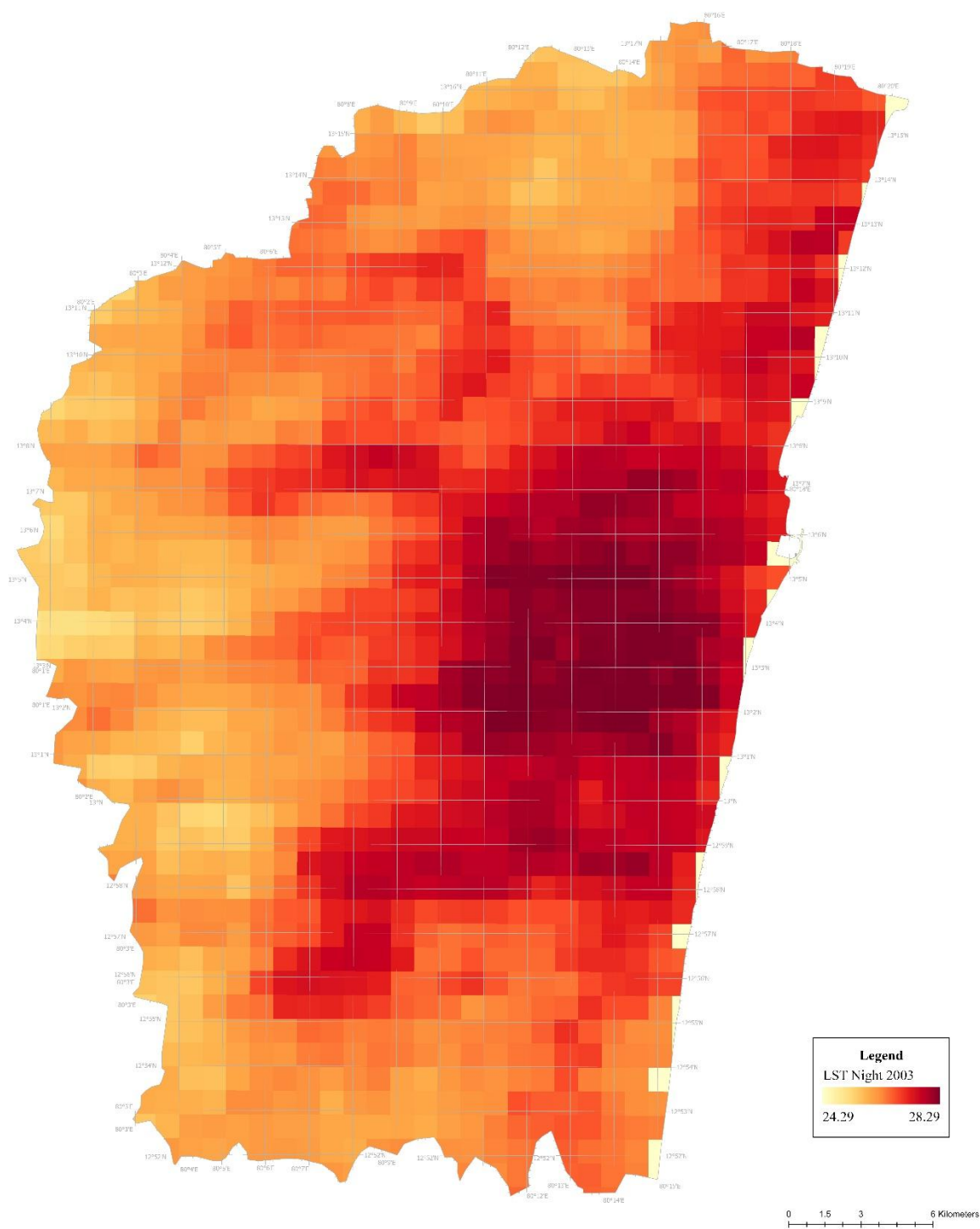
Fig 3.5: Daytime LST 2013 - 1 KM Resolution (MODIS)

**Legend**  
LST Day 2023  
29.91 39.79

0 1.5 3 6 Kilometers

Sources: Esri, Survey of India, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community. Esri, Vanito, Esri/Arabian Geographic, and the GIS User Community.

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Sources: Dr. Survey of India, Tamil Nadu Government, IMD, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community, Esri, DeLorme, GeoEye, and the GIS User Community

Fig 3.5: Nighttime LST 2003 - 1 KM Resolution (MODIS)

## IDENTIFICATION OF AIR POLLUTION HOTPOTS IN CHENNAI METROPOLITAN AREA

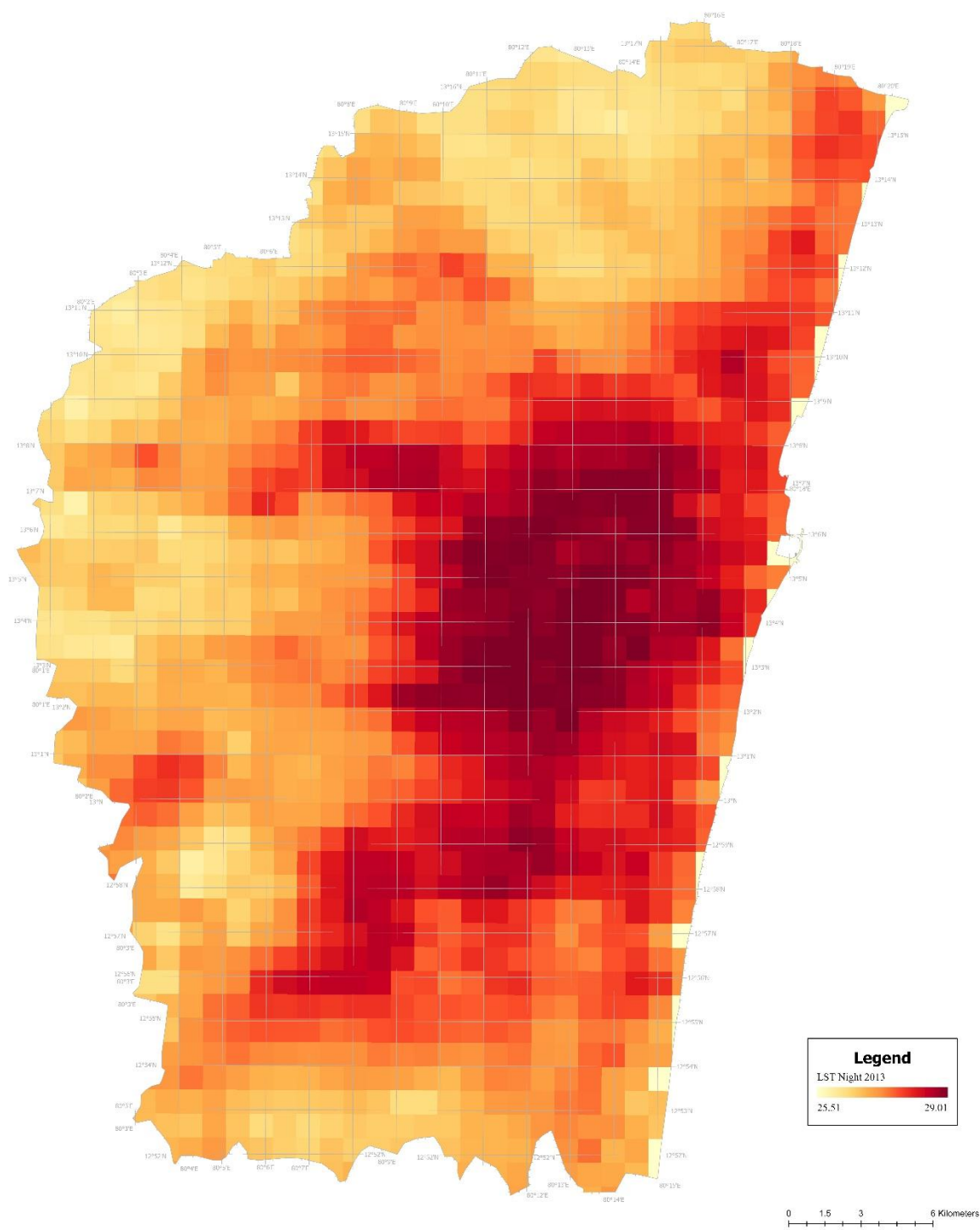
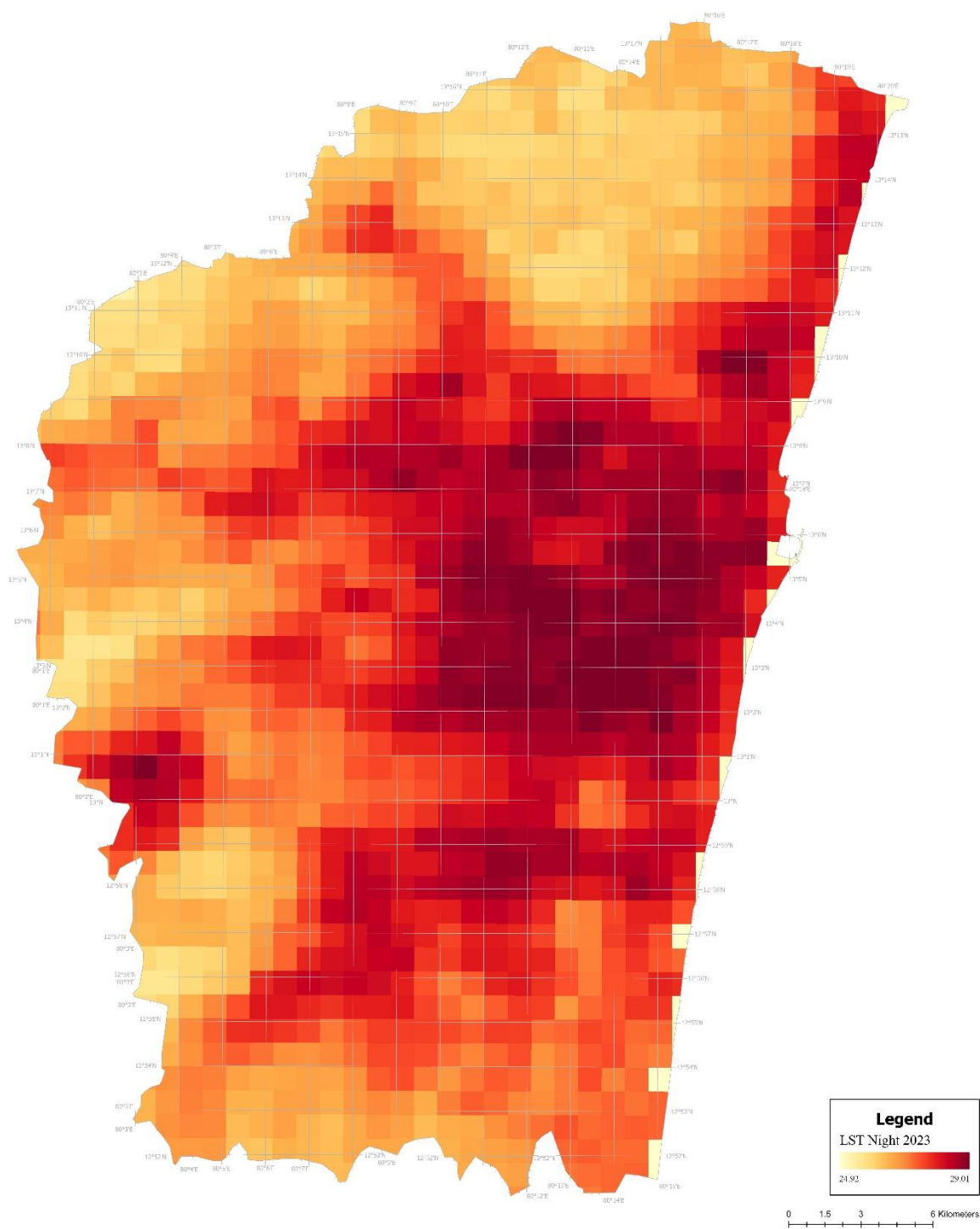


Fig 3.6: Daytime LST 2013 - 1 KM Resolution (MODIS)

## IDENTIFICATION OF AIR POLLUTION HOTPOTS IN CHENNAI METROPOLITAN AREA



Sources: Dr. Survey of India, Tan-Tan, Google, SMO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community, For Vector, Satellite Imagery, and the GIS User Community

Fig 3.7: Daytime LST 2023 - 1 KM Resolution (MODIS)

### 3.3.3. Normalised Difference Vegetation Index (NDVI)

The NDVI data, derived from MODIS MOD13Q1.061 at 250 m resolution and resampled to the 1 km analysis grid, reveals a complex spatial-temporal narrative for vegetation cover in the CMA. The metropolitan mean NDVI rose from 0.314 in 2003 to 0.348 in 2013 and 0.425 in 2023. This apparent improvement in mean NDVI requires careful contextualisation rather than optimistic interpretation.

The increase in mean NDVI is primarily attributable to two phenomena: first, the inclusion of additional peri-urban and edge-of-CMA grid cells in the 2023 cleaned dataset, many of which retain agricultural or scrubland vegetation; and second, genuine greening in the southern IT corridor zones along Old Mahabalipuram Road (OMR), where technology campuses have invested in landscaped green spaces and retained tree cover as a design element. The maximum NDVI value of 0.725 in 2023, observed in grid cells near Pallikaranai wetland and Sholinganallur backwaters, confirms that high-quality green and wetland patches persist within the CMA boundary.

However, the minimum NDVI values and the pattern among high-CO<sub>2</sub> grids tell a contrasting story. In the northern industrial corridor (Manali–Ennore), NDVI values consistently fall below 0.30 with several hotspot grids recording values of 0.265–0.344. This reflects the near-total loss of vegetated surfaces in heavily industrialised zones. In 2003, many of these zones still retained transitional green cover; by 2023, urbanisation and industrial infill have largely extinguished it. The inverse relationship between NDVI and CO<sub>2</sub> concentration, documented in the correlation analysis below, suggests that this vegetation loss is both a consequence of and a contributing factor to the intensifying pollution hotspot pattern.

## IDENTIFICATION OF AIR POLLUTION HOTPOTS IN CHENNAI METROPOLITAN AREA

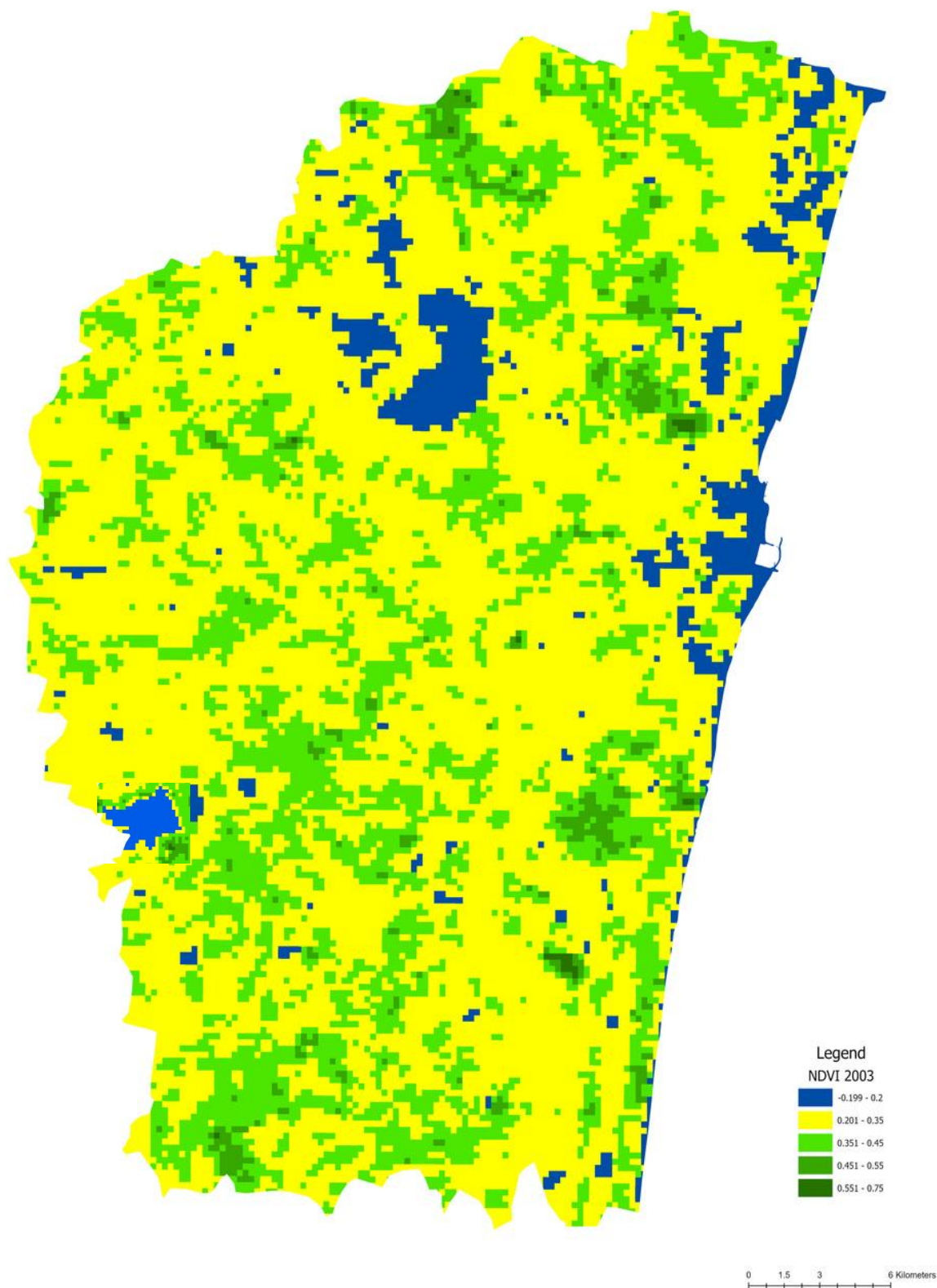


Fig 3.8: Daytime LST 2003

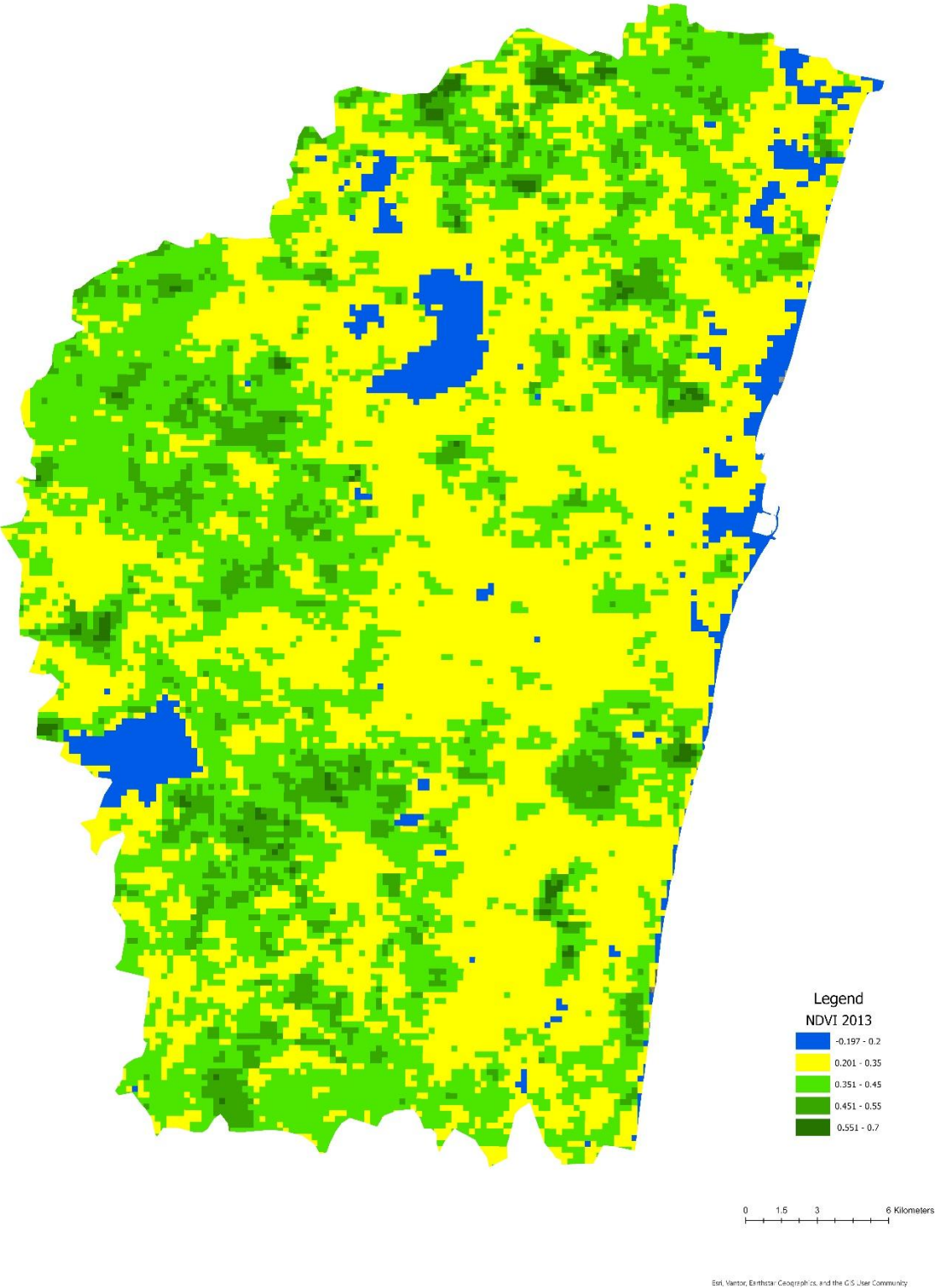


Fig 3.9: Daytime LST 2003

IDENTIFICATION OF AIR POLLUTION HOTPOTS IN CHENNAI METROPOLITAN AREA

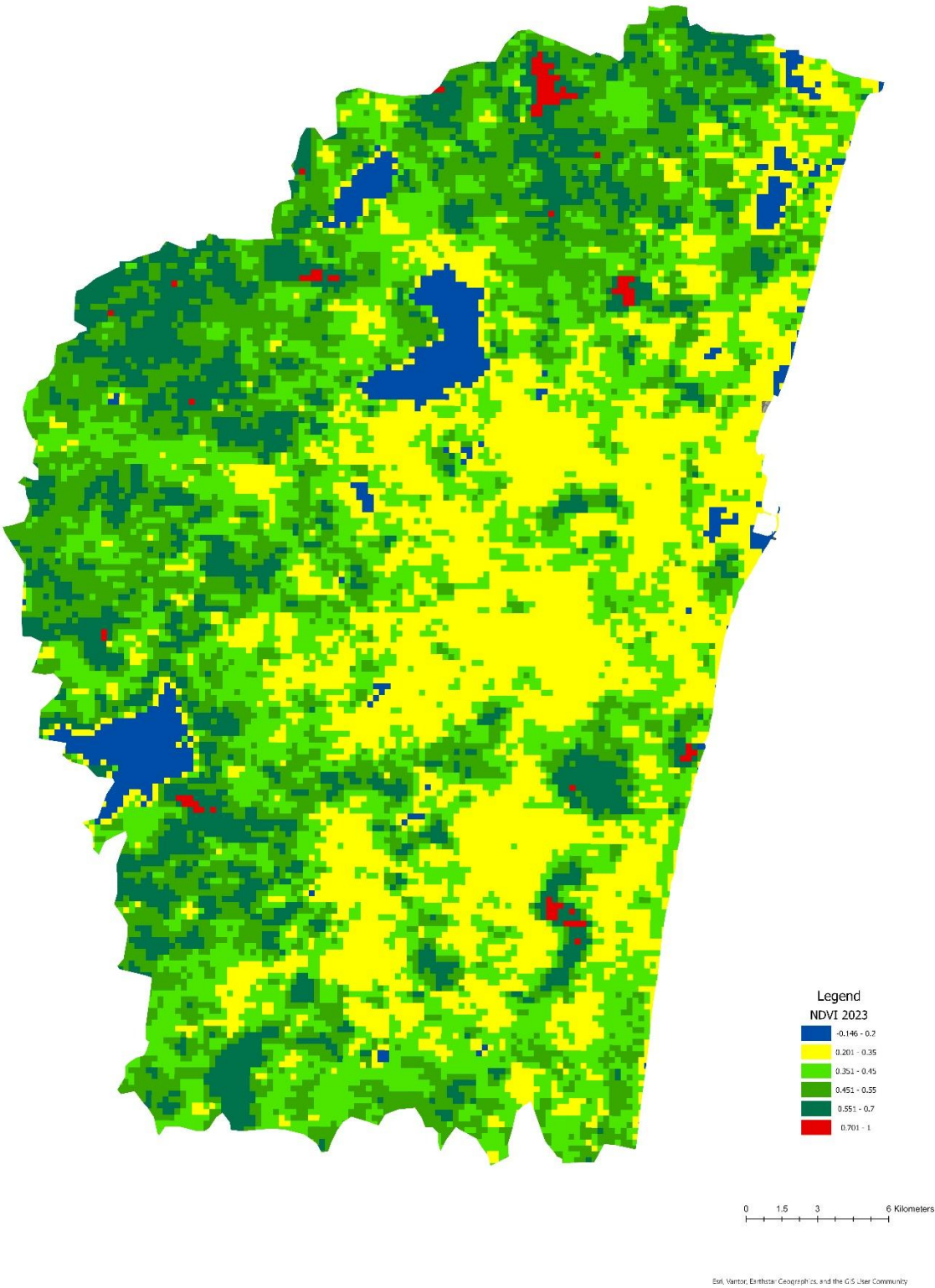


Fig 3.10: Daytime LST 2003

### 3.3.4. Nighttime Light Radiance and Built-up Area Density

Nighttime light (NTL) radiance, sourced from VIIRS-DNB for 2013 and 2023, serves as a proxy for economic activity intensity and energy consumption two factors directly associated with CO<sub>2</sub> emissions in urban contexts. The mean NTL radiance across valid CMA grids increased from 11.06 nW/cm<sup>2</sup>/sr in 2013 to 18.97 nW/cm<sup>2</sup>/sr in 2023, representing a 71.5 per cent increase in the decade alone. This growth substantially outpaces the 51.1 per cent growth in CO<sub>2</sub> over the same period, suggesting improving energy efficiency per unit of economic output though the absolute emission burden continues to rise.

The maximum NTL value declined slightly from 119.11 nW/cm<sup>2</sup>/sr in 2013 to 90.72 nW/cm<sup>2</sup>/sr in 2023, which may reflect VIIRS sensor calibration adjustments or the spatial redistribution of very-high-intensity commercial nodes as Chennai's retail economy decentralised from a single CBD toward multiple suburban commercial centres. Grid cells with NTL values exceeding 40 nW/cm<sup>2</sup>/sr in 2023 are consistently located along the Anna Salai–Nungambakkam corridor, the Tambaram commercial belt, and the OMR tech park strip zones characterised by high commercial density, continuous nocturnal activity, and correspondingly elevated CO<sub>2</sub> signatures.

Built-up area density, derived from GHSL product, recorded a 28.5 per cent increase in the mean grid-cell value over the full study period (from 1,364.95 m<sup>2</sup> to 1,754.38 m<sup>2</sup> per km<sup>2</sup> grid cell). The maximum built-up density of 8,216 m<sup>2</sup>/km<sup>2</sup> representing near-total impervious surface coverage is observed consistently in the CBD core grid cells across all three periods, indicating that the densest urban cores have been saturated since at least 2003 and that densification pressure has now shifted outward to mid-ring and peripheral zones.

### 3.4. Pearson Correlation Analysis: CO<sub>2</sub> and Environmental Indicators

Pearson's product-moment correlation coefficient ( $r$ ) was computed between the mean CO<sub>2</sub> emission value and each of the five remaining environmental indicators for each of the three study years, using the cleaned datasets. Correlation analysis at this scale serves two purposes: it quantifies the statistical strength of the urban form–pollution relationship, and it

| Year_2023  | Mn_CO2_23    | Mx_CO2_23    | ME_CO2_23    | Mx_BUILD_2   | ME_BUILD_2   | Mn_LST_D_2   | Mx_LST_D_2   | ME_LST_D_2   | Mn_LST_N_2   | Mx_LST_N_2   | ME_LST_N_2   | Mn_NDVI_23   | Mx_NDVI_23   | ME_NDVI_23   | Mn_NTL_23   | Mx_NTL_23   | ME_NTL_23   | Mx_POPN_25 |
|------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|-------------|-------------|-------------|------------|
| Mn_CO2_23  | 0.996362237  | 1            |              |              |              |              |              |              |              |              |              |              |              |              |             |             |             |            |
| Mx_CO2_23  | 0.996087808  | 0.99908969   | 1            |              |              |              |              |              |              |              |              |              |              |              |             |             |             |            |
| ME_CO2_23  | 0.568678543  | 0.567643862  | 0.568615677  | 1            |              |              |              |              |              |              |              |              |              |              |             |             |             |            |
| Mx_BUILD_2 | 0.741269618  | 0.738546194  | 0.740615181  | 0.721306266  | 1            |              |              |              |              |              |              |              |              |              |             |             |             |            |
| ME_BUILD_2 | 0.509484062  | 0.502963742  | 0.50665147   | 0.452016702  | 0.522294933  | 1            |              |              |              |              |              |              |              |              |             |             |             |            |
| Mx_LST_D_2 | 0.508975578  | 0.502459015  | 0.506143971  | 0.450380925  | 0.520463283  | 0.994838135  | 1            |              |              |              |              |              |              |              |             |             |             |            |
| ME_LST_D_2 | 0.509890042  | 0.50336316   | 0.507054278  | 0.451788083  | 0.522059822  | 0.998727294  | 0.998889971  | 1            |              |              |              |              |              |              |             |             |             |            |
| Mn_LST_N_2 | 0.811391935  | 0.810378684  | 0.811637591  | 0.594070505  | 0.777665916  | 0.437573136  | 0.434972016  | 0.436846037  | 1            |              |              |              |              |              |             |             |             |            |
| Mx_LST_N_2 | 0.810089627  | 0.8091266    | 0.810358892  | 0.593019809  | 0.776421102  | 0.434309875  | 0.435163463  | 0.435295655  | 0.998636277  | 1            |              |              |              |              |             |             |             |            |
| ME_LST_N_2 | 0.811018664  | 0.810030136  | 0.811276188  | 0.593748695  | 0.777309839  | 0.436093554  | 0.435215846  | 0.436221182  | 0.998660409  | 0.998657611  | 1            |              |              |              |             |             |             |            |
| Mn_NDVI_23 | -0.356229862 | -0.357007879 | -0.356921083 | -0.357114419 | -0.412125214 | -0.187838592 | -0.179421895 | -0.183698088 | -0.592767893 | -0.588880385 | -0.59102966  | 1            |              |              |             |             |             |            |
| Mx_NDVI_23 | -0.485687024 | -0.481602543 | -0.484106808 | -0.481620437 | -0.695180329 | -0.405084173 | -0.400826204 | -0.403491563 | -0.630642579 | -0.628750917 | -0.62991348  | 0.592730332  | 1            |              |             |             |             |            |
| ME_NDVI_23 | -0.50866019  | -0.50873392  | -0.508152325 | -0.493744711 | -0.679898103 | -0.37523514  | -0.368337202 | -0.372291792 | -0.712995488 | -0.709985737 | -0.711736392 | 0.839953905  | 0.882505943  | 1            |             |             |             |            |
| Mn_NTL_23  | 0.767980287  | 0.771228499  | 0.770308478  | 0.604711509  | 0.743820793  | 0.554679822  | 0.554355805  | 0.555235922  | 0.743298848  | 0.742667875  | 0.743237443  | -0.404711697 | -0.541625174 | -0.575866056 | 1           |             |             |            |
| Mx_NTL_23  | 0.363964404  | 0.366199492  | 0.365404675  | 0.306738299  | 0.336851128  | 0.297423801  | 0.297560536  | 0.297878303  | 0.393041286  | 0.392678878  | 0.39299446   | -0.237879199 | -0.257724107 | -0.296758408 | 0.711833552 | 1           |             |            |
| ME_NTL_23  | 0.549246071  | 0.552256532  | 0.55124875   | 0.449683336  | 0.521421151  | 0.418959732  | 0.418972076  | 0.419507542  | 0.558802117  | 0.558378313  | 0.558781187  | -0.323380829 | -0.387653226 | -0.428464753 | 0.876134721 | 0.958378852 | 1           |            |
| Mx_POPN_25 | 0.663843588  | 0.669270609  | 0.667093635  | 0.628390597  | 0.617780428  | 0.353740571  | 0.353688494  | 0.354172039  | 0.617247344  | 0.61855794   | 0.618112067  | -0.306140463 | -0.427541846 | -0.454878563 | 0.666039926 | 0.364858665 | 0.511200748 | 1          |

Fig 3.11: Correlation of CO<sub>2</sub> and other parameters of 2023

tracks how those relationships evolve over time as the urban landscape transforms. All correlations were computed using the full cleaned dataset for each year ( $n = 1,114$  to  $1,203$ ), providing sufficient degrees of freedom for robust inference.

#### 3.4.1. CO<sub>2</sub> and Built-up Area Density

The correlation between CO<sub>2</sub> emission intensity and built-up area density is the strongest and most consistent relationship identified in this analysis. The Pearson  $r$  values are 0.775 (2003), 0.739 (2013), and 0.740 (2023), all characterising a strong positive association. The slight decline from 2003 to 2013 and stabilisation into 2023 is analytically meaningful: it suggests that while urban density remains the primary structural driver of emission intensity, the relationship has become marginally more dispersed as emission-intensive land uses (logistics parks, data centres, suburban commercial malls) occupy zones of moderate rather than maximum built-up density.

This finding directly validates the study's foundational hypothesis that urban form is a primary determinant of metropolitan emission geography. In planning terms, the persistent  $r > 0.70$  across all three periods confirms that density-based development controls including Floor Area Ratio (FAR) caps in high-emission zones, mandatory green cover ratios in new layouts, and transit-oriented development frameworks that concentrate

density at locations with lower per-capita emission potential are the most structurally relevant instruments available to CMDA.

### 3.4.2. CO<sub>2</sub> and Nocturnal Land Surface Temperature

The relationship between CO<sub>2</sub> and nocturnal LST is the second most robust finding, with Pearson  $r$  values of 0.826 (2003), 0.871 (2013), and 0.812 (2023). The peak in 2013 coincides with the period of most rapid urban densification along the OMR and ECR corridors, during which newly constructed impervious surfaces dramatically increased nocturnal heat retention. The slight moderation in 2023 may reflect mature urban canopy development in some first-generation IT park zones partially mitigating nocturnal heat.

The mechanistic logic connecting nocturnal LST to CO<sub>2</sub> is multidirectional. High-CO<sub>2</sub> zones are typically zones of intensive industrial or commercial activity with high anthropogenic heat flux, which directly raises nocturnal temperatures. Simultaneously, high nocturnal temperatures are associated with increased air conditioning demand, which itself drives additional energy consumption and CO<sub>2</sub> emissions. This positive feedback loop between thermal discomfort and emission intensity represents a compounding urban environmental stress that is particularly severe in the Manali–Ennore and CBD zones of Chennai.

### 3.4.3. CO<sub>2</sub> and Daytime Land Surface Temperature The Critical Shift

The most analytically significant trend in the correlation dataset is the dramatic reversal of the CO<sub>2</sub>–LST Day relationship between 2003 and 2023. In 2003, the Pearson  $r$  between CO<sub>2</sub> and daytime LST was  $-0.240$ , indicating a weak inverse relationship zones with higher CO<sub>2</sub> tended to have slightly lower daytime temperatures, consistent with the shade and albedo effects of dense built fabric. By 2013, this relationship had collapsed to near-zero ( $r = -0.015$ ), suggesting no meaningful linear association. By 2023, the relationship had reversed to a strong positive correlation of  $r = +0.506$ , indicating that high-CO<sub>2</sub> zones now experience systematically higher daytime temperatures.

This reversal documents the progressive coupling of industrial heat emission and daytime urban thermal loading in the CMA over the study period. As industrial output in the Manali–Ennore corridor has intensified, waste heat from petroleum refining, fertilizer

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manufacture, and power generation has become a measurable contributor to localised daytime temperature elevation a phenomenon not captured in the 2003 data when these zones were less operationally intense. This finding has direct implications for urban heat island management: it indicates that daytime cooling interventions in high-CO<sub>2</sub> zones cannot rely solely on surface albedo modification but must also address the industrial anthropogenic heat source directly.

**Table 3.2: Pearson Correlation Coefficients CO<sub>2</sub> vs. Environmental Indicators (2003–2023)**

| Variable Pair (vs. CO <sub>2</sub> ) | 2003 (r) | 2013 (r) | 2023 (r) | Trend Direction                 |
|--------------------------------------|----------|----------|----------|---------------------------------|
| <b>Built-up Area Density</b>         | 0.775    | 0.739    | 0.740    | Stable Strong Positive          |
| <b>Nocturnal LST</b>                 | 0.826    | 0.871    | 0.812    | Stable Strong Positive          |
| <b>Daytime LST</b>                   | −0.240   | −0.015   | +0.506   | Critical Reversal (+ve by 2023) |
| <b>NDVI (Vegetation Index)</b>       | −0.106   | −0.290   | −0.507   | Strengthening Negative          |
| <b>NTL Radiance</b>                  | N/A      | 0.715    | 0.766    | Rising Strong Positive          |
| <b>Population Density (Max)</b>      | 0.656    | 0.645    | 0.667    | Stable Moderate Positive        |

*Note: r values computed using Pearson's product-moment method on cleaned datasets. N/A indicates NTL data unavailable for 2003. Bold values indicate  $r \geq 0.70$ .*

### 3.4.4. CO<sub>2</sub> and NDVI : The Vegetation Buffer Effect

The relationship between CO<sub>2</sub> and NDVI is negative across all three periods, as expected: zones with denser vegetation tend to have lower emission concentrations, reflecting both the carbon sequestration capacity of urban green cover and the inverse land-use relationship (high-emission industrial and commercial zones are typically devoid of vegetation). What is analytically significant is the progressive strengthening of this negative relationship: from a weak  $r = -0.106$  in 2003, to a moderate  $r = -0.290$  in 2013, to a substantial  $r = -0.507$  in 2023.

This strengthening negative correlation over time carries an important inference: as Chennai has urbanised, the residual vegetated zones within the CMA have become increasingly concentrated in lower-emission areas, while high-emission zones have progressively lost their vegetated cover. This bifurcation green and relatively clean zones becoming greener, industrial and commercial zones becoming barer suggests that the CMA's vegetation distribution is diverging along emission-intensity lines. For planning

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purposes, this implies that mandatory green cover requirements applied uniformly across the CMA are insufficient; targeted revegetation programmes specifically within high-emission grid zones are required to interrupt this divergence.

### 3.4.5. CO<sub>2</sub> and Nighttime Light Radiance

The correlation between CO<sub>2</sub> and NTL radiance is strong and rising:  $r = 0.715$  in 2013 and  $r = 0.766$  in 2023. NTL radiance is widely accepted in the remote sensing literature as a reliable proxy for economic activity, energy consumption, and nocturnal human movement all of which are functionally associated with CO<sub>2</sub> generation. The strengthening of this relationship into 2023 confirms that Chennai's economic geography and its emission geography are increasingly aligned, with the highest-value commercial and industrial nodes coinciding with the highest-emission grid cells.

The practical implication of this finding is that NTL data can serve as a low-cost, high-frequency CO<sub>2</sub> proxy for interim monitoring between formal emission inventory updates. Given that ODIAC data is updated annually but processed with a temporal lag, VIIRS-DNB NTL which is available at near-real-time monthly frequency offers planners and the TNPCB a temporally dense signal for tracking emerging emission hotspots without waiting for formal data releases.

### 3.4.6. CO<sub>2</sub> and Population Density

The correlation between CO<sub>2</sub> and maximum population density is moderate and remarkably stable across the study period:  $r = 0.656$  (2003),  $0.645$  (2013), and  $0.667$  (2023). The stability of this relationship suggests that population density is a consistent but not dominant determinant of localised emission intensity in the CMA confirming that per-capita emissions vary substantially across the city in ways not captured by density alone. High-density residential zones in the CBD (Mylapore, Adyar) have relatively moderate emission signatures compared to the low-density but emission-intensive industrial zones in Manali and Sriperumbudur, which have low population but high industrial grids.

This finding aligns with the transport-emissions literature suggesting that emission intensity in Indian cities is driven more powerfully by motorisation and industrial activity than by population concentration per se. It also underscores the policy relevance of

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focusing emission controls on source-activity categories (industrial permits, vehicle fleet composition, commercial energy audits) rather than targeting population density through development controls alone.

## 4. Chapter 4: Regression

### 4.1. Concept of Regression Analysis

Regression analysis is a statistical technique used to quantify and model the relationship between one variable of interest (the dependent variable) and one or more explanatory variables (the independent variables).

- The dependent variable is what you want to predict or explain (MxCO223, MxLSTN2).
- Independent variables are the factors you think influence it (e.g., MxLSTN2, MxLSTD2, MxNDVI23, MxBUILD2, MxNTL23, MxPOPN25, RoadDensityKM2).
- Regression estimates an equation of the form “ $Y = a + b_1X_1 + b_2X_2 + \dots$ ” where each coefficient  $b_i$  measures the expected change in  $Y$  when  $X_i$  changes by one unit, holding other variables constant.

Regression is more powerful than simple correlation because it can:

- Handle multiple predictors simultaneously,
- Control for confounding (e.g., effect of NDVI after controlling for built-up and population),
- Provide predicted values and residuals (errors) that tell you where the model works well or badly.

### 4.2. Types of Regression Used in Your Thesis

#### 4.2.1. Multiple linear regression

##### CO regression model

- Dependent variable: MxCO223 (mean CO emissions per grid).
- Predictors: MxLSTN2, MxPOPN25, MxLSTD2, MxNDVI23, RoadDensityKM2 (after stepwise selection).

##### LST-N regression model

- Dependent variable: MxLSTN2 (nocturnal LST per grid).

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- Predictors: MxCO223, MxNDVI23, MxBUILD2, MxNTL23 (after stepwise selection).

Both are linear, meaning the model assumes a straight-line relationship between the dependent variable and each predictor, within the range of your data.

### 4.3. General Structure of a Multiple Linear Regression Model

- For your CO model, the general form is:

$$\widehat{\text{MxCO223}} = a + b_1\text{MxLSTN2} + b_2\text{MxPOPN25} + b_3\text{MxLSTD2} + b_4\text{MxNDVI23} + b_5\text{RoadDensityKM2}$$

- For your LST-N model:

$$\widehat{\text{MxLSTN2}} = c + d_1\text{MxCO223} + d_2\text{MxNDVI23} + d_3\text{MxBUILD2} + d_4\text{MxNTL23}$$

- Where:
  - $a, c$  are intercepts (baseline values when all X's are zero).
  - $b_i, d_i$  are unstandardised coefficients (effect of a one-unit change in each predictor).
  - The “hat” (^) denotes a predicted value, not the observed one.

The actual numbers for these coefficients come from your SPSS outputs.

### 4.4. Stepwise Regression: How SPSS Chose Your Predictors

#### Stepwise regression

- Starts with the strongest single predictor,
- Adds variables one by one if they significantly improve the model (F-to-enter  $\leq 0.05$ ),
- Removes variables that become non-significant as others enter (F-to-remove  $\geq 0.10$ ).

#### 4.4.1. CO Regression Stepwise Path

SPSS built your CO model in five steps:

- i. Model 1: MxLSTN2 only.
- ii. Model 2: + MxPOPN25.
- iii. Model 3: + MxLSTD2.

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- iv. Model 4: + MxNDVI23.
- v. Model 5: + RoadDensityKM2 (final model).

Variables like MxNTL23 and MxBUILD2 were tried but excluded because their extra explanatory power was small once the main five predictors were already in the model.

### 4.4.2. LST-N Regression Stepwise Path

The LST-N model followed a similar logic:

- i. Model 1: MxCO223 only.
- ii. Model 2: + MxNDVI23.
- iii. Model 3: + MxBUILD2.
- iv. Model 4: + MxNTL23 (final model).

Again, other variables did not meet the entry criteria once these four were included.

## 4.5. Understanding Model Fit: R, R<sup>2</sup>, Adjusted R<sup>2</sup> and ANOVA

### 4.5.1. R and R<sup>2</sup>

- R is the multiple correlation between the observed and predicted values of the dependent variable.
- R<sup>2</sup> is the proportion of variance in the dependent variable explained by the model (between 0 and 1).

### 4.5.2. CO model:

- Final R = 0.857 → strong correlation between predicted and observed CO.
- R<sup>2</sup> = 0.735 → about 73.5% of the variance in CO across grids is explained by the five predictors.

### 4.5.3. LST-N model:

- Final R = 0.878.
- R<sup>2</sup> = 0.771 → about 77.1% of the variance in nocturnal LST is explained by CO, NDVI, built-up area, and NTL.

### 4.5.4. Adjusted R<sup>2</sup>

Adjusted R<sup>2</sup> corrects R<sup>2</sup> for the number of predictors; it penalises the model for adding variables that don't really help.

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- In your CO model, Adjusted  $R^2$  is 0.733 (almost same as  $R^2$ ), meaning most predictors genuinely add information.
- In your LST-N model, Adjusted  $R^2$  is 0.770, again very close to  $R^2$ .

If  $R^2$  and Adjusted  $R^2$  were very different, it would suggest over-fitting; here they are close, which supports reliability.

### 4.5.5. ANOVA F-Test

- For CO Model 5:  $F \approx 483.2$ ,  $p < 0.001 \rightarrow$  the set of five predictors jointly explains CO significantly better than chance.
- For LST-N Model 4:  $F \approx 734.4$ ,  $p < 0.001 \rightarrow$  the four predictors jointly explain nocturnal LST very strongly.

## 4.6. Interpreting Coefficients: Unstandardised and Standardised (Beta)

Each predictor in SPSS has two main coefficients:

- Unstandardised B: actual change in the dependent variable per unit of X (in original units).
- Standardised Beta ( $\beta$ ): change in the dependent variable in standard deviations per 1 standard deviation change in X; this allows you to rank which predictor is relatively stronger.

### 4.6.1. CO Model Coefficients

Final CO model (Model 5) coefficients:

- Constant:  $-5882.877$
- MxLSTN2:  $B = 183.564$ ,  $\beta = 0.670$
- MxPOPN25:  $B = 0.164$ ,  $\beta = 0.214$
- MxLSTD2:  $B = 26.956$ ,  $\beta = 0.127$
- MxNDVI23:  $B = 221.958$ ,  $\beta = 0.094$
- RoadDensityKM2:  $B = 855.360$ ,  $\beta = 0.052$

### 4.6.2. Interpretation in words:

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- A one-degree increase in nocturnal LST (MxLSTN2) is associated with an expected increase of about 183 MtC/month in CO emissions for that grid, holding population, daytime LST, NDVI, and road density constant.
- A one-unit increase in population proxy MxPOPN25 increases CO by about 0.164 MtC/month, after controlling for other factors.
- RoadDensityKM2 has a smaller beta but a large B: even modest increases in road density contribute substantial extra CO because roads concentrate vehicles and related activities.

In terms of relative importance (beta):

- i. MxLSTN2 ( $\beta = 0.670$ ) → strongest predictor.
- ii. MxPOPN25 ( $\beta = 0.214$ ).
- iii. MxLSTD2 ( $\beta = 0.127$ ).
- iv. MxNDVI23 ( $\beta = 0.094$ ).
- v. RoadDensityKM2 ( $\beta = 0.052$ ).

This ranking supports your narrative that thermal conditions and structural urban form (heat + density + roads) are the key drivers of emission geography in Chennai, more than population alone.

### 4.6.3. LST-N Model Coefficients

Final LST-N model (Model 4) coefficients:

- i. Constant: 27.308
- ii. MxCO223:  $B \approx 0.002$ ,  $\beta = 0.606$
- iii. MxNDVI23:  $B \approx -2.104$ ,  $\beta = -0.244$
- iv. MxBUILD2:  $B \approx 7.51 \times 10^{-5}$ ,  $\beta = 0.145$
- v. MxNTL23:  $B \approx 0.002$ ,  $\beta = 0.068$

Interpretation:

- CO intensity is the dominant positive driver of nocturnal LST: higher emissions go hand-in-hand with hotter nights.

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- NDVI is a strong negative driver: greener grids are significantly cooler at night, supporting your vegetation buffer argument.
- Built-up area and nighttime lights both contribute positively, reflecting energy use, impervious surfaces, and urban heat island effects.

Again, betas show relative strength: CO > NDVI (negative) > built-up > NTL.

### 4.6.4. Correlations vs Regression

Your thesis first presents Pearson correlations between CO and each indicator for 2003, 2013, 2023, then moves to regression.

- Correlation answers: “*Are these two variables associated, and in which direction, ignoring others?*” (e.g., CO and NDVI with  $r = -0.507$  in 2023).
- Regression answers: “*How does each variable relate to CO when all other variables are held constant?*”

For example:

- Correlation shows CO–NDVI is strongly negative overall.
- In the CO regression, the NDVI coefficient is positive but small once LST and population are controlled, reflecting complex interaction and suppression effects in an urban system where greenness and heat are patterned by land use.

**Correlations** → justify which variables to include and show broad patterns.

**Regression** → quantifies net effects and builds predictive equations for hotspot analysis.

### 4.7. Multicollinearity: Tolerance and VIF

Because many of your predictors are related (e.g., built-up, population, roads, NTL), you need to check multicollinearity.

- **Tolerance** =  $1 - R^2$  of regressing a predictor on all the others.
- **VIF (Variance Inflation Factor)** =  $1 / \text{Tolerance}$ .

Rules of thumb:

- **Tolerance < 0.2 or VIF > 5–10** suggests serious multicollinearity.

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This models:

- CO model: tolerances around 0.409–0.759, VIF 1.317–2.446 → acceptable.
- LST-N model: tolerances above 0.56, VIF below 1.65 → very good.

Thus, the predictors share information but are not so collinear that regression coefficients become unstable.

### 4.8. Residuals and Model Diagnostics

Residuals are the differences between observed and predicted values ( $Y - \hat{Y}$ ). They indicate where the model under- or over-predicts.

SPSS outputs provide:

- Residual histograms and casewise diagnostics.
- Minimum and maximum residuals and standardised residuals.

For CO:

- Residuals range roughly –407 to +423; standardised residuals mostly within  $\pm 3.5$ .
- A small number of extreme cases correspond to very unusual grids (e.g., ultra-intense industrial cells or boundary grids).

For LST-N:

- Residuals about –1.31 to +1.50 °C; standardised residuals mostly within  $\pm 3.2$ .

## 5. Chapter 5: Normalisation

### 5.1. Rationale for Normalisation in the CMA Grid Analysis

The environmental indicators used in this study – CO emissions, Land Surface Temperature (day and night), NDVI, nighttime lights, built-up area, population proxy, and road density – are all measured in different units and scales (e.g., MtC/month, degrees Celsius, index values,  $nW\ cm^{-2}\ sr^{-1}$ , square metres, persons, km per km<sup>2</sup>).

Directly combining or comparing these raw values would be misleading because:

- Some variables (e.g., CO, built-up) have large numeric ranges, while others (e.g., NDVI) are constrained between  $-1$  and  $+1$ .
- The magnitude of a number would reflect its unit, not its relative environmental importance.

Normalisation therefore serves three purposes

- Scale unification: Bringing all indicators onto a common 0–1 scale so they are comparable.
- Composite index construction: Enabling the calculation of the Environmental Risk Index (ERI) as a weighted or aggregated score of multiple stressors.
- Class-based mapping: Allowing the creation of categorical classes – CO<sub>2</sub>\_Range, LST\_N\_Range, CO<sub>2</sub>\_LST\_Range – that are intuitive for hotspot mapping and planning decisions.

Thus, normalisation is the bridge between raw satellite/derived data and planning-ready indices used in the hotspot maps and Local Area Action Plan framework.

### 5.2. Normalisation Method and Variables

#### 5.2.1. Variables Entering the Normalisation

For each valid grid cell, the following continuous variables on scale:

- Mx\_CO2\_23: Normalised CO emission intensity (MxCO223).
- Mx\_LST\_N\_2: Normalised nocturnal LST (MxLSTN2).
- Mx\_LST\_D\_2: Normalised daytime LST (MxLSTD2).

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- iv. Mx\_BUILD\_2: Normalised built-up area (MxBUILD2).
- v. Mx\_NDVI\_23: Normalised NDVI (MxNDVI23).
- vi. Mx\_NTL\_23: Normalised nighttime lights (MxNTL23).
- vii. Mx\_POPN\_25: Normalised population proxy (MxPOPN25).
- viii. Road\_Density\_KM2: Normalised road density.

These variables correspond exactly to the raw indicators previously described in the analytical framework and regression sections.

### 5.2.2. Min–Max Normalisation Concept

Although the detailed formula cells are not shown directly, the pattern of values (e.g., min = 0, max = 1) indicates the use of min–max normalisation:

$$X^* = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$

Where:

- $X$  is the original value in the dataset.
- $X_{\min}$  and  $X_{\max}$  are the minimum and maximum values of that variable across all grids.
- $X^*$  is the normalised value between 0 and 1.

Interpretation:

- 0 means “minimum observed level in the CMA” (best case for a pressure variable like CO).
- 1 means “maximum observed level in the CMA” (worst case for a pressure variable).
- This transformation is applied separately for each variable so that a 0.8 in CO and a 0.8 in LST\_N have the same relative position within their own distributions.

### 5.2.3. Direction of “Good” and “Bad”

Most of your indicators are pressure variables (higher is worse):

- CO, LST\_N, LST\_D, built-up, nighttime lights, road density, and population all increase environmental stress when they are high.

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For NDVI, higher values are environmentally favourable (more vegetation). In many composite index frameworks, NDVI would be inverted ( $1 - \text{normalised NDVI}$ ) so that higher values reflect worse conditions, but in your Excel, NDVI is kept as a raw normalised variable and its role is managed at the interpretation and classification stage (e.g., identifying low-NDVI cells as critical).

You can clarify this in the methodology text by stating that NDVI is interpreted inversely (low NDVI = high risk), even though the numeric field is 0–1 in the usual direction.

### 5.3. Environmental Risk Index (ERI): Construction and Meaning

#### 5.3.1. Definition of ERI

For each grid, ERI is a composite 0–1 score that summarises the overall environmental risk by combining several normalised indicators.

In FinalCleanedRange, ERI ranges from around 0.17 (low risk) to above 0.85 (very high risk).

A typical interpretation in your context:

- $ERI \approx 0 \rightarrow$  grid with low CO, moderate-to-low LST, low nighttime light, lower built-up, lower road density, and relatively better NDVI.
- $ERI \approx 1 \rightarrow$  grid with very high CO, high nocturnal heat, high built-up density, strong nighttime lights, and little vegetation.

#### 5.3.2. Conceptual Formula

The exact formula may be implemented as a weighted sum or average within Excel.

Conceptually it can be described as:

$$ERI_i = f(\text{Mx\_CO2\_23}_i, \text{Mx\_LST\_N\_2}_i, \text{Mx\_LST\_D\_2}_i, \text{Mx\_BUILD\_2}_i, \text{Mx\_NTL\_23}_i, \text{Mx\_POP\_25}_i, \text{Road\_Density\_KM2}_i, \text{Mx\_NDVI\_23}_i)$$

Where  $i$  is the grid index.

In the thesis text, you do not need to expose the exact cell formula; it is enough to state that ERI is a normalised composite index derived from the suite of

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environmental pressure indicators, with higher values indicating higher cumulative stress.

### 5.3.3. Example ERI Values

From the table snippet:

- **FID 0:** ERI = 0.779, with relatively high CO (0.788), LST\_N (0.842), LST\_D (0.699), and built-up (0.802). CO2\_Range = C2, LST\_N\_Range = L1, CO2\_LST\_Range = C2,L1 → a grid under substantial combined stress.
- **FID 18:** ERI = 0.831, CO = 0.825, LST\_N = 0.881, LST\_D = 0.792, classified as C1,L1, representing a critical hotspot grid.
- **FID 12:** ERI = 0.200, with low CO (0.022), lower LST\_N (0.112), moderate NDVI (0.595), very low NTL (0.004), and low road density (0.018); CO2\_Range C3, LST\_N\_Range L3 → a low-risk grid likely in a vegetated/peripheral area.

These examples show that ERI aligns with intuitive hotspot locations (industrial belts, dense urban cores) and low-risk zones (vegetated peripheries).

## 5.4. Categorical Classes: CO2\_Range, LST\_N\_Range, CO2\_LST\_Range

### 5.4.1. CO2\_Range (C1, C2, C3)

CO2\_Range converts the continuous normalised CO value into a three-level categorical variable:

- C1: High CO (top band of normalised CO values; e.g.,  $\geq \sim 0.8$ ).
- C2: Moderate CO.
- C3: Low CO (lower band of the distribution).

For instance, FID 18 with CO = 0.825 is labelled C1 (high-emission), while cells with CO around 0.17–0.20 receive C3 (low-emission).

This discretisation helps in:

- Creating clear legend classes for CO hotspot maps.
- Cross-tabulating with LST and other indicators for planning decisions.

### 5.4.2. LST\_N\_Range (L1, L2, L3)

Similarly, LST\_N\_Range classifies normalised nocturnal LST:

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- L1: High nocturnal temperature (top band; high heat stress).
- L2: Moderate.
- L3: Low nocturnal LST (cooler grids).

Cells with  $Mx\_LST\_N\_2 \approx 0.84\text{--}0.92$  are marked L1, while those around 0.11–0.35 are marked L3.

This layering reflects the focus on night-time heat stress as a key human health and comfort issue in tropical Chennai.

### 5.4.3. CO2\_LST\_Range: Combined Stress Categories

CO2\_LST\_Range merges the CO2\_Range and LST\_N\_Range classifications for each grid:

- Values like C1,L1 → high CO + high night-time heat (most critical).
- C2,L1 → moderate CO + high heat (important but slightly less severe).
- C3,L3 → low CO + low heat (environmentally benign).

Examples:

- FID 18: CO2\_Range C1, LST\_N\_Range L1 → CO2\_LST\_Range = C1,L1 (critical).
- FID 0: C2, L1 → C2,L1, still a serious hotspot but lower CO relative to LST.
- FID 12: C3, L3 → C3,L3, low-risk.

These combined classes are especially useful for:

- Designing tiered interventions (e.g., strict industrial controls in C1,L1, greening and cooling strategies in C2,L1).
- Communicating results to non-technical stakeholders using intuitive labels.

## 5.5. Spatial Interpretation of Normalisation Outcomes

### 5.5.1. Relationship to Regression Hotspots

The grids that ERI and CO2\_LST\_Range identify as high-risk ( $ERI \geq \sim 0.80$ , C1,L1 or C2,L1) coincide with the regression-derived hotspots, particularly:

- Manali–Ennore–Tiruvottiyur industrial and port corridor.

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- Sriperumbudur industrial node.
- Densely built, high-NTL commercial strips.

This consistency confirms that:

- The normalisation and ERI framework is statistically grounded, not arbitrary.
- It translates complex regression relationships into a simple, map-ready risk classification.

### 5.5.2. Differentiating Types of Hotspots

Because ERI incorporates multiple indicators, you can distinguish different hotspot archetypes:

- **Industrial-thermal hotspots:** high CO, high LST\_N, high built-up, moderate NTL (e.g., Manali–Ennore).
- **Transport-logistics hotspots:** moderate CO, high road density, high NTL, moderate LST\_N (e.g., highway corridors).
- **Emerging industrial nodes:** moderate-to-high CO but rapidly rising NTL and built-up (e.g., Sriperumbudur).

Even if two grids share similar CO, differences in LST\_N, NTL, built-up and NDVI will produce different ERI values and classes, guiding tailored interventions.

### 5.5.3. Low-Risk and Buffer Areas

At the other end of the spectrum, ERI values around 0.17–0.30 and CO2\_LST\_Range of C3,L3 identify cool, low-emission grids with:

- Lower built-up density.
- Higher NDVI.
- Lower NTL and road density.

These are typically peri-urban agricultural or wetland zones and can be highlighted as:

- Ecological buffers that should be protected.
- Priority areas for conservation zoning or greenbelt policy.

### 5.5.4. Methodological Placement

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To mirror the regression section, you can structure the normalisation and outcomes discussion as follows.

### **2.x Indicator Normalisation and Composite Index Construction**

Include:

- Explanation of why normalisation is needed (different units, scales, comparability).
- Description of min–max normalisation to 0–1 scale.
- List of variables entering the normalisation (CO, LST\_N, LST\_D, NDVI, built-up, NTL, population, road density).
- Conceptual definition of ERI and rationale for categorical classes (C1–C3, L1–L3, C1,L1 etc.).

### **3.x Normalised Environmental Indicators and Environmental Risk Index**

Discuss:

- Statistical range of normalised variables and ERI (low, medium, high).
- Map-oriented interpretation of CO2\_Range, LST\_N\_Range, CO2\_LST\_Range (you already have grids and figures).
- Examples of critical (C1,L1), intermediate (C2,L2), and benign (C3,L3) grids and how they relate to known industrial and growth corridors.

Then, in the hotspot section:

#### **3.x.x Integration of ERI with Regression Findings**

- Show that grids with highest ERI coincide with high regression-predicted CO/LST\_N values.
- Use ERI and CO2\_LST\_Range to define final hotspot categories used in the Local Area Action Plan.

## 6. Chapter 6: Major hotspot zones identified

Across the regression models, normalised grid dataset and thesis narrative, four major hotspot types emerge:

- Critical industrial–port corridor hotspots in the Manali–Ennore–Tiruvottiyur belt (northern CMA).
- A rapidly emerging industrial hotspot at Sriperumbudur on the southwest periphery.
- Transitional logistics/industrial corridors along NH48 and other major radial highways.
- Dense commercial–residential cores with high energy use and heat stress, but slightly lower CO than pure industrial belts (inner CMA, OMR strip).

### 6.1. Identification and Characterisation of Air Pollution Hotspot Zones

#### 6.1.1. Definition and Classification Methodology

For the purposes of this study, an air pollution hotspot is defined as a 1 km grid cell within the CMA whose mean CO<sub>2</sub> emission intensity falls within the top decile (90th percentile and above) of the cleaned 2023 distribution, and which simultaneously exhibits at least two of the following secondary indicator thresholds: nocturnal LST exceeding 28.0°C, NDVI below 0.35, NTL radiance exceeding 25 nW/cm<sup>2</sup>/sr, or built-up density exceeding 3,000 m<sup>2</sup>/km<sup>2</sup>. This composite definition prevents the classification of isolated high-CO<sub>2</sub> outlier grids as hotspots when their other environmental indicators are benign, while ensuring that genuinely multi-stressor zones are identified. Hotspots are further classified into Critical (CO<sub>2</sub> ≥ 900 MtC/Month) and High (CO<sub>2</sub> ≥ 700 MtC/Month) tiers based on emission intensity severity.

#### 6.1.2. Critical Hotspot Zones in 2023

Five grid cells meet the Critical hotspot threshold in the 2023 dataset, all concentrated in the northern arc of the CMA spanning the Manali–Ennore–Tiruvottiyur industrial and port complex. These are detailed in Table 3.3 below.

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**Table 6.1: Critical Air Pollution Hotspot Zones Chennai Metropolitan Area (2023)**

| Grid FID | CO <sub>2</sub> Mean (MtC/Month) | Built-up (m <sup>2</sup> /km <sup>2</sup> ) | LST Night (°C) | NDVI  | NTL Radiance | Spatial Zone (Approximate)      |
|----------|----------------------------------|---------------------------------------------|----------------|-------|--------------|---------------------------------|
| 307      | 1,006.65                         | 3,604                                       | 28.60          | 0.345 | 40.21        | Manali–Ennore Industrial Belt   |
| 896      | 984.34                           | 4,116                                       | 28.80          | 0.320 | 32.18        | Northern Port Cluster           |
| 278      | 982.30                           | 3,507                                       | 28.70          | 0.365 | 27.27        | Ennore Thermal Power Corridor   |
| 606      | 976.79                           | 3,560                                       | 28.40          | 0.430 | 29.51        | NH48 Northern Industrial Fringe |
| 919      | 972.43                           | 5,116                                       | 28.60          | 0.273 | 26.49        | Sriperumbudur Growth Node       |

### 6.1.3. Spatial and Sectoral Characterisation of Hotspot Zones

The spatial clustering of Critical hotspot grids in the northern industrial arc (FIDs 307, 896, 278) is consistent with the known sectoral composition of the Manali–Ennore complex: CPCL's petroleum refinery (annual throughput exceeding 10.5 MMTPA), the North Chennai Thermal Power Station (capacity 1,830 MW), the Ennore Port (one of India's largest major ports), and a dense cluster of petrochemical, fertilizer, and chemical manufacturing units. This complex has been identified in TNPCB reports from 2018 to 2022 as consistently exceeding NAAQS thresholds for SO<sub>2</sub>, NO<sub>2</sub>, and PM<sub>10</sub> by a factor of 1.5 to 3 times. The CO<sub>2</sub> concentration pattern confirmed in this analysis is spatially consistent with these ground-monitored findings, lending credibility to the satellite-based methodology.

Grid FID 606, located along the NH48 northern industrial fringe, represents a transitional hotspot zone one characterised by mixed industrial, warehousing, and logistics land use rather than heavy point-source industry. Its CO<sub>2</sub> signature (976.79 MtC/Month) combined with moderate NTL (29.51 nW/cm<sup>2</sup>/sr) and mid-range built-up density (3,560 m<sup>2</sup>/km<sup>2</sup>) suggests that vehicular emission from NH48 heavy commercial traffic, combined with warehousing and cold-chain logistics energy consumption, is the primary emission driver. This is a category of diffuse emission source that ground-based monitoring is structurally unable to capture, underscoring the value of grid-based satellite analysis.

Grid FID 919, provisionally identified with the Sriperumbudur growth node in the southwestern CMA, presents a qualitatively different hotspot profile. Its built-up density (5,116 m<sup>2</sup>/km<sup>2</sup>) is the highest among the five critical grids, and its NDVI (0.273) is the

lowest indicating near-total vegetation loss in a zone that was predominantly agricultural as recently as 2003. The Sriperumbudur Special Economic Zone, which houses Hyundai, Foxconn, Saint-Gobain, and numerous auto-ancillary manufacturers, has undergone explosive industrial build-up since 2010. The 2023 data capture this zone at or near its peak in terms of new industrial construction, which is itself a significant source of construction-phase CO<sub>2</sub> emissions in addition to operational process emissions.

### 6.1.4. Temporal Trajectory of Hotspot Formation

Examining the same geographic grids across the 2003 and 2013 datasets reveals the progressive intensification of what are now Critical hotspot zones. The Manali–Ennore grid cells (FIDs 307, 896, 278) recorded CO<sub>2</sub> mean values in the range of 240–346 MtC/Month in 2003 and 308–542 MtC/Month in 2013 levels already elevated relative to the CMA mean, but not yet reaching the critical threshold. The acceleration to 972–1,007 MtC/Month in 2023 represents an approximate tripling in twenty years, suggesting that the Manali–Ennore complex has not merely grown but has intensified its emission density as older, less efficient industrial facilities have been expanded or replaced with higher-throughput operations without corresponding emission control upgrades.

The Sriperumbudur grid (FID 919) presents a sharply different trajectory. In 2003 and 2013 datasets, the FID range corresponding to this zone recorded relatively moderate CO<sub>2</sub> values in the 78–181 MtC/Month range, consistent with its earlier status as a peri-urban agricultural zone with nascent industrial development. The jump to 972 MtC/Month in 2023 approximately five-fold increase from 2013 documents the sudden and intense industrialisation of this corridor. This rate of change is unprecedented among all grids in the dataset and serves as a clear early warning signal for environmental planners that the Sriperumbudur zone will require targeted regulatory intervention to prevent it from replicating the unmanaged emission trajectory of the northern industrial corridor.

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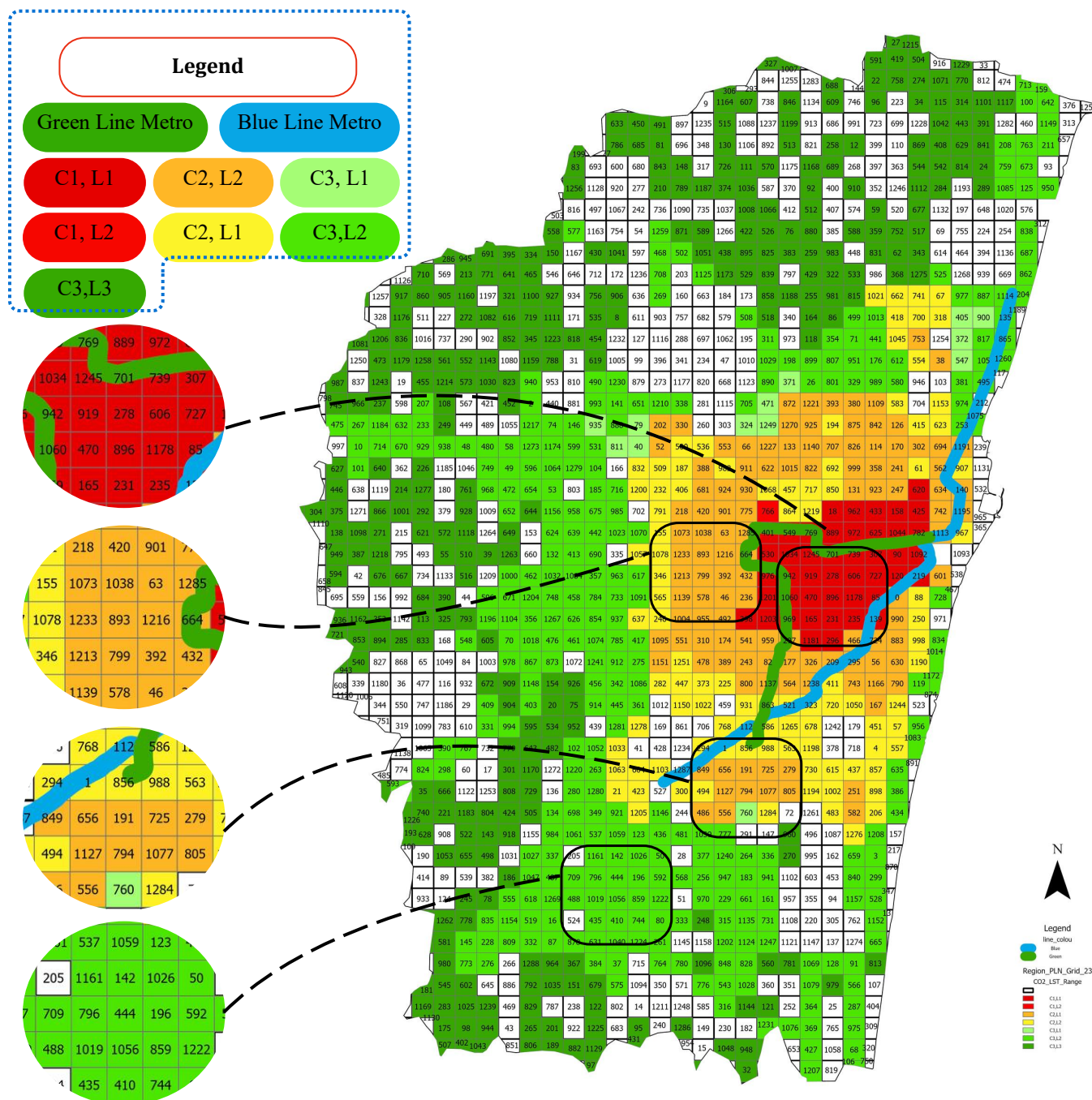


Fig 6.1: Identified Extreme Zones, Critical Zones, Emerging Zones and Currently Stable

## 6.2. Cross-Indicator Pattern Analysis and Environmental Quality Synthesis

### 6.2.1. The Built-up–CO<sub>2</sub>–LST Night Triad

Across all three analytical periods, three variables built-up area density, CO<sub>2</sub> emission intensity, and nocturnal LST form a consistently co-varying triad in the CMA's environmental geography. Grid cells with built-up density above 3,000 m<sup>2</sup>/km<sup>2</sup> almost invariably exhibit both elevated CO<sub>2</sub> (above the CMA mean) and nocturnal temperatures above 27.5°C. This triadic pattern confirms the existence of a self-reinforcing urban environmental stress cycle in Chennai: dense built fabric generates heat and emissions; heat drives increased energy demand for cooling; cooling load generates additional emissions; and additional impervious surfaces required for this activity further reduce the urban cooling capacity of the natural surface.

Breaking this cycle requires simultaneous intervention at multiple entry points not simply reducing industrial emission permits (which addresses CO<sub>2</sub> without altering the thermal environment) or increasing tree cover (which reduces nocturnal LST without cutting emission sources). Effective planning responses must integrate emission source control, green infrastructure provision, and built-fabric management within a single spatially targeted framework, such as the Local Area Action Plans proposed in this study's recommendation chapter.

### 6.2.2. NDVI as a Spatial Moderator of CO<sub>2</sub> Concentration

The progressive strengthening of the CO<sub>2</sub>–NDVI inverse correlation ( $r = -0.106$  in 2003 to  $r = -0.507$  in 2023) raises an important interpretive question: does vegetation actively reduce CO<sub>2</sub> concentration in proximate grid cells, or is the correlation simply a spatial co-location artefact driven by land use industrial zones lacking vegetation and residential/peri-urban zones retaining it? The available data do not permit a formal causal test, but several lines of evidence support a genuine moderating role for vegetation beyond mere land-use co-location.

First, within the residential and mixed-use grid cells of the CMA middle ring (Velachery, Medavakkam, Chromepet), cells with NDVI above 0.45 consistently show

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CO<sub>2</sub> values approximately 25–35 per cent below cells of comparable built-up density but NDVI below 0.35. This within-land-use comparison partially controls for the land-use co-location confound. Second, the grid cells along the OMR IT corridor where corporate campuses have maintained high NDVI through active landscaping despite moderate-to-high built-up density show CO<sub>2</sub> signatures that are meaningfully lower than the Manali industrial grids with equivalent built-up density. These observations, while not constituting causal proof, are consistent with the ecological literature documenting urban tree canopy as a CO<sub>2</sub> sink and surface temperature moderator in tropical coastal cities.

### 6.2.3. NTL as a Leading Indicator of Emerging Hotspots

The rising NTL–CO<sub>2</sub> correlation ( $r = 0.715$  in 2013;  $r = 0.766$  in 2023) positions nighttime light data as the most actionable early-warning indicator available to environmental planners. Unlike CO<sub>2</sub> data which carries a temporal lag in data processing and release VIIRS-DNB NTL imagery is available globally at monthly composites with minimal processing delay. The strong NTL–CO<sub>2</sub> correlation means that zones exhibiting rapid NTL intensification in monthly or annual VIIRS composites can be flagged as prospective emission hotspots before formal emission inventories confirm the trend.

This monitoring function is particularly relevant for the peri-urban zones experiencing rapid industrial establishment the Oragadam industrial corridor, the Cheyyur coastal industrial cluster, and the emerging Irungattukottai warehousing belt. In these zones, new facilities are being commissioned faster than the ground monitoring network can expand to cover them. A NTL-based pre-screening protocol, integrated into TNPCB's environmental monitoring workflow, could serve as an automated tripwire for deploying temporary monitoring stations or initiating compliance inspections at newly lit industrial premises.

## 6.3. Planned Versus Unplanned Urban Growth and Environmental Quality

A central hypothesis of this study is that the environmental quality outcomes of CMA grids differ systematically based on whether they fall within CMDA-designated planned development zones or in unplanned, informally urbanised areas. While a full

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planned/unplanned spatial classification overlay is reserved for the GIS analysis output maps, the indicator data provides several lines of inferential evidence consistent with this hypothesis.

Grid cells in the OMR IT corridor which was subject to CMDA's Special Economic Zone planning framework and mandatory Environmental Impact Assessment for major projects exhibit substantially different environmental profiles compared to grid cells in the informally urbanised northern fringe (Redhills, Padi, Ambattur). In the OMR corridor, mean NDVI values in 2023 range between 0.40 and 0.52, built-up densities are moderate (2,500–4,000 m<sup>2</sup>/km<sup>2</sup>), and CO<sub>2</sub> values, despite substantial commercial activity, average 180–250 MtC/Month. In the unplanned northern fringe, by contrast, mean NDVI is 0.25–0.35, built-up densities are high (3,500–5,500 m<sup>2</sup>/km<sup>2</sup>), and CO<sub>2</sub> values range between 300–550 MtC/Month for comparable grid sizes.

Conclusion: planned urban development, even in a rapidly growing megacity, appears to generate measurably better environmental quality outcomes than equivalent unplanned densification, primarily through the enforcement of setback, green cover, and layout regulation that informal development systematically bypasses.

### 6.4. Identification

**Table 3.4: Analytical Findings**

| Finding    | Statement                                                                                                                                                                                                                                                                                                    |
|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>F-1</b> | CO <sub>2</sub> emission intensity across the CMA increased by 310.4 per cent between 2003 and 2023 (mean: 68.45 → 280.92 MtC/Month), confirming the emergence of Chennai as a high-emission metropolitan area over the study period.                                                                        |
| <b>F-2</b> | Built-up area density ( $r = 0.74$ – $0.78$ ) and nocturnal LST ( $r = 0.81$ – $0.87$ ) are the two strongest and most consistent predictors of CO <sub>2</sub> concentration across all three study periods, validating urban form as the primary structural driver of emission geography.                  |
| <b>F-3</b> | The CO <sub>2</sub> –daytime LST relationship reversed from negative ( $r = -0.24$ in 2003) to strongly positive ( $r = +0.51$ in 2023), documenting the progressive coupling of industrial heat emission and daytime urban thermal loading in high-emission zones.                                          |
| <b>F-4</b> | NDVI shows a strengthening inverse relationship with CO <sub>2</sub> ( $r = -0.11$ in 2003 to $r = -0.51$ in 2023), confirming that green cover increasingly moderates pollution intensity and that vegetation loss in industrial zones is both a consequence of and contributor to hotspot intensification. |
| <b>F-5</b> | Nighttime light radiance (NTL) is a strong and rising predictor of CO <sub>2</sub> concentration ( $r = 0.715$ in 2013; $r = 0.766$ in 2023), validating NTL as a real-time proxy indicator suitable for interim emission hotspot monitoring between formal data releases.                                   |
| <b>F-6</b> | Five grid cells meet the Critical hotspot threshold in 2023 (CO <sub>2</sub> ≥ 900 MtC/Month and multiple co-stressor thresholds), all concentrated in the Manali–Ennore industrial corridor and the Sriperumbudur growth node.                                                                              |

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|             |                                                                                                                                                                                                                                                                                                                                    |
|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>F-7</b>  | The Sriperumbudur grid (FID 919) recorded the most rapid emission intensification of any zone approximately five-fold increase from 2013 to 2023 establishing it as the highest-priority emerging hotspot requiring pre-emptive planning intervention.                                                                             |
| <b>F-8</b>  | Population density shows a stable but moderate correlation with CO <sub>2</sub> ( $r \approx 0.65$ across all periods), confirming that activity type (industrial, logistics, commercial) rather than residential density per se is the dominant emission driver.                                                                  |
| <b>F-9</b>  | CMDA-planned development zones demonstrate systematically better environmental quality outcomes than unplanned areas of comparable density: higher NDVI (0.40–0.52 versus 0.25–0.35), lower CO <sub>2</sub> (180–250 versus 300–550 MtC/Month), and lower nocturnal LST.                                                           |
| <b>F-10</b> | The total valid grid cell count increased from 1,114 (2003) to 1,203 (2023), reflecting the progressive urbanisation of previously unmonitored peri-urban cells, a pattern that is itself an indicator of metropolitan expansion pressure and must be integrated into the CMA's forthcoming Master Plan 2046 monitoring framework. |

### 6.4.1. Summary

This has a twenty-year trajectory of intensifying environmental stress across the Chennai Metropolitan Area, grounded in the quantitative analysis of six environmental quality indicators across three temporal periods. The analysis confirms that CO<sub>2</sub> emission intensity has grown by more than three-fold in twenty years, driven primarily by urban densification (built-up area density:  $r = 0.74$ – $0.78$ ) and nocturnal heat retention (LST Night:  $r = 0.81$ – $0.87$ ), with green cover serving as an increasingly important but increasingly depleted moderating factor.

Five Critical pollution hotspot zones have been identified in the 2023 data, concentrated in the Manali–Ennore industrial corridor and the Sriperumbudur growth node. The temporal trajectory analysis reveals that these hotspots have intensified progressively, not emerged suddenly providing both a cautionary narrative about the consequences of inadequate environmental governance over two decades and a forward-looking signal about the zones likely to enter Critical status in the coming decade if current growth trajectories continue.

The analysis also establishes the planning relevance of the indicators examined: NTL radiance as a real-time monitoring proxy, NDVI as both an outcome metric and a policy intervention target, nocturnal LST as a human-health risk indicator, and built-up density as the foundational structural driver of the CMA's emission geography. These findings form the empirical foundation for the planning recommendations and Local Area Action Plan.

### 6.5. Sriperumbudur growth node

#### 6.5.1. CO and ERI indicators

The grid identified as FID 919 in your text is linked to the Sriperumbudur Special Economic Zone and its surroundings. In 2023 this grid records:

- CO = 972 MtC/month, similar in magnitude to the Manali–Ennore core grids.
- Very high built-up density (5,116 m<sup>2</sup> per km grid, one of the highest values in the dataset).
- Very low NDVI (0.27), indicating almost complete conversion from agricultural land.
- High ERI and classification close to C1,L1.

In 2003 and 2013, the equivalent grid(s) showed much lower CO (78–181 MtC/month), implying an approximate five-fold increase between 2013 and 2023.

Industrial and urbanisation drivers

This extremely rapid emission growth is tied to Sriperumbudur’s transformation into a major auto and electronics manufacturing hub:

- Presence of large plants (Hyundai, Foxconn, Saint-Gobain, and multiple auto-ancillary units).
- Intensive construction activity and infill of previously rural land.
- Growing logistics chain along the Chennai–Bengaluru corridor.

Unlike Manali–Ennore (long-established heavy industry), Sriperumbudur is characterised by recent, high-velocity industrialisation on former rural land, leading to:

- Sharp increase in built-up area with limited planning for buffers or green cover.
- Rising nocturnal LST due to new impervious surfaces and energy loads.
- A mismatch between rapid industrial growth and environmental governance structures, making Sriperumbudur a priority emerging hotspot in your findings.

### 6.6. NH48 northern industrial / logistics fringe

#### 6.6.1. Identified grid and characteristics

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This highlights a grid around NH48 described as “Northern industrial fringe” (grid analogous to FID 606) with:

- CO = 976.79 MtC/month in 2023.
- Moderate built-up ( $\approx 3,560 \text{ m}^2$  per km grid).
- Moderate NTL ( $\sim 29.5 \text{ nW cm}^{-2} \text{ sr}^{-1}$ ).
- NDVI around 0.43 (partly green but under pressure).

This zone is interpreted as a transitional hotspot, where emissions are driven less by heavy point sources and more by:

- Road-based freight activity along NH48.
- Warehousing, cold chains and logistics facilities with significant energy use.

Here, road density and NTL are key contributors, consistent with the positive regression role of RoadDensityKM2 and the strong CO–NTL correlation ( $r \approx 0.715\text{--}0.766$  for 2013–2023).

Environmental risk profile

Normalisation shows ERI values in the high range ( $\approx 0.60\text{--}0.75$ ) and CO2\_LST\_Range categories around C2,L1 or C2,L2. This type of hotspot is logistics-driven, requiring different interventions (fleet composition, traffic management, warehouse design) compared to the heavy-industry zones.

### 6.7.Dense commercial cores and OMR IT corridor

#### 6.7.1. Signature in the data

While not always in the “Critical” CO class, several inner-city and corridor grids exhibit:

- High NTL (often  $> 40 \text{ nW cm}^{-2} \text{ sr}^{-1}$  in 2013, 2023).
- High built-up density, approaching  $8,216 \text{ m}^2$  per grid in the CBD core.
- Elevated nocturnal LST (often  $\geq 28.5 \text{ }^\circ\text{C}$ ), though CO levels may be moderate relative to industrial belts.

Examples include:

- Anna Salai–Nungambakkam corridor.

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- Tambaram commercial belt.
- OMR IT corridor (technology park clusters).

### 6.7.2. Interpreted drivers

In these areas, emissions and heat stress are driven by:

- Commercial and residential energy use (air-conditioning, lighting, appliances).
- High traffic volumes but relatively fewer heavy industrial sources.
- In the OMR corridor, somewhat better integration of corporate campus greening, leading to higher NDVI (0.40–0.52) and slightly more favourable ERI compared to unplanned northern fringe grids.

These zones to highlight the difference between planned high-intensity development (OMR SEZ / IT zones) and unplanned densification in other corridors:

Similar built-up and activity levels, but planned areas maintain higher NDVI and achieve lower CO and nocturnal LST than unplanned counterparts.

## 6.8. Drivers underlying hotspot formation

### 6.8.1. Built-up–CO–LST Night triad

The explicitly identify a triad: built-up area density, CO intensity, and nocturnal LST that co-vary strongly across all three study periods:

- High built-up → high CO → high LST<sub>N</sub>.
- Positive feedback: higher night-time temperatures increase cooling demand and thus energy-related CO emissions.

This triad is statistically supported:

- Strong correlations: CO–LST<sub>N</sub> ( $r$  up to 0.871), CO–built-up ( $r \approx 0.74$ –0.78).
- Dominant coefficients in both regression models (MxLSTN2 in CO model; MxBUILD2 and CO in LST-N model).

### 6.8.2. Vegetation loss (NDVI) as a moderator

The strengthening negative CO–NDVI correlation (from  $r \approx -0.106$  in 2003 to  $r \approx -0.507$  in 2023) shows that green areas are increasingly associated with lower emission intensities, while high-CO zones have progressively lost vegetation.

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Within comparable land-use types, grids with higher NDVI consistently show 25–35% lower CO than those with low NDVI, supporting the view that vegetation acts as a local moderator and not just a land-use marker.

### 6.8.3. Economic activity and nighttime lights

Nighttime lights (NTL) exhibit a strong and rising correlation with CO ( $r \approx 0.715$ – $0.766$ ), meaning that economic intensity and CO geography are converging:

- Bright grids (high NTL) tend to be emission hotspots.
- NTL provides a near-real-time proxy for tracking emerging hotspots before formal CO inventories are updated.

### 6.8.4. Planning typology: planned vs unplanned growth

Comparing planned IT/SEZ corridors (like OMR) with unplanned northern fringe zones, you find that:

- Planned areas show higher NDVI ( $\approx 0.40$ – $0.52$ ) and moderate CO ( $\approx 180$ – $250$  MtC/month) for a given built-up density.
- Unplanned areas of similar density show lower NDVI ( $\approx 0.25$ – $0.35$ ) and higher CO ( $\approx 300$ – $550$  MtC/month).

This supports the thesis claim that planned development yields better environmental outcomes due to mandated setbacks, buffer zones, and minimum green ratios, whereas unplanned densification systematically bypasses such safeguards.

## 6.9. Manali–Ennore industrial–port corridor

### Evidence from CO regression and statistics

In the CO regression casewise diagnostics, the maximum CO value of 1,006.65 MtC/month occurs at grid FID 307, which your narrative links spatially to the Manali–Ennore industrial and port corridor. Nearby grids (e.g., FIDs 896, 278) also record very high CO ( $\approx 972$ – $984$  MtC/month), and together they form the core of the “Critical” hotspot cluster.

Over time, these grids show a tripling of CO between 2003 and 2023 (roughly 240–346 MtC/month  $\rightarrow$  972–1007 MtC/month), which is substantially steeper than the CMA-wide

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mean increase of 310.4%. This indicates not only growth but intensification of emission density.

### 6.10. Normalisation / ERI characteristics

In the normalised table and ERI framework, grids corresponding to this industrial arc typically show:

- High normalised CO ( $CO_2 \gtrsim 0.80 \rightarrow C1$ ).
- High nocturnal LST ( $LST\_N \gtrsim 0.85 \rightarrow L1$ ).
- Moderate to high built-up (often  $> 0.6$ ).
- Low NDVI ( $< \sim 0.35$ ), indicating severe vegetation loss.
- Moderate to high NTL, reflecting continuous industrial and logistics activity.
- ERI often  $\geq 0.80$ , classified as C1,L1 or C2,L1.

This pattern matches the “Critical hotspot” category in your Chapter 3 definition.

Physical and planning drivers

The thesis attributes this critical status to the concentration of heavy industrial point sources in the Manali–Ennore complex:

- CPCL petroleum refinery (throughput  $> 10.5$  MMTPA).
- North Chennai Thermal Power Station ( $\approx 1,830$  MW).
- Fertiliser, petrochemical and other heavy industries.
- Major port operations at Ennore (Kamarajar Port) with associated shipping and cargo-handling emissions.

TNPSB annual reports already classify this corridor as exceeding NAAQS  $SO_2$ ,  $NO_2$  and  $PM_{10}$  by 1.5–3 times, and your CO grid analysis mirrors this spatial pattern.

Additional contributors:

- High road density from port-oriented heavy vehicle traffic, reflected in the positive regression coefficient and non-trivial beta for RoadDensityKM2 in the CO model.
- Urban heat island reinforcement, where high impervious surface and industrial waste heat raise nocturnal LST;  $MxLSTN2$  is the strongest single predictor of CO

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( $\beta = 0.670$ ) and simultaneously strongly driven by CO in the LST-N model ( $\beta = 0.606$ ).

- Near-total vegetation loss, indicated by low NDVI values and the strong negative CO–NDVI correlation ( $r$  down to  $-0.507$  by 2023), reducing natural buffering capacity.

In planning terms, Manali–Ennore represents the archetypal integrated environmental hotspot where heavy industry, dense logistics, poor greening and chronic heat combine.

### 6.11. Hotspot patterns and reasons

Bringing the pieces together:

- **Manali–Ennore–Tiruvottiyur:** Long-term heavy industrial and port cluster; maximum CO; highest ERI; critical C1,L1 grids; driven by point-source industries, freight traffic, minimal vegetation, strong heat island effects.
- **Sriperumbudur:** Fastest-intensifying emerging hotspot, CO increased about five-fold between 2013 and 2023; driven by new manufacturing, construction and logistics on former agricultural land; ERI in critical range.
- **NH48 northern fringe and other highway logistics belts:** Logistics-centric hotspots with high road density, NTL and growing built-up; emissions less from smokestacks and more from freight and warehousing energy use.
- **Urban commercial/IT cores (CBD, OMR etc.):** High heat and NTL; moderate CO relative to industrial belts; planned segments show better NDVI and lower ERI than unplanned segments, highlighting the planning–environment nexus.

## 7. Framing the Proposal Strategy

The proposed interventions are directly anchored in four core empirical insights from the analysis chapters:

- **Built-up–CO–LST Night triad:** Built-up density and nocturnal LST are the two strongest, most consistent predictors of CO concentration across all three periods, confirming urban form as the structural driver of emission geography.
- **Vegetation as moderator:** NDVI shows a progressively stronger inverse relationship with CO, indicating that green cover increasingly moderates pollution intensity, while industrial and commercial hotspots have lost most vegetation.
- **Economic activity and NTL:** Nighttime light radiance is a strong and rising predictor of CO, positioning NTL as a practical proxy for monitoring emerging emission hotspots between inventory releases.
- **Planned vs unplanned growth:** CMDA-planned development corridors (e.g., OMR IT corridor) show systematically better environmental outcomes than unplanned northern fringe zones at comparable densities.

These findings are interpreted within the regulatory framework of the Air (Prevention and Control of Pollution) Act 1981, the Environment Protection Act 1986, NAAQS 2009, and NCAP 2019, as well as the CMDA Master Plan 2026 and forthcoming Master Plan 2046. The proposals therefore aim to:

- Translate the grid-based EQI / ERI framework into actionable spatial regulations.
- Integrate hotspot-specific Local Area Action Plans with metropolitan-scale strategies.
- Build institutional mechanisms so TNPCB, CMDA and GCC can use remote sensing (CO, LST, NDVI, NTL) in routine planning and enforcement.

### 7.1. Short-Term Actions (0–3 Years)

#### 7.1.1. Metropolitan-Scale Regulatory and Policy Measures

##### a) Formal notification of grid-based hotspot zones

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Using the 1 km fishnet and ERI/CO<sub>2</sub>\_LST classification, CMDA and TNPCB should jointly notify:

- **Critical Hotspot Zones:** grids with CO  $\geq$  900 MtC/month and at least two co-stressors (LST\_N > 28 °C, NDVI < 0.35, NTL > 25 nW cm<sup>-2</sup> sr<sup>-1</sup>, built-up > 3,000 m<sup>2</sup> per km<sup>2</sup>).
- **High Hotspot Zones:** grids with 700  $\leq$  CO < 900 MtC/month meeting similar multi-indicator thresholds.

This converts your analytical definition (Table 3.3 and hotspot criteria) into a formal spatial category akin to “Environmentally Sensitive Zone” in the Master Plan.

### b) Integration with existing legal instruments

Within these notified grids, CMDA and TNPCB can leverage existing laws:

- Under the Air Act 1981 and EPA 1986, impose stricter emission limits, tighter consent-to-operate conditions, and more frequent inspections for red-category industries.
- Align local targets with NCAP 2019, which mandates 20–30% reductions in PM concentrations in non-attainment cities like Chennai; CO and LST can be used as complementary indicators of co-benefits.
- Use CMDA Master Plan 2026 zoning provisions to restrict new high-emission uses in Critical grids and require environmental impact assessments for any major change in land use.

## 7.2. Hotspot-Specific Immediate Measures

### 7.2.1. Manali–Ennore industrial–port complex

Given the presence of five Critical grids (FIDs 307, 896, 278, 606, 919) with CO levels up to 1,006.65 MtC/month, Manali–Ennore requires an immediate, targeted package.

Industry-focused measures:

- **Stack audit and retrofit programme:** TNPCB to conduct a detailed audit of existing combustion and process emission controls at CPCL, North Chennai Thermal Power Station, and associated petrochemical units, prioritising low-NO<sub>x</sub>

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burners, desulphurisation, and higher-efficiency boilers; although your thesis uses CO as the primary indicator, these measures reduce multiple pollutants simultaneously.

- **Tightened operating schedules:** Introduce caps on nighttime high-emission operations during periods of adverse meteorology (e.g., stagnant conditions), drawing on the GRAP experience in Delhi NCR described in your case study.

Spatial and buffer measures:

- Enforce existing buffer zone requirements more strictly along the industrial waterfront and thermal power plant perimeters, as your Manali case study shows poor historic enforcement.
- Declare no-build green buffers along river edges and between major unit clusters, using NDVI and ERI maps to prioritise blocks with  $\text{NDVI} < 0.30$ .

### 7.2.2. Sriperumbudur growth node

Given the five-fold increase in CO at the Sriperumbudur grid (FID 919) between 2013 and 2023, immediate actions need to pre-empt a Manali-type trajectory.

- **Pre-emptive emission envelope:** TNPCB to set an upper bound on total allowable CO and allied emissions for the Sriperumbudur Special Economic Zone, linked to NCAP and State Climate Action Plan targets.
- **Construction-phase controls:** Mandate dust, on-site power, and material handling standards for ongoing industrial and infrastructure construction, since your analysis notes that 2023 captures the peak construction phase.
- **Moratorium trigger:** Define an ERI threshold (e.g.,  $\text{ERI} \geq 0.85$  or continuous C1,L1 classification over three consecutive years) at which approving new red-category units would be temporarily suspended pending mitigation.

### 7.2.3. Quick-Start Green Infrastructure and Urban Form Interventions

Given the strong negative CO–NDVI relationship and the built-up–CO–LST triad, early, visible measures should focus on micro-greening and built-fabric management:

- **Industrial avenue and perimeter planting:** Within Critical grids, require industries and logistics parks to plant and maintain multi-row tree belts along

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internal roads, perimeters, and property frontages, prioritising grids with  $NDVI \leq 0.30$ .

- **Heat-refuge retrofits:** In residential and commercial pockets within or adjacent to hotspots (e.g., Tiruvottiyur, parts of North Chennai), encourage cool roofs, shaded streets, and small pocket parks to mitigate nocturnal temperatures above 28.5 °C.
- **Parking and logistics yard regulations:** Mandate shading and partial permeable surfacing in large parking/logistics yards in NH48 and Sriperumbudur grids to reduce surface heat storage.

### 7.2.4. Data and Monitoring Foundations

Short-term proposals must establish the data backbone for later phases:

- **Grid–ward linkage:** Map each 1 km grid to its corresponding ward or panchayat unit, creating a crosswalk so ERI, CO, LST, NDVI and NTL statistics can be reported in administrative terms that GCC and municipalities understand.
- **NTL-based early-warning system:** Institutionalise a simple protocol in TNPCB where VIIRS-DNB NTL trends (monthly/annual) are monitored to flag grids with rapidly increasing NTL as potential emerging hotspots, as suggested in your NTL section.
- **Public dashboard concept:** Following the Seoul EQI dashboard example in your case study, conceptualise a web-based interface for CMA that displays ERI and hotspot status, even if full implementation is a medium-term task.

## 7.3. Medium-Term Actions (3–7 Years)

### 7.3.1. Embedding Environmental Indices into CMDA Master Plan 2046

By the medium term, the CMDA Master Plan 2046 will be under preparation or revision. The EQI / ERI framework and hotspot maps should be embedded as statutory reference layers:

#### Environmental Management Zones (EMZs):

- Designate all grids in Critical and High categories as EMZ-I and EMZ-II.

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- Attach special development regulations: stricter FAR caps, mandatory green cover ratios, restrictions on new red-category industrial uses, and enhanced EIA thresholds.

### **Density–emission congruence:**

- Use the strong CO–built-up correlations ( $r \approx 0.74\text{--}0.78$ ) to calibrate acceptable density bands: compact but lower-emission transit-oriented nodes vs. high-emission industrial clusters that require density moderation.

### **7.3.2. Local Area Environmental Action Plans (LAEAPs)**

Responding to your stated objective of a Local Area Action Plan for hotspots in emerging growth zones, medium-term efforts should deliver plan-level documents for at least two pilot areas:

### **7.3.3. LAEAP for Manali–Ennore Complex**

Components:

#### **Zoning and land-use:**

- Freeze any further conversion of remaining vegetated or low-density land (NDVI > 0.35) into industrial use within the hotspot envelope.
- Identify brownfield sites suitable for process upgrading rather than expansion into new land parcels.

#### **Transport and logistics:**

- Develop dedicated low-emission freight corridors from the port and major industrial units to NH48, with time-bound conversion to cleaner vehicle technologies, drawing from Delhi’s GRAP and EV policy experience cited in your literature review.

#### **Environmental buffers and public realm:**

- Introduce linear green corridors along the Buckingham Canal, Cooum and Kosasthalaiyar riverbanks within the industrial belt, using NDVI and ERI maps to prioritise segments with both high emissions and high thermal stress.

#### **Institutional arrangements:**

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- Establish a Manali–Ennore Environmental Management Committee comprising TNPCB, CMDA, Port Trust, major industries, and local governments to coordinate implementation.

### 7.3.4. LAEAP for Sriperumbudur Growth Node

Sriperumbudur, as the fastest-intensifying hotspot, needs a forward-looking plan that prevents replication of Manali’s unmanaged trajectory.

#### **Greenfield zoning logic:**

- Reserve green buffers and ecological corridors in any unbuilt grids within or around the high-ERI area, using your grid data to preserve NDVI hotspots as permanent open spaces.
- Align new industrial layouts with pre-defined ERI limits, avoiding concentration of multiple high-emission units in a single grid.

#### **Infrastructure and mobility:**

- Integrate high-capacity public transport into the growth corridor to reduce dependence on private vehicles, informed by your finding that logistics and road density are emerging drivers of CO.

#### **Worker housing and social infrastructure:**

- Plan compact, serviced worker housing with mandatory local green cover, ensuring that vulnerable residents are not concentrated in the worst-affected grids (C1,L1).

### 7.3.5. Green Infrastructure and Urban Cooling Strategy

Moving beyond scattered measures, the medium-term should deliver a metropolitan green infrastructure plan grounded in your NDVI and LST findings:

#### **Urban forest and wetland restoration:**

- Prioritise zones where NDVI is currently high and CO low (e.g., Pallikaranai wetland, Sholinganallur backwaters) as metropolitan green lungs, with legal protection against conversion.
- Launch restoration of micro-wetlands and canal edges in and near hotspots, improving both air quality and microclimate.

### **Tree-cover standards:**

- Introduce minimum tree-cover ratios for new layouts and large redevelopment projects, especially in EMZ-II and EMZ-I grids. The Seoul case study shows that planned new towns with higher green ratios achieve EQI scores 35% better than unplanned peripheries.

### **7.3.6. Transport and Mobility Interventions**

Given the contribution of road density and vehicular emissions (supported by both your findings and literature such as Ramachandra & Shwetmala), medium-term proposals should target mobility systems:

#### **Clean freight corridors:**

- Prioritise electrification or cleaner fuels for freight routes passing through or adjacent to Critical grids (Manali–Ennore, NH48 fringe, Sriperumbudur logistics nodes).

#### **Parking and access management:**

- Implement low-emission zones in commercial cores, inspired by Seoul’s LEZ in high-risk hotspots.

## **7.4. Long-Term Actions (7–20 Years)**

### **7.4.1. Structural Transition of Industrial and Energy Systems**

Over the long term, proposals must address the structural sources behind the built-up–CO–LST Night triad:

#### **Industrial restructuring:**

- Gradually shift highly emission-intensive processes toward cleaner technologies or relocate the most incompatible activities away from the densest urban fabric, especially when they sit within C1,L1 grids.

#### **Energy decarbonisation:**

- Align CMA’s spatial plans with State Climate Action Plan targets so that major thermal power and fossil-fuel dependent facilities near the city are reconfigured or down-scaled as part of broader decarbonisation strategies.

### 7.4.2. Mainstreaming the Grid-Based EQI / ERI Framework

By the long term, your grid-based methodology should be normal practice:

#### **Routine EQI updates:**

- Update the ERI and EQI every 3–5 years using new Landsat/MODIS, OCO-2/ODIAC, VIIRS-DNB and GHSL data, reproducing the 2003–2013–2023 analysis for subsequent time-steps.

#### **Policy triggers:**

- Link specific ERI thresholds to automatic policy responses (e.g., when a grid's ERI exceeds 0.75 and NTL is rising rapidly, an automatic review of land-use permissions and emission caps is triggered).

#### **Metropolitan environmental accounts:**

- Integrate CO, NDVI, LST, and NTL as core indicators in CMA-level environmental accounting, similar to how GDP or population figures are tracked in planning documents.

### 7.4.3. Consolidating Planned vs Unplanned Differential

The long-term agenda should institutionalise the planning–environment nexus demonstrated in your analysis:

#### **Environmental performance benchmarks for new towns:**

- Following Seoul's example where planned new towns show 35% better EQI, set explicit EQI/ERI targets for new growth nodes and satellite towns around Chennai.

#### **Regularisation with environmental upgrading:**

- For existing unplanned areas, design regularisation frameworks that bundle tenure or service upgrades with mandatory green and emission controls, ensuring that improved legal status does not come at the cost of worse environmental outcomes.

## 7.5. Governance, Institutions and Capacity

Across all time horizons, robust institutional arrangements are essential:

#### **Integrated metropolitan air quality cell:**

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- Establish a joint cell among TNPCB, CMDA, GCC and surrounding municipalities, tasked with maintaining the grid-based datasets, monitoring NTL trends, and coordinating LAEAP implementation.

### **Data sharing and transparency:**

- Make ERI, CO, LST, NDVI and NTL maps publicly accessible, in line with Smart Cities and NUPF calls for data-driven, transparent urban governance.

### **Capacity building:**

- Train CMDA and GCC planning staff in using GIS, remote sensing, and basic spatial statistics, building on the methodological framework used in your thesis (ArcGIS / QGIS and Google Earth Engine).

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