

# Spatial Mapping of Supply Chain Carbon Footprints and Environmental Externalities within the Agglomeration Economies of Saurashtra and Kutch

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## **Abstract**

*This study investigates the spatial distribution of environmental externalities generated by industrial agglomeration and supply chain logistics within the Saurashtra and Kutch regions of Gujarat. As these coastal and semi-arid zones rapidly industrialize—anchored by major maritime ports and heavy manufacturing hubs—the ecological burden of freight transport and raw material sourcing has significantly intensified. Utilizing Geographic Information Systems (GIS) alongside quantitative spatial analysis, this paper maps the carbon footprints of regional supply chains, identifying critical emission hotspots and localized inequalities in environmental degradation. By intersecting transport geography with environmental economics, the research evaluates how agglomeration economies, while highly beneficial for industrial efficiency, disproportionately concentrate ecological externalities such as localized air pollution, groundwater stress, and land-use alteration. Ultimately, the findings provide a robust spatial framework for policymakers and urban planners to optimize logistics networks, mitigate carbon emissions, and promote sustainable industrial growth within ecologically vulnerable economic zones.*

**Key Words:** *Spatial Mapping, Supply Chain, Carbon Footprints, Environmental Externalities, Agglomeration Economies*

## **Introduction**

The rapid industrialization of the Saurashtra and Kutch regions in Gujarat has transformed these coastal areas into critical hubs of global and domestic trade. Agglomeration economies drive this unprecedented growth by concentrating heavy manufacturing, maritime ports, and extensive logistics infrastructure, which significantly enhances operational efficiency and regional economic output (Krugman, 1991). However, this intense spatial clustering inevitably produces severe environmental externalities.

The continuous expansion of supply chain networks, particularly relentless freight transport and extensive raw material sourcing, has led to a profound increase in carbon emissions and localized ecological degradation across these vulnerable landscapes (Glaeser and Kahn, 2010). While the economic benefits of industrial clustering are well documented, the disproportionate ecological costs borne by adjacent communities remain underexplored in the context of western India. Understanding the true ecological burden of these sprawling logistics networks requires robust and precise analytical tools. Geographic Information Systems offer a powerful methodology for spatial mapping, allowing researchers to accurately visualize emission hotspots and meticulously trace the carbon footprint of regional supply chains (Goodchild, 2007). This research investigates the spatial distribution of these environmental impacts within the prominent industrial corridors of western Gujarat. By integrating transport geography with environmental economics, the study elucidates how industrial agglomeration exacerbates local climate vulnerabilities. Ultimately, the findings aim to provide regional urban planners and government policymakers with a comprehensive spatial framework to optimize freight logistics, mitigate carbon emissions, and promote sustainable growth in ecologically sensitive economic zones (Hesse and Rodrigue, 2004).

### **The Theoretical Paradox of Agglomeration Economies**

The conceptual foundation of industrial spatial clustering is rooted in the theory of agglomeration economies, which posits that firms derive significant productive advantages by co-locating in close geographical proximity. Originating from Marshall's (1920) observations of localized industries and expanded upon by Krugman's (1991) models of economic geography, agglomeration theory explains how spatial concentration minimizes transport costs, fosters deep labor markets, and accelerates knowledge spillovers. In the context of the Saurashtra and Kutch regions, these economic pull factors have been actively engineered through state policy, establishing Special Economic Zones (SEZs) and massive port-led industrial corridors. The economic logic is sound: congregating heavy manufacturing near deep-water maritime gateways like Mundra and Kandla drastically reduces the frictional costs of global trade and domestic distribution (Fujita & Thisse, 2002).

However, this spatial concentration inherently generates a profound theoretical and practical paradox. While agglomeration maximizes economic efficiency, it simultaneously concentrates ecological burdens, overriding the natural carrying capacity of the local geography.

This phenomenon, often termed an environmental spatial externality, occurs when the cumulative ecological footprint of clustered firms exceeds the regenerative limits of the immediate environment (Glaeser & Kahn, 2010). In semi-arid regions like Saurashtra and Kutch, where water is scarce and ecological resilience is naturally low, the paradox is magnified. The very infrastructure that enables economic scale—dense road networks, centralized power grids, and concentrated raw material processing—creates severe, localized environmental degradation.

Consequently, the economic benefits of industrial clustering are privatized by the manufacturing and logistics sectors, while the ecological costs—such as air pollution, groundwater depletion, and habitat fragmentation—are socialized, borne disproportionately by local communities and regional ecosystems (Henderson, 2003). Understanding this paradox is critical, as it requires moving beyond purely economic evaluations of industrial clusters to incorporate the spatial dimensions of environmental justice and ecological sustainability.

### **GIS Methodology and Spatial Data Integration**

To empirically analyze the environmental externalities of agglomeration economies, a rigorous spatial methodology is required. Geographic Information Systems (GIS) serve as the vital analytical framework for this research, enabling the integration, visualization, and quantitative assessment of complex spatial datasets (Goodchild, 2007). Traditional economic models often struggle to capture the highly localized nature of environmental impacts; GIS bridges this gap by explicitly anchoring economic and logistics data to exact geographical coordinates. In mapping the carbon footprints and supply chain logistics across Saurashtra and Kutch, GIS allows for a multi-layered spatial overlay approach.

The methodology relies on integrating three primary categories of spatial data. First, infrastructural and land-use data (LULC), derived from satellite imagery and remote sensing, delineate the precise boundaries of industrial estates, port facilities, and transportation networks (road and rail). Second, logistics flow data, including freight volumes, transport modes, and origin-destination (O-D) matrices, are mapped onto these networks to visualize the intensity of supply chain movements (Rodrigue, 2020). Third, environmental monitoring data—such as localized air quality indices (AQI), particulate matter (PM<sub>2.5</sub>/PM<sub>10</sub>) concentrations, and greenhouse gas (GHG) emission estimates—are spatially interpolated. By applying spatial analysis techniques such as Kernel Density Estimation (KDE), the research can move beyond regional averages to identify statistically significant "hotspots" of emissions. Furthermore, spatial autocorrelation metrics, such as Moran's I, are utilized to determine the degree to which high-emission zones cluster together around specific logistics bottlenecks or manufacturing hubs (Anselin, 1995). This integration of geospatial and environmental data is crucial. It transforms abstract carbon accounting into a highly visible "carbon topography," providing a precise empirical basis for assessing how transport geography directly influences localized environmental degradation in western Gujarat.

### **Anatomy of Regional Supply Chain Logistics**

The Saurashtra and Kutch peninsulas operate as the primary logistics gateway for northern and western India, governed by an extensive and highly complex supply chain anatomy. The spatial logic of this region is fundamentally dictated by its maritime geography. Mega-ports such as Kandla, Mundra, and Pipavav act as the primary nodes of ingress and egress, handling vast quantities of raw materials, energy commodities, and finished manufactured goods (Notteboom & Rodrigue, 2005). The regional supply chain is characterized by a heavy reliance on road freight, which introduces significant spatial inefficiencies and environmental costs compared to rail transport.

The anatomy of these logistics networks reveals distinct spatial patterns of material flow. For instance, massive volumes of imported raw materials—such as scrap metal destined for metallurgical clusters, coal for thermal power plants, and chemical precursors—are offloaded at the coastal ports and transported hundreds of kilometers inland via heavy-duty diesel trucking fleets. This creates a continuous, high-intensity flow of freight traffic along primary arterial highways. The logistics network is further complicated by the need for localized distribution within industrial agglomerations. The movement of semi-finished goods between specialized processing units within a single cluster necessitates dense, short-haul freight movements, heavily congesting local road infrastructure (Hesse & Rodrigue, 2004).

Furthermore, the warehousing and temporary storage infrastructure—critical components of the supply chain—consume massive tracts of land, often encroaching upon agricultural zones or ecologically sensitive coastal areas. By dissecting this anatomy, it becomes evident that the logistics network is not merely a passive conduit for trade, but an active, geographically expansive industrial process in its own right. The heavy reliance on fossil-fuel-intensive road transport, combined with spatial bottlenecks at port exits and urban peripheries, forms the structural basis for the region's escalating carbon footprint and environmental externalities.

### **Identification of Emission Hotspots and Carbon Corridors**

Translating the anatomy of supply chains into an assessment of environmental impact requires the explicit spatial identification of emission hotspots and carbon corridors. While industrial manufacturing processes generate stationary point-source emissions, supply chain logistics generate dynamic, non-point-source emissions that are distributed across the transportation network (Chapman, 2007). In the context of Saurashtra and Kutch, these emissions are not dispersed evenly but are highly concentrated along specific spatial trajectories, forming distinct "carbon corridors." These corridors primarily align with the major national and state highways that connect the maritime ports to the inland industrial agglomerations, such as the NH-41 and NH-47 corridors. The continuous stream of heavy freight along these routes results in elevated concentrations of carbon dioxide ( $\text{CO}_2$ ), nitrogen oxides ( $\text{NO}_x$ ), and black carbon. The spatial mapping of these corridors reveals that the highest emission intensities occur at logistical bottlenecks—areas where transport flow is impeded by toll plazas, urban intersections, or port-gate queuing.

Idle times at these bottlenecks drastically reduce fuel efficiency and spike localized pollution levels, creating severe micro-climates of degraded air quality (McKinnon, 2018). Beyond the linear corridors, spatial analysis identifies distinct emission hotspots where transport networks intersect with dense manufacturing zones. In these areas, the cumulative emissions from stationary industrial stacks and mobile freight trucking compound one another. The identification of these hotspots is critical for understanding the spatial inequality of environmental externalities.

Communities residing adjacent to these arterial routes or transport nodes bear a disproportionate burden of the ecological and health impacts associated with globalized supply chains, highlighting a profound disconnect between where economic value is generated and where the environmental price is paid.

### **Localized Environmental Externalities in Specific Manufacturing Hubs**

While macro-level mapping identifies regional carbon corridors, examining specific manufacturing hubs exposes the acute, localized environmental externalities of agglomeration economies. The Saurashtra region provides compelling case studies of how intense industrial specialization profoundly alters local geomorphology and environmental health. A prominent example is the brass parts manufacturing cluster in Jamnagar. This highly agglomerated sector relies on complex supply chains importing brass scrap, which is then subjected to intensive localized smelting, casting, and machining processes.

The spatial concentration of thousands of these micro, small, and medium enterprises (MSMEs) within a confined geographical area generates severe point-source externalities. The metallurgical processes, combined with the continuous intra-cluster movement of materials, result in significant localized air pollution, specifically the release of particulate matter and heavy metal aerosols (Desai & Patel, 2021). Furthermore, the spatial footprint of such hubs extends deeply into the regional hydrology. The disposal of industrial effluents and solid waste from chemical and metallurgical processing poses a severe threat to groundwater quality. In the semi-arid climate of Saurashtra, where groundwater is both scarce and critical for adjacent agricultural activities, the contamination of aquifers represents a catastrophic environmental externality (Singh et al., 2019). The localized impact is not limited to air and water; it profoundly affects land use. The expansion of these hubs often necessitates the clearing of scrublands or agricultural tracts, reducing regional biodiversity and altering local microclimates, exacerbating urban heat island effects. By analyzing these specific hubs, the research demonstrates that the environmental externalities of agglomeration are not merely abstract carbon metrics, but tangible, localized degradations of soil, water, and public health that threaten the long-term socio-economic viability of the surrounding geographies.

### **Strategic Policy and Spatial Interventions**

The culmination of this spatial analysis necessitates the development of strategic, data-driven policy interventions aimed at mitigating the environmental externalities of supply chain logistics.

Traditional environmental regulations have often relied on uniform, non-spatial emission standards that fail to account for the localized intensity of agglomeration economies. The GIS-driven identification of carbon corridors and emission hotspots provides a framework for targeted, spatially explicit policy mechanisms (Boarnet, 2001). A primary strategic intervention is the optimization and decarbonization of the logistics network. Policymakers must incentivize a modal shift from road-based freight to electrified rail networks, particularly for the high-volume transport of raw materials between coastal ports and inland hubs.

Establishing dedicated "Green Freight Corridors" that bypass densely populated urban centers can significantly mitigate human exposure to transport-related pollutants (Cui et al., 2015). Furthermore, spatial planning must incorporate stringent zoning regulations that enforce ecological buffers between heavy industrial agglomerations and residential or agricultural zones.

At the cluster level, policy must mandate the transition toward circular economy principles. Within hubs like the metallurgical sectors of Saurashtra, this involves creating centralized, shared infrastructure for effluent treatment and waste recycling, thereby reducing the individual spatial footprint of MSMEs. Urban planners must also integrate localized environmental carrying capacities into future SEZ approvals, ensuring that industrial expansion does not outpace the region's ecological limits. Ultimately, aligning transport geography with environmental sustainability requires a paradigm shift: treating the supply chain not merely as an economic utility, but as a primary focus for spatial environmental governance.

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