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Review Article

How Do Road Networks Impact Land Use/Land Cover Change? A PRISMA-Guided Analysis

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Abstract: Transportation infrastructure promotes economic growth but causes environmental degradation, highlighting conflicts in sustainable development. As human activity intensifies pressure on land resources, understanding how roads influence land-use and land-cover (LULC) change is essential for balancing development with environmental protection. This review consolidates findings from 2010 to 2025, following PRISMA guidelines, and synthesises evidence from 79 studies across five continents on the impacts of roads on five different LULC categories. The thematic synthesis examines road-effect zones, LULC impact patterns, and the geographic and institutional factors influencing their variability. The results confirm that road networks accelerate LULC change, driving agricultural land conversion, forest fragmentation, built-up expansion, and waterbodies degradation. Road-effect zones range from 100 m in regulated landscapes to over 10,000 m in frontier regions, suggesting that standardised buffer guidelines may not fully capture observed impacts. Furthermore, the review introduces a mediation–moderation framework in which accessibility mediates, and distance from roads, development stage, and governance capacity moderate road-induced LULC outcomes. These findings challenge traditional infrastructure models, especially in developing countries, emphasizing that sustainable progress requires governance-enabling strategies. These should integrate land-use regulation, environmental enforcement, and institutional capacity with physical construction as prerequisites for sustainable infrastructure, rather than just relying on reactive mitigation.

Keywords: Land Use and Land Cover; Road Networks; Transportation Infrastructure; Road-Effect Zones; Accessibility; Governance; PRISMA; Sustainable Development

Highlights:

- Roads represent development ambitions but entail serious socio-ecological trade-offs.
- Roads drive agricultural conversion, urban expansion, forest and waterbodies degradation.
- Road-effect zones range from 100 m in regulated landscapes to >10,000 m in frontier areas.
- Road-LULC relationship is mediated by accessibility, and moderated by development and governance.
- A mediation–moderation framework is proposed, generating testable hypotheses for future studies.

1. Introduction

Infrastructure provides essential services such as electricity, water, transportation, sanitation, and communication, affecting people directly or indirectly. Currently, 58% of the global population lives in cities, with projections indicating this will rise to 67% by 2050 (United Nations, 2025). This rapid urbanization is straining transportation networks, especially roads, which are expected to expand by over 25 million kilometres by 2050, with 90% of this growth occurring in developing countries (Rodrigue, 2024). Recent infrastructure development emphasises transportation corridors connecting megacities, industrial zones, and ports, thereby shaping spatial development (Suhas et al., 2024). Roads are vital for transport and require significant investment to improve mobility, accessibility, and connectivity (Labi et al., 2019). Studies show that roads attract investment, boost tourism, support infrastructure, and promote trade and industry (S. Wang et al., 2024). However, they fragment landscapes, harm ecosystems, and cause environmental costs (Dannenberg et al., 2018).

Land, the primary substrate for transport infrastructure, faces increasing pressure from resource extraction, urban growth, and development (Xiong et al., 2018). Understanding land use and land cover (LULC) dynamics is essential for sustainable regional planning. Land use refers to human activities, such as agricultural or residential uses, while land cover includes natural elements, such as vegetation and waterbodies (Pandian et al., 2014). This distinction is crucial for understanding human-environment interactions. Unregulated LULC change driven by development pressure raises concerns due to its cascading environmental and socioeconomic impacts, including resource depletion, landslides, habitat fragmentation, biodiversity loss, flood risk, pollution, wildlife displacement, soil erosion, reduced carbon sequestration, and urban heat (Abdo, 2025; Abdo et al., 2026; Karmoka & Hanjagi, 2025; Moisa et al., 2025; Sanggoro et al., 2022; S. Wang et al., 2024; Z. Wang et al., 2024). Therefore, understanding the spatial and temporal patterns of LULC change is essential for managing environmental impacts and promoting sustainability. Many environmental impacts of roads are recognised, but identifying their scope, extent, and mechanisms remains challenging. The impacts are diverse, extend beyond the road surface, and vary for different roads. According to Forman & Deblinger (2000), the impact zone can expand with increased road density and is often asymmetrical.

Roads impact LULC through two main mechanisms: directly, by occupying land for infrastructure construction, and indirectly, by altering accessibility patterns that spur further development (Litman, 2016). The interdependence between transport infrastructure and LULC has been recognised for nearly a century. This relationship functions as a feedback cycle, with each system continuously influencing the other and creating complex, dynamic interactions. According to Dieleman & Wegener (2004), theories explaining this relationship fall into three main groups: (i) technical theories, which argue that prevailing transport technologies determine urban mobility patterns and spatial structure; (ii) economic theories, which emphasise that land use patterns respond to location costs and influence household and firm location decisions through bid-rent mechanisms; and (iii) social theories, which see urban evolution as a process of spatial appropriation by individuals and social groups.

The land use-transport feedback cycle proposed by Wegener & Fuerst (1999) synthesises these perspectives, positioning accessibility as the crucial link between infrastructure and land transformation (Figure 1). According to this framework, new or improved transport infrastructure reduces travel time and costs, enhancing the accessibility of specific locations. This accessibility premium makes these areas more attractive for development, triggering LULC changes. Subsequently, altered land-use patterns modify activity distributions and travel behaviours, generating demand for further infrastructure improvements, thereby perpetuating the cycle. This review focuses on the first segment of the cycle, where the road network drives LULC change.

The Road-Effect Zone (REZ) concept has emerged to analytically evaluate the impacts of roads on surrounding environments. It denotes the spatial extent over which the environmental, ecological, and socioeconomic consequences of roads spread into adjacent areas (Forman & Deblinger, 2000). The dimensions of road-effect zones vary considerably depending on several factors: road characteristics (such as width, traffic volume, design speed, vehicle composition, and traffic intensity), landscape properties, meteorological conditions, species-specific sensitivities to disturbance, regional development stage, and land tenure patterns. As a result, the range extends from a few hundred meters to several thousand meters (Lisiak-Zielińska et al., 2022).

Existing reviews have advanced understanding of road-driven LULC change but have revealed persistent gaps. Kasraian et al. (2016) examined transport–land use relationships in developed regions but excluded developing countries and focused mainly on economic indicators. Allan et al. (2022) identified transport as a key LULC driver but provided limited mechanistic or spatial evidence. In Sub-Saharan Africa, Mtweve et al. (2025) found that only 5% of studies examined socioeconomic and environmental impacts together, while Biber-Freudenberger et al. (2025) called for holistic approaches, balancing development and environment without providing a systematic empirical synthesis. Recent evidence further suggests that socioeconomic factors, particularly local community, moderate road-induced LULC change beyond the well-documented roles of accessibility, road type, and distance (Younes & Nusrath, 2026). Yet, critically, the geographic, ecological, and institutional conditions governing the magnitude and spatial extent of road-induced LULC change remain poorly synthesised globally.

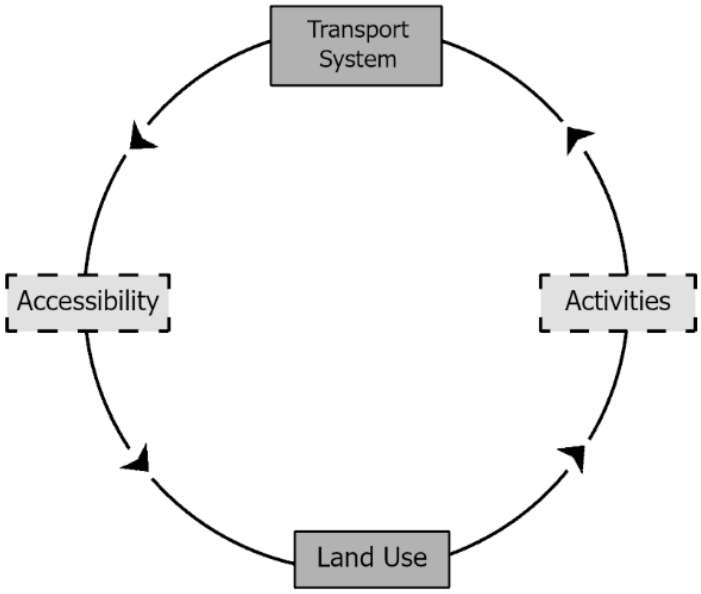

Figure 1. The Land Use–Transport Feedback Cycle, redesigned by the authors based on Wegener & Fuerst (1999)

To investigate how road networks affect LULC change, this systematic review synthesises global evidence from both developed and developing contexts. It focuses on the following areas: (i) impacts on agricultural land, built-up areas, forests, grasslands and waterbodies; (ii) the spatial extent and controlling factors of REZs as a context-dependent gradient; and (iii) the influence of development stage and governance capacity on road-induced LULC outcomes. It provides geographers, planners, and policymakers with a theoretically informed model, inductively derived from convergent empirical patterns, to understand how infrastructure, ecology, and governance interact to shape landscapes across diverse global contexts, going beyond a descriptive account of road–LULC relationships. It produces transferable insights into where, why, and under what circumstances road expansion drives LULC change. This knowledge is critically needed as global road networks continue to expand into ecologically sensitive and institutionally fragile regions.

2. Methodology

2.1 Systematic Review Protocol

To ensure rigour, transparency, and reproducibility, this systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Moher et al., 2009, 2015). Based on predetermined eligibility criteria pertinent to road network influences on LULC change, the PRISMA framework provided a standardised process for systematically identifying, screening, and selecting studies (Figure 2).

2.2 Search Strategy

Systematic searches were performed in Scopus and Google Scholar for peer-reviewed journal articles published between 2010 and 2025, capturing contemporary trends during a period of rapid global infrastructure expansion. The most recent search was carried out on January 1st, 2026.

In Scopus, the following search string was applied across titles, abstracts, and keywords:

TITLE-ABS-KEY (("impact*" OR "influence*" OR "effect*") AND ("road network*" OR "road*" OR "transport* infrastructure" OR "highway*" OR "expressway*" OR "motorway*") AND ("land use*" OR "land cover*" OR "land use/land cover" OR "LULC" OR "landscape*" OR "land pattern*")).

And the following string was applied in Google Scholar:

("impact" OR "influence" OR "effect") AND ("road network" OR "road" OR "transport infrastructure" OR "highway" OR "expressway" OR "motorway") AND ("land use" OR "land cover" OR "LULC" OR "landscape" OR "land pattern").

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Given that Google Scholar returns results ranked by relevance rather than exhaustively, screening was limited to the first 350 results, consistent with established systematic review practice (Haddaway et al., 2015).

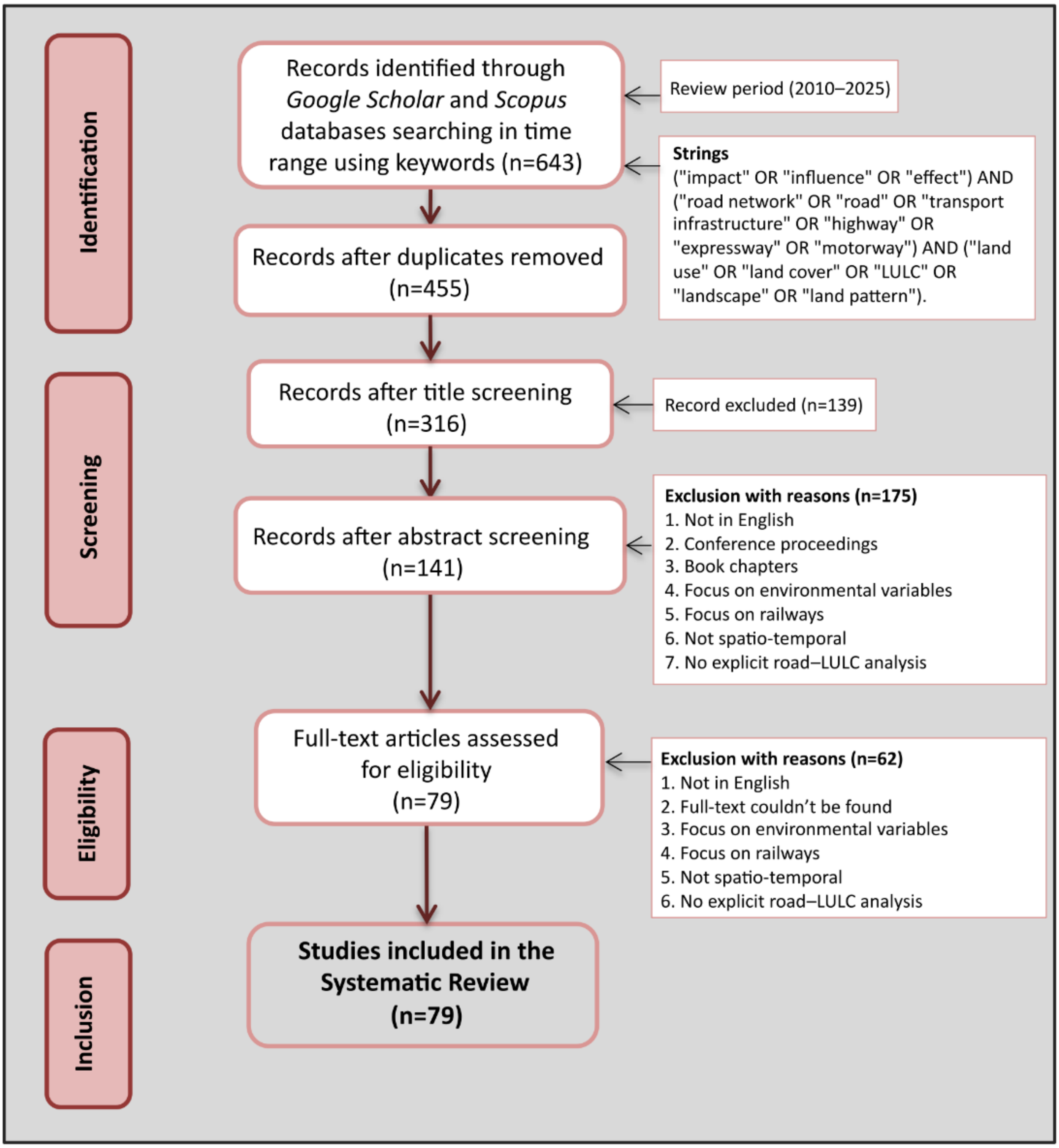

Figure 2. The PRISMA-guided methodological flowchart, prepared by the authors based on Moher et al. (2009)

2.3 Eligibility Criteria

2.3.1 Inclusion criteria

Eligible studies were empirical, peer-reviewed journal articles published in English that explicitly analysed the impact of road networks on at least one LULC category within a spatiotemporally defined study area. Studies were required to use transparent, replicable methodologies and to address a direct road–LULC relationship through unidirectional analysis.

2.3.2 Exclusion criteria

Studies were excluded if they: (1) were not published in English; (2) were conference proceedings, book chapters, technical reports, or grey literature; (3) focused solely on non-road infrastructure (e.g., railways); (4) analysed environmental variables without an explicit LULC analysis; (5) lacked a spatio-temporal dimension; or (6) did not have a direct road–LULC analytical focus.

2.4 Study Selection and Screening

The database searches returned 300 records from Scopus and 343 from Google Scholar, for a total of 643 records. Duplicates were identified through a systematic cross-database comparison and removed, eliminating 188 records and leaving 455 unique records for screening. Two reviewers independently screened titles, abstracts, and full texts against predefined eligibility criteria. Disagreements were resolved through discussion and consensus.

Title screening excluded an additional 139 records, and subsequent abstract screening excluded 175 records under the eligibility criteria above. The remaining 141 records were retrieved for full-text assessment. Of these, 62 were excluded for the following reasons: full text unavailable; focus on environmental variables without explicit LULC analysis; focus on non-road infrastructure; absence of spatio-temporal analysis; and no direct road–LULC analytical focus. Following this appraisal, 79 peer-reviewed journal articles met all eligibility criteria and were included in the review.

No formal risk-of-bias tool was used, as heterogeneity in study designs precluded the consistent application of a standardised appraisal instrument, and thematic synthesis does not require quality scoring for pooled effect estimation. Methodological quality was instead ensured through the eligibility criteria, which restricted inclusion to peer-reviewed articles with explicit objectives, spatiotemporally defined study areas, and replicable methods.

2.5 Data Extraction and Variable Operationalisation

A standardized data extraction form was developed to code study characteristics, methodologies, and key findings. Coding was conducted independently by two reviewers. Any discrepancies were resolved through discussion and consensus.

To ensure methodological transparency and alignment with PRISMA guidelines, key variables extracted from each included study are summarised in tables and figures. They include study-level characteristics, such as geographic context, study period, and analytical methods, as well as primary variables of interest: road type, REZ distances, and LULC change metrics. Operationalisation is recorded where applicable; for example, whether REZ was derived from buffer analysis or distance decay gradients, and whether LULC change was expressed as area or percentage. This structured extraction protocol facilitated systematic cross-study comparison and supports the reproducibility of the synthesis.

To address the role of governance, and given the absence of a standardised governance metric in the reviewed literature, evidence on governance was captured wherever reported, encompassing regulatory, incentive-based, and enforcement and compliance mechanisms, as well as institutional arrangements affecting road-adjacent LULC. Governance categories were identified inductively from the included studies through thematic synthesis and organised by governance function rather than as formally coded variables established a priori.

2.6 Data Synthesis

The 79 studies were thematically synthesised to answer the research questions. Each reported road network impacts on at least one LULC category, such as agricultural land, forests, built-up areas, waterbodies, or grasslands, via direct land conversion or accessibility-mediated mechanisms. Data covered impact magnitude, spatial extent, temporal dynamics, and contextual factors. Evidence was organised by LULC category to identify patterns, contradictions, and context dependencies across different settings, development stages, and road types. Due to heterogeneity in spatial scales, methods, and LULC classifications, a formal meta-analysis was not possible; instead, a thematic synthesis was used. Over 90% of studies employed geospatial methods, including remote sensing (RS) and GIS, complemented by spatial statistics, modelling, field surveys, and socioeconomic approaches.

To enable structured cross-study comparison, the studies were classified post hoc by development stage, which indicates infrastructure and socio-economic development around roads, classified as: (1) Frontier/remote—previously inaccessible areas with minimal land-use regulation; (2) Developing/transitional—regions with rapid LULC change due to urbanisation or agriculture; (3) Established/urbanised—densely populated areas with mature infrastructure and stable LULC; (4) Established/managed—similar to (3) but with strong LULC regulation; (5) Frontier to developing—dynamic shifts following road expansion.

3. Results

3.1 General Characteristics of the Reviewed Studies

3.1.1 Geographic Distribution and Continental Representation

The 79 reviewed studies span five continents and 34 countries, with regional imbalances shaped by infrastructure, research capacity, and data availability. Asia dominated the corpus (n = 62, 78%), acting as a hotspot for landscape change and academic focus (Figure 3). China and India accounted for 68% of the total, driven by rapid road construction and LULC investment. Türkiye contributed 8%, while Pakistan, Iran, and Bangladesh collectively accounted for 15%, indicating diverse regional research. Other continents were less represented: South America had six studies (8%), mainly Brazil, with one including Peru and Bolivia. Europe had 5 studies (6%) across Spain, Switzerland, Poland, Greece, and the Czech Republic, showing modest, uneven distribution. North America had three studies (4%), all in the U.S. and one in Canada. Africa had one study (1%) from Egypt, and two intercontinental studies (3%) linked multiple regions.

The geographic focus highlights a structural reality: road–LULC dynamics are most well documented in areas of intensive activity, making Asian dominance a central part of the analysis rather than an incidental factor. However, patterns mostly reflect rapidly urbanising economies with state-led expansion and high conversion rates. These may not fully capture road–LULC relationships across contexts, especially in Africa and Latin America, where infrastructure expansion is rapid yet less studied. Global generalisations should be seen as reflecting current literature, not as exhaustive accounts of global dynamics.

3.1.2 Publication Trends and Regional Patterns

Publication frequency from 2010 to 2025 varied, peaking in 2021 (18%) and 2017 (10%), with secondary highs in 2019 and 2023 (8% each). Minimal output occurred in 2015 (3%) and 2024 (1%). Asian studies were evenly distributed, showing sustained momentum, while European and American research was episodic, with clustering over time (Figure 3).

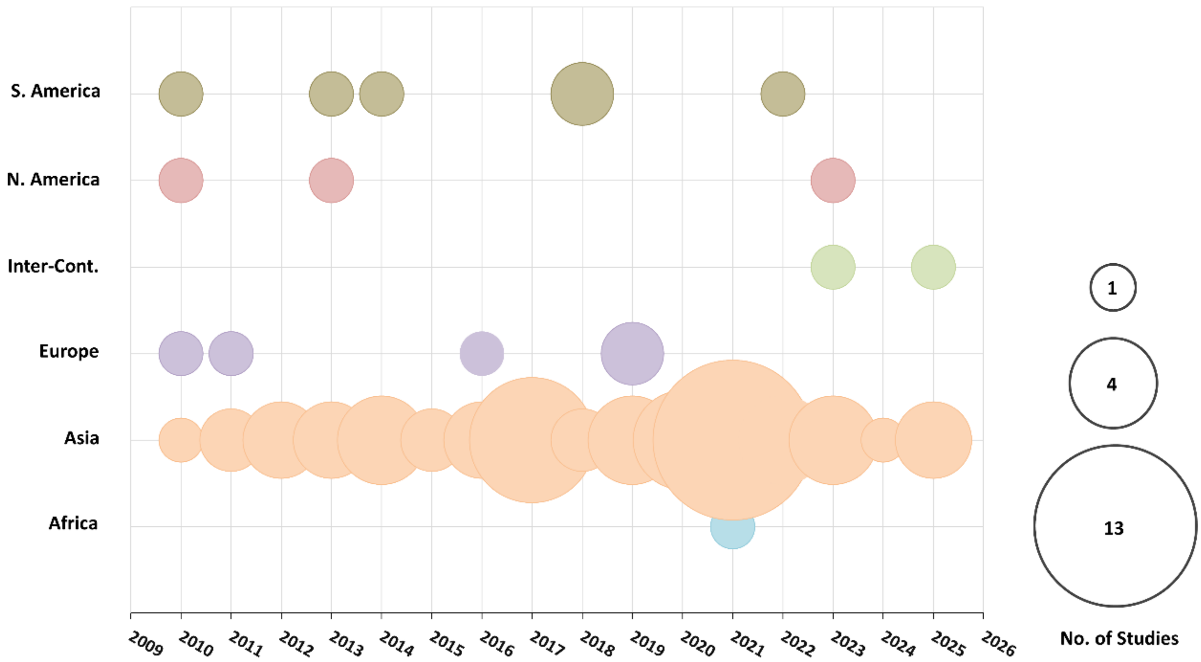

Figure 3. Geographic spread and temporal coverage of the studies (Prepared by the authors)

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3.1.3 Temporal Coverage and Historical Depth

Study periods ranged from 1 to 170 years, covering objectives from recent infrastructure to long-term landscape changes. Nearly half (46%) spanned 20+ years, allowing analysis of cumulative impacts and non-linear responses (Figure 4). Most studies (90%) used data from 1980 onward, a turning point marked by the transformation of LULC science by digital geospatial, GIS, and RS tools.

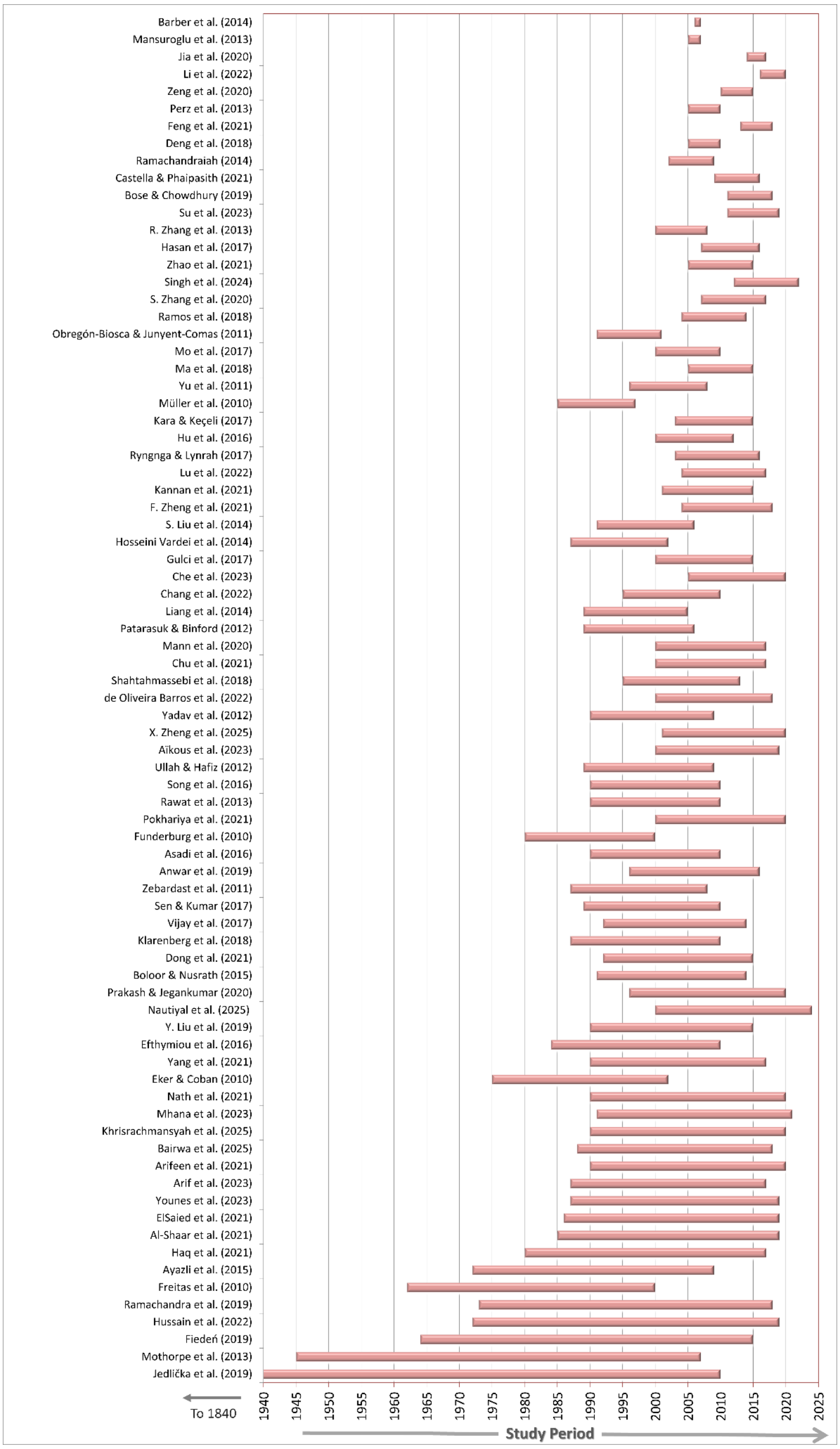

Figure 4. Chronological span of the included studies, from smallest to largest (Prepared by the authors)

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3.1.4 Governance Reporting

Only 20% (n = 16) of the studies explicitly reported governance-related content relevant to road–LULC relationships, distributed across four functionally distinct governance categories, with some studies contributing to more than one (Table 1).

Table 1. Governance-related evidence across included studies: distribution by functional category

Governance Category	Definition	No. of Studies*	Key Studies
Regulatory instruments	Laws, zoning, land protection designations, access controls, and tenure rules constraining or directing road-adjacent land use	7	Aïkous et al. (2023), Che et al. (2023), Mo et al. (2017), Obregón-Biosca & Junyent-Comas (2011), Perz et al. (2013), Song et al. (2016) and R. Zhang et al. (2013)
Incentive-based instruments	Payment for ecosystem services, subsidies, and investment policies shaping LULC outcomes through positive incentives	6	Chu et al. (2021), Dong et al. (2021), Lu et al. (2022), Nautiyal et al. (2025), Patarasuk & Binford (2012) and Yu et al. (2011)
Enforcement and compliance mechanisms	Enforcement capacity, regulatory compliance failures, and informal road construction beyond formal planning systems	4	Castella & Phaipasith (2021), Hussain et al. (2022), Perz et al. (2013) and Ullah & Hafiz (2012)
Institutional arrangements	Formal and informal institutions governing resource use, including communal management systems and inter-agency coordination	4	Castella & Phaipasith (2021), Hussain et al. (2022), Mo et al. (2017) and Perz et al. (2013)

*Some studies contributed evidence to more than one category.

3.2 Overview of the Impacts of Road Network on LULC Dynamics

This review reveals that road networks consistently reshape LULC. While impacts follow patterns, outcomes vary by factors, showing roads as powerful yet context-dependent agents of opportunity and degradation (Table 2) and (Appendix A, Table A **1**).

Table 2. Key variables extracted from included studies and their operationalisation

Study	Major Impacts*					Measurement of impacts	Analytical Methods
	AL	BA	FC	GL	WB		
Aïkous et al. (2023)		↑				Binary indicator	Panel event-study
Al-Shaar et al. (2021)	↓	↑	↓			Area (m^2) and %	RS, GIS, correlation analysis
Anwar et al. (2019)	↓	↑	↑		↓	Area (Km^2) and %	RS, GIS, socioeconomic survey
Arif et al. (2023)	↓	↑	↓		↓	Area (Km^2) and %	RS, GIS, intensity analysis
Arifeen et al. (2021)	↓	↑	↑		↓	Area (Km^2) and %	RS, GIS
Asadi et al. (2016)	↓	↑				Area (ha) and %	RS, GIS, chi-square analysis

Ayazli et al. (2015)	↓	↑	↓			%	RS, GIS, CA-SLEUTH model
Bairwa et al. (2025)	↓	↑	↓			Area (Km^2) and %	RS, GIS, ANN–Markov–CA simulation
Barber et al. (2014)			↓			Area (Km^2) and %	RS, GIS, scenario modelling
Boloor & Nusrath (2015)	↓	↑	↓		↓	Area (Km^2) and %	RS, GIS
Bose & Chowdhury (2019)	↓	↑	↓		↓	Area (Km^2) and %	RS, GIS, regression, ANOVA
Castella & Phaipasith (2021)	↑		↓			%	RS, household surveys, qualitative analysis
Chang et al. (2022)	↓	↑			↓	Landscape metrics and %	RS, landscape metrics
Che et al. (2023)	↓	↑	↓	↓		LER index	GIS, landscape ecological risk modelling
Chu et al. (2021)	↓	↑			↓	Area (Km^2)	RS, GIS, time series analysis
de Oliveira Barros et al. (2022)	↓	↑				Area (ha) and %	GIS, CA modelling, logistic regression
Deng et al. (2018)	↑					Area (ha)	RS and Econometric analysis
Dong et al. (2021)	↑	↑	↓	↑	↓	Area (Km^2) and %	RS, GIS, spatial modelling
Efthymiou et al. (2016)	↓	↑				Binary change and area (ha)	RS, spatial econometric modelling
Eker & Coban (2010)			↓			Landscape metrics	GIS, landscape metrics
ElSaied et al. (2021)	↑	↑	↑		↑	Area (Km^2) and %	RS, GIS, statistical analysis
F. Zheng et al. (2021)	↓	↑	↓		↓	Area (ha) and %	GIS, dynamic indices, land-use transition analysis
Feng et al. (2021)	↓	↑	↓			Area (Km^2) and %	RS, GIS, landscape metrics
Fiedeń (2019)	↓	↑	↓			SHDI index and %	GIS, landscape diversity index
Freitas et al. (2010)	↑	↑	↓			Area (ha) and %	GIS, regression modelling
Funderburg et al. (2010)		↑				Population and employment change	Quasi-experimental, regression modelling
Gulci et al. (2017)			↓			Vegetation index and %	RS, GIS
Haq et al. (2021)	↑		↓			Area (ha) and %	RS, GIS
Hasan et al. (2017)	↓	↑			↓	Area (ha) and %	RS, GIS
Hosseini Vardei et al. (2014)			↓			Landscape metrics	RS, GIS, landscape metrics
Hu et al. (2016)			↓			Area (Km^2) and %	RS, GIS, Multinomial logistic regression
Hussain et al. (2022)	↑		↓			%	RS, GIS, correlation analysis
Jedlička et al. (2019)	↑	↑	↑	↓		%	GIS analysis
Jia et al. (2020)			↓			Area (Km^2) and %	RS, GIS, grey relational analysis
Kannan et al. (2020)	↓	↑			↓	Area (ha) and %	RS, GIS, econometric models
Kara & Keçeli (2017)			↓			Area (ha) and %	RS, GIS
Khrisrachmansyah et al. (2025)	↓	↑	↓			%	RS, GIS, landscape metrics
Klarenberg et al. (2018)			↓			Vegetation index	RS, dynamic factor analysis
Li et al. (2022)	↑	↑	↑	↓	↑	Area (Km^2) and %	GIS, landscape modelling, spatial autocorrelation
Liang et al. (2014)	↑	↑	↓			% and landscape indices	RS, logistic regression, landscape fragmentation analysis

Lu et al. (2022)	↑					Index-based	Spatial Durbin model, panel threshold model
Ma et al. (2018)		↑				Area (Km^2) and %	GIS, kernel density estimation, corridor effect modelling
Mann et al. (2020)	↓	↑	↓			%	RS, GIS and landscape metrics
Mansuroglu et al. (2013)	↓		↓		↓	Area (ha) and %	RS, GIS, landscape metrics
Mhana et al. (2023)	↓	↑	↓	↓		Area (Km^2) and %	RS, GIS, kernel density estimation
Mo et al. (2017)	↓	↑				%	GIS, kernel density, ecological risk index
Mothorpe et al. (2013)	↓	↑				Area (acres)	Panel econometric analysis
Müller et al. (2010)		↑				Log-transformed growth rates	Spatial statistical analysis
Nath et al. (2021)		↑				Area (Km^2) and %	RS, GIS
Nautiyal et al. (2025)		↑	↑			Area (Km^2) and %	RS, GIS, Shannon Entropy analysis
Obregón-Biosca & Junyent-Comas (2011)		↑				Area (ha) and %	Socioeconomic and land-use comparative analysis
Patarasuk & Binford (2012)	↑	↑	↓			%	RS, GIS
Perz et al. (2013)			↓			%	RS, GIS, regression analysis
Pokhariya et al. (2021)		↑				Area (ha) and %	RS, GIS
Prakash & Jegankumar (2020)		↑				Area (Km^2)	RS, GIS
R. Zhang et al. (2013)	↓	↑	↓	↑	↓	Area (ha) and %	RS, GIS, LUDD indices
Ramachandra et al. (2019)			↓		↓	Area (ha) and %	RS, GIS, fragmentation metrics, CA modelling
Ramachandraiah (2014)	↓					Area (acres/ha) and %	Household surveys, before–and–after comparison
Ramos et al. (2018)			↓			Area (ha) and %	GIS, CA simulation, scenario modelling
Rawat et al. (2013)		↑				Area (Km^2) and %	RS and GIS
Ryngnga & Lynrah (2017)	↓		↓			Area (sq. ft.) and %	GIS, field survey
S. Liu et al. (2014)			↓			%	GIS, landscape metrics, connectivity analysis
S. Zhang et al. (2020)		↑				Area (Km^2) and %	GIS, Kernel Density, Corridor Effect Modelling
Sen & Kumar (2017)	↓	↑	↓		↑	%	RS and GIS
Shahtahmassebi et al. (2018)		↑				Area (ha) and %	RS, wavelet analysis, Theil–Sen slope
Singh et al. (2024)	↑	↑	↓	↑	↑	Area (Km^2) and %	RS, GIS, road density analysis, Spearman correlation
Song et al. (2016)	↓	↑				Area (Km^2) and %	RS, GIS, landscape metrics
Su et al. (2023)		↑				economic indicators	Difference-in-Differences econometric model
Ullah & Hafiz (2012)			↓			Area (Km^2) and %	RS and GIS
Vijay et al. (2017)					↓	%	RS and GIS
X. Zheng et al. (2025)	↑		↓	↑		RII Index and %	RS, RII modelling, causal matching
Y. Liu et al. (2019)	↓	↑	↓	↓	↓	Area (Km^2) and %	Traffic accessibility analysis, PCA
Yadav et al. (2012)			↓			Area (Km^2) and %	RS and GIS

Yang et al. (2021)	↓	↑	↓			Area (Km²) and %	RS, GIS, landscape indices, ESV evaluation
Younes et al. (2023)		↑				Area (Km²) and %	RS and GIS
Yu et al. (2011)	↓	↑	↑		↓	Area (ha) and index measures	GIS, quantitative land-use models, and transect analysis
Zebardast et al. (2011)			↓			%	GIS, effective mesh size
Zeng et al. (2020)		↑				Index-based	Spatial econometric analysis, network modelling
Zhao et al. (2021)	↓	↑	↑	↓		Area (Km²) and %	GIS, landscape metrics, land-use transition modelling

**(AL)=Agricultural Lands / (BA)=Built-up Areas / (FC)=Forest Cover / (GL)=Grasslands / (WB)=Waterbodies.*

3.2.1 Agricultural Land

Road expansion affects agricultural land through two mechanisms — direct appropriation and accessibility-driven conversion to non-agricultural uses — counterbalanced in some contexts by market-enabled intensification. The direction and magnitude of these effects are associated with the development stage and governance capacity, rather than with road construction alone.

Agricultural conversion is documented universally, but its scale and spatial pattern vary systematically with the development context. In established economies, conversion is peri-urban and incremental: each additional interstate mile in the United States reduced farmland by 468 acres between 1945 and 2007, with urban counties experiencing 70% higher rates than rural areas (Mothorpe et al., 2013), and nearly 300 km² were lost near Madrid between 1991 and 2021 (Mhana et al., 2023). In rapidly urbanising developing contexts, losses are larger and more spatially diffuse: farmland near Wujing Highway, China, declined from 24% to 18% (Feng et al., 2021); 77,000 ha were lost along Bangkok–Kunming Highway between 2004 and 2018 (F. Zheng et al., 2021); and agricultural land along the Dhaka-Aricha Highway collapsed from 62% to 28% between 2007 and 2016 (Hasan et al., 2017). These losses carry socioeconomic consequences beyond area statistics: road construction separated Hyderabad farmers from their lands (Ramachandraiah, 2014), while roads in northern Laos improved market access, they also intensified inequality among smallholder farmers (Castella & Phaipasith, 2021) — confirming that resource-poor communities asymmetrically bear conversion costs.

Where governance frameworks or market conditions actively support agricultural productivity, roads intensify rather than convert. Chinese expressway infrastructure improved the efficiency of cultivated land use through spatial spillover effects (Lu et al., 2022), and irrigated farmland expanded by 27.5% near the G214 National Road between 1989 and 2005 (Liang et al., 2014). In Thailand, road expansion shifted production toward higher-value cash crops (Patarasuk & Binford, 2012), and in Pakistan, road improvements increased yields in previously inaccessible highland areas (Anwar et al., 2019; Haq et al., 2021; Hussain et al., 2022). These contrasting outcomes suggest that road impacts on agricultural land are not deterministic; rather, they depend on contextual factors that influence whether roads are linked to land conversion or agricultural intensification.

3.2.2 Forest Cover

Forests are the most affected LULC type across the reviewed literature, with road-induced accessibility serving as the primary mechanism of deforestation by enabling timber harvesting, agricultural encroachment, and settlement establishment. Critically, the magnitude and reversibility of forest loss vary systematically with context, rather than solely with road construction.

Pantropical evidence highlights substantial variation in road-associated forest loss. The contrast between 10.9% deforestation in protected areas and 43.6% in unprotected areas along Amazonian roads (Barber et al., 2014) suggests that governance capacity is an important factor associated with differences in deforestation outcomes. This pattern holds at the pantropical scale: road impact indices across 15 tropical countries were 2.45 times higher within 1 km of roads than beyond (X. Zheng et al., 2025), and paving the Inter-Oceanic Highway increased non-forest land from 11.64% to 18.04% between 2005 and 2010 in the absence of effective enforcement (Perz et al., 2013).

Regional evidence confirms that forest loss scales with development stage and institutional weakness. In frontier and transitional contexts, losses are severe: 50% of forest cover was lost in Kurram District, Pakistan, between 1972 and 2019 (Hussain et al., 2022); 17,000 ha in the Hindu Kush Himalayas between 1980 and 2017 (Haq et al., 2021); 90,000 ha along Bangkok–Kunming Highway between 2004 and 2018 (F. Zheng et al., 2021); and 21,100 km^2 along China–Mongolia–Russia Economic Corridor, primarily converted to cropland (Dong et al., 2021). In established but rapidly urbanising contexts, losses are more localised but cumulative: a 28% reduction near the Bosphorus bridges between 1972 and 2009 (Ayazli et al., 2015), 2,530 ha damaged in northern Istanbul over 15 years (Kara & Keçeli, 2017), and the evergreen forest in Kodagu, India, declining from 40% to 24% between 1973 and 2018 under cumulative network pressure (Ramachandra, Sellers, et al., 2019). Bridge construction near Manaus demonstrates that infrastructure triggers both immediate and temporally lagged deforestation through induced accessibility cascades (Klarenberg et al., 2018; Ramos et al., 2018).

Where governance frameworks actively counteract road-induced pressure, forest cover expands rather than contracts. In China, proactive ecosystem programmes converted grassland and farmland to forest during the construction of Qumei–Gangba Highway between 2016 and 2020 (Li et al., 2022), with consistent patterns across Beijing, Hebei, and Henan (Mo et al., 2017; Yu et al., 2011). These positive deviant cases suggest that road-induced forest loss is not inevitable and that governance conditions may play an important role in shaping forest outcomes associated with road development.

3.2.3 Built-Up Areas

Road network development is the most documented driver of built-up expansion, operating through two complementary mechanisms: reducing transport costs to attract economic activity, and shaping the spatial form and functional character of urban development along corridors. Critically, governance capacity and development stage are important contextual factors associated with whether this expansion takes compact, productive forms or sprawling, resource-intensive ones.

The scale of road-induced urban expansion scales systematically with the development context. In frontier and rapidly urbanising settings, rates are dramatic: construction land in the Pearl River Delta increased 6.6-fold from 1.69% to 16.67% between 1990 and 2015 (Y. Liu et al., 2019); urban land along Dhaka-Aricha Highway quadrupled from 14% to 57% between 2007 and 2016 (Hasan et al., 2017); and built-up area in Ibiúna Plateau, Brazil, grew by 1,020% between 1981 and 2000 (Freitas et al., 2010). The 1,200% increase near Wadi Al-Natroun–Al-Alamin Road in Egypt reflects expansion from a near-zero baseline in a newly accessible desert margin rather than typical urban growth dynamics (ElSaied et al., 2021). In established contexts, expansion is more moderate but structurally consistent: 10,500 ha created near Athens over 26 years (Efthymiou et al., 2016), industrial and residential growth near motorways across Poland, Switzerland, and the Czech Republic (Fiedeń, 2019; Jedlička et al., 2019; Müller et al., 2010), and econometric evidence of employment-related development induced by highway infrastructure in urbanising U.S. counties (Funderburg et al., 2010).

Beyond quantity, roads systematically shape the spatial form and functional character of urban expansion, reflecting the interaction among infrastructure, topography, and planning capacity. In South Asia, urban growth consistently aligns with transportation axes — southward along NH 121 in Ramnagar (Rawat et al., 2013), southeast along NH 37 in Guwahati (Nath et al., 2021), and along Dhaka–Mymensingh Highway in Bangladesh (Arifeen et al., 2021) — confirming that road corridors define urban growth directionality across diverse planning contexts. In China, expressway development in Jilin Province drove a functional transformation, shifting Changchun from an industrial to a residential city between 2007 and 2017 (S. Zhang et al., 2020), while spillover effects in Beijing–Tianjin–Hebei generated inefficient sprawl beyond planned boundaries (Zeng et al., 2020). Where biophysical constraints intersect with weak planning capacity — as in Indonesia and the Indian Himalayas — road proximity produces fragmented ribbon development rather than compact growth (Khrisrachmansyah et al., 2025; Nautiyal et al., 2025), confirming that topography and institutional capacity jointly moderate the spatial translation of accessibility into urban form.

Patterns across the reviewed studies indicate that governance capacity may play a key role in shaping whether road-related urban expansion is associated with more sustainable development trajectories or with greater urban sprawl. Highway 30 near Montreal generated industrial and commercial construction despite legal constraints, demonstrating that accessibility improvements override regulatory frameworks without vigorous enforcement (Aïkous et al., 2023). Conversely, the Chinese expressway policy, coupled with living-condition improvement programmes, produced concentrated, planned growth near Nanping expressways (Zhao et al., 2021). These contrasting outcomes confirm that roads are necessary but insufficient for sustainable urbanisation — institutional capacity determines whether road-facilitated growth translates into prosperity or unregulated sprawl.

3.2.4 Waterbodies

Waterbodies are adversely affected by road development, with losses driven by three compounding mechanisms: direct conversion to impervious surfaces, hydrological disruption through altered drainage and increased surface runoff, and slope instability from road cuttings in riparian zones. The severity of these impacts scales with road network density and proximity to water-sensitive landscapes.

Waterbodies loss is documented consistently across Chinese and South Asian contexts, with magnitude increasing in proportion to road network density and urbanisation pressure. In China, Hangzhou Bay Bridge construction alone converted 98 km² of waterbodies to impervious land and 110 km² to agricultural use (Chu et al., 2021), while dense road networks in the Pearl River Delta eliminated 1,863 km² of waterbodies — 77% to construction land (Y. Liu et al., 2019). Road network densification in Hang-Jia-Hu Plain accelerated waterbodies conversion by approximately 16% over 20 years (Song et al., 2016), a pattern replicated across multiple Chinese urban and peri-urban contexts (Chang et al., 2022; Dong et al., 2021; Feng et al., 2021; Mo et al., 2017; Yu et al., 2011; R. Zhang et al., 2013; F. Zheng et al., 2021). In South Asia, losses are proportionally severe: waterbodies declined by 50–52% along Bangalore–Mysore and Siliguri–Jalpaiguri corridors (Bose & Chowdhury, 2019; Kannan et al., 2020), from 19% to 8% along Dhaka-Aricha Highway between 2007 and 2016 (Hasan et al., 2017), and from 4.5% to 3.9% along Mysore–Mandya Highway between 1991 and 2014 (Boloor & Nusrath, 2015). Beyond area loss, impervious road surfaces increase surface runoff transporting sediments, heavy metals, and pollutants into adjacent waterbodies, compounding both water quality and quantity degradation independently of land conversion.

Isolated cases of waterbodies expansion alongside road development do not contradict this pattern — they reflect deliberate investments in water infrastructure rather than road benefits. Waterbodies increase during Qumei–Gangba Highway construction (Li et al., 2022), pisciculture expansion near Loktak Lake, India (Singh et al., 2024), and waterbodies restoration in Egypt following road construction (ElSaied et al., 2021), are all attributable to co-occurring irrigation systems, reservoirs, and retention infrastructure. These cases confirm that expansion of waterbodies requires active intervention — it does not arise from road construction itself.

3.2.5 Grasslands

Grasslands respond to road expansion in a distinct way that sets them apart from forests. Rather than progressive fragmentation, they tend toward wholesale conversion to agricultural or built-up areas, facilitated by roads that render previously marginal lands economically viable. This pattern is consistent across development contexts and geographic scales, suggesting that grasslands are particularly vulnerable to the accessibility-driven land valorisation generated by road construction.

Evidence of wholesale conversion is documented across diverse contexts and scales. In the Yangtze River Delta, declining fragmentation indices alongside expanding road networks between 2005 and 2020 confirm a complete transformation rather than gradual attrition (Che et al., 2023) — a pattern that distinguishes grassland dynamics from the fragmentation-dominated responses observed in forest systems. Substantial losses were recorded along Qumei–Gangba Highway, i.e., 12% decline (Li et al., 2022), in the Pearl River Delta, i.e., 358 km² (Y. Liu et al., 2019), and in Nanping City, i.e., 1,025 km², (Zhao et al., 2021). Long-term European evidence confirms that this pressure is cumulative and irreversible without active intervention: grasslands in Hodonin, Czech Republic, contracted from 26% in 1840 to 7% in 2010 as road-enabled intensification progressively converted grassland to agricultural and built-up uses over nearly two centuries (Jedlička et al., 2019).

Marginal grassland gains reported in isolated cases — a 0.3% increase along China–Mongolia–Russia Economic Corridor (Dong et al., 2021) and a negligible expansion from 635 to 638 ha in Qixia District between 2000 and 2008 (R. Zhang et al., 2013) — are insufficient to offset the dominant conversion trend and most plausibly reflect localised restoration efforts or agricultural land abandonment rather than any road-induced benefit.

3.3 Road-Effect Zones (REZs): Spatial Variability and Controlling Factors

Synthesising across 14 studies (18%) reveals a universal distance-decay pattern, but the decay rate and extent are influenced by factors such as development stage, road hierarchy and governance capacity (

Table **3**). REZ extent is not fixed; it results from interactions that shape the spatial reach of road-induced LULC change in systematic and often compounding ways (Figure 5). For example, in Georgia, USA, only urban counties experienced significant LULC change (Mothorpe et al., 2013), mainly due to highways, indicating that urbanisation boosts land conversion. Roads near cities cause more sprawl (Mann et al., 2020), as urban areas capitalise on improved accessibility, whereas rural regions face restrictions.

Table 3. REZ extents by biome, development stage, and analytical approach

REZ Extent	Biome*	Development Stage	Analytical Approach	Reference
≤5500 m	Tropical & Subtropical Moist Broadleaf Forests	Frontier/remote	Distance–decay with breakpoint threshold	Barber et al. (2014)
600-1000 m	Temperate Broadleaf & Mixed Forests	Established/urbanised	Buffer analysis	Chang et al. (2022)
>10,000 m	Tropical & Subtropical Moist Broadleaf Forests and Tropical & Subtropical Dry Broadleaf	Frontier→developing	Buffer with land-use dynamic index	F. Zheng et al. (2021)
≤1000 m	Tropical & Subtropical Moist Broadleaf Forests	Developing/transitional	Buffer analysis	Feng et al. (2021)
≤100 m	Mediterranean Forests, Woodlands & Scrub	Established/managed	Fixed-width buffer	Gulci et al. (2017)
≤1000 m	Temperate Coniferous Forests and Montane Grasslands and Shrublands	Frontier→developing	Buffer and Euclidean distance	Haq et al. (2021)
171-684 m	Temperate Broadleaf & Mixed Forests and Temperate Conifer Forests	Developing/transitional	Multi-distance buffer with ANOVA	Hosseini Vardei et al. (2014)
1000-3000 m	Tropical & Subtropical Moist Broadleaf Forests	Established/managed	Distance-to-road gradient	Hu et al. (2016)
≤2000 m	Montane Grasslands & Shrublands and Deserts & Xeric Shrublands	Frontier→developing	Buffer analysis	Hussain et al. (2022)
≤1000 m	Temperate Broadleaf & Mixed Forests	Established/urbanised	Buffer analysis	Jedlička et al. (2019)
≤3500 m	Tropical & Subtropical Moist Broadleaf Forests	Developing/transitional	Buffer analysis	Mann et al. (2020)
≤2000 m	Temperate Broadleaf & Mixed Forests	Developing/transitional	Buffer analysis	Song et al. (2016)
≤1000 m	Tropical & Subtropical Moist Broadleaf Forests	Frontier/remote	Distance-band buffer with RII	X. Zheng et al. (2025)
≤2000 m	Tropical & Subtropical Moist Broadleaf Forests	Developing/transitional	Buffer analysis	Zhao et al. (2021)

** Biome classification follows the WWF Terrestrial Ecoregions framework (Olson et al., 2001), and it is provided for contextual reference only.*

On the other hand, agricultural productivity influences road impacts. In India, fertile agricultural areas with intensive cultivation showed minimal built-up expansion along highways despite improved access, because land value exceeded development returns; conversely, highways traversing less productive landscapes expanded rapidly into built-up uses (Prakash & Jegankumar, 2020).

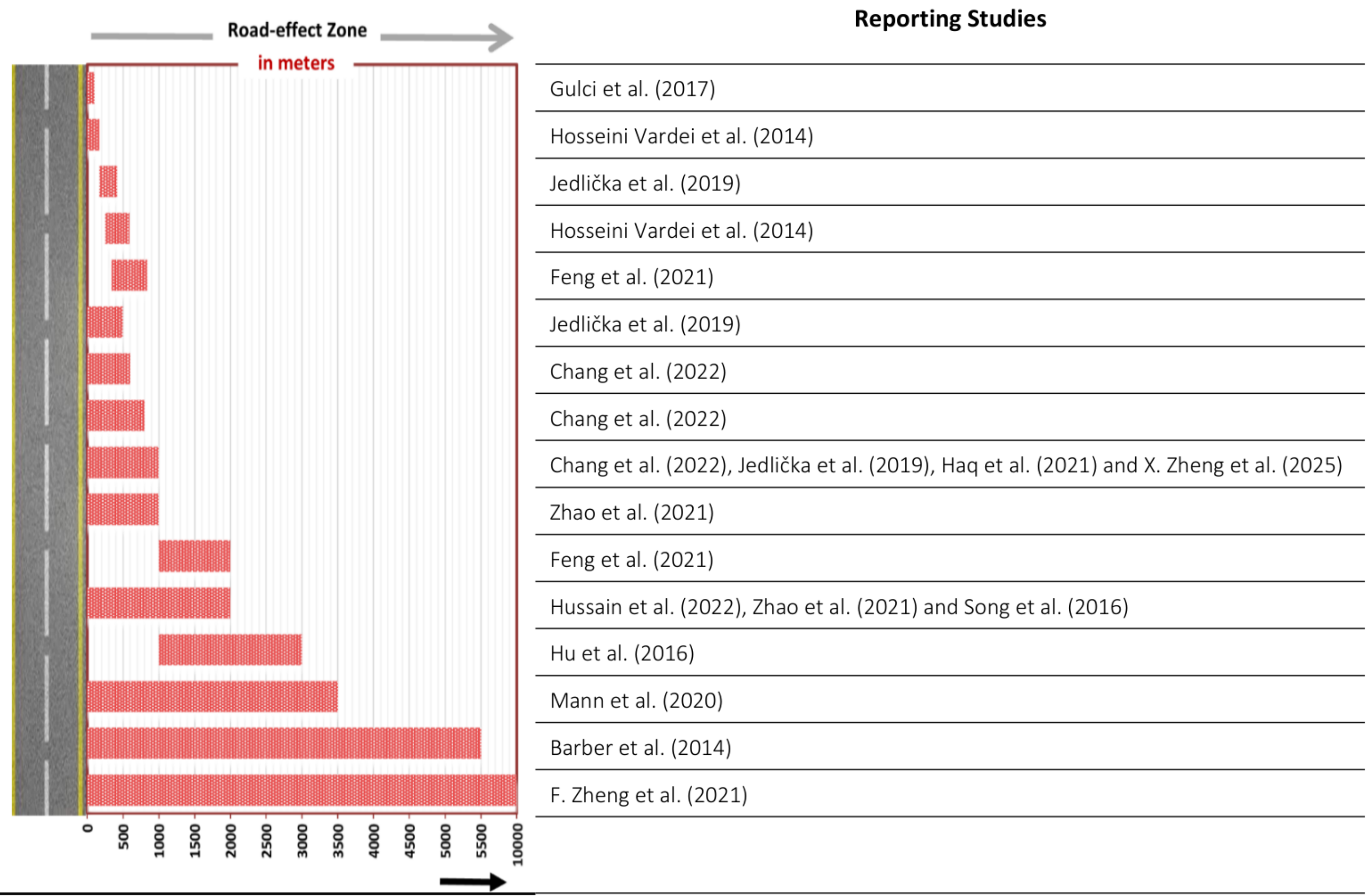

Figure 5. Spatial extent of road-effect zones identified in the reviewed studies (Prepared by the authors)

3.3.1 Development Stage

The development stage is associated with variation in REZ extent across biomes, underscoring the potential role of governance in shaping road impacts. Managed landscapes typically exhibit the most constrained REZs, potentially reflecting stronger governance, more saturated LULC patterns, and ecological management practices. In Mediterranean coniferous forests under active silviculture, degradation was limited to within 100 m, i.e., the smallest REZ noted (Gulci et al., 2017). In stable Central European agricultural landscapes, road influence on intensification peaked within 250–500 m, grassland conversion at 500–1,000 m, and built-up expansion up to 1,000 m (Jedlička et al., 2019). Even in the high-density megacity context of Shanghai, where development pressure is intense, landscape pattern effects were constrained to within 600–1,000 m, varying by road hierarchy (Chang et al., 2022).

Developing and transitional contexts create intermediate REZs, usually 1,000–4,000 m in size, where road construction intersects with expanding land uses amid unstable governance. In Chinese highland forests, LULC change is concentrated within 500 m of roads, with REZ extending to 1,000 m as ecological recovery and construction disturbance compete within the same buffer (Feng et al., 2021). In Chinese expressway networks, construction land actively responded within 2,000 m (Zhao et al., 2021). Similarly, forest cover changes in Chinese urban–rural fringe zones occurred within 1,000–3,000 m (Hu et al., 2016), and land conversion around the Himalayan road corridors was documented up to 3,500 m (Mann et al., 2020), reflecting population growth, agricultural demand, and infrastructure access in sensitive montane areas. These expanding REZs align with the complex, multi-scale road-induced land use changes in transitional economies, where urbanisation, agricultural intensification, and forest fragmentation occur simultaneously.

At the widest gradient end, frontiers create REZs much larger than those in established landscapes, driven by roads that penetrate inaccessible terrain with little regulation. These roads trigger land-use cascades, such as logging and settlement expansion, along transportation corridors, which are absent in regulated areas. For example, in the mountain frontier zones of Pakistan, forest decline occurred within 2,000 m of roads (Hussain et al., 2022), and LULC change extended to 3,000 m as roads enabled progressive smallholder encroachment into highland forests (Haq et al., 2021). In the Amazon, about 95% of forest loss occurred within 5,500 m of roads, with a clear boundary of road influence (Barber et al., 2014). The largest REZ in this review, over 10,000 m, occurred after highway opening in a mountainous border corridor, shifting from frontier to development, with LULC changes as deforestation, agriculture, and settlement spread far beyond usual buffer zones (F. Zheng et al., 2021). In frontier settings, roads not only support land-use pressures but also create them by unlocking new landscapes for agriculture, logging, and settlement.

3.3.2 Road Type

Road type is another key factor, but evidence shows contradictory patterns. Urban routes influence LULC by attracting or excluding commercial, residential, and industrial areas. In Changchun, secondary trunk roads are most closely associated with residential land, whereas branch roads are most closely associated with commercial land (Ma et al., 2018). Expressways and trunk roads promote commercial and residential growth but push industry outward. In Sichuan, expressway corridors undergo industrial transformation from manufacturing to tourism and services, optimising industrial structures (Su et al., 2023). Some studies show that lower-level roads lead to more significant LULC changes; Ullah & Hafiz (2012) found that footpaths affect forest cover in Bangladesh more than metal roads, and Hu et al. (2016) reported that forest conversion near lower-density roads was greater than near expressways. Liang et al. (2014) and Yang et al. (2021) found that county and rural roads were more closely linked to landscape change than expressways. R. Zhang et al. (2013) noted that highways have a greater impact on agricultural and urban expansion than expressways.

Conversely, evidence also suggests that higher-order roads have a greater impact: Hu et al. (2016) and Barber et al. (2014) found that expressways exert greater clearing pressure on tropical forests in Brazil and China, respectively. Mann et al. (2020) found that built-up areas expand mainly along primary roads, expressways, and highways, then along tertiary and secondary roads. Asadi et al. (2016) reported that national roads affect landscape diversity more than provincial roads, and Chang et al. (2022) observed that their impact area exceeds that of highways and provincial roads.

These contradictions resolve when the development stage and spatial context are fixed. In frontier areas, lower-order roads primarily trigger initial land conversion by enabling access to previously inaccessible areas, leading to forest fragmentation, smallholder farming, and informal settlements beyond formal planning. In urban and developed areas, higher-capacity roads focus transformation around planned nodes, driving larger, broader LULC changes through increased demand and investment. Road effects vary and appear to be associated with differences in development stage, infrastructure characteristics, and governance conditions, suggesting limitations to the application of universal buffer guidelines. This highlights the need for context-sensitive REZ frameworks that account for development stage and road type in impact assessment and conservation.

3.4 Role of Governance Capacity in Road–LULC Relationships

Thematic synthesis of the literature identified four functionally distinct governance categories that may influence how road–LULC relationships are expressed across different contexts. Regulatory instruments, i.e., the most widely reported category, operated primarily by constraining and spatially redirecting road-induced development rather than preventing it entirely. Agricultural land protection laws are limited, but have redirected conversion toward unprotected areas in Canada (Aïkous et al., 2023) and China (Che et al., 2023; Song et al., 2016), while zoning designations demonstrably overrode expressway influence on conversion in Nanjing (R. Zhang et al., 2013) and concentrated ecological protection around critical water sources in Beijing (Mo et al., 2017).

Incentive-based instruments demonstrated that positive governance interventions may help mitigate degradation under certain conditions: large-scale payment for ecosystem services programmes in China and Mongolia reversed deterioration driven by road-enabled land-use pressure (Dong et al., 2021; Yu et al., 2011), and afforestation initiatives restored forest cover in the Himalayan road corridors (Nautiyal et al., 2025). Enforcement and compliance mechanisms revealed the consequences of governance failure: deforestation in Amazonian settlements exceeded legal limits by substantial margins due to institutional weakness (Perz et al., 2013), enforcement was systematically absent in remote areas accessible only by informal paths (Ullah & Hafiz, 2012), and more than half of feeder roads in Lao PDR frontier zones were constructed informally and remained unregistered, with formal regulations lagging far behind crop boom-driven road expansion (Castella & Phaipasith, 2021).

Finally, institutional arrangements highlighted the critical but often overlooked role of informal governance systems: the erosion of traditional communal Rafaqyan forest management institutions in Pakistan directly accelerated road-enabled deforestation in the absence of formal institutional substitutes (Hussain et al., 2022), while informal norms and practices in Lao PDR frontier zones outpaced the adaptive capacity of formal institutions (Castella & Phaipasith, 2021).

80% of the studies did not explicitly include governance-related content, indicating a systematic underreporting of institutional variables in the road–LULC literature rather than an absence of governance effects. This limitation hampers cross-study comparisons of governance. Nevertheless, the findings do demonstrate that governance influences road–LULC relationships as a complex, context-dependent factor that can constrain, redirect, or amplify LULC change.

4. Discussion

4.1 Road Infrastructure and LULC Change: Confirming and Extending the Evidence Base

The findings confirm and expand existing evidence on road-driven LULC change. Although the main patterns of agricultural conversion, forest fragmentation, built-up expansion, waterbodies degradation, and grassland loss align with earlier reviews (Allan et al., 2022; Kasraian et al., 2016), this synthesis advances the field by showing these patterns are not uniform; their magnitude, extent, and reversibility appear to vary across contexts characterized by different development stages and governance capacities. It shifts the literature from just describing road impacts to understanding when, where, and why they happen.

Critically, the findings both confirm and challenge prevailing models. The land use–transport feedback cycle (Wegener & Fuerst, 1999), where infrastructure reduces the friction of distance, expands accessibility, and triggers development that generates further demand, is broadly supported across contexts. However, Chinese evidence shows that policy architecture can outweigh the presence of infrastructure: enforced farmland protection laws, ecosystem payment programmes, and afforestation mandates prevented the expected degradation from road expansion. This challenges deterministic interpretations of the feedback cycle and aligns with the finding of Mtweve et al. (2025), which suggests that governance is an important factor associated with environmental outcomes alongside road expansion.

The variation in REZs reveals limitations in standardised buffer guidelines and impact assessments. REZ extent is not just a biophysical property but an emergent result of road hierarchy and development stage. Standardised buffer-distance guidelines, largely derived from developed-country contexts, systematically underestimate road impacts in frontier and transitional settings, where road-effect zones can extend to 5,000–10,000 m — an order of magnitude beyond conventional assessment boundaries.

The divergence between infrastructure paradigms in developed and developing countries is itself a substantive finding. While Chinese infrastructure investment as a share of GDP tripled from 8% in 2002 to 24% in 2016 (Dinlersoz & Fu, 2022), European countries typically invest only 0.8–1.2% of GDP in road networks (International Road Federation, 2021), with focus long shifted from expansion to maintenance and optimisation, i.e., institutionally embedded in the TEN-T framework and the European Green Deal (European Environment Agency, 2024a, 2024b). The frontier-opening, large-scale LULC conversion processes that dominate the Asian literature are structurally absent in European contexts, where road-related landscape change operates through incremental, well-regulated mechanisms. This contrast confirms that road–LULC dynamics cannot be reduced to a single universal trajectory and reinforces the case against direct policy transfer across development contexts.

The dominance of Chinese and broader Asian literature in this review is not merely a geographic artefact but reflects a fundamentally distinct institutional paradigm. State-led development contexts — characterised by centralised planning capacity, coordinated infrastructure programmes, and direct government intervention in land use — generate road–LULC dynamics that differ structurally from those in market-driven, institutionally fragmented settings. This institutional divergence is itself a substantive finding: it confirms that road–LULC relationships are not only context-dependent in ecological and developmental terms, but also in institutional ones. Importantly, the governance analysis in this review draws on institutionally diverse contexts, including Canada, Laos, Pakistan, the Amazon, Spain, Thailand, India, and China, providing cross-contextual evidential grounding that transcends the state-led paradigm. The development stage classification further reinforces this by contextualising findings within developmental rather than purely geographic categories, enabling comparison across institutional settings rather than conflating them.

4.2 Roads, Sustainability, and Spatial Justice

Road infrastructure has a dual, often contradictory, relationship with sustainability. According to UNEP (2022), roads influence 76 SDG targets across all 17 goals, generating approximately 2.4 million jobs globally and increasing GDP by 0.34% annually, thereby supporting SDGs 1, 8, and 9. Yet the same infrastructure drives habitat fragmentation, biodiversity loss, and carbon release estimated at 883 million tonnes from vegetation and soils, threatening SDGs 13, 15, and 6. This tension confirms that accessibility improvements are necessary but insufficient for sustainability, without strong institutional governance, road expansion risks catalysing environmental degradation that undermines long-term resilience.

Beyond its environmental impacts, road expansion reshapes political and economic landscapes, raising urgent questions about the concept of spatial justice advanced by Lefebvre (1968). Infrastructure designed to enhance mobility, accessibility, and connectivity often paradoxically isolates and marginalises disadvantaged populations, particularly rural communities, who bear disproportionate environmental costs while capturing fewer economic benefits. The synthesised evidence indicates that road-induced accessibility improvements generate asymmetric outcomes, disproportionately benefiting economically powerful actors, while marginalising resource-poor communities and smallholder farmers who bear the livelihood costs of road expansion without equitably sharing its gains. This aligns with Younes & Nusrath (2026), who found that in developing countries, road initiatives often mirror development models imported from developed countries without adequate adaptation to local institutional realities, a pattern that risks entrenching rather than mitigating spatial disparities.

4.3 Formalising Road–LULC Relationships: A Conceptual Framework

The synthesised evidence supports a framework that proposes a conceptual structure of road–LULC relationships across diverse geographic and institutional contexts (Figure 6). The framework positions the road network as an independent variable driving LULC change as the dependent variable, with the strength of this relationship mediated and moderated by a structured set of intervening conditions.

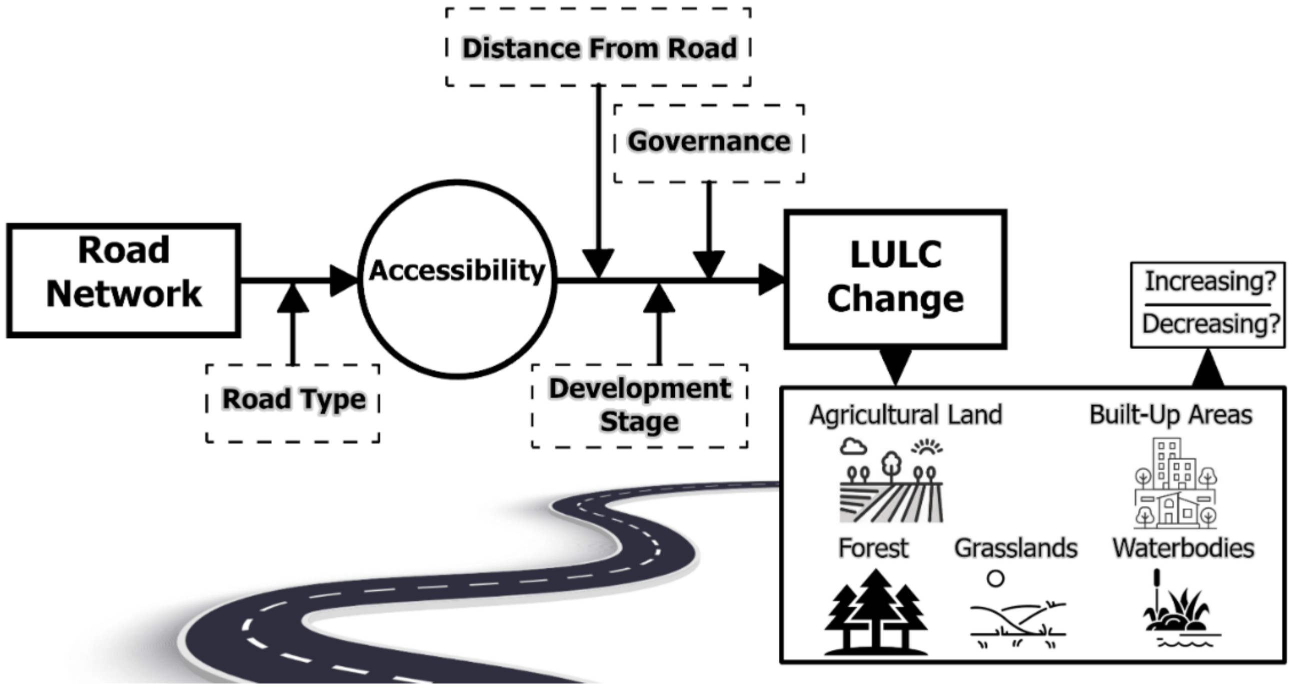

Figure 6. Proposed conceptual framework for understanding Road–LULC Relationship (Prepared by the authors)

https://doi.org/10.48088/ejg.a.you.17.1.231.259

Accessibility functions as the primary mediator — the mechanism through which roads generate LULC change by reducing transport costs, attracting population and economic activity. Road type moderates this mechanism at the road-accessibility junction. In other words, how road hierarchy delineates various levels of accessibility. Distance from the road then moderates the spatial translation of accessibility into LULC change, operationalising the proximity-dependent development-intensity gradients and distance-decay patterns documented in the reviewed literature as road-effect zones.

At the accessibility-LULC change junction, an additional two moderating conditions decisively shape how strongly accessibility improvements translate into LULC transformation. Traditional road–LULC narratives emphasise technical variables while overlooking institutional and socioeconomic conditions, a gap this framework directly addresses by proposing that development stage and governance may influence how road–LULC relationships are expressed across different contexts.

The development stage, i.e., the level of infrastructure and socioeconomic development surrounding the road, determines how effectively accessibility improvements influence LULC change. Frontier contexts consistently amplify road impacts across landscape scales, while established and managed contexts constrain them through saturated land-use patterns and mature planning frameworks. Identical road investments produce dramatically different LULC responses depending on the development stage of the receiving context.

Governance appears to be an important contextual factor in road–LULC relationships. Across the reviewed studies, stronger governance is generally associated with less pronounced land-use responses to accessibility improvements, whereas weaker governance is often associated with greater change, highlighting substantial variation across institutional settings. This framework is inductively derived from diverse literature via thematic synthesis, and its proposed causal relationships lack empirical validation through formal statistical tests. The placement of mediators and moderators is a theoretically informed interpretation of empirical patterns, not a statistically confirmed causal structure.

4.4 Methodological Reflection

PRISMA, originally developed in the health sciences, is increasingly applied in geography and environmental research to synthesise heterogeneous evidence bases. Recent applications in LULC change (Afuye et al., 2024), urban studies (Russo et al., 2026), and RS and GIS (Pradana & Dimyati, 2024), demonstrate its growing relevance. In this review, the PRISMA protocol enabled rigorous screening across a highly heterogeneous literature, varying in geographic scope, methodological approach, and outcome measure, reducing selection bias and facilitating thematic synthesis across contexts that would be difficult to compare without a structured framework.

4.5 Limitations

First, this review searched only Scopus and Google Scholar, potentially missing studies elsewhere. Second, inclusion was limited to peer-reviewed English articles, ensuring methodological rigour but causing language bias. Third, studies on non-road infrastructure, environmental variables without explicit LULC analysis, or lacking a clear road–LULC focus were excluded, which, while necessary for thematic coherence, may limit contextual breadth. Fourth, as with all reviews, publication bias cannot be excluded, since studies showing significant or adverse impacts are more likely to be published than those with null results. Fifth, heterogeneity in spatial scales, methods, and LULC systems across studies prevented a meta-analysis; instead, thematic synthesis was used. Sixth, the predominance of Chinese studies may affect the external validity of findings in regions with different institutional and governance contexts. Practitioners applying these findings to other settings should therefore account for the possibility that governance effectiveness is overestimated and informal land-use dynamics are underestimated where centralised planning capacity is limited. Finally, the proposed conceptual framework is inductively derived from a heterogeneous literature base and has not been empirically validated. Its variables and causal positions are based on convergent patterns across the reviewed studies, and the framework should therefore be understood as a heuristic model that generates testable hypotheses rather than a validated predictive tool.

5. Conclusions

This review sets out to answer: how road networks impact LULC change. The answer is unequivocal: roads do not impact landscapes in fixed or predictable ways. Instead, the outcomes vary substantially across contexts, with development stage and governance capacity emerging as important factors alongside road type.

Across all geographic contexts, road expansion drives consistent patterns of agricultural conversion, forest fragmentation, built-up expansion, waterbodies degradation, and grassland loss, but with magnitudes and spatial extents that vary by orders of magnitude. Road-effect zones range from less than 100 m in well-regulated, established landscapes to over 10,000 m in tropical frontier transitions, a structured gradient that directly challenges the adequacy of uniform buffer-distance guidelines in environmental impact assessment. Where stronger governance capacity is present, roads are not always associated with net environmental degradation. Positive outcomes, including forest recovery, agricultural intensification, and ecological restoration, are achievable, but arise exclusively from deliberate institutional intervention, not from infrastructure design alone.

The principal novelty in this review lies in formalizing these patterns into a conceptual framework endowed with heuristic and interpretive value that delineates mediating mechanisms from moderating conditions. Furthermore, the review suggests that governance is an important contextual factor associated with whether road-related LULC change aligns with intended regional development objectives or is accompanied by more fragmented and unplanned patterns of urban expansion.

The key message for geographers and planners is direct: the context in which a road is built matters as much as the road itself. In frontier and transitional settings, proactive land-use regulation must precede infrastructure construction, not follow it. Sustainable infrastructure requires governance-enabled strategies that integrate land-use planning, environmental enforcement, and spatial controls alongside physical construction. Without this integration, accessibility improvements risk generating long-term environmental costs that far exceed short-term economic gains.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A 1. Contextual characteristics of reviewed studies, including road type and geographic setting

Study	Road Type	Geographic Context
Aïkous et al. (2023)	Highway 30	Suburban, Montreal, Canada
Al-Shaar et al. (2021)	Khaldeh–Beirut Highway	Peri-urban, Beirut, Lebanon
Anwar et al. (2019)	Karakoram Highway	Mountainous Gilgit-Baltistan, Pakistan
Arif et al. (2023)	National Highway 2 and Grand Trunk Road	Peri-urban, Burdwan, India
Arifeen et al. (2021)	Dhaka–Mymensingh Highway and Dhaka Bypass	Peri-urban, Dhaka, Bangladesh
Asadi et al. (2016)	Freeways, highways and main roads	Agricultural, Qazvin, Iran
Ayazli et al. (2015)	Istanbul Third Bridge	Metropolitan, Istanbul, Türkiye
Bairwa et al. (2025)	Mixed	Semi-Arid, Rajasthan, India
Barber et al. (2014)	Highways and unofficial roads	Tropical forest, Amazon, Brazil
Boloor & Nusrath (2015)	Bangalore-Mysore Highway	Urbanising corridor, Karnataka, India
Bose & Chowdhury (2019)	Asian Highway 2 and Siliguri–Jalpaiguri Corridor	Urbanising corridor, West Bengal, India
Castella & Phaipasith (2021)	Rural and feeder roads	Forest frontier, Laos
Chang et al. (2022)	Highways, national & provincial roads	Megacity, Shanghai, China
Che et al. (2023)	Mixed	Urban, Yangtze River Delta, China
Chu et al. (2021)	Hangzhou Bay Bridge	Coastal urban, Hangzhou Bay, China
de Oliveira Barros et al. (2022)	BR-408 Highway	Forest, Pernambuco, Brazil
Deng et al. (2018)	Expressways	Agricultural, Shandong, China
Dong et al. (2021)	Mixed	Mixed forest–grassland–desert, China–Mongolia–Russia

Efthymiou et al. (2016)	Major highway (Attica Tollway)	Metropolitan, Athens, Greece
Eker & Coban (2010)	Rural and public roads	Mediterranean mountainous forest, Türkiye
ElSaied et al. (2021)	Arterial road network	Arid coastal–desert, Egypt
F. Zheng et al. (2021)	Kunming–Bangkok Highway	Mountainous rural, Laos–Thailand cross-border corridor
Feng et al. (2021)	Wujing Highway	Hilly subtropical, Hunan, China
Fiedeń (2019)	A4 motorway	Rural–peri-urban, Poland
Freitas et al. (2010)	Secondary roads	Fragmented Atlantic Forest, São Paulo, Brazil
Funderburg et al. (2010)	Multiple highways	Urban-rural-suburban, California, USA
Gulci et al. (2017)	Single forest road	Mediterranean forest, Kahramanmaraş, Türkiye
Haq et al. (2021)	Mixed road network	Mountainous, Kohistan, Pakistan
Hasan et al. (2017)	Dhaka–Aricha Highway	Peri-urban, Dhaka, Bangladesh
Hosseini Vardei et al. (2014)	Mixed road network	Forest–agricultural, Golestan, Iran
Hu et al. (2016)	Mixed	Forested, Fujian, China
Hussain et al. (2022)	Thall–Parachinar Road and village roads	Mountainous, Kurram, Pakistan
Jedlička et al. (2019)	Mixed road network	Agricultural, semi-rural, Hodonín, Czech Republic
Jia et al. (2020)	Zhadao Highway	High-altitude, fragile ecosystem, Qinghai–Tibet Plateau, China
Kannan et al. (2020)	Multiple highway corridors	Peri-urban, Bangalore, India
Kara & Keçeli (2017)	Mixed	Metropolitan, Istanbul, Türkiye
Khrisrachmansyah et al. (2025)	Mixed	Urban watershed, Jakarta, Indonesia
Klarenberg et al. (2018)	Inter-Oceanic Highway	Tri-national Amazon frontier, Peru-Brazil-Bolivia
Li et al. (2022)	Qumei–Gangba Highway	High-altitude Tibetan Plateau, China
Liang et al. (2014)	Mixed	Three Parallel Rivers region, Yunnan, China
Lu et al. (2022)	Mixed	Provincial-level, China
Ma et al. (2018)	Mixed	Urban, Changchun, China
Mann et al. (2020)	Mixed	Mountainous, Uttarakhand, India
Mansuroglu et al. (2013)	Antalya–Alanya Highway	Agriculture–tourism coastal, Antalya, Türkiye
Mhana et al. (2023)	Mixed	Metropolitan, Kuala Lumpur, Malaysia and Madrid, Spain
Mo et al. (2017)	Mixed	Urban, Beijing, China
Mothorpe et al. (2013)	Interstate highways	Urban–rural, Georgia, USA
Müller et al. (2010)	Motorways A1, A2 and A13	National-scale, Switzerland
Nath et al. (2021)	National Highway 37	Urban, Guwahati, India
Nautiyal et al. (2025)	Mixed	Himalayan hill region, Uttarakhand, India
Obregón-Biosca & Junyent-Comas (2011)	C-25 Eix Transversal	Multi-municipality corridor, Catalonia, Spain
Patarasuk & Binford (2012)	Provincial road network	Agricultural, Lop Buri, Thailand
Perz et al. (2013)	Inter-Oceanic Highway and regional roads	Tri-national Amazon frontier, Peru-Brazil-Bolivia
Pokhariya et al. (2021)	NH 9 and NH 309	Urban-agricultural-forest, Uttarakhand, India
Prakash & Jegankumar (2020)	Multiple national highways	Metropolitan, Tiruchirappalli, India
R. Zhang et al. (2013)	Expressways and highways	Urban–rural fringe, Nanjing, China
Ramachandra et al. (2019)	Mixed highway corridors	Ecologically fragile forest, Western Ghats, India
Ramachandraiah (2014)	Hyderabad Outer Ring Road	Peri-urban, Hyderabad, India
Ramos et al. (2018)	Mixed	Peri-urban Amazon, Manaus, Brazil
Rawat et al. (2013)	National Highway 121	Central Himalayan foothills, Uttarakhand, India
Ryngnga & Lynrah (2017)	Shillong Bypass (NH 40)	Hill region, Meghalaya, India
S. Liu et al. (2014)	Mixed	Lancang River Valley, Yunnan, China
S. Zhang et al. (2020)	Mixed	Urban industrial, Changchun, China
Sen & Kumar (2017)	Mixed national and state highways	Agricultural, Gaya, Bihar, India

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Shahtahmassebi et al. (2018)	Hangzhou Bay Bridge and connected highways	Coastal, Zhejiang, China
Singh et al. (2024)	Mixed	Fragile mountainous, Manipur, India
Song et al. (2016)	Mixed	Urban-agricultural, Zhejiang, China
Su et al. (2023)	Expressways	Rugged terrain, Sichuan, China
Ullah & Hafiz (2012)	Metal roads and Footpaths	Coastal reserved forest, Teknaf, Bangladesh
Vijay et al. (2017)	National Highway 7	Waterbodies, Kanyakumari and Tirunelveli, Tamil Nadu, India
X. Zheng et al. (2025)	Mixed	Pan-tropical, Latin America-Africa-Southeast Asia
Y. Liu et al. (2019)	Mixed	Urban, Pearl River Delta, China
Yadav et al. (2012)	Mixed national and state highways	Protected forest corridor, Maharashtra, India
Yang et al. (2021)	Mixed	Urban, Pearl River Delta, China
Younes et al. (2023)	Mixed road network	Coastal, agricultural, Tartous, Syria
Yu et al. (2011)	China National Highway 106	201 Metropolitan–agricultural–mountainous, Beijing–Hebei–Henan, China
Zebardast et al. (2011)	Highway crossing Golestan National Park	Protected forest, Golestan, Iran
Zeng et al. (2020)	Mixed	Urban, Beijing–Tianjin–Hebei, China
Zhao et al. (2021)	Expressways	Mountainous forest, Fujian, China

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