frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 12 February 2026
DOI 10.3389/fsufs.2026.1766589

OPEN ACCESS

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RECEIVED 12 December 2025
REVISED 22 January 2026
ACCEPTED 26 January 2026
PUBLISHED 12 February 2026

CITATION
Zhang L, Li X and Wei M (2026) Does transportation accessibility achieve sustainable forestry? Assess the impact of highway construction on rural forest resources.
Front. Sustain. Food Syst. 10:1766589.
doi: 10.3389/fsufs.2026.1766589

Does transportation accessibility achieve sustainable forestry? Assess the impact of highway construction on rural forest resources

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Introduction: Enhancing transportation accessibility is often viewed as a catalyst for rural revitalization, yet its compatibility with sustainable forestry remains a critical challenge. This study examines the impact of highway construction on rural forest resources in China's underdeveloped regions.

Methods: Using town-level transportation and forestry data from 2009 to 2019, we exploit spatial variation in highway openings and implement a difference-in-differences (DID) framework. To address endogeneity concerns, we further employ an instrumental variable (IV) strategy based on hypothetical least-cost path spanning tree networks. Dynamic specifications and multiple validity checks are used to ensure causal interpretation.

Results: We find a significant negative spatial spillover effect of highway openings. Specifically, highways built in neighboring townships substantially reduce forest cover in townships that lack direct highway access, whereas the construction of non-highway roads has no statistically discernible effect. This adverse impact is transient and gradually attenuates over time. Mechanism analyses grounded in a core–periphery framework show that highways lower transportation costs and accelerate the outflow of timber and ecological capital from peripheral rural areas to central markets. Heterogeneity analyses indicate that forest loss is most pronounced near highway exits, in commercially valuable broadleaf forests, and in regions dominated by timber extraction and tourism but lacking institutional protection. Ecologically, highway-induced deforestation significantly increases greenhouse gas emissions by weakening carbon sinks, while effects on vehicle exhaust pollutants are negligible.

Discussion: Our findings highlight a trade-off between infrastructure-led connectivity and ecological sustainability. Achieving rural revitalization without exacerbating environmental degradation requires differentiated infrastructure investment and stronger ecological governance, particularly in peripheral rural areas vulnerable to market-driven deforestation.

KEYWORDS
deforestation, rural ecosystem services, rural sustainable development, spatial spillovers, transportation infrastructure

1 Introduction

Enhancing transportation accessibility is widely recognized as a catalyst for rural revitalization and poverty alleviation globally. By reducing spatial transaction costs and improving the mobility of agricultural goods and personnel, infrastructure networks facilitate the integration of rural hinterlands into national markets, thereby enhancing resource allocation efficiency (Faber, 2014). Yet, as infrastructure networks expand into deep rural areas, concerns have mounted over their compatibility with sustainable land use, particularly in ecologically sensitive zones. Whether infrastructure-led development promotes rural prosperity at the expense of natural ecosystems has become a central question for researchers and policymakers aiming to balance livelihood improvement with ecological security.

Existing studies indicate that investments in transport infrastructure significantly improve market access and trade flows (Banerjee et al., 2020; Wu et al., 2023; Morten and Oliveira, 2024). Theoretically, these improvements could yield positive environmental externalities in China's specific context. Lower transport costs may facilitate outbound labor migration to urban manufacturing centers, reducing the labor supply for agricultural expansion and thereby alleviating pressure on forests, which is a phenomenon consistent with the "forest transition" hypothesis. Furthermore, China has implemented rigorous institutional safeguards, such as strict land-use regulations and the "Ecological Redline" policy, explicitly designed to limit deforestation. However, these potential benefits face a powerful counterforce. In the absence of effective enforcement, road expansion can induce irreversible impacts on local ecosystems. Forests are not merely timber resources, but they are vital components of the rural life-support system (Jayachandran et al., 2017). Nevertheless, if the market incentives for extraction outweigh the forces of labor migration and policy constraints, the unchecked spread of transportation networks may lead to forest fragmentation and ecological capital depletion (Garg, 2019; Asher et al., 2020).

This fundamental tension between connectivity, institutional constraints, and conservation motivates our core inquiry. While improved accessibility stimulates economic activity and theoretically encourages non-agricultural employment, it inherently alters the comparative advantage of peripheral regions. Specifically, by lowering the cost of extracting and shipping natural resources from the periphery to core markets, highways may primarily facilitate the outward shipment of timber and ecological capital. Consequently, underdeveloped rural areas risk incurring disproportionate environmental losses while capturing only limited long-run gains. This concern is particularly relevant in less developed regions, where abundant forest endowments combined with local industrial constraints make natural resource extraction a comparatively attractive, yet ecologically destructive, response to improved market access, potentially overpowering existing regulatory barriers.

China offers a distinct setting to investigate this trade-off due to the sheer speed of its infrastructure expansion. Since 2009, the government has aggressively extended the national highway network into underdeveloped hinterlands. This rapid expansion creates a clear shock to local ecosystems, contrasting sharply with the gradual infrastructure evolution observed in developed economies. A critical geographical overlap further distinguishes the Chinese context. Although China accounts for 25% of the global net growth in forest area (FAO, 2022), our data indicate that 65% of domestic forest resources are concentrated in the exact underdeveloped regions targeted for highway construction. Consequently, these areas face a direct collision between intensive engineering projects and ecological conservation. This makes China a critical case for examining whether rural economic integration inevitably compromises the ecosystem services essential for long-term resilience.

Accordingly, our analysis focuses exclusively on underdeveloped regions. Following Chu et al. (2024), we classify cities by per capita disposable income in the base year 2009 and define the bottom half as underdeveloped. We restrict the sample to townships located in these underdeveloped cities and study highway construction from 2009 to 2019, merged with high-resolution 30-m forest cover data. Within this underdeveloped sample, we document a significant negative spatial spillover. Highway openings in neighboring townships reduce forest cover in local townships that lack direct highway access, indicating that connectivity improvements can shift extraction incentives and land use even beyond the treated locations. Dynamic analyses further reveal the temporal heterogeneity of this impact: the negative shock is transient, manifesting as a sharp extraction effect in the short run that gradually attenuates over the long term.

To validate the causal interpretation of these findings, we implement a rigorous identification strategy. First, to mitigate endogeneity concerns arising from non-random route planning, we construct an instrumental variable (IV) based on the cost-minimizing Minimum Spanning Tree (MST) network. Second, we subject our baseline estimates to a series of robustness checks. We employ the interaction-weighted estimator to rule out potential biases from staggered treatment timing and conduct sensitivity analyses using the Rambachan and Roth (2023) framework to ensure that our conclusions are not driven by pre-trend violations. Furthermore, our results remain consistent when utilizing alternative control groups, such as third-order neighbors and non-treated townships within the same county, and after controlling for confounding factors related to agricultural productivity.

Mechanism evidence, guided by a core periphery framework, suggests that lower transport costs strengthen the pull of central markets and accelerate market driven exploitation, facilitating the flow of timber and ecological capital out of peripheral rural areas. In contrast, non-highway road construction does not generate statistically meaningful forest loss, implying that not all connectivity improvements entail the same environmental costs. Consistent with an extraction and shipment channel, the effects are stronger in townships closer to highway toll gates and in broadleaf forest areas with higher commercial value.

This paper makes three contributions to the literature on roads and forest cover, particularly the strand emphasizing that transport infrastructure can generate sizable but heterogeneous ecological externalities (Busch and Ferretti-Gallon, 2017; Pfaff et al., 2018; Kaczan, 2020). First, we contribute causal evidence on how market access affects forest outcomes in lagging regions, where the development–conservation trade-off is typically most binding. Existing work for China has largely documented correlations between road density or proximity and forest loss (Hu et al., 2016; Zhao et al., 2020), while broader evidence highlights that road impacts depend on institutions and development levels (Kaczan, 2020). We advance this literature by focusing exclusively on underdeveloped regions and implementing a buffer-zone difference-in-differences design to identify spillover deforestation in townships that do not receive direct highway access, consistent with the idea that market integration can reallocate extraction incentives along a core–periphery gradient.

Second, we contribute improved measurement and identification for forest dynamics at a fine spatial scale. A large literature emphasizes that forest cover change responds to multiple confounding forces, including policies, economic development, and agricultural transitions (Deng et al., 2011; Heß et al., 2021; Li and Zhu, 2023). To isolate the role of transport infrastructure, we combine the newly released 30-m China

Annual Tree Cover Dataset with an instrumental-variable strategy based on hypothetical least-cost path spanning-tree networks, providing a framework designed to address the non-random placement of highways.

Third, we contribute policy-relevant evidence on heterogeneity by road hierarchy. Prior studies show that highways and lower-grade roads can have fundamentally different ecological consequences (Hu et al., 2016; Asher et al., 2020), yet evidence remains limited on whether these differences persist once one credibly accounts for selection and spatial spillovers. By explicitly separating highways from non-highway roads within the same empirical framework, we show that forest loss is driven by highways rather than by local road upgrades, reinforcing the case for differentiated infrastructure strategies when pursuing rural revitalization alongside ecological sustainability.

2 Literature review

2.1 Determinants of forest cover change

Forest cover serves as a vital measure of ecological sustainability and has long been a focus of research in environmental economics, geography, and ecology. Forests deliver key ecosystem services that underpin both ecological integrity and human well-being, including soil and water conservation, carbon sequestration, and biodiversity preservation. Simultaneously, they support economic activities through the supply of timber and non-timber forest products. Identifying the drivers of forest cover change is thus essential for designing effective conservation strategies and land-use policies. Existing studies have established that forest dynamics are influenced by a complex set of factors, including natural environmental conditions, demographic trends, institutional arrangements, economic development, agricultural productivity, and infrastructure expansion.

Natural conditions constitute the ecological basis for forest distribution, with topographic and climatic factors systematically influencing land-use returns and, consequently, forest cover outcomes. Areas characterized by steep slopes or high elevation tend to exhibit higher forest persistence, largely due to the elevated costs of agricultural conversion and construction in such settings. In contrast, sun-facing slopes experience greater human pressure, reflecting rational land-use responses to differential productivity and accessibility (Zhao et al., 2020). Climatic variables, particularly precipitation and temperature, further shape forest patterns through their effects on ecological productivity. While increased rainfall generally supports forest growth and economic returns to forest retention, warming in arid regions can induce water stress, lowering regeneration potential and reducing the viability of forest-based land uses (Gong et al., 2020).

Demographic and socioeconomic factors shape forest cover through multiple mechanisms rooted in resource demand, land-use decisions, and technological change. Increased population density raises demand for fuelwood, agricultural land, and built-up areas, often leading to forest clearance and land conversion (Carr et al., 2005). Conversely, urbanization concentrates populations in cities, raising the opportunity cost of rural labor and inducing agricultural land abandonment, which can facilitate forest regeneration in peripheral regions. Technological progress and improved agricultural efficiency may further alleviate pressure on forests by raising crop yields and reducing the need for land expansion. These dynamics resonate with the Environmental Kuznets Curve (EKC) hypothesis, which suggests that environmental degradation tends to increase during early development stages but may decline as economies grow and preferences shift toward environmental quality.

Policy and institutional settings play a decisive role in mediating forest outcomes by altering incentives for conservation and exploitation. China's Grain for Green Program, initiated in 1999, has become a benchmark large-scale reforestation policy, significantly increasing forest cover in participating regions, especially the rural West (Deng et al., 2011). Other major initiatives, such as the Three-North Shelterbelt Program and the Natural Forest Protection Project, have expanded institutional and financial support for afforestation and sustainable management (Gao and Huang, 2020). Accompanying tenure reforms and ecological redlining policies have strengthened property rights over forest resources and improved local governance. Meanwhile, forest certification, payments for ecosystem services, and public welfare forest programs have helped align economic incentives with ecological objectives (Durst et al., 2006; Li et al., 2018).

Agricultural productivity exerts an ambiguous influence on forest dynamics through competing economic channels. On one hand, total factor productivity (TFP) growth in agriculture can generate land-sparing effects by enabling output growth without extensive land conversion, thereby mitigating deforestation pressure. As demonstrated by Li and Zhu (2023), efficiency gains in agricultural production reduce dependence on chemical inputs and associated ecological damage. On the other hand, enhanced agricultural profitability may create expansionary incentives, particularly where property rights are ill-defined or environmental regulation is weakly enforced, leading to encroachment into forest margins (Heß et al., 2021). Zhang et al. (2025) quantify this trade-off, estimating that a 1% increase in agricultural TFP in China correlates with a 0.012% reduction in forest cover, suggesting that under certain institutional conditions, technological progress may induce frontier expansion rather than conservation.

Economic development and land-use transitions further mediate forest outcomes through structural transformation. During early industrialization phases, rising demand for timber and urban land typically accelerates forest resource depletion (Zhang et al., 2017). However, as economies undergo structural change, increased environmental investment and shifting social preferences often facilitate forest recovery, which is consistent with the Environmental Kuznets Curve framework. Transportation infrastructure plays a particularly significant role in this process: Hu et al. (2016) identified a strong correlation between highway density and forest loss in Fujian, whereas lower-grade roads exhibited minimal impact. Complementing this, Zhao et al. (2020) documented sharply elevated forest loss within 20 km of major roads, revealing spatially delimited ecological externalities from transport networks.

In summary, forest cover dynamics emerge from complex interactions among environmental constraints, demographic pressures, institutional arrangements, and eco-nomic incentives, with their relative importance exhibiting substantial heterogeneity across temporal and spatial contexts.

2.2 The ecological impact of road construction on forest cover

The global proliferation of road infrastructure in recent decades has raised significant ecological concerns among economists and environmental scientists. Projections indicate that by 2050, the world's road network will expand by approximately 25 million kilometres (an increase of nearly 60% compared to 2010 levels), with over 90% of this growth occurring in developing nations (Laurance et al., 2014). Much of this development overlaps biologically critical zones, including tropical forests that serve as vital global reservoirs of biodiversity and carbon (Barrett et al., 2016). This spatial convergence underscores a fundamental tension in development policy: balancing the economic benefits of improved transport access against the preservation of ecologically significant forest systems.

From an economic standpoint, road development enhances factor mobility, reduces transaction costs, and improves market integration, contributing positively to regional growth and productivity. Yet these gains are often accompanied by considerable environmental externalities. Empirical studies reflect a dualistic impact: transportation infrastructure can either intensify or mitigate forest loss depending on mediating factors such as institutional quality, market structure, and the stringency of land-use regulations (Deng et al., 2011; Asher et al., 2020; Kaczan, 2020).

On the negative side, road construction is widely identified as a major proximate driver of deforestation. By improving market access and raising agricultural profitability, roads encourage the expansion of farmland into forested areas (Chomitz and Gray, 1996; Busch and Ferretti-Gallon, 2017). This effect is especially pronounced in remote, resource-rich regions where improved accessibility triggers agricultural frontier expansion (Kaczan, 2020). Roads also promote in-migration and settlement in forest regions, amplifying deforestation pressure. Cross-country studies across the Amazon, Southeast Asia, and Central Africa confirm that road development accelerates land conversion and forest loss (Cropper et al., 2001; Deininger and Minten, 2002; Rudel et al., 2009; Pfaff et al., 2018).

Roads also contribute to indirect ecological degradation through land-use conversion and forest fragmentation. Increased accessibility raises land values and investment intensity, encouraging conversion of forest land to construction land (Chomitz and Gray, 1996). Moreover, the physical presence of roads fragments contiguous forest areas, disrupting habitat connectivity and biodiversity (Laurance et al., 2014). In China, Zhao et al. (2020) found that forest loss is most pronounced within 20 km of highways, largely due to improved access for illegal logging and the disruption of ecological corridors.

On the positive side, under strong governance and well-functioning markets, road development can facilitate forest protection through the "Forest Transition" pathway. Improved transportation enhances the profitability of sustainable forestry and plantation management (Foster and Rosenzweig, 2003). Crucially, by lowering migration costs, roads enable rural labor to shift toward non-agricultural sectors in urban centers. This structural transformation reduces the labor supply for agricultural expansion and alleviates pressure on forest margins (Singh et al., 2017). Furthermore, better road connectivity can reduce the cost of alternative energy sources, decreasing household dependence on fuelwood and alleviating pressure on forest ecosystems (DeFries and Pandey, 2010; Aggarwal, 2018).

The impact of road construction on forest cover exhibits substantial regional heterogeneity. In economically advanced regions with well-developed agricultural sectors, road improvements may paradoxically contribute to forest recovery through various economic mechanisms. In contrast, in remote, economically marginalized areas characterized by weaker governance capacity, road infrastructure often accelerates forest degradation and resource over-exploitation. Kaczan (2020) empirical study in India demonstrates these pronounced regional disparities in road impacts, while.

Moreover, the ecological consequences vary significantly across different road hierarchies. National highways and local rural roads differ fundamentally in their transport functions, economic spillover effects, and induced land-use changes. Hu et al. (2016), analyzing data from Fujian province, China (2000–2012), found that while overall road density showed no significant relationship with forest benefits, highways density specifically correlated positively with forest loss. Similarly, Asher et al. (2020), using microdata from India, demonstrated that new rural roads had negligible impacts on forest cover, whereas highway expansion significantly exacerbated forest loss, possibly due to increased timber demand during construction. This heterogeneity underscores the necessity of adopting a differentiated analytical framework that distinguishes between road types in environmental impact assessments.

In summary, road infrastructure manifests a dual character in forest cover dynamics, with outcomes determined by an interplay of regional development levels, institutional arrangements, resource management regimes, and complementary socioeconomic policies. In lagging regions, roads typically exacerbate forest degradation by accelerating agricultural frontier expansion, promoting resource extraction, and inducing migration into forested areas. Conversely, in regions with stronger governance and developed market institutions, road improvements can enhance forestry returns, facilitate labor transition to non-farm sectors, and promote energy substitution, which collectively alleviating pressure on forests and potentially enabling their sustainable management and restoration.

3 Data and research design

3.1 Data

Our study draws on multiple data sources to examine the ecological impacts and underlying mechanisms of highway construction in China's underdeveloped regions from 2009 to 2019. The start date of 2009 corresponds to the initiation of China's aggressive infrastructure investment strategy in less developed regions. The endpoint is set at 2019 to exclude the exogenous systemic shocks caused by the COVID-19 pandemic. The subsequent nationwide lockdowns and supply chain disruptions in 2020 would severely confound the identification of market-driven mechanisms, particularly the mobility of goods and personnel, which are central to our analysis.

3.1.1 Road network

Road Vector Data Road vector data were sourced from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC). Although the raw dataset covers multiple years (1995, 2012, 2016, and 2018) and categories (including highways, national, provincial, county, and township roads), it does not provide the continuous annual series required for our analysis. To ensure accuracy and temporal continuity, we used the 2018 road vector map as the baseline and performed manual year-by-year backcasting. This process involved digitizing changes by referencing authoritative annual atlases, such as the China Highways and Rural–Urban Road Network Atlas, following the methodology of Faber (2014) and

Baum-Snow et al. (2020). This process resulted in a vector dataset of the road network distribution for each respective year.

In constructing the specific variable for "Non-Highway Roads," we restricted our scope to National Roads and Provincial Roads, explicitly excluding county and township roads. This exclusion was necessary for two reasons: (1) data consistency: historical records for lower-tier roads in underdeveloped regions often suffer from poor quality and inconsistent updates, making them unreliable for long-term panel analysis; and (2) functional distinction: unlike National and Provincial roads which act as regional connectors, county and township roads primarily serve as local feeders with limited impact on inter-regional market access. Consequently, the final constructed database integrates precise annual spatial data for Highways, Highway Toll Stations, and Non-Highway Roads.

3.1.2 Forest cover

This study employs China's Annual Tree Cover Dataset (CATCD), developed by Cai et al. (2024), as its primary measure of forest cover. As China's first annual tree cover dataset combining high temporal frequency with 30-m spatial resolution, CATCD provides continuous coverage from 1985 to 2023. The dataset is constructed using long-term time-series remote imagery from the Landsat satellite program and integrates a random forest algorithm with multi-source geospatial data to generate raster layers with values from 0 to 100, representing the percentage of tree cover within each grid cell.

To enhance measurement accuracy and robustness, CATCD incorporates multiple auxiliary data sources. These include atmospherically corrected Landsat surface reflectance data from the Google Earth Engine platform, a 30-m resolution Digital Elevation Model (DEM) from NASA for topographic correction, global surface water data from the Joint Research Centre (JRC) for improved wetland forest identification, and cropland distribution data from China's Ministry of Agriculture and Rural Affairs to better distinguish vegetation types in agro-forestry transition zones. These methodological refinements significantly improve classification precision across complex land cover conditions, establishing CATCD as the most comprehensive, spatially consistent, and highest-resolution annual tree cover dataset currently available for China.

For robustness checks, this study additionally utilizes the global annual forest cover dataset employed by Asher et al. (2020). Derived from reprocessed 250-m resolution MODIS seasonal imagery, this dataset provides a globally consistent tree cover series suitable for cross-regional comparative analysis.

Compared to traditional vegetation indices such as the Normalized Difference Vegetation Index (NDVI), forest cover data can more effectively distinguish tree-covered forests from other vegetation types (e.g., plantations or shrubs), thereby more accurately capturing true forest dynamics (Foster and Rosenzweig, 2003; Asher et al., 2020).

3.1.3 Company registration information

In the mechanism analysis, this study examines how highways reshape resource allocation efficiency across regions, with a particular focus on their effect in stimulating demand growth in the timber industry within economically developed areas. To this end, we use the number of new firm entries in timber demand-related industries at the township level as the dependent variable in our empirical test.

The firm registration data used in this study are sourced from the business registration database of the State Administration for Market Regulation (SAIC). This database covers information on all newly registered enterprises across China, which includes information such as firm establishment date, registered address, industry classification, business scope, registered capital, and geographic coordinates. Using firms' latitude and longitude information, we accurately match each firm to its corresponding township and aggregate the data to obtain the annual number of newly registered firms in each township from 2009 to 2019. To construct township-level firm stock data, we merged records of firm de-registrations and revocations with the main firm registration database, creating a comprehensive firm stock series that accounts for all firms deregistered between 1949 and 2019. Furthermore, individual businesses were excluded from the database.

Following Bu and Liao (2022), which commonly uses the number of registered firms, standardized registration counts, or the new firm entry rate to measure regional firm entry levels. This study adopts the entry rate of new firm entries in timber-related industries at the township level as a proxy for entrepreneurial dynamism.

3.2 Methodology

The empirical design adopts a "buffer-zone" DID design to address the endogeneity of road placement by separating the direct ecological disturbances of highway construction from the economic effects of improved market accessibility. Regions directly traversed by highways often experience significant ecological disturbances during construction, such as soil erosion, land degradation, and vegetation loss resulting from large-scale works (Han et al., 2018), making it difficult to accurately identify the pure effects of market accessibility.

Therefore, we adopt a spatial difference-in-differences design to disentangle the economic mechanism from construction disturbances. We define the treatment group as the immediate neighbors (first-order adjacency) of highway-hosting towns, while explicitly excluding the hosting towns themselves. This exclusion is vital because the deforestation in directly traversed zones likely reflects a mix of land conversion and resource extraction, whereas our focus is solely on the latter. Correspondingly, the control group consists of second-order neighboring townships. This design ensures comparability in geographic characteristics while strictly isolating the spillover effects of improved market access.

More specifically, we specify the baseline model (Equation 1) as follows:

$$\begin{aligned} ForestCover_{i,t} &= \alpha_0 + \alpha_1 Nbr\_hw_{i,t} + \alpha_2 X_{i,t} + \alpha_3 D_{i,j,t} \\ &+ \alpha_4 C_{i,c,t} + \left[Sf\left(t\right)\right]' \theta + \mu_i + \upsilon_{p,t} + \varepsilon_{i,t} \end{aligned} \tag{1}$$

The dependent variable, $Forest\ Cover_{i,t}$ represents forest cover for township i at year t. The key explanatory variable, $\mathrm{Nbr\_hw}\{i,t\}$ is a dummy variable that takes the value of 1 if a new highway has opened in a first-order neighboring township of township i by year t, and 0 otherwise.

$X_{i,t}$ represents township-level control variables relevant to forest cover, including connectivity to non-highway roads, railways, and high-speed rail, distance to the nearest highway, the number of township enterprises, forestry land area, and meteorological factors such as annual mean temperature, sunshine duration, precipitation, and humidity (Zhang et al., 2017). We include county-level economic characteristics $(D_{i,j,t})$ such as population, night-time lights, and carbon emissions, along with city-level controls for built-up green space ($C_{i,c,t}$). To account for the influence of non-time-varying economic and geographical factors on the estimation, we include interactions ($Sf(t)$) between township-level characteristics (elevation, night-time lights, and distance to the nearest urban center) and a linear time trend t. Here, μ_i and $\upsilon_{p,t}$ denotes the township-level fixed effects and the province-by-year fixed effects, respectively. $\varepsilon_{i,t}$ the error term, and standard errors are clustered at the city level.

3.3 Summary statistics

Table 1 presents the summary statistics for the key variables used in this study, covering a total of 84,508 observations. The dependent variable, *Forest Cover*, has a mean value of 32.28% with a standard deviation of 27.07%. The values range widely from 0.35 to 84.04%, indicating significant variation in forest resources across the sampled underdeveloped regions. Regarding the core independent variables, the mean of highway presence (*Nbr_hw*) is 0.426, suggesting that approximately 42.6% of the observations in our sample have highway access. In contrast, High-Speed Rail (*HSR*) is relatively scarce in these regions, with a mean of only 0.031. The control variables encompass a comprehensive set of town, city, and county-level characteristics. Notably, climatic factors (temperature, humidity, precipitation) and socio-economic indicators (population, night time light, number of firms) also exhibit varying degrees of heterogeneity, which are controlled for in our empirical model to isolate the net effect of infrastructure construction.

4 Empirical results

4.1 Baseline results

Table 2 presents the baseline estimates of the impact of road construction on forest cover in underdeveloped regions. Columns (1) through (3) progressively introduce county- and city-level controls, as well as interactions between township characteristics and time trends, to absorb potential confounding factors. Across all specifications, the coefficient for highway construction remains consistently negative and statistically significant, confirming that highway expansion in neighbor townships significantly exacerbates forest loss in these local rural townships. To further validate measurement accuracy, column (4) replicates the analysis using the 250-m resolution global forest cover dataset from Asher et al. (2020), yielding results consistent with our primary findings.

Crucially, column (5) serves as a falsification test by examining the impact of non-highway roads. Unlike highways, non-highway road construction shows no statistically discernible negative effect on forest cover. This comparison is motivated by the need to distinguish the ecological externalities of high-speed market integration from general rural connectivity. The null result for non-highway roads suggests that the observed deforestation is not merely a consequence of physical road paving, but rather driven by the specific economic mechanism of highways. Namely, the reduction in transportation costs that facilitates large-scale resource extraction from rural peripheries. To further verify this, we decomposed the non-highway measure into National Roads and Provincial Roads. As reported in Appendix Table A1, neither category shows a significant negative impact on forest cover, reinforcing the conclusion that the environmental shock is unique to the high-speed expressway network.

Finally, a supplemental analysis of directly traversed townships yields a significantly larger coefficient of −0.5633 Appendix Table A2, likely reflecting the combined impact of construction damage and resource extraction. This result justifies our baseline exclusion of highway-hosting towns, confirming that our design successfully filters out physical engineering noise to strictly isolate the economic spillover effects of market access.

TABLE 1 Summary statistics.

Variable type	Variable	No. of observations	Mean	SD	Min	Max
Dependent variable	Forest cover	84,508	32.276	27.074	0.349	84.043
Independent variables	Nbr_hw	84,508	0.426	0.494	0	1
	Nbr_Road	84,508	0.293	0.455	0	1
Town level control variables	Non-highway road	84,508	0.534	0.499	0	1
	Railway	84,508	0.182	0.386	0	1
	HSR	84,508	0.031	0.172	0	1
	Distance to highway	84,508	2.751	0.744	0.191	5.744
	No. of firms	84,508	4.324	1.402	0	9.716
	Forestry land area	84,508	2.521	1.842	0	4.595
	Temperature	84,508	13.985	4.897	−2.195	23.332
	Humidity	84,508	8.858	0.153	8.059	9.074
	Sunshine duration	84,508	7.501	0.280	6.610	8.164
	Precipitation	84,508	6.783	0.536	4.256	7.674
City level control variables	Green space	84,508	7.784	0.824	3.219	10.373
County level control variables	Carbon emissions	84,508	14.190	0.982	11.423	19.358
	Population	84,508	12.060	1.128	4.920	14.250
	Nighttime light	84,508	2.784	4.116	0.008	53.569

TABLE 2 Baseline results.

Variables	Forest cover				
Road type	Highways				Non-highway roads
Grid resolution	30 m	30 m	30 m	250 m	30 m
	(1)	(2)	(3)	(4)	(5)
Nbr_hw	−0.4288***	−0.4120***	−0.3821***	−0.4495***	
	(0.0939)	(0.0891)	(0.0837)	(0.1446)	
Nbr_Road					−0.1439
					(0.1571)
Town controls	Y	Y	Y	Y	Y
County and city controls	N	Y	Y	Y	Y
Town characteristics × time trend	N	N	Y	Y	Y
Fixed effects	Y	Y	Y	Y	Y
Observations	84,508	84,508	84,508	84,508	73,547
R^2	0.9965	0.9966	0.9966	0.9859	0.9972

*, *, and *** indicate significance at the 10, 5, and 1% levels, respectively. Robust standard errors are reported in parentheses and clustered at the city level. All regressions include township-level fixed effects (μ_i) and province-by-year fixed effects ($\upsilon_{p,t}$). Columns (1) to (4) examine the impact of highway construction on forest coverage, while column (5) investigates the effect of non-highway roads on forest coverage. Columns (1) to (3) and (5) use 30-m high-resolution nationwide annual tree cover grid data (CATCD), and column (4) employs a 250-m resolution global forest cover dataset for robustness checks.

4.2 Dynamic effects

To ensure the validity of the difference-in-differences (DID) estimation, this study first tests the parallel trends assumption. This assumption requires that the treatment and control groups exhibit similar trends in forest cover change prior to the policy intervention, namely the opening of highways. Specifically, the treatment group consists of townships adjacent to newly constructed highways, while the control group comprises second-order neighbouring townships without direct highway access. Any divergence in trends should occur only after the highways become operational, thereby reflecting the causal impact of construction. Accordingly, a parallel trends test is con-ducted to determine whether the groups followed comparable trajectories before the highway opening and whether a significant difference emerged thereafter. The assumption is considered valid if no significant pre-treatment differences are observed, yet a persistent divergence appears following the policy implementation.

Figure 1 plots event-study coefficients and their 95% confidence intervals, where the horizontal axis indicates years relative to the opening of the highways. The omitted category is the year immediately prior to opening ($t = -1$), which serves as the baseline. Due to limited observations at longer horizons, event-time indicators at the extremes are binned. Specifically, the leftmost coefficient ($t = -5$) represents an aggregated pre-treatment period covering 5 to 10 years before highway opening, while the rightmost coefficient ($t = +5$) corresponds to an aggregated post-treatment period covering 5 to 10 years after opening. All other coefficients represent single-year indicators.

As shown in Figure 1, prior to the opening of highways, there is no statistically significant difference in forest cover between the treatment and control groups. However, beginning in the year of highway operation, a discernible gap emerges and remains statistically significant for at least 4 years after the opening. This pattern provides strong empirical support for the validity of the parallel trends assumption and reinforces the robustness of the DID identification strategy.

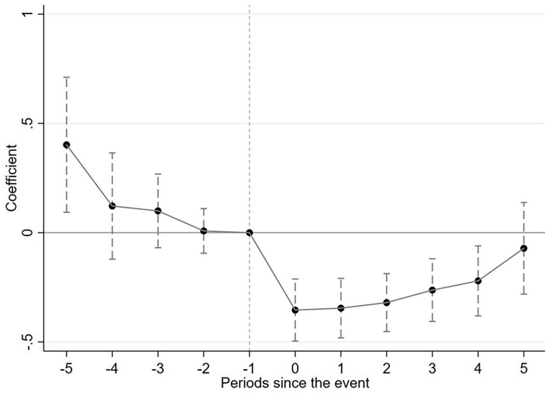

FIGURE 1
Dynamic spillover effects of highway openings on forest cover in adjacent towns.

To rigorously disentangle the temporal dynamics of infrastructure impacts, we follow the strategy proposed by Song et al. (2023) to distinguish between short-run (first 2 years) and long-run (third year onward) effects. The estimates reported in Table 3 corroborate the dynamic patterns observed in Figure 1. Specifically, while we observe a pronounced decline in forest cover in the short run, this negative impact attenuates and turns marginally positive in the long run.

This recovery trajectory mirrors the inverted U-shaped pattern posited by the Environmental Kuznets Curve (EKC) hypothesis (Grossman and Krueger, 1995). Specifically, improved accessibility initially precipitates a surge in timber harvesting due to immediate arbitrage opportunities. Over the longer term, however, sustained

TABLE 3 Temporal heterogeneity test.

Variables	Forest cover	
	Short-term effects	Long-term effects
	(1)	(2)
Short	−0.2180***	
	(0.0550)	
Long		0.1299*
		(0.0783)
Controls	Y	Y
Fixed effects	Y	Y
Observations	84,508	84,508
R^2	0.9966	0.9966

*, *, and *** indicate significance at the 10, 5, and 1% levels, respectively. Robust standard errors are reported in parentheses and clustered at the city level.

reductions in transport costs reshape the regional comparative advantage (Baum-Snow et al., 2020). This structural shift drives the reallocation of labor and capital from resource-extraction sectors toward manufacturing and services. As the local economy climbs the value chain, the reliance on timber-derived income diminishes, thereby allowing forest ecosystems to recover from the initial disturbance.

4.3 IV analysis

To address potential endogeneity concerns stemming from the non-random placement of transport infrastructure (e.g., planners prioritizing areas with high growth rates that correlate with forest cover changes), we introduce an instrument based on hypothetical least-cost path spanning tree networks. Following Faber (2014), we construct an instrumental variable based on the predicted highway network that connects regional economic hubs along routes minimizing construction costs determined by terrain characteristics. The key insight is that, conditional on the set of connected cities to be connected, the exact routing of highways is primarily governed by geographic construction costs, such as slope, elevation, and terrain ruggedness, rather than by local economic fundamentals. As argued in Faber (2014), once planners' decisions regarding which cities to connect are taken as given, variation in highway alignments largely reflects engineering constraints instead of anticipated regional economic outcomes.

Building on this principle, we use a minimum spanning tree (MST) algorithm to simulate the counterfactual highway network. The MST connects major cities while minimizing total construction costs implied by geographic features, thereby closely approximating the actual routing logic of highway construction. Because terrain and topographic characteristics are predetermined and plausibly exogenous to contemporary economic and environmental outcomes, the resulting predicted highway exposure satisfies the exclusion restriction. This approach allows us to isolate exogenous variation in highway placement arising from geographic cost minimization, strengthening the causal interpretation of the estimated effects.

Table 4 reports the two-stage regression results using the instrumental variable. The results indicate that highway construction has a significant negative impact on forest cover in underdeveloped regions, and the coefficients from the two-stage regression are similar to the baseline estimates, confirming the robustness of our main findings. The F-statistics show that the regressions pass the weak instrument test, suggesting that our estimates are reliable.

TABLE 4 IV analysis.

Variables	IV first stage	IV second stage
	(1)	(2)
Nbr_hw	0.9217***	−0.4027***
	(0.0064)	(0.1087)
Controls	Y	Y
Fixed effects	Y	Y
Kleibergen-Paap F statistic	20566.15	
Kleibergen-Paap LM statistic	106.16	
Observations	84,508	84,508
R^2	0.9586	0.1573

*, *, and *** indicate significance at the 10, 5, and 1% levels, respectively. Robust standard errors are reported in parentheses and clustered at the city level.

4.4 Robustness analysis

We begin our robustness checks by verifying the stability of our baseline results against alternative control group definitions. As reported in columns (1) to (3) of Table 5, we assess the robustness of our results by successively employing alternative control groups: (i) third-order neighbors of towns traversed by highways; (ii) non-treated towns within the same county; and (iii) non-treated towns within the same city where new highways were constructed. Across all alternative control group definitions, the negative effect of highways openings on forest cover remains statistically significant. Moreover, the results in Table 5 indicate that the adverse impact on forest cover is more pronounced when the control group is restricted to towns within the same county.

To further verify the sensitivity of our findings to the definition of transport accessibility, we employed three alternative continuous and nuanced indicators: (1) Euclidean distance to the nearest highway ramp; (2) road density, defined as the total length of highways per unit of land area; and (3) population-weighted accessibility, an indicator capturing the intensity of transport infrastructure relative to human activity. To ensure comparability with our baseline binary identification strategy, we categorized townships into "High Accessibility" (Treat = 1) and "Low Accessibility" (Control = 0) groups based on the median values of these metrics within each city-year cell. The results, reported in Appendix Table A3, indicate that the coefficients remain statistically significant and negative across all three specifications. The magnitudes are highly consistent with our baseline estimates. This confirms that our core finding, which shows that highway access precipitates forest cover loss, is robust to the specific measurement of accessibility.

To rigorously address the statistical significance observed at $t = -5$ and mitigate potential pre-testing biases as cautioned by Roth (2022), we employ the sensitivity analysis framework proposed by Rambachan and Roth (2023) to test the robustness of our results against potential violations of the parallel trends assumption. Specifically, we construct

TABLE 5 Robustness analysis: alternative control group.

Variables	Forest cover		
Treatment group	First-order neighboring		
Control group	Third-order neighboring	Other towns within county	Other towns within city
	(1)	(2)	(3)
Nbr_hw	−0.3925***	−0.5016***	−0.3729***
	(0.0935)	(0.1001)	(0.0832)
Controls	Y	Y	Y
Fixed effects	Y	Y	Y
Observations	77,167	76,784	117,939
R^2	0.9968	0.9966	0.9968

*, *, and *** indicate significance at the 10, 5, and 1% levels, respectively. Robust standard errors are reported in parentheses and clustered at the city level. In Table 5, the treatment group remains the same as in the baseline regression, consisting of the first-order neighboring townships of towns with newly constructed highways. For columns (1) to (3), the control groups are defined as follows: the third-order neighboring townships of new highway towns, other townships within the same county, and other townships within the same city, respectively.

95% robust confidence intervals under the "Relative Magnitude" assumption, and the results (Figure 2) demonstrate that our estimated treatment effect remains statistically significant (excluding zero) even when allowing for post-treatment biases to be as large as the maximum observed pre-treatment deviation ($\bar{M} = 1$), thereby confirming that the specific pre-trend fluctuation is insufficient to invalidate our main conclusions (Figure 2).

Furthermore, we re-estimate our dynamic specifications using the interaction-weighted estimator proposed by Sun and Abraham (2021) to mitigate potential biases associated with staggered treatment timing. This approach constructs an unbiased counterfactual by interacting cohort indicators with relative event-time dummies, employing only never-treated (or last-treated) units as the effective control group to avoid contamination from already-treated cohorts. As shown in Figure 3, the estimates and their 95% confidence intervals derived from the interaction-weighted estimator closely mirror the magnitude and temporal pattern of our baseline results: a significant treatment effect emerges immediately upon highway opening, persists for several periods, and gradually attenuates over time. This consistency confirms that our findings are not driven by TWFE weighting failures.

Agricultural dynamics represent another critical source of potential confounding factors. To isolate the causal effect of infrastructure, we introduce multiple sets of control variables in Table 6. Existing literature presents contrasting pathways through which agriculture may influence forest cover. Some studies suggest that rising agricultural productivity can reduce rural households' reliance on forest resources, thus supporting short-term forest conservation (Borlaug, 2007; Abman and Carney, 2020). Structural shifts within the agricultural sector, such as the growing share of livestock and fisheries, improved cropland use efficiency, and policies like the Grain for Green Program, may also alleviate pressure on forests. Conversely, other research highlights that agricultural expansion can drive land-use conversion and intensify deforestation (Asher et al., 2020).

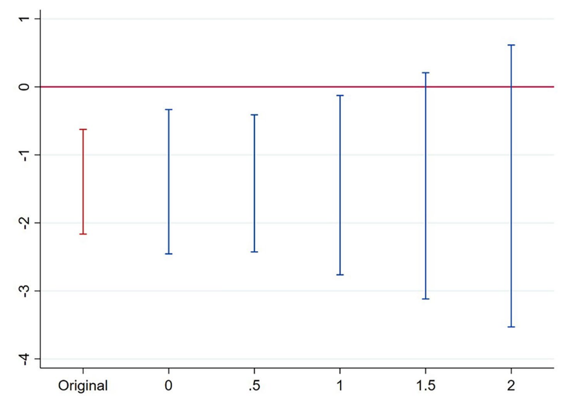

FIGURE 2
Sensitivity analysis using Honest DID.

Specifically, columns (1) and (2) of Table 6 control for agricultural output at the county level and primary industry output at the city level, respectively, to capture regional agricultural productivity changes. Columns (3) and (4) further incorporate provincial timber production and the implementation intensity of the "Grain for Green Program" to control for macro-level influences on forest resource use. The results indicate that even after accounting for these agricultural factors, the opening of highways in less developed regions continues to exhibit a statistically significant negative effect on forest cover.

4.5 Mechanism analysis

We argue that highways construction may contribute to the decline in forest cover through two potential mechanisms, as illustrated in Figure 4. First, improved highway access may stimulate local demand-driven deforestation. By enhancing rural connectivity, highways could promote the expansion of agricultural land at the expense of forest cover and increase local consumption of forest products such as firewood, thereby intensifying timber harvesting. Second, highways may reshape interregional supply chains. Enhanced transport infrastructure strengthens the linkage between peripheral forested areas and central urban markets, facilitating the flow of timber and other forest products to economically dynamic regions. As demand for timber, pulp, and construction materials grows in urban centers, reduced transportation costs provide less-developed areas with a comparative advantage in supplying these resources, accelerating both harvesting and outbound shipment of forest products.

4.5.1 Validating the interregional supply chain channel

Table 7 provides robust evidence supporting the interregional supply chain mechanism, suggesting that Highway connections accelerate the extraction of forest resources to satisfy external market demand.

Panel A, columns (1) and (2), analyzed at the county level, show that Highway openings led to a significant increase in the entry of new firms in timber-demanding sectors (e.g., construction). This indicates an expanded aggregate demand for forest products at the regional level. Corroborating this, Panel B uses employee data from the 2010 and 2015 China Population Censuses to reveal that an increase in the number of Highway toll stations within a county significantly raised

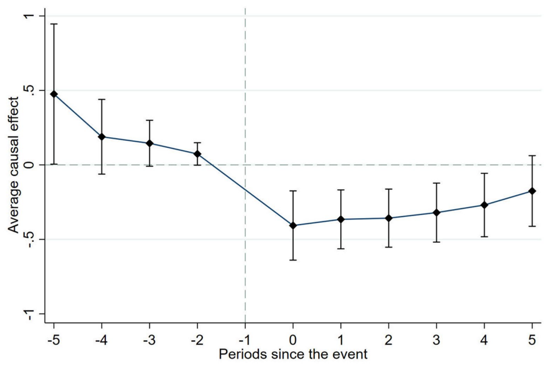

FIGURE 3
Event-study estimates using the Sun and Abraham (2021) robust estimator.

employment in timber-related industries. This highlights the role of transport infrastructure in fostering job growth in these resource-intensive sectors.

Panel C offers a more granular perspective by demonstrating that Highway access significantly promoted the entry of new firms in timber-demanding industries, particularly in economically developed townships within the region. This heterogeneity reflects the "siphon effect": improved transport spurs demand for timber resources in stronger local economic centers, which in turn draws raw materials from the surrounding rural hinterlands.

In sharp contrast, columns (3) and (4) show that non-highway Road construction did not significantly stimulate timber demand either at the county level or in economic centers. In other words, unlike the Highway network, non-highway Roads did not substantially reshape interregional resource allocation or drive a systematic expansion in the forest products market.

4.5.2 Ruling out local agricultural and industrial expansion

Having established the demand-side channel, we next rule out alternative local drivers. Specifically, we examine whether deforestation is driven by the expansion of local agricultural land or the growth of local timber-processing industries.

First, our empirical analysis rules out the mechanism of agricultural encroachment. As shown in column (1) of Table 8 Panel A, the agricultural land area in treated townships did not exhibit significant growth following Highway openings. This indicates that agricultural expansion is not the primary driver of forest cover loss in our context.

Second, we examine whether Highway openings stimulate local timber-dependent industrialization. Following FAO (2022) and mapping major timber-use sectors to China's two-digit industry codes, we define timber-dependent industries to include wood processing, furniture manufacturing, paper products, and construction activities[1]. Using this definition, Column (2) shows that Highway construction does not significantly increase new-firm entry in local timber-dependent industries; if anything, the coefficient is negative. This null result is crucial: it suggests that the harvested timber is not being processed locally but is instead being shipped out to external markets, reinforcing the "extraction" narrative over "local development."

Column (3) likewise indicates no significant change in new-firm entry in forestry-related sectors (e.g., forest breeding and cultivation), further ruling out a local supply-side expansion channel. In contrast, Panel B examines the impact of non-highway Road construction. Similar to Highways, non-highway Roads did not significantly drive agricultural expansion or boost local timber-consuming industries. However, column (3) indicates a notable increase in the number of new forestry-related firms in areas adjacent to non-highway Roads. This suggests that, unlike the extractive nature of Highways, non-highway Roads may primarily enhance local circulation and supply capacity within the forestry sector.

The combined evidence reveals a clear spatial pattern: Highway openings trigger deforestation in the periphery (Table 8) while simultaneously boosting timber industries in regional economic centers (Table 7), with no concurrent expansion in local processing capacity. Although we do not directly observe trade flows, this 'extraction in the periphery, expansion in the core' pattern is consistent with the view that Highways strengthen the economic integration between resource-rich hinterlands and central cities.

4.6 Heterogeneity analysis

4.6.1 Heterogeneity by proximity to highway toll stations

Figure 5 presents the results of a heterogeneity analysis based on the proximity of treated towns to highway toll stations. Error bars represent 95% confidence intervals. The empirical findings indicate that forest cover decreases significantly in towns located within 10 km of a toll station, suggesting that closer access to highways entry and exit points exerts a stronger influence on forest resources. This pattern implies that reduced transportation costs for timber in areas near interchange facilities lower the cost of shipping timber to regional hubs or consumer markets, thereby creating stronger incentives for deforestation.

4.6.2 Heterogeneity by vegetation type

China's natural vegetation comprises six primary types, including coniferous forests, deciduous broadleaf forests, evergreen broadleaf forests, tropical monsoon forests, grasslands, and deserts, all of which exhibit distinct ecological and economic attributes. Coniferous forests, predominantly found in temperate zones, are characterized by long growth cycles and high adaptability, rendering them suitable for greening initiatives and construction timber. In contrast, broadleaf forests host a wide array of species with considerable commercial value, including high-quality timber trees such as camphor and nanmu, alongside fruit-bearing resources. Broadleaf timber is extensively utilized in construction, manufacturing, packaging, shipbuilding, and furniture making, while these forests also supply non-timber products including oils, fruits, rubber, cork, and medicinal materials.

Table 9 presents empirical evidence on the heterogeneous impact of highways expansion across regions with different vegetation profiles and conservation status. Columns (1) and (2) indicate that the adverse effect on forest cover is concentrated mainly outside the Three-North Shelterbelt Program area, suggesting that improved road connectivity lowers timber transport costs and facilitates the outflow of forest resources from less-protected, vulnerable regions. Meanwhile,

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[1] These sectors specifically include wood processing and products made of wood, bamboo, rattan, palm, and grass; furniture manufacturing; paper and paper products; rubber and plastic products; and construction activities.

TABLE 6 Robustness analysis: control for agricultural and forestry development.

Variables	Forest cover			
Control	County agricultural output	City primary production	Provincial timber production	Provincial afforestation area
	(1)	(2)	(3)	(4)
Nbr_hw	−0.4251***	−0.3826***	−0.4326***	−0.4326***
	(0.1029)	(0.0839)	(0.1150)	(0.1151)
Controls	Y	Y	Y	Y
Fixed effects	Y	Y	Y	Y
Observations	53,108	84,368	46,037	46,037
R^2	0.9966	0.9966	0.9954	0.9954

*, *, and *** indicate significance at the 10, 5, and 1% levels, respectively. Robust standard errors are reported in parentheses and clustered at the city level. Columns (1) and (2) include county-level agricultural output and city-level primary industry output as control variables to capture regional differences in agricultural productivity, with data sourced from the China County Statistical Yearbook and the China City Statistical Yearbook. Columns (3) and (4) incorporate province-level timber production and the intensity of the "Grain-to-Green" reforestation program to control for macro-level factors affecting forest resource use, with data obtained from the China Provincial Statistical Yearbook and the China Forestry and Grassland Statistical Yearbook.

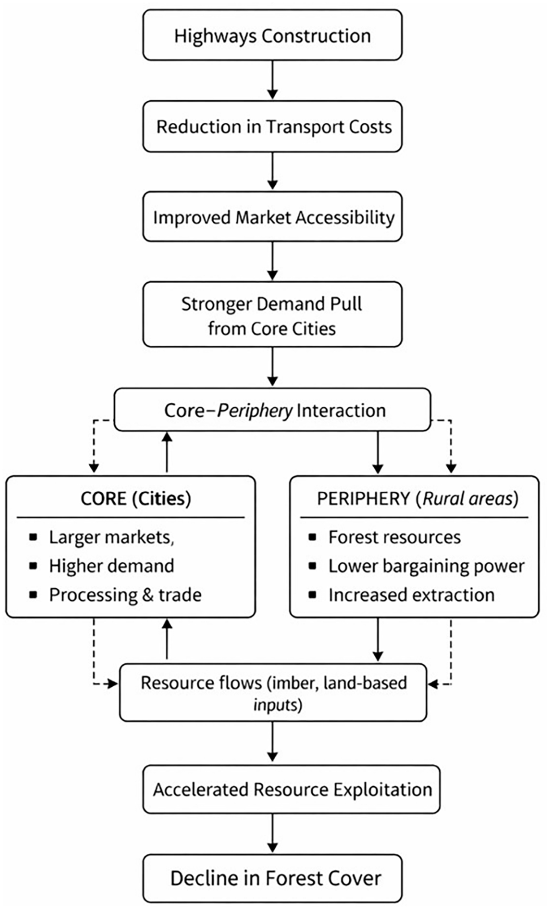

FIGURE 4
Core–periphery framework linking highways to forest loss.

columns (3) to (5) reveal a more pronounced negative effect in broadleaf-dominated zones. This pattern can be explained by the higher economic value of broadleaf timber, which increases its sensitivity to market incentives and transport cost reductions. As shipping becomes cheaper, harvesting and distribution intensify, accelerating deforestation in these ecologically and economically significant forests.

Overall, the findings underscore that the environmental consequences of transport infrastructure are not uniform but shaped by the interplay of local resource endowments and conservation frameworks. Highway construction tends to exacerbate forest cover loss in areas lacking formal protection and in those rich in high-value species such as broadleaf trees.

4.6.3 Heterogeneity by regional industrial and ecological characteristics

To investigate how initial industrial structure and development paths moderate the impact of highways, we stratified the sample based on resource endowments and institutional constraints, with results reported in Table 10. First, regarding timber production capabilities, we utilized provincial timber output data from the *China Statistical Yearbook 2009* as a proxy due to data limitations at the local level. Using the median provincial output as a cutoff, the results in columns (1) and (2) indicate that the deforestation effect is significantly stronger in timber-rich regions compared to timber-poor regions. This finding confirms the path dependence of resource extraction: in areas with established timber supply chains, improved transport infrastructure lowers trade costs, thereby amplifying the "siphon effect" and accelerating the liquidation of forest stocks to meet external demand.

Second, we distinguish between strict institutional protection and commercial tourism development to analyze the "eco-tourism" channel. To capture the conservation aspect, we employed the National Ecological Civilization Construction Demonstration Zones designation. Columns (3) and (4) reveal that while highways cause a significant decline in forest cover in non-demonstration zones, the impact is statistically insignificant in demonstration zones, suggesting that binding "protection-first" mandates effectively neutralize negative environmental externalities. Conversely, when examining commercial tourism resources (proxied by the presence of National 5A-level Tourist Attractions as of 2019), columns (5) and (6) show that townships with top-tier tourism endowments experience a more severe decline in forest cover. This indicates that without strict ecological

TABLE 7 Mechanism analysis: the restructuring of regional supply chains.

Road type	Highways		Non-highway roads	
	(1)	(2)	(3)	(4)
Industries	Timber-dependent	Construction	Timber-dependent	Construction
Panel A: county level				
Variables	Enterprise entry rate			
No. of toll stations	0.1451**	0.1815**		
	(0.0728)	(0.0835)		
No. of non-highway roads			−0.1773	0.4104
			(0.3614)	(0.5894)
Observations	14,960	14,960	14,960	14,960
R^2	0.6466	0.6044	0.6464	0.6042
Panel B: county level				
Variables	Number of employees			
No. of toll stations	2.3783***	2.1555***		
	(0.7897)	(0.6668)		
No. of non-highway roads			6.2067*	0.1124
			(3.5990)	(1.3337)
Observations	2,518	2,518	2,518	2,562
R^2	0.7440	0.7504	0.7421	0.4595
Panel C: economically dynamic towns within city				
Variables	Enterprise entry rate			
No. of toll stations	0.0521**	0.0885**		
	(0.0234)	(0.0383)		
No. of non-highway roads			−0.0661**	−0.0251
			(0.0265)	(0.0282)
Observations	67,830	67,830	77,880	77,880
R^2	0.2916	0.2483	0.2610	0.2474
Controls	Y	Y	Y	Y
Fixed effects	Y	Y	Y	Y

*, *, and *** indicate significance at the 10, 5, and 1% levels, respectively. Robust standard errors are reported in parentheses and clustered at the city level. No. of toll stations and non-highway roads: number of towns within a county (or city) with toll stations, and number of towns traversed by non-highway roads. Panel C: economically dynamic towns within cities are defined as those ranking in the top third for 1992 nighttime lights within cities.

constraints, tourism development often follows a path of intensified commercialization, where the pressure from infrastructure construction and visitor traffic outweighs the conservation effect.

4.6.4 Heterogeneity by forest tenure reform and fiscal pressure

In addition to industrial structure, we examined how institutional maturity and government incentives moderate the impact of highways, with results reported in Table 11. First, we focused on the maturity of property rights as defined by the Collective Forest Tenure Reform (CFTR). Based on the implementation timeline documented by Zheng et al. (2025), we stratified the sample into “Early Reform” regions (initiated before 2008) and “Late Reform” regions (initiated in or after 2008). The results in columns (1) and (2) indicate that the negative impact of highways on forest cover is significantly weaker in Early Reform regions compared to Late Reform regions. This finding suggests that clearer and more mature property rights help internalize the long-term benefits of forest management. In regions where farmers have held secure titles for longer, forests are more likely to be treated as long-term assets to be managed sustainably, thereby buffering against the extraction shocks triggered by reduced transport costs.

Second, to capture the trade-offs between economic growth and environmental protection, we examined the role of Local Fiscal Pressure. Following the methodology of Peng et al. (2020), we measured fiscal pressure using the ratio of the budget deficit (expenditure minus revenue) to general public budget revenue, dividing the sample into high- and low-pressure groups based on the annual median to control for time trends. The results in columns (3) and (4) reveal that the deforestation effect is nearly twice as large in regions with high fiscal pressure compared to those with low fiscal pressure. This confirms that fiscal incentives drive local government behavior: fiscally strained governments are more likely to leverage improved infrastructure for immediate resource monetization to generate revenue. In

TABLE 8 Mechanism analysis: ruling out the effect of increased local demand.

Dependent variable	Agricultural land area	Entry rate of new firms in timber-demanding industries	Entry rate of new firms in the forestry and logging industries
	(1)	(2)	(3)
Panel A: highways			
Nbr_hw	−0.1396**	−0.5597*	−0.0334
	(0.0620)	(0.3027)	(0.7610)
Observations	84,508	84,508	84,508
R^2	0.9977	0.2231	0.1500
Panel B: non-highway roads			
Nbr_road	−0.0953	−0.2397	2.7609**
	(0.1554)	(0.4445)	(1.2100)
Observations	50,094	50,094	50,094
R^2	0.9976	0.2275	0.1500
Controls	Y	Y	Y
Fixed effects	Y	Y	Y

*, *, and *** indicate significance at the 10, 5, and 1% levels, respectively. Robust standard errors are reported in parentheses and clustered at the city level.

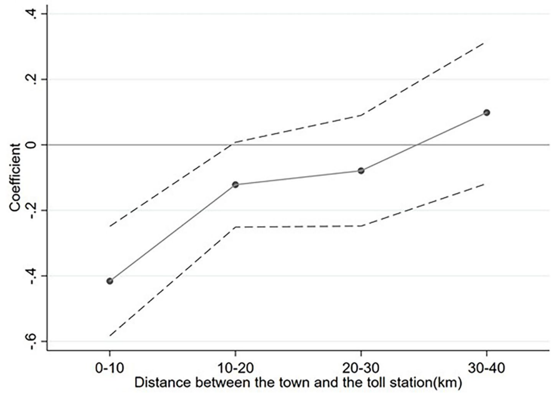

FIGURE 5
Heterogeneity by proximity to highway toll stations.

contrast, governments with sufficient fiscal space possess greater capacity to enforce environmental regulations, effectively mitigating the negative externalities of infrastructure expansion.

4.7 Further analysis

TABLE 9 Heterogeneity analysis by vegetation type.

Dependent variable	Forest cover		
Vegetation type	Broadleaf forest zones	Coniferous forest zones	Grassland, desert, rainforest zones
	(1)	(2)	(3)
Nbr_hw	−0.3947***	0.0165	−0.1913
	(0.0877)	(0.1484)	(0.1385)
Controls	Y	Y	Y
Fixed effects	Y	Y	Y
Observations	71,346	12,528	10,683
R^2	0.9966	0.9983	0.9957

*, *, and *** indicate significance at the 10, 5, and 1% levels, respectively. Robust standard errors are reported in parentheses and clustered at the city level.

Finally, this study further investigates the ecological externality costs associated with highway construction. The empirical results (Table 12, Panel A) indicate that the reduction in forest cover caused by highway openings significantly increases local greenhouse gas emissions, particularly carbon dioxide (CO_2) and fluorinated gases. This suggests that forest loss may undermine the region's carbon sequestration capacity, thereby contributing to the accumulation of greenhouse gases. Additionally, from a vehicle exhaust perspective (Panel B), although highway openings do increase vehicle traffic in the region, they do not have a significant impact on emissions of carbon monoxide (CO), ozone (O_3), nitrogen oxides (NO_x), or sulfur dioxide (SO_2). This discrepancy suggests that while expressways primarily impact the environment through the permanent loss of ecological assets (forests), their direct contribution to localized air pollution in rural hinterlands may be secondary or mitigated by the non-congested nature of rural transit.

5 Conclusion and policy implications

5.1 Conclusion

This study investigates the ecological consequences of transport infrastructure expansion in China's rural hinterlands, focusing on the fundamental trade-off between accessibility and sustainable forestry. Leveraging town-level panel data and a Minimum Spanning Tree (MST) instrumental variable strategy, we provide robust causal evidence on how different types of infrastructure reshape the distribution of rural ecological capital.

Our findings reveal a significant negative spatial spill-over effect: the opening of highways in neighboring townships reduces forest cover in local underdeveloped hinterlands that lack direct highway access. However, dynamic analyses clarify that this is a transient "extraction shock" rather than a permanent structural decline, with the negative impact attenuating significantly over the long term. In contrast, non-highway rural roads show no statistically discernible negative impact, suggesting they offer a more ecologically sustainable path for connectivity.

Mechanism analysis, grounded in the core-periphery model, elucidates the economic drivers of this deforestation: highways lower transportation costs, thereby accelerating the extraction of timber and forest resources from peripheral rural areas to serve demand in central markets. This "siphon effect" is most pronounced near highway exits, in broadleaf forests with higher commercial value, and in regions with weaker economic foundations. Furthermore, we find that this infrastructure-induced deforestation contributes to increased greenhouse gas emissions, undermining regional climate resilience.

TABLE 10 Heterogeneity by regional industrial and ecological characteristics.

Variables	Forest cover					
	Timber-processing areas		Eco-zone		5A-level tourist	
	YES	NO	YES	NO	YES	NO
	(1)	(2)	(3)	(4)	(5)	(6)
Nbr_hw	−0.4307***	−0.2194*	−0.0208	−0.3124***	−0.5681***	−0.3479***
	(0.1255)	(0.1109)	(0.0948)	(0.0731)	(0.1303)	(0.0924)
Controls	Y	Y	Y	Y	Y	Y
Fixed effects	Y	Y	Y	Y	Y	Y
Observations	39,217	45,291	19,369	64,818	15,741	68,767
R^2	0.9954	0.9976	0.9997	0.9977	0.9969	0.9966

*, *, and *** indicate significance at the 10, 5, and 1% levels, respectively. Robust standard errors are reported in parentheses and clustered at the city level.

TABLE 11 Heterogeneity by forest tenure reform and fiscal pressure.

Variables	Forest cover			
	(1)	(2)	(3)	(4)
	CFTR		Fiscal pressure	
	Early reform	Late reform	High	Low
Nbr_hw	−0.2182*	−0.4465***	−0.4438***	−0.2226**
	(0.1139)	(0.1172)	(0.1143)	(0.0920)
Controls	Y	Y	Y	Y
Fixed effects	Y	Y	Y	Y
Observations	33,047	51,461	41,499	42,326
R^2	0.9978	0.9957	0.9967	0.9977

*, *, and *** indicate significance at the 10, 5, and 1% levels, respectively. Robust standard errors are reported in parentheses and clustered at the city level.

TABLE 12 Further analysis: pollutant gas emissions.

Dependent variable	Pollutant gas emissions			
	(1)	(2)	(3)	(4)
Panel A: greenhouse gas	CO_2	N_2O	Fluoride	CH_4
Nbr_hw	0.0038*	0.0023	0.0078*	0.0042
	(0.0020)	(0.0015)	(0.0040)	(0.0030)
Observations	84,597	84,597	84,597	84,597
R^2	0.9985	0.9980	0.9918	0.9918
Panel B: vehicle exhaust	CO_1	O_3	NO_x	SO_2
Nbr_hw	0.0027	0.0001	0.0047	0.0061
	(0.0039)	(0.0012)	(0.0035)	(0.0068)
Observations	84,597	84,607	84,597	58,754
R^2	0.9964	0.9560	0.9953	0.9628
Controls	Y	Y	Y	Y
Fixed effects	Y	Y	Y	Y

*, *, and *** indicate significance at the 10, 5, and 1% levels, respectively. Robust standard errors are reported in parentheses and clustered at the city level.

5.2 Policy implications

Overall, these results highlight a fundamental tension between infrastructure-led integration and rural ecological security. While high-speed connectivity facilitates market access, it risks depleting rural natural capital if not managed with strict safeguards. Consequently, achieving sustainable rural development requires a paradigm shift in infrastructure planning from distinct projects to a holistic, spatially differentiated strategy. Specifically, policymakers should prioritize the upgrade of rural and secondary roads over the excessive expansion of highways in ecologically sensitive areas, as our evidence suggests that non-highway roads offer a sustainable pathway for enhancing local livelihoods without compromising ecosystem integrity.

Furthermore, to mitigate the unintended "siphon effect" of high-speed networks, it is imperative to strengthen rural forest governance by integrating transport planning with Ecological Redlines. Drawing on our heterogeneity analysis, enforcement should be precise rather than uniform: monitoring efforts must be specifically intensified within a 10 km radius of highway exits and in zones dominated by high-value broadleaf forests, as these areas are identified as the primary hotspots of market-driven exploitation. Crucially, this targeted protection extends beyond biodiversity conservation to the preservation of rural life-support systems. Forests act as essential ecological barriers that safeguard long-term agricultural productivity through soil retention, water regulation, and local climate stabilization. Unchecked deforestation in these critical zones' risks exacerbating soil erosion and increasing the vulnerability of farmland to extreme weather, thereby threatening regional food security. Thus, maintaining forest integrity must be viewed as a strategic imperative to ensure that short-term resource extraction does not undermine the natural foundations of grain production.

Moreover, recognizing that highways facilitate the flow of resources from rural peripheries to urban cores, fiscal mechanisms such as Payment for Ecosystem Services (PES) should be established to transfer benefits from downstream urban consumers to upstream rural conservators. By reallocating a portion of highway revenue to fund local reforestation, the environmental costs of connectivity can be internalized, ensuring that China's rural revitalization pursues a resilient trajectory that reconciles economic progress with long-term environmental sustainability.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

LZ: Conceptualization, Data curation, Methodology, Software, Visualization, Writing – original draft. XL: Conceptualization, Formal analysis, Methodology, Validation, Writing – review & editing. MW: Conceptualization, Formal analysis, Validation, Writing – review & editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was used in the creation of this manuscript. During the preparation of this manuscript, the author(s) used Gemini 3.0 pro to polish and refine the manuscript. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2026.1766589/full#supplementary-material

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