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Competing for International Discourse Power in the Digital Platform Era: An Embedded Model and Case Analysis

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International Discourse Power;
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ABSTRACT

Discourse possesses the capacity to shape reality, and the concept of "discourse power" continues to evolve alongside transformations in global communication. Digital platforms, by virtue of their vast user bases and extensive data resources, have restructured multiple dimensions of social life and emerged as a key arena for contesting international discourse power. This study develops an embedded model of digital platforms and international discourse power by examining their theoretical implications, strategic orientations, and structural interconnections. Using TikTok and Twitter as illustrative cases, it analyzes how major powers engage in discourse competition within the digital platform environment. The findings suggest that international discourse power in the platform era follows a logic of contestation for dominance, characterized by competition over capital, content, and technology—injecting new variables and uncertainties into the global communication order. Looking ahead, artificial intelligence will play an increasingly central role, discourse dissemination mechanisms will continue to innovate, and the development of autonomous, internationally recognized digital platforms will be imperative.

INTRODUCTION

Discourse possesses the power to construct reality and embodies the interplay of power relations. As an essential component of national power, discourse power serves as a key indicator of a nation's strength, influence, and appeal on the global stage (Sun, 2019). The configuration of international discourse power, in particular, determines an international actor's global influence, representing its authority to define, interpret, and evaluate people, events, and phenomena—thereby reflecting transformations in the international order (Shen, 2022).

Contemporary digital space, shaped by the convergence of artificial intelligence, cloud computing, and big data, has fundamentally restructured politics, economics, and culture. Accelerated digitalization has turned platforms into new organizational and infrastruc-

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tural forms for social life. Unlike traditional media structures, digital platforms concentrate massive capital and user bases, thereby aggregating power as a form of socio-technical infrastructure (van Dijck, 2018).

Competition among nations provides the driving force for changes in the international system and global order. The rise of digital platforms extends this competition beyond the political and economic spheres into the realm of information and communication, introducing new demands on states' comprehensive governance capacities.

LITERATURE REVIEW

Competition for International Discourse Power

The construction of international discourse power is closely linked to the nature of "discourse" and "power." Influenced by the distribution of power in the international system, its formation is shaped by multiple factors and operates according to its own distinctive mechanisms (Tang, 2017).

Competition over discourse is inseparable from the interplay of discourse power. Discourse power has thus become an indispensable component of international political power. In essence, the struggle for global discourse power is a contest over the rights and authority embedded within discourse—encompassing ideological confrontation, political values, institutional models, and narrative framing. It also extends to the production of discourse in international affairs, the formulation of global rules and standards, and the competition for interpretive and evaluative authority (Yu, 2023). In this process, powerful states seek to disseminate their values, political systems, and cultural influence to expand their spheres of influence and impose their national will. Conversely, weaker states are often marginalized in this hierarchical discourse order, risking discursive silence and exclusion.

Traditional patterns of discourse competition among international actors have been widely observed. For example, hegemonic states often shape global public opinion to establish discursive authority, using it as a tool to contain rising powers (Newman & Zala, 2018). This dominance allows hegemonic states to secure institutional advantages, laying the groundwork for agenda-setting and narrative control in international discourse. In response, emerging powers strategically deploy discursive tools to counter hegemonic suppression, construct favorable narratives, and project a positive international image (Hardy & Maguire, 2016; John, Catherine & Alexander, 2019).

Joseph Nye (2012) analyzed competition over international discourse power through the lens of soft power, emphasizing its reliance on attraction rather than coercion. Other scholars have further explored how a state's international status (Larson, Paul & Wohlforth, 2014), nation branding (Van Ham, 2002), framing strategies, strategic narratives, and prestige collectively shape its participation in the struggle for global discourse power.

Digital Platforms as a New Arena for Global Communication

Given their central role in producing and organizing infrastructural resources, digital platforms have gained increasing prominence in the international system, becoming a major site for information production and global communication (Helmond, 2015; Plantin, 2018; Tworek, 2019; Ji, 2020; Kuang, 2021).

On the one hand, digital platforms embody the logic of digital geopolitics and are deeply intertwined with the trajectory of international communication. Under the platformization trend, micro-level platforms, meso-level platform ecosystems, and macro-level geopolitical configurations are increasingly interwoven (van Dijck, 2018). As a result, the previously clear boundaries between states have become increasingly blurred, and the actors participating in global communication have grown more diverse (Nieborg, 2019; Ji, 2020).

On the other hand, digital platforms empower individuals and multiple actors, thereby introducing new variables into international communication dynamics. By enabling diverse participants to engage in communication, digital platforms significantly facilitate cross-border discourse production (Zhang, 2019). More importantly, the integrative function of social platforms in shaping communicative contexts has become increasingly salient. The adage "whoever controls the platform controls the narrative" has emerged as a new maxim of international communication and public diplomacy in the digital era (Shi, 2020).

This study adopts case analysis and process-tracing methods to examine the mechanisms of discourse competition within the digital platform environment. It further proposes a theoretical framework of platform communication to address three core research questions:

- Why have digital platforms become a new arena for the construction of international discourse power?
- What are the representative cases of international discourse power competition among major powers on digital platforms?
- What are the likely trajectories for future competition over international discourse power in the platform era?

THE EMBEDDEDNESS OF DIGITAL PLATFORMS AND INTERNATIONAL DISCOURSE POWER

International discourse power is not only constructed within the environment of digital platforms but is also deeply embedded in them. The larger and more pervasive a platform becomes, the greater its capacity to shape the formation of international discourse power. This section clarifies how digital platforms become new arenas for the construction of discourse power by analyzing three dimensions—theoretical implications, goal orientation, and intrinsic connections—and seeks to explain the mechanisms through which platformization and discourse power mutually reinforce each other.

Theoretical Implications: the Embedding of Discourse Space and Communication Structure

By virtue of their inherent attributes, digital platforms have not only reorganized the basic forms of communication, the patterns of relational connectivity, and the modes of information distribution, but have also reconfigured the global discourse space and the architecture of communication. As emergent socio-technical infrastructures, platforms have fostered a progressive embedding of online discourse space and communication structures, which is manifested in several key ways.

First, the discourse space has expanded on an unprecedented scale. Discourse space constitutes the arena through which a nation exercises international discourse power and reflects its strength in shaping the global communication order. The rise of digital platforms has created a new environment for discourse production, endowing it with novel characteristics (Chen, 2020). In this environment, diverse communicative actors not only collaborate within the shared discourse space but also inevitably engage in competition for discursive influence. These actors must leverage the available discourse space to maximize their discursive functions, thereby playing an essential role in the construction of international discourse power.

Second, communication structures have been optimized through more targeted resource allocation. Under conditions of rapidly advancing media technology, digital platforms have become central coordinators of information resources. This transformation has occurred at two levels: in the physical layer, platforms have penetrated nearly every aspect of daily life, becoming indispensable information infrastructures; and in the communicative layer, they have reshaped the modes through which communication spaces are connected. As communication activities feed data back into platform operations, they simultaneously generate new informational resources, enabling increasingly precise and targeted allocation of communicative resources.

Finally, the distribution of power within discourse space and communication structures has been fundamentally reconfigured. Algorithms and data technologies, as socio-technical and cultural systems, inevitably introduce new dynamics of power struggle. The integration and redistribution of power relations create an emergent power system, embedding discourse space and communication structures within one another and producing new characteristics for the global communication ecology. Communication structures oscillate between decentralization and recentralization, with enhanced capacity and efficiency of resource allocation. This mutual reinforcement consolidates their embedded relationship. Moreover, the evaluative mechanisms established by digital platforms—based on the data generated within discourse space and communication structures—further strengthen this embeddedness by intensifying the management and distribution of information resources (Lee, 2015).

Goal Orientation: Constructing Digital Soft Power

The Digital Transformation Index Report 2023 highlights that digital platforms serve as a critical catalyst for enterprise digital transformation. Functioning as a bridge between digitalization and soft power, platforms compensate for the limitations of mass communication in regulating and integrating information resources, elevating soft power to new levels. This development also extends and updates Joseph Nye's classical theory of soft power. To effectively build digital soft power, three interrelated elements are essential: digital cognition, digital thinking, and digital transformation.

Digital cognition constitutes the fundamental prerequisite for constructing digital soft power. Soft power—often defined as the ability to attract, persuade, or co-opt—traditionally comprises three core dimensions: culture, political values, and foreign policy. In the era of platformized communication, soft power increasingly manifests in more subtle and diffused forms of influence. Through the widespread dissemination of digital cognition, platforms coordinate diverse global communication actors and integrate massive information resources, thereby establishing discursive authority and legitimizing the construction of digital soft power (Guo, 2021). Moreover, by leveraging their robust capacities for information transmission and content generation, platforms deepen cultural identification among both existing and emerging user communities, fostering common ground while accommodating differences.

Digital thinking represents the guiding principle for building digital soft power. By cultivating a mindset that prioritizes digital connectivity and centrality, platforms can reinforce the connective function of the internet, acting as mediators between nodes to create stronger relational ties. This process enables the deep integration and reorganization of information resources while consolidating the central position of platforms within communication structures. Digital thinking thus provides the normative foundation for constructing digital soft power, extending the base established by digital cognition.

Digital transformation serves as the inevitable pathway for advancing digital soft power. Digital technologies reshape the internal elements of discourse systems and their interrelations, creating an organic linkage between online and offline spheres and acting as a core driver for discourse power construction in the digital age. The technological advancement of digital tools brings vast developmental potential, enabling the more rational allocation of communication resources under the coordination of multiple actors. By cultivating digital cognition and embedding digital thinking, societies can guide comprehensive digital transformation, thereby creating favorable conditions for the development of international discourse power. Ultimately, the construction of digital soft power maximizes the role of digital technology in allocating informational resources and strengthens nations' capacities to participate in global discourse competition.

Intrinsic Connection: Communicative Power in the Information Society

Communicative power serves as a mirror of both discourse systems and communication structures, and its evolution inevitably reshapes the configuration of power relations. As the foundation of social organization, power relations are often constructed and reinforced in people's minds through processes of communication and interaction (Castells, 2013). In this sense, communicative power becomes the intrinsic linkage through which digital platforms and international discourse power are mutually embedded.

Information Society Theory posits that technology shapes specific modes of development, and that the core elements of productivity define the trajectory of social progress. These modes of development penetrate all layers of society and influence the formation of social behavior. The technological revolutions spurred by scientific innovation have provided the driving force for what has been called a "techno-economic paradigm," with the information technology revolution in particular resolving key challenges of communication and information processing, eventually ushering in an "information technology paradigm" (Freeman & Perez, 1988).

The emergence of the information society has also transformed the modes of power control. During previous periods of social transition—such as agricultural and industrial society—information sources were largely concentrated at the upper echelons of communication structures, resulting in a top-down, hierarchical flow of information. The development of internet technologies redistributed communicative agency, granting greater power to nodes at the periphery and gradually enabling bottom-up modes of power control to gain prominence. Nevertheless, as digital platforms consolidate their position as the central nodes of communication activities, they have progressively strengthened their control over peripheral nodes, further entrenching their centrality. Within this environment, the formation and operation of international discourse power increasingly follow this organizational logic of centralized platform governance.

CASE STUDIES OF INTERNATIONAL DISCOURSE POWER COMPETITION ON DIGITAL PLATFORMS

TikTok: a New Focal Point of Digital Geopolitical Competition

ByteDance was among the first Chinese technology companies to integrate artificial intelligence with mobile internet scenarios. Its short-video platform TikTok leverages AI and big data technologies to precisely match user preferences with content, thereby disrupting the traditional relationship between users and media content. Short-video platforms, accessed via mobile smart devices, distribute videos typically ranging from a few seconds to several minutes in length. They satisfy a wide spectrum of social needs, including self-expression and exposure, fragmented-time audiovisual entertainment, structured emotional resonance, and connection in highly mobile social contexts.

TikTok represents one of the most successful cases of reverse market expansion from a developing country into developed markets. As of September 2021, its monthly active users surpassed one billion, placing it among the small group of digital platforms globally to achieve this milestone.

Geopolitical contestation surrounding TikTok has become increasingly prominent in recent years. In 2020, then-U.S. President Donald Trump issued an executive order to ban TikTok, sparking widespread user backlash. The order was blocked by federal judges before taking effect and later rescinded by the Biden administration. Nevertheless, Western governments' scrutiny of TikTok has not abated: the United States, European Union, and Canada have successively prohibited government employees from using the platform on security grounds. These developments illustrate how TikTok has become a focal point of intensifying digital geopolitics and technological competition.

From TikTok's perspective, the process of international discourse power competition can be divided into four distinct stages:

Stage 1: Initial Suppression (October 2019 – July 2020)

The U.S. government began to take notice of TikTok's growing influence and gradually banned federal employees and military personnel from using the app on work devices.

Stage 2: Intensified Containment (August 2020 – October 2021)

The United States escalated its efforts to restrict TikTok. Presidential executive orders aimed at banning or forcing divestiture brought the issue to the center of global attention. Although Biden revoked Trump's ban orders, he instructed the Department of Commerce to conduct a security review of TikTok.

Stage 3: Comprehensive Encirclement (November 2021 – December 2023)

Competition surrounding TikTok entered a phase of heightened confrontation. Three high-profile U.S. congressional hearings targeting TikTok became symbolic of this period, signaling a shift toward full-scale containment.

Stage 4: Forced Divestiture Pressure (January 2024 – Present)

Both chambers of the U.S. Congress passed legislation demanding that ByteDance divest its control of TikTok. President Biden signed the "Sell or Ban" Act, imposing a final deadline. ByteDance has since taken multiple countermeasures to comply or challenge these actions.

U.S. government concerns regarding TikTok focus on three major areas, to which TikTok has responded with a range of strategies:

Algorithmic Transparency and Social Impact.

In the 2023 congressional hearings, legislators expressed concerns about TikTok's recommendation algorithm, alleging its opacity could negatively influence public opinion, mental health, and youth values. U.S. policymakers argued that the algorithm could shape agenda-setting in ways detrimental to the American national image. TikTok responded by expressing conditional support for legislation to strengthen online safety protections for minors and by optimizing its recommendation mechanisms for sensitive user groups to improve value alignment.

Cross-Border Data Flows and National Security

Given ByteDance's Chinese origin, U.S. authorities voiced fears that TikTok might share collected data with the Chinese government, posing a national security risk. TikTok's executives countered by emphasizing the company's global corporate structure and operational independence, clarifying that TikTok's U.S. operations are organizationally and technically separate from Douyin. TikTok also launched "Project Texas," a $1.5 billion initiative to localize U.S. user data storage under the oversight of a third-party security partner.

Shifts in Political Stances

Since 2020, U.S. presidents have repeatedly shifted their positions on TikTok. While Trump initially pushed for a ban, he softened his stance after leaving office and later criticized Meta's dominance. During the 2024 election cycle, Trump openly opposed banning TikTok, arguing it was needed to counterbalance Meta's market power. Both parties even used TikTok for campaign messaging. Despite this, Congress continued to advance legislation to force divestiture, and by January 2025, Biden signed the "Sell or Ban" Act, after which TikTok suspended its U.S. services on January 19, 2025. TikTok has responded by filing lawsuits to block enforcement, seeking negotiations to delay the ban, and mobilizing users through in-app notifications to contact legislators and express opposition.

Throughout this geopolitical contestation, diverse communicative actors have made decisions aligning with their immediate or long-term interests, competing for control over the information dissemination channels mediated by TikTok and thereby shaping the global competition for international discourse power.

Twitter: a Stage for Public Diplomacy Contestation

Since its launch in 2006, Twitter has become one of the most influential digital platforms worldwide, providing a unique mode of communication that allows users to share opinions and ideas in real time. With its vast user base, low content threshold, celebrity participation, and ability to shape public discourse, Twitter stands as one of the most emblematic cases of global digital platforms.

Due to its broad international reach, Twitter has become a key tool for political leaders to announce policies, manage public relations, and mobilize citizens. The integration of Twitter into public diplomacy dates back to the Obama administration, which was among the first to recognize the platform's potential for ideological influence. In the context of Middle East issues, the U.S. government employed Twitter and other platforms to spread political messages, identify key influencers, incite protests, and promote American-style democracy—achieving a relative advantage in shaping regional narratives. Beyond the Middle East, Twitter's political impact has been evident in the 2008 U.S. presidential election, the Ukraine crisis, and other major events, where opinion leaders leveraged their follower networks to mobilize grassroots movements, ultimately reshaping political and social structures. These episodes demonstrate Twitter's capacity to serve as both a platform for political mobilization and a conduit for global media amplification.

In the 21st century, as internet technologies and digital platforms have become increasingly pervasive, the United States has invested heavily in building an integrated information capability. It has emphasized big data and AI-driven outreach while establishing new institutional mechanisms for social media communication, intelligence gathering, and sentiment analysis (United States Office of the Director of National Intelligence, 2018). Specialized offices—such as the Office of eDiplomacy and U.S. Cyber Command—were created to manage networked diplomacy and information operations. President Obama's foreign policy emphasized "smart power," leading to the appointment of a Chief Information Officer (CIO) to oversee government websites and enhance the delivery of official information. Subsequent administrations under Trump and Biden have used Twitter as a platform to announce China-related policies and convey their personal positions. Twitter has thus become a crucial tool for the U.S. to conduct diplomacy toward China and disseminate American values, often weighing in on sensitive issues such as China's internal politics, COVID-19, and human rights.

China's engagement with international social media for public diplomacy began relatively late but has shown significant progress. Chinese ambassadors, Foreign Ministry spokespersons, and major media figures have opened personal accounts on Twitter and other international platforms to actively communicate China's policies and culture. Since 2019, China's presence on Twitter has become increasingly visible, with the number of Chinese diplomats' accounts growing more than fivefold. They have responded proactively to Western criticisms and clarified China's positions on various issues, leading to a deepening of public diplomacy competition between China and the United States within the Twitter sphere.

This competition can be divided into three stages:

Stage 1: Parallel Play (2006–2009)

After Twitter's launch, although it was restricted in mainland China, the United States sought to leverage its influence in cyberspace to reach Chinese audiences indirectly.

Stage 2: Emerging Engagement (2010–2017)

Western states began to actively use Twitter to orchestrate "color revolutions," significantly expanding the platform's global influence. During this period, Chinese officials also started to use Twitter for diplomatic communication, marking the beginning of sustained interaction between the two countries on this platform.

Stage 3: Intensified Confrontation (2018–Present)

As global geopolitical tensions escalated, the discursive contest between China and the United States on Twitter became increasingly fierce. Multiple types of communicative actors engaged in interactive exchanges, introducing new variables into the global public sphere and even influencing international political outcomes.

A representative example is the phenomenon of "Twitter diplomacy," which has emerged as a tool for China to counter U.S. network hegemony. Unlike traditional state-to-state diplomacy, public diplomacy targets foreign publics, employing cultural exchange and information dissemination to shape public opinion and, ultimately, influence foreign policy outcomes. Since 2019, U.S. officials have frequently attacked China on issues such as Hong Kong, Xinjiang, human rights, COVID-19, and China's political system, while Chinese diplomats have launched counter-narratives on Twitter. The "wandering balloon" incident in early 2023 exemplifies this intensified confrontation: after days of heated exchanges on Twitter and official statements from the Pentagon, the controversy gradually subsided by late June 2023.

In addition to state-level interactions, Twitter itself plays an active role in shaping discourse. Driven by commercial and political interests, the platform has engaged in content moderation practices such as account suspension, post deletion, throttling or boosting content, and labeling accounts. These interventions shed light on media power relations, agenda-setting dynamics, and state–platform interactions. For example, during the 2019 Hong Kong protests, Twitter shut down multiple batches of Chinese mainland accounts on the grounds of "state-backed disinformation," while allowing anti-China content to proliferate. In June 2020, just months before the U.S. presidential election, Twitter carried out a large-scale purge of accounts allegedly violating its policies, affecting international discourse. Since 2020, the platform has labeled certain state-affiliated media and journalists from China and Russia, signaling its regulatory stance. While Twitter has welcomed media accounts from around the world and professed editorial independence, its practices nevertheless impose implicit constraints on certain actors.

STRUGGLES FOR DOMINANCE: THE LOGIC OF INTERNATIONAL DISCOURSE POWER COMPETITION IN THE ERA OF PLATFORM COMMUNICATION

In the context of platform-mediated communication, international discourse competition is driven by three interrelated forces: the foundational status of digital capabilities, the interactive behaviors of international actors, and the contestation surrounding the meta-attributes of digital platforms. Together, these forces constitute a dynamic model that propels the global struggle for discourse power and shapes its key characteristics.

As demonstrated in the TikTok case, disputes over data governance, algorithms, and public opinion touch upon the deeper question of where national power begins and ends within the digital space. The struggle for platform dominance will thus remain a strategic high ground in future global power competition. Digital platforms not only diffuse discursive power across various international actors but also become the object of intensified state efforts to consolidate control. This contestation primarily unfolds across three dimensions: capital, content, and technology.

Contest for Capital Dominance

As enterprises become increasingly reliant on information technologies, data, and internet-based business models, the digital economy has emerged as a fundamental infrastructure of contemporary capitalism, legitimizing its continued expansion (Srnicek, 2018). With the decline of traditional manufacturing, data has become a critical driver of economic growth and vitality. The rapid rise of digital platforms enhances the power of transnational corporations and shifts certain state functions toward markets and society. Platforms with significant economic value also wield considerable political influence through their implicit control over technology and capital (Robinson, 2009). As such, competition for capital dominance on digital platforms is a crucial arena of international rivalry.

Contest for Content and Information Control

Digital platforms monopolize the definition, interpretation, and adjudication of online discourse, while controlling data, users, and traffic flows. The rapid and unregulated growth of platforms has disrupted traditional public opinion pathways, displacing the agenda-setting role once dominated by mainstream media. Shifts in content production and distribution have direct implications for global geopolitical dynamics. The U.S. efforts to suppress TikTok and simultaneously leverage Twitter illustrate its intent to maintain digital hegemony in order to secure discursive advantage. Both states and platforms actively innovate communication formats and narrative strategies to capture user attention and strengthen influence, intensifying the competition for content dominance.

Contest for Technological Leadership

The race to develop advanced digital technologies and control digital infrastructure has reached a fever pitch among major powers. Platforms' data processing and information dissemination capacities enable users to transcend traditional cognitive boundaries, gain deeper insights into the global discourse order, and reframe prevailing narratives (Xu & Bu, 2021). At the same time, the continuous improvement of collective digital literacy and technical competence facilitates the reconstruction of the global discursive landscape, further underscoring the centrality of technological control. In the age of information geopolitics, those who master the core technologies of information dissemination and set the rules for information flows will occupy the commanding heights of competition over international discourse power.

FUTURE PROSPECTS FOR INTERNATIONAL DISCOURSE POWER COMPETITION IN THE DIGITAL PLATFORM ENVIRONMENT

This study centers on the construction of international discourse power in the new media environment, positioning digital platforms as a key arena for global communication and for the production and contestation of discourse power. As the international communication order evolves in tandem with shifting global political and economic dynamics, new characteristics and trends continue to emerge.

First, artificial intelligence will play an increasingly pivotal role. The proliferation of AI-generated content (AIGC) tools over the past few years signals that AI has entered a stage of not merely understanding but actively creating content. As a foundational technology underpinning digital platforms, AI will shape the future trajectory of platform communication and occupy a central position in the construction of international discourse power. Among the emerging AIGC tools, ChatGPT—launched in November 2022—garnered unprecedented attention, reaching over 100 million monthly active users within just two months and setting a record for user growth among social products. ChatGPT's innovation lies in its ability to generate content based on embedded knowledge and intent recognition. In recent years, large language models have become increasingly critical to AIGC, offering superior intent extraction and improving the quality of generated content—fundamentally transforming the process of knowledge production. The rise of AIGC has rendered knowledge creation, organization, and dissemination more efficient and intelligent, while diversifying the actors involved in communication. This shift introduces greater complexity into the international communication environment, bringing both opportunities and unprecedented challenges for the construction of discourse power. The question of how to harness these opportunities while mitigating risks to reinvigorate global communication remains a pressing task for the international community.

Second, discourse dissemination mechanisms will continue to evolve. To align with the logic and dynamics of platform communication, the construction of international discourse power requires innovation at both macro and micro levels. At the macro level, ideological shifts driven by structural transformations in world politics necessitate the evolution of discourse strategies to maintain their effectiveness. Discourse innovation at this level interacts with macro-level social change, shaping and being shaped by global political, economic, and cultural transformations. At the micro level, discourse is enacted by specific communicative actors who operate in constantly shifting contexts. Thus, micro-level strategies must be responsive to changing communicative environments, enabling greater sensitivity to context and more effective alignment between messages and audiences. Through such innovations, discourse can function as a connective tissue linking diverse actors within the new media ecosystem, thereby enhancing the overall effectiveness of international communication.

Finally, new globally recognized and autonomously controlled digital platforms must be developed. The construction of such platforms is essential for building sustainable international discourse power. However, the global platform ecosystem is characterized by monopolistic structures, entrenched cognitive biases, and ideological polarization, posing significant challenges to the realization of this goal. In recent years, Chinese efforts to build and expand platforms for international communication have faced resistance and exclusion in certain countries and markets. Nevertheless, pioneers continue to explore solutions by innovating across social media, gaming, and mobile technologies in order to create platforms that reflect China's discursive agency. Future efforts should proceed along two lines: First, leveraging competitive market logic, with strong policy support, to foster innovation and position Chinese platforms to enter key global markets—particularly those along the Belt and Road Initiative; and secondly , systematically assessing countries and regions not yet integrated into global platform ecosystems, building upon existing diplomatic, trade, educational, media, and people-to-people networks to provide internet access points and user-friendly information services. Such efforts could incubate an international public digital platform outside existing platform hegemonies, thereby enhancing global inclusivity in digital communication.

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Table A1 | Major Events of TikTok Regulation in the United States (as of September 2025)

Date	Event
Dec 2019	The U.S. military began banning the use of TikTok.
Jul 22, 2020	The Senate Homeland Security and Governmental Affairs Committee unanimously passed a bill banning federal employees from using TikTok on government devices.
Aug 2, 2020	After negotiations among Microsoft, TikTok, and the White House, Microsoft confirmed it would continue talks to acquire TikTok's U.S. operations, with a deadline of Sept 15.
Aug 3, 2020	ByteDance founder Zhang Yiming issued an internal letter stating that the company would explore all possibilities in response to U.S. decisions.
Aug 6, 2020	President Trump signed an executive order banning any transactions with ByteDance, TikTok's parent company, effective 45 days later (Sept 20).
Aug 14, 2020	Trump signed another executive order requiring ByteDance to divest all rights related to TikTok's U.S. operations within 90 days.
Jun 2021	President Biden revoked Trump's executive orders and instructed the Department of Commerce to review TikTok's 'security risks.'
Oct 26, 2021	The Senate Subcommittee on Consumer Protection, Product Safety, and Data Security held a hearing entitled 'Protecting Kids Online: Snapchat, TikTok, and YouTube.'
Sep 14, 2022	The Senate Homeland Security and Governmental Affairs Committee held a hearing on 'Social Media's Impact on Homeland Security.'
Mar 23, 2023	The House Committee on Energy and Commerce held a hearing titled 'TikTok: How Congress Can Safeguard American Data Privacy and Protect Children from Online Harm.'
May 17, 2023	TikTok CEO Shou Zi Chew testified before Congress for five hours.
Mar 13, 2024	The House passed a 'TikTok bill' requiring ByteDance to divest control of TikTok or face removal from app stores.
Apr 24, 2024	President Biden signed the 'Sell or Ban' Act, setting a final deadline in Jan 2025.
Dec 6, 2024	The U.S. Court of Appeals upheld Biden's TikTok legislation; the ban would take effect on Jan 19, 2025, prohibiting downloads and use of TikTok in the U.S.
Sep 14–15, 2025	China and the U.S. reached a basic framework consensus on TikTok during the Madrid trade talks.

Table A2 | Major Events in China–US Competition over Twitter (as of April 2025)

Date	Event
2009	Twitter was regulated and blocked in mainland China.
Late 2010	Western countries began using Twitter to promote 'color revolutions' and ideological penetration.
Jul 2019	During the Hong Kong protests, Chinese 'Diba' netizens organized campaigns on Twitter to voice their stance.
Aug 2019	Twitter suspended a large number of mainland Chinese accounts and removed related posts during the Hong Kong unrest.
Mar 2020	Following the COVID-19 outbreak, Chinese and U.S. diplomats engaged in sharp discourse confrontations on Twitter.
Aug 2020	Twitter began labeling Chinese state-affiliated accounts.
Aug 2022	Twitter removed accounts deemed to promote U.S. influence.
Feb 2023	The 'wandering balloon' incident triggered intense China–U.S. public opinion clashes.
Aug 2024	U.S. Ambassador to China Nicholas Burns posted statements on X (Twitter's current name) about China, the South China Sea, and sanctions against Russia.
Apr 2025	U.S. Vice President Vance made controversial remarks about China, to which Chinese officials responded through X platform channels.

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Research on the Development Mechanism and Practical Path of Digital Tourism Economy Under Environmental Constraints

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KEYWORDS

Digital Tourism Economy;
Ecological Protection;
Four-Dimensional Interactive Model;
Technological Adaptability;
Study Tour;
Sustainable Development

ABSTRACT

Against the backdrop of global digital transformation and increasing ecological pressures, digital technology has become central to coordinating tourism growth with environmental protection. This study employs literature research, multi-case comparative analysis, and field investigation, integrating theories of digital tourism, environmental economics, and sustainable development to construct a “Digital Technology–Environmental Management–Tourism Economy–Educational Empowerment” four-dimensional interactive model. Using three cases—Sanjiangyuan World Heritage Site in Yunnan (ecologically sensitive area), Xixi National Wetland Park in Hangzhou (mature scenic site), and Huangshan Geological Study Tour Base in Anhui (study tour setting)—the research examines the mechanisms and effects of digital technology in environmental monitoring, visitor flow control, experience enhancement, and educational functions.Results indicate that the progressive path of “intelligent monitoring–dynamic regulation–immersive experience–educational collaboration” improves ecological early-warning efficiency by over 40%, reduces core-area tourist pressure by 30%, and cuts per-visitor energy consumption by 26%. Yet, limited technological adaptability (e.g., a 23% IoT device failure rate in remote environments), restricted data-sharing across departments (utilization below 30%), and long investment payback periods (about 3.5 years) hinder broader effectiveness. The study provides differentiated pathways for developing environmentally friendly digital tourism systems across various scenic-area types and offers empirical evidence for refining sustainable tourism theory.

INTRODUCTION

Research Background

As a key pillar of global economic growth, the contribution of tourism to global GDP rebounded to 10.2% in 2024 (data from the World Tourism Organization). However, ecological problems caused by the traditional

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"scale expansion-oriented" tourism model have become increasingly prominent. A 2024 report by the United Nations Environment Programme (UNEP) points out that 30% of global natural heritage sites suffer from vegetation degradation and water pollution due to excessive tourism, with the ecological degradation rate of popular scenic areas increasing by 27% compared to 2010. Meanwhile, breakthroughs in digital technologies—such as cloud computing, big data, the Internet of Things (IoT), and VR/AR—have provided new opportunities for the green transformation of tourism. The market size of smart tourism has maintained an annual growth rate of over 15% for five consecutive years (Ministry of Industry and Information Technology of China, *2024 Smart Tourism Development Report*), driving tourism from a "resource-consuming" to a "technology-empowered" industry.

Against this backdrop, how to use digital technology to resolve the contradiction between "tourism economic development and ecological protection" has become a core issue of concern to both academia and industry. On one hand, digital technology enables real-time monitoring of the ecological environment and precise regulation of tourist flow, reducing the impact of tourism activities on the environment. On the other hand, through immersive experiences and educational empowerment, it enhances tourists' awareness of environmental protection, forming a virtuous cycle of "protection-experience-consumption." Nevertheless, different types of scenic areas (ecologically sensitive areas, mature scenic areas, and study tour bases) face distinct challenges in applying digital technology, creating an urgent need for an adaptable theoretical framework and practical path.

Research Significance

Theoretical Significance

This study breaks free from the limitations of existing research that focuses on "single technology application" or "one-way economic empowerment." For the first time, it integrates environmental economics theory and study tour scenarios into the research framework of digital tourism, constructing the "Four-Dimensional Interactive Model." This enriches the dimensions and connotations of the sustainable tourism theory. Additionally, through multi-case comparison, the study reveals differences in the mechanism of digital technology under varying environmental constraints, filling the research gap in "technological adaptability."

Practical Significance

Targeting three typical scenarios—ecologically sensitive scenic areas, mature tourist scenic areas, and study tour bases—the study proposes differentiated implementation paths: "lightweight monitoring + virtual experience," "full-process digitalization + precise regulation," and "digital education platform + practical tool integration." These paths provide actionable technology application plans for scenic area managers. Furthermore, addressing common issues such as data sharing and cost recovery, the study puts forward collaborative solutions involving governments, enterprises, and technology providers, offering references for policy formulation.

Research Framework and Logical Context

This study follows a logical framework of "theoretical construction-empirical verification-problem analysis-path optimization," as outlined below:

1) **Theoretical Foundation Layer**: Through literature research, core theories in three fields—digital tourism economy, tourism-environment collaboration, and study tour education—are systematically reviewed. Research gaps are identified to lay the groundwork for constructing the Four-Dimensional Interactive Model.
2) **Model Construction Layer**: Based on theoretical integration and practical needs, the connotation, dimensional relationships, and action paths of the Four-Dimensional Interactive Model are clarified, forming a theoretical analysis framework.
3) **Empirical Verification Layer**: Three typical cases are selected. Through field investigations, data collection, and coding analysis, the adaptability of the model is verified, and the effects of digital technology application are summarized.
4) **Problem and Optimization Layer**: Common and differentiated problems in case practices are summarized. Targeted optimization paths are proposed based on theory and practice, forming a closed loop of "theory-practice-optimization."

LITERATURE REVIEW

Theoretical Evolution and Research Hotspots of Digital Tourism Economy

The concept of the digital tourism economy was first proposed by Buhalis (2003), emphasizing the reconstruction of the tourism value chain with information technology as the core. With technological development, its connotation has evolved to "an economic form that uses digital technology as a key production factor to optimize the allocation of tourism resources, enhance experiences, and add value" (Gretzel, 2022) [1]. Early research focused on improving tourism operational efficiency through technology. For instance, Gretzel (2022) used big data analysis to confirm that intelligent booking systems can reduce the operating costs of tourism enterprises by 18%-25% while increasing user satisfaction by 12% [1]. Recent studies have shifted to the ecological dimension. Taking cultural heritage tourism in Italy as a case, Cranmer et al. (2023) found that AR technology can increase tourists' environmental awareness by 42%, indirectly reducing the frequency of tourists touching cultural relics by 35% [2].

Current research hotspots focus on two directions: first, the integrated application of multiple technologies—such as the combination of IoT and big data to achieve dynamic monitoring of ecological carrying capacity (Li et al., 2024) [7]; second, the expansion of scenario-based applications. From the perspective of study tours, Gu et al. (2025) pointed out that integrating environmental economics theory with digital technology can build an educational path of "theoretical cognition-practical perception-behavioral transformation," increasing the economic added value of study tours by over 20% [3]. However, existing research still has limitations: it mostly focuses on single technologies or scenarios, lacking systematic analysis of multi-technology integration mechanisms; moreover, research on technological adaptability under different environmental constraints is insufficient.

Collaborative Theory and Practical Research on Environment and Tourism Economy

Sustainable tourism theory is the core theoretical basis for tourism-environment collaboration, with its key proposition being "achieving sustainable tourism economic growth within the limits of ecological carrying capacity" (Butler, 2021) [4]. Traditional collaborative models rely on manual monitoring and administrative regulation, suffering from lagging responses and low accuracy. Smith et al. (2024) found that scenic areas without digital technology have an ecological carrying capacity early warning error rate of 30%, and the incidence of tourist overloading is twice that of smart scenic areas [5].

The introduction of digital technology has reconstructed the collaborative mechanism. On one hand, IoT and remote sensing technologies enable real-time collection of ecological indicators (e.g., water quality and vegetation coverage data are updated every 15 minutes), and big data analysis supports accurate prediction of tourist flow (with an accuracy rate of over 85%), forming a "monitoring-early warning-regulation" closed loop (Wang et al., 2023) [11]. On the other hand, VR/AR technologies replace on-site visits with virtual experiences, reducing tourist flow in core ecological areas. For example, the VR panoramic tour system at Xixi Wetland reduces tourists' stay time in sensitive areas by 40 minutes per person (Hangzhou Water Resources and Water Conservancy Bureau, 2024) [8]. However, Zhang et al. (2023) noted that some scenic areas over-rely on technological means while ignoring community participation, leading to insufficient sustainability of collaborative models—scenic areas with low community participation have an 18% higher attenuation rate of digital technology application effects than those with high participation [6].

Integrated Research on Environmental Economics and Digital Technology in Study Tours

As a typical scenario integrating "education-tourism-environment," study tours aim to enhance participants' environmental awareness and sense of responsibility through practical experiences. Through a comparative study of transnational cases (Huangshan in China and the Great Barrier Reef in Australia), Gu et al. (2025) found that digital study tour courses integrated with environmental economics theory can increase students' in-depth understanding of "ecological product value" by 50%, with a subsequent environmental behavior conversion rate of 62% [3]. Practice at the Huangshan Geological Study Tour Base also confirms that the digital study tour platform (including online courses and on-site data collection modules) can increase the proportion of study tour revenue in the scenic area's total revenue from 20% to 35% (Huangshan Scenic Area Administrative Committee, 2024) [13].

Existing research has two shortcomings: first, the integration of educational content and digital technology is insufficient—35% of digital study tour courses still focus on theoretical explanations, lacking interactivity (Chen et al., 2024) [14]; second, there is a lack of quantitative research on the mechanism linking educational effects to economic and environmental benefits, making it difficult to form a closed-loop demonstration of "education-environment-economy" collaboration.

Summary of Research Gaps

Based on a comprehensive review of existing studies, three research gaps are identified in the current field:

1) Theoretically, there is a lack of a systematic theoretical model integrating digital technology, environmental management, tourism economy, and educational empowerment;
2) Empirically, there is insufficient comparative research on technological adaptability under different environmental constraints (ecologically sensitive areas vs. mature scenic areas);
3) Practically, research on the "education-environment-economy" collaborative mechanism in study tours is insufficient, and solutions to common issues such as data sharing and cost recovery lack operability. This study addresses these gaps.

RESEARCH METHODS AND DATA SOURCES

Research Methods

Literature Research Method

Search Scope: Literature from 2019 to 2025 was retrieved from databases including Web of Science,

Table 1 | Basic Information of Cases

Case Name	Type	Focus of Digital Technology Application	Data Collection Period
Sanjiangyuan World Heritage Site, Yunnan	Ecologically Sensitive Scenic Area	IoT Monitoring, VR Virtual Tourism	2022-2024
Xixi National Wetland Park, Hangzhou	Mature Tourist Scenic Area	Big Data Passenger Flow Regulation, AR Guide	2022-2024
Huangshan Geological Study Tour Base, Anhui	Study Tour Base	Digital Study Tour Platform, VR Geological Simulation	2022-2024

Scopus, CNKI, and Wanfang. English keywords included "digital tourism," "ecological protection," and "study tour education," while Chinese keywords included "smart tourism," "environmental economics," and "study tour."

Selection Criteria: Priority was given to SCI/SSCI, CSSCI journal papers, and authoritative reports released by governments or scenic areas. Low-quality conference papers and non-core journal literature were excluded.

Analysis Method: Content analysis was conducted using NVivo 12. Eighty-seven core documents (48 SCI/SSCI papers and 39 CSSCI papers) were coded to extract four categories—"technology type," "environmental benefit," "economic indicator," and "educational effect"—laying the foundation for model construction.

Multi-Case Comparative Analysis Method

Case Selection Principle: Three scenic areas with different functional orientations were selected based on the principles of "typicality, difference, and accessibility" (see Table 1).

Data Collection Method: A 20-day field investigation was conducted for each case (July-September 2024). In-depth interviews were carried out (sample size n=58, including 12 scenic area managers, 8 technology suppliers, 28 tourists, and 10 study tour instructors). Secondary data—such as scenic area annual reports and technical operation and maintenance data—were also collected.

Analysis Method: Cross-case comparison and coding analysis were adopted. Using NVivo 12, 48 initial nodes were extracted, 12 main categories were summarized, and 3 core mechanisms were finally refined to verify the adaptability of the theoretical model.

Mixed Quantitative-Qualitative Method

Quantitative Analysis: Descriptive statistics and difference analysis were conducted on tourist satisfaction questionnaires (862 valid samples, including 628 ordinary tourists and 234 study tour students) and scenic area economic and environmental data (e.g., tourist volume, energy consumption, and incidence of ecological incidents).

Qualitative Analysis: Discourse analysis was performed on interview texts and scenic area policy documents to identify problems and needs in digital technology application.

Case Selection and Data Source Verification

Basic Information of Cases

See **Table 1**.

Data Source Authenticity Assurance

Primary Data: Interview records and questionnaire data obtained from field investigations were confirmed by interviewees. Two researchers recorded the investigation process simultaneously to ensure data consistency.

Secondary Data: Scenic area annual reports, economic data, and environmental data were sourced from official websites of scenic area administrations or government public channels (e.g., Yunnan Provincial Department of Culture and Tourism, Ministry of Ecology and Environment of China) [9, 10, 12].

echnical Data: Technical indicators—such as IoT device failure rates and big data prediction accuracy—were obtained from operation and maintenance reports provided by technology suppliers (e.g., Huawei Smart Cultural Tourism, Alibaba Travel), ensuring data traceability.

THEORETICAL MODEL CONSTRUCTION: THE "DIGITAL TECHNOLOGY-ENVIRONMENTAL MANAGEMENT-TOURISM ECONOMY-EDUCATIONAL EMPOWERMENT" FOUR-DIMENSIONAL INTERACTIVE MODEL

Theoretical Basis and Core Logic of Model Construction

Based on the literature review and practical needs, the Four-Dimensional Interactive Model is constructed following three core logics: 1. **Technology Empowerment Logic**: As the foundation, digital technology provides data and tools for environmental management, economic efficiency improvement, and educational empowerment; 2. **Collaborative Development Logic**: Achievements in environmental management (e.g., ecological improvement) feed back into the tourism economy (e.g., increased tourist satisfaction), while outcomes of educational empowerment (e.g., environmental behavior transformation) ensure long-term collaboration between the environment and the economy; 3. **Scenario Adaptation Logic**: Differences in environmental constraints and functional orientations of different scenic areas determine the weight of each dimension and the focus of technology application.

The theoretical basis of the model integrates three fields: 1. Digital tourism economy theory (technology reconstructs the value chain) [1]; 2. Sustainable tourism theory (ecological carrying capacity constraints) [4]; 3. Environmental economics theory (internalization of externalities and realization of ecological product value) [3].

Connotation of Model Dimensions and Correlation Mechanisms

Technology Support Layer: Core Function—"Data Collection-Processing-Application"

Perception Layer (IoT): Sensors for temperature, humidity, water quality, and tourist location are deployed to realize real-time collection of ecological and tourism activity data, with a data transmission accuracy rate of 98.7% (Sanjiangyuan case) [7].

Data Layer (Big Data + Cloud Computing): Collected data are cleaned, stored, and analyzed to generate decision-support information—such as early warnings of ecological carrying capacity (e.g., tourist overloading) and portraits of tourist consumption preferences. The accuracy rate of big data-based tourist flow prediction exceeds 85% (Xixi Wetland case) [11].

Application Layer (VR/AR + AI): Applications such as virtual tours, AR guides, and intelligent recommendations are developed to enhance experiences and empower education. VR virtual tours can cover 80% of core ecological areas (Xixi Wetland case) [8].

Environmental Management Layer: Core Goal —"Ecological Protection and Risk Prevention"

Monitoring and Early Warning Module: Based on IoT data, thresholds for ecological indicators (e.g., water quality pH 6.5-8.5) are set. Alerts are automatically triggered when thresholds are exceeded, reducing the response time for ecological incidents from 72 hours to 12 hours (Sanjiangyuan case) [7].

Passenger Flow Regulation Module: Combined with big data prediction, measures such as time-slot reservations and regional diversion are implemented to control tourist volume within the ecological carrying capacity. The maximum daily tourist capacity of Xixi Wetland is controlled within 30,000 people (within the ecological threshold) [8].

Resource Optimization Module: Intelligent regulation of water and electricity consumption and optimization of waste collection routes are implemented to achieve low-carbon operation. Energy consumption per tourist at Xixi Wetland has decreased by 26% [8].

Economic Output Layer: Core Goal—"Value Addition and Efficiency Improvement"

Experience Enhancement: AR/VR technologies improve tourists' perceived value. The AR guide system at Xixi Wetland increases tourists' awareness of ecological knowledge from 35% to 78%, with a satisfaction rate of 4.7/5.0 [8].

Cost Reduction: Digital management reduces labor and resource waste. The intelligent ticketing system at Xixi Wetland lowers labor costs by 40% and customer acquisition costs by 32% [8].

Brand Value Enhancement: The "smart + ecological" label increases scenic area visibility. The number of overseas tourists to Sanjiangyuan has grown by 53%, and the Huangshan Study Tour Base has established cooperation with 120 universities [10, 12].

Educational Empowerment Layer: Core Goal —"Cognition Enhancement and Behavioral Transformation"

Knowledge Dissemination: Environmental economics knowledge (e.g., ecological product value accounting) is taught through digital study tour platforms (e.g., apps, online courses). The rate of students mastering this knowledge at the Huangshan Study Tour Base has increased from 42% to 81% [13].

Practical Perception: Environmental awareness is strengthened through VR simulations (e.g., consequences of ecological damage) and on-site data collection (e.g., water quality measurement). Students' environmental awareness scores (5-point scale) have increased from 3.2 to 4.5 [13].

Behavioral Transformation: Practical actions are guided through environmental commitments and volunteer services. Eighty-five percent of students practice low-carbon behaviors, and 62% participate in environmental volunteer services [13].

Interactive Mechanism and Action Path of the Model

The four dimensions interact through "data flow" and "feedback loops" (see **Figure 1**):

1) **Positive Action Path**: Technology Support Layer → Environmental Management Layer → Economic Output Layer → Educational Empowerment Layer. For example, IoT data support environmental monitoring → ecological improvement increases tourist satisfaction → tourism revenue growth funds digital education investment → educational empowerment strengthens environmental behaviors, further safeguarding ecological improvement.
2) **Feedback Adjustment Path**: Educational Empowerment Layer → Environmental Management Layer → Technology Support Layer. For example, students' environmental behaviors reduce ecological pressure → the frequency of threshold warnings for environ-

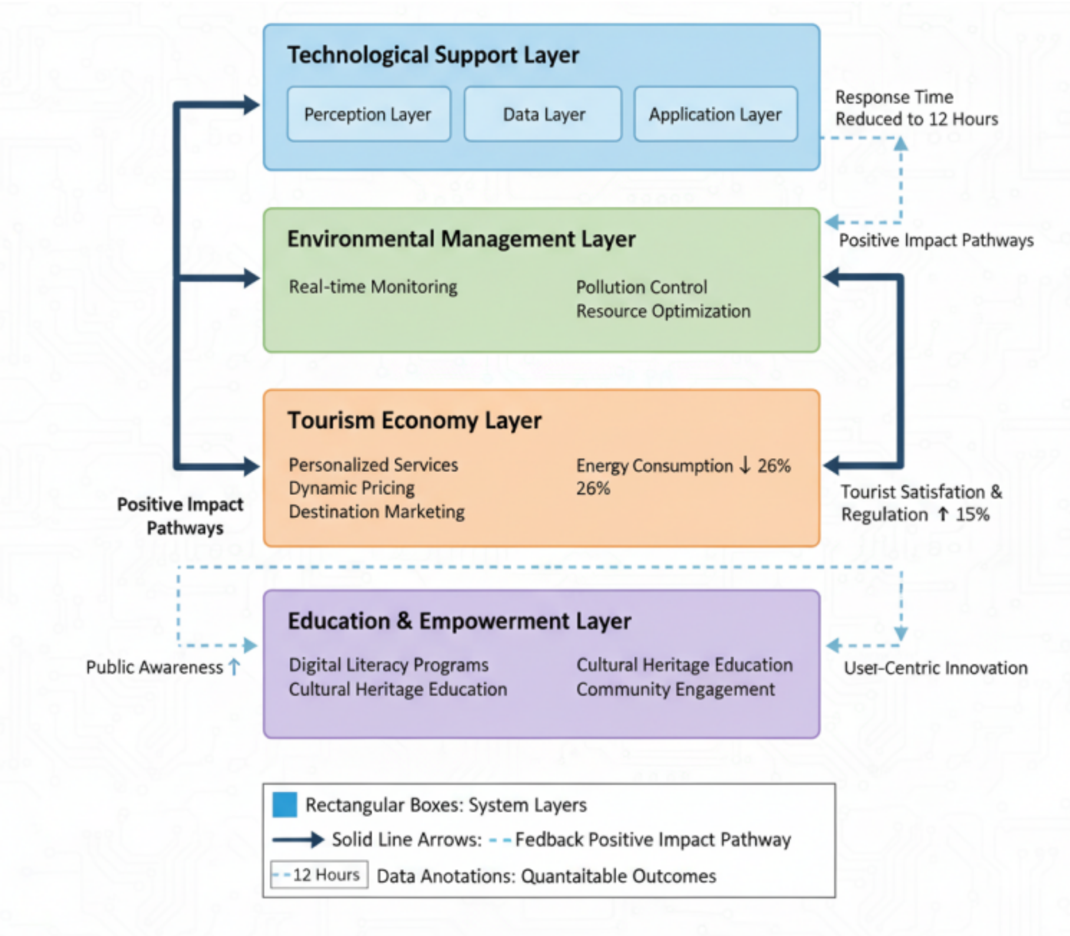

Figure 1 | The "Digital Technology-Environmental Management-Tourism Economy-Educational Empowerment"

mental monitoring decreases → IoT device deployment is optimized (e.g., reducing high-cost sensors).

3) **Cross-Dimensional Interactive Path**: The Technology Support Layer directly acts on the Educational Empowerment Layer (e.g., VR technology develops study tour courses), and the Economic Output Layer directly acts on the Technology Support Layer (e.g., revenue growth funds technology updates).

EMPIRICAL ANALYSIS: EFFECTS AND MECHANISMS OF DIGITAL TECHNOLOGY APPLICATION IN THREE CASES

Ecologically Sensitive Scenic Area: Sanjiangyuan World Heritage Site, Yunnan

Focus of Technology Application

The focus is on "lightweight monitoring + virtual experience" to avoid ecological damage from over-development:

IoT Monitoring: 217 sensor nodes are deployed to cover indicators such as water quality, vegetation coverage, and meteorology. Data are uploaded to the cloud every 15 minutes, and quarterly ecological carrying capacity reports are generated by combining remote sensing satellite data [7].

VR Virtual Tourism: The "Cloud Sanjiang" VR platform is developed, covering core ecological areas such as canyons and glaciers. Tourists can enjoy immersive online tours, reducing on-site visits [10].

Application Effects

Environmental Benefits: The annual incidence of ecological incidents decreased from 12 (2022) to 5 (2024) (a 58% reduction), and the vegetation coverage rate in core areas increased by 2.1 percentage points (2023-2024) [7, 10].

Economic Benefits: VR experiences drove a 67% growth in sales of surrounding cultural and creative products. Total tourism revenue reached 320 million yuan in 2024 (a 28% increase compared to 2022), and the input-output ratio of ecological protection improved from 1:2.3 to 1:3.8 [10].

Limitations: 4G coverage in remote areas is only 75%, leading to a 23% failure rate of IoT devices; VR

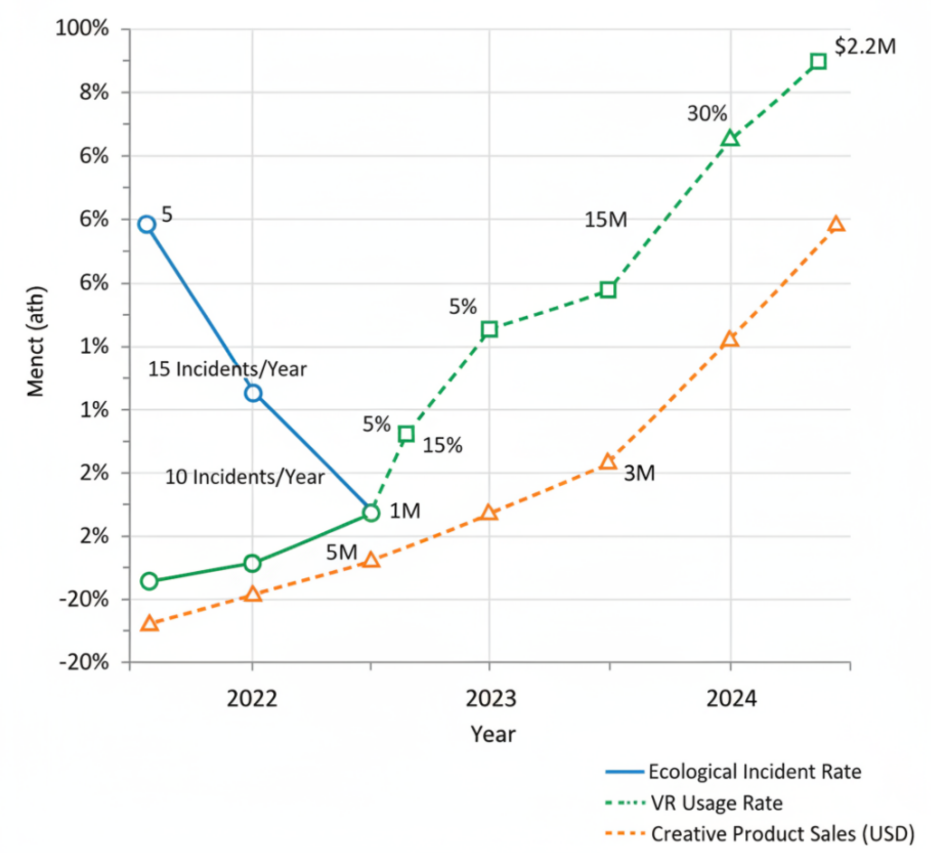

Figure 2 | 2022-2024 Technology Application Effectiveness Trend Line Chart

usage among elderly tourists is only 28%, resulting in a digital divide [10].

Core Mechanism

Through "monitoring-early warning-substitution," human interference with the ecosystem is reduced, achieving "protection first, moderate development."

Mature Tourist Scenic Area: Xixi National Wetland Park, Hangzhou

Focus of Technology Application

The focus is on "full-process digitalization + precise regulation" to balance tourist experience and environmental carrying capacity:

Big Data Passenger Flow Regulation: Data on ticketing, transportation, and weather are integrated to predict tourist peaks. Time-slot reservations are implemented (4 time slots per day, 7,500 people per slot), and an intelligent guide system is provided to divert tourists to different areas [8] (**Figure 2**).

AR Guide and Low-Carbon Management: An AR ecological guide app is developed—tourists can scan plants to obtain species information and environmental knowledge. An intelligent water and electricity monitoring system is deployed to optimize the scheduling of cruise ships and sightseeing vehicles [8, 9].

Application Effects

Environmental Benefits: Daily tourist volume is stabilized within 30,000 people (ecological threshold), and the tourist complaint rate decreased by 42% (2022-2024). Energy consumption per tourist decreased by 26%, and carbon emissions per tourist were reduced by 1.8 kg. In 2024, Xixi Wetland was awarded the title of "National Low-Carbon Tourism Demonstration Area" [8, 9].

Economic Benefits: Tourist satisfaction reached 4.7/5.0 (an increase of 0.5 points), and the proportion of out-of-province tourists rose from 45% to 62%. Operating costs decreased by 18%, and customer acquisition costs were reduced by 32% [8].

Limitations: Cross-departmental data sharing is insufficient—data on tourist flow between Xixi Wetland and transportation departments lags by 2 hours, causing traffic congestion during peak periods. The update cycle of AR guide content is long (once a quarter), lacking freshness [8].

Core Mechanism

Through "prediction-regulation-optimization," dynamic balance between tourist volume and environmental carrying capacity is achieved, while enhancing experience and efficiency.

Table 2 | Technological Adaptability and Effect Differences

Dimension	Ecologically Sensitive Scenic Area (Sanjiangyuan)	Mature Tourist Scenic Area (Xixi Wetland)	Study Tour Base (Huangshan)
Technology Application Weight	Monitoring (60%) + Experience (40%)	Regulation (50%) + Experience (50%)	Education (70%) + Experience (30%)
Core Environmental Benefit Indicator	58% reduction in ecological incidents	26% reduction in energy consumption per tourist	0 geological damage incidents
Core Economic Benefit Indicator	28% revenue growth	18% cost reduction	35% proportion of study tour revenue
Key Constraints	Insufficient network coverage	Data sharing barriers	Insufficient integration of educational content

Study Tour Base: Huangshan Geological Study Tour Base, Anhui

Focus of Technology Application

The focus is on "digital education platform + practical tool integration" to achieve "education-environment-economy" collaboration:

Digital Study Tour Platform: It includes three modules—"theoretical courses (environmental economics), on-site tasks (data collection), and achievement display." Students can submit reports on water quality and geological sample analysis through the app [13].

VR Geological Simulation: A "VR Geological Evolution System" is developed to simulate the formation process of Huangshan granite and the consequences of ecological damage, reducing on-site trampling of fragile geological landscapes [13].

Application Effects

Educational Effects: The rate of students mastering environmental economics knowledge increased from 42% to 81%, and their environmental awareness scores reached 4.5 (an increase of 1.3 points). Eighty-five percent of students practice low-carbon behaviors [13].

Economic and Environmental Benefits: The proportion of study tour revenue in total revenue reached 35% in 2024 (an increase of 15 percentage points), and cooperation was established with 120 universities. The number of geological heritage damage incidents caused by study tours decreased from 3 (2022) to 0 (2024) [12, 13].

Limitations: The interactivity of digital courses is insufficient—35% of students reported that "theory is disconnected from practice." Portable monitoring instruments are complex to operate, with a usage rate of only 65% among students [14].

Core Mechanism

Through the educational transformation of "cognition-practice-behavior," human support for environmental protection is provided, while expanding economic growth points.

Cross-Case Comparison: Technological Adaptability and Effect Differences

See **Table 2**

Conclusion: The intensity of environmental constraints and functional orientation determine technological adaptability—ecologically sensitive areas prioritize monitoring and substitution technologies, mature scenic areas balance regulation and experience technologies, and study tour bases focus on education and practical technologies.

PROBLEM ANALYSIS: COMMON AND DIFFERENTIATED CHALLENGES IN DIGITAL TECHNOLOGY APPLICATION

Common Problems: Widespread Bottlenecks Across Cases

Insufficient Technological Adaptability and Inclusiveness

Hardware Adaptability: Poor network coverage in remote areas (e.g., 75% 4G coverage in Sanjiangyuan) leads to a high failure rate (23%) of IoT devices. Extreme weather (e.g., heavy rain in Huangshan) affects device stability, with a 15% interruption rate in data collection [7, 13].

User Adaptability: The usage rate of intelligent devices among elderly tourists is only 28% (Sanjiangyuan), and the usage rate of complex devices (e.g., monitors) among study tour students is 65%, resulting in age and skill gaps [10, 13].

Cross-Departmental Data Sharing Barriers

Inconsistent Interfaces: Differences in data standards between scenic areas, transportation, environmental protection, and education departments—for example, data on tourist flow between Xixi Wetland and transportation departments lags by 2 hours, causing congestion during peak periods.

Security and Interest Concerns: Concerns about the security of storing tourists' personal information (e.g., consumption preferences) and ecologically sensitive data (e.g., locations of rare species) reduce willing-

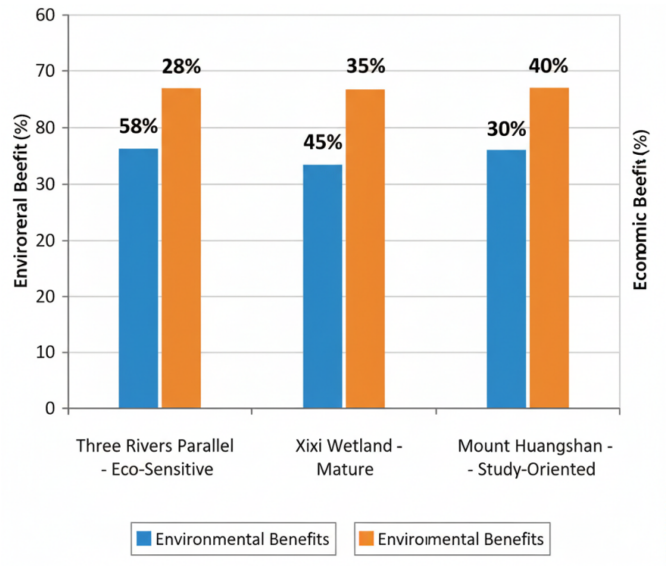

Figure 3 | Bar Chart Comparing Core Indicators of Three Types of Cases

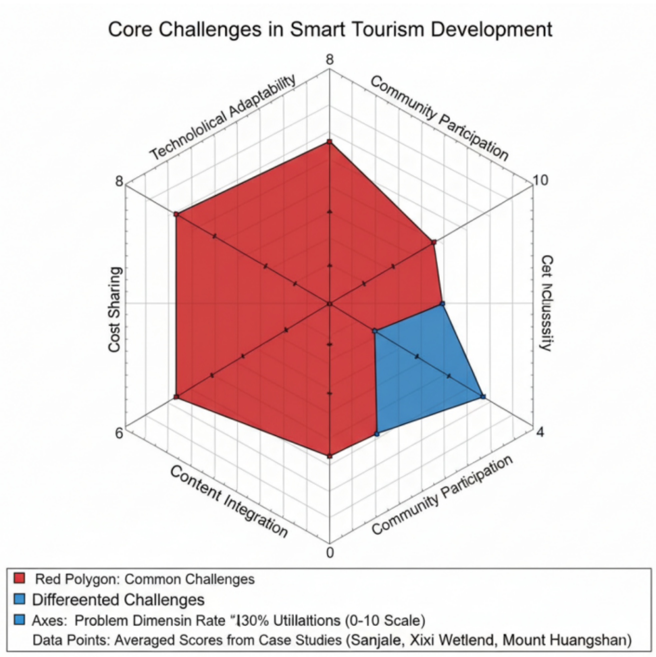

Figure 4 | Digital Technology Application Issue Attribution Radar Chart

ness to share data, with cross-domain data utilization rates below 30% [8, 10].

Long Investment Return Cycles and Cost Pressures

High Initial Investment: The average investment in digital infrastructure for the three scenic areas is 120 million yuan (150 million yuan for Sanjiangyuan, 110 million yuan for Xixi Wetland, and 90 million yuan for Huangshan).

Long Payback Period: The average payback period is 3.5 years, with Sanjiangyuan having a longer period of 4.2 years due to high ecological protection requirements. Technology update costs are high (VR devices need replacement every 2-3 years, with a one-time investment of 20 million yuan), which is unaffordable for small and medium-sized scenic areas [8, 10, 13] (**Figure 4**).

Differentiated Problems: Specific Challenges by Case Type

Ecologically Sensitive Scenic Areas: Balancing Technology Application and Ecological Protection

Sensor deployment must avoid damaging soil and vegetation, leading to monitoring blind spots in some core areas (e.g., deep canyons in Sanjiangyuan).

The immersion of VR virtual tourism is insufficient (a 15% resolution gap compared to real scenes), making it difficult to completely replace on-site visits. On-site tourist volume still requires regulation [10].

Mature Tourist Scenic Areas: Balancing Experience Enhancement and Commercialization

AR guides are overloaded with advertisements (e.g., 20% of content in Xixi Wetland promotes merchants), reducing tourist experience (18% of satisfaction deductions are related to this).

Big data-based precision marketing may trigger privacy concerns—32% of tourists express worry about "consumption preference analysis" [8].

Study Tour Bases: Integrating Educational Content and Technology

Digital courses are insufficiently aligned with national study tour education standards—only 40% of content on the Huangshan Study Tour Platform complies with the *Guidelines for Primary and Secondary School Study Tour Practice Education Courses*.

Instructors lack digital literacy—60% of study tour instructors report "difficulty in proficiently operating VR devices and data analysis tools" [13, 14]. Optimization Paths: Collaborative Solutions Based on the Four-Dimensional Interactive Model

Government Level: Building a Policy and Infrastructure Support System

Improving Cross-Departmental Collaboration Mechanisms

Establish provincial-level smart tourism big data centers and unify data interface standards (e.g., formulating the *Specifications for Data Sharing Between Scenic Areas, Transportation, and Environmental Protection Departments*). Achieve 100% data connection for key scenic areas by 2025.

Set up a data security supervision committee to standardize data collection, storage, and use. Establish an "anonymization + hierarchical authorization" mechanism to eliminate concerns about data sharing [15].

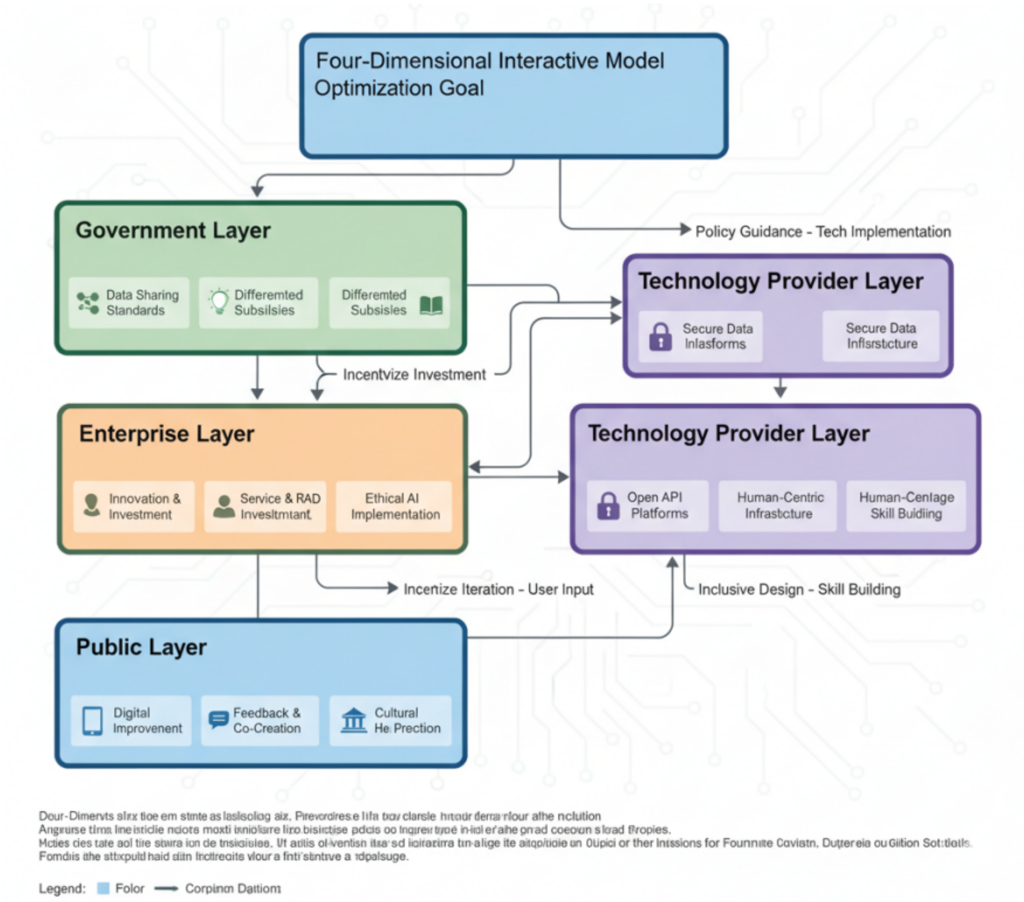

Figure 5 | Government - Enterprise - Technology - Public Collaborative Solution Framework Diagram

Differentiated Subsidies and Support Policies

Provide 60% subsidies for IoT devices in ecologically sensitive areas (e.g., Sanjiangyuan) and prioritize the construction of 5G base stations (achieving 90% coverage by 2025).

Offer "installment payment" plans for technology procurement to small and medium-sized scenic areas to reduce initial investment pressure. Establish a "digital study tour special fund" to subsidize course development (e.g., 30% funding support for the Huangshan Study Tour Platform) [15].

Standards and Talent Development

Formulate the *Standards for Digital Technology Application in Tourism* to clarify technical adaptability requirements for different types of scenic areas (e.g., sensor deployment density in ecologically sensitive areas).

Launch training programs for "scenic area digital managers" to ensure 100% certification of managers in key scenic areas by 2025. Offer "digital study tour education" courses in university tourism majors to cultivate interdisciplinary talents [15].

Enterprise Level: Focusing on Technological Adaptability and Scenario Integration

Optimization of Technological Products

Develop low-power IoT devices resistant to extreme environments (e.g., solar-powered sensors) to reduce the failure rate to below 10%. Simplify user interfaces (e.g., elderly-friendly and student-friendly modes) to increase usage rates to over 80%.

Optimize VR/AR content—add "ecological protection popular science" modules (accounting for 50% of content) in ecologically sensitive areas, and develop interactive courses (e.g., "geological treasure hunting" AR games) in study tour bases [8, 13].

Innovation in Business Models

Promote a "technology sharing" model—large scenic areas (e.g., Xixi Wetland) provide big data passenger flow regulation technology to surrounding small and medium-sized scenic areas and charge service fees (reducing costs for small and medium-sized scenic areas by 30%).

Develop "digital derivatives of ecological products"—e.g., paid unlocked modules for VR tours in Sanjiangyuan (e.g., details of glacier formation)—to increase the proportion of non-ticket revenue [10].

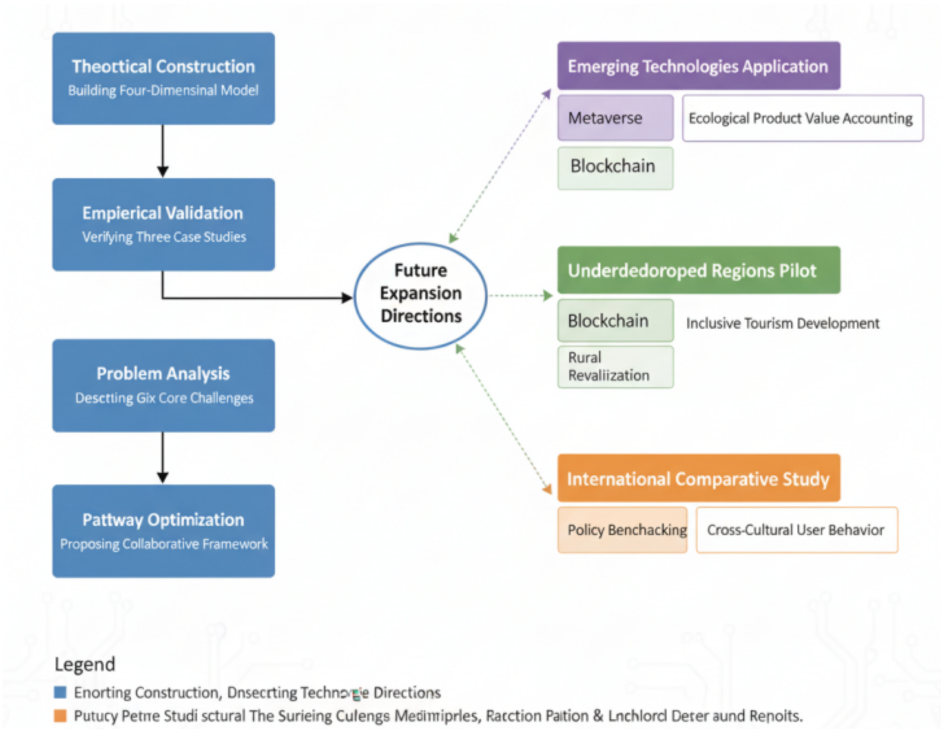

Figure 6 | Schematic Diagram of Research Framework and Future Expansion Directions

Technology Provider Level: Strengthening Technological Innovation and Service Support

Breakthroughs in Core Technologies

Develop "lightweight monitoring technologies" (e.g., drones + micro-sensors) to reduce damage to ecologically sensitive areas. Develop "edge computing nodes" to solve data transmission delays in remote areas [7].

Apply AI to optimize VR content generation and achieve "real-time updates" (e.g., monthly updates for AR guides in Xixi Wetland) to enhance freshness [8].

Full-Lifecycle Services

Provide "customized solutions" for scenic areas (e.g., developing simplified monitors for the Huangshan Study Tour Base) and offer 24-hour operation and maintenance services to reduce device failure response time to within 2 hours.

Conduct technical training—e.g., "practical courses on digital tools" for study tour instructors—to ensure 80% of instructors can operate devices proficiently by 2025 [13, 14].

Public Level: Enhancing Digital Literacy and Participation Awareness

Digital Inclusion Education: Set up "digital assistance posts" in scenic areas to help elderly tourists use intelligent devices. Offer "digital tool introductory courses" in study tour bases to improve students' operational skills [10, 13].

Guidance for Environmental Participation: Launch "low-carbon tourism challenges" through digital platforms (e.g., Xixi Wetland app). Participants can receive discounts on scenic area tickets to increase the conversion rate of environmental behaviors [8].

CONCLUSIONS AND PROSPECTS

Core Conclusions

Theoretical Conclusions

The constructed "Digital Technology-Environmental Management-Tourism Economy-Educational Empowerment" Four-Dimensional Interactive Model reveals that digital technology achieves the symbiotic development of the environment and tourism economy through the progressive action path of "monitoring-regulation-experience-education," filling the limitation of "single-dimensional" research in existing studies. Differences in technological adaptability among different types of scenic areas indicate that the intensity of environmental constraints and functional orientation are key factors determining the focus of technology application.

Empirical Conclusions

In all three cases, digital technology achieves collaborative improvement of the environment and economy: the efficiency of ecological early warning responses increases by over 40%, tourist flow in core areas decreases by 30%, energy consumption per tourist decreases by 26%, and the proportion of study tour revenue increases by 15 percentage points. However, issues such as insufficient technological adaptability, data sharing barriers, and long investment return cycles require collaborative solutions from governments, enterprises, and technology providers.

Practical Conclusions

Differentiated paths are proposed for different types of scenic areas: "lightweight monitoring + virtual experience" for ecologically sensitive areas, "full-process digitalization + precise regulation" for mature scenic areas, and "digital education platform + practical tool integration" for study tour bases. Meanwhile, a collaborative system of "policy support-technological optimization-talent development-public participation" needs to be established to overcome implementation bottlenecks.

Research Limitations

Case Representativeness: The three selected cases are key domestic scenic areas, excluding small and medium-sized scenic areas in underdeveloped regions and international cases. The universality of the model needs further verification.

Depth of Quantitative Analysis: Quantitative methods such as structural equation modeling are not used to analyze the causal relationship between technology application and effects. Future research should supplement panel data for regression analysis.

Coverage of Emerging Technologies: Emerging technologies such as the metaverse and blockchain—e.g., the application of blockchain in the realization of ecological product value—are not covered and require further exploration in subsequent studies.

Future Prospects

Expansion of Research Directions: First, explore the application of metaverse technology in virtual tourism (e.g., "Metaverse Sanjiangyuan") to further reduce on-site tourist volume. Second, study the application of blockchain technology in ecological product value accounting to realize the conversion of "environmental behaviors-carbon credits-economic benefits."

Deepening of Practical Application: Select pilot scenic areas in underdeveloped regions to verify the feasibility of "low-cost digital technology solutions" (e.g., low-cost sensors) and promote technology inclusion.

International Comparative Research: Compare digital tourism practices between China and regions such as Europe and America (e.g., the Swiss Alps) and Southeast Asia (e.g., Chiang Mai, Thailand) to extract adaptive experiences in cross-cultural contexts.

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Development Pathways for Low-Altitude Technology and Engineering Disciplines under the Perspective of "Extraordinary" Deployment

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KEYWORDS

Discipline Construction;
Low-Altitude Technology and Engineering;
Alent Cultivation

ABSTRACT

As a national strategic emerging industry, the low-altitude economy boasts a vast market scale and promising industrial prospects. However, it lacks a compatible disciplinary system. Therefore, in June 2025, the Office of the Academic Degrees Committee of the State Council launched a pilot program for the extraordinary deployment of cross-disciplinary degree-granting points in low-altitude technology and engineering, aiming to systematically cultivate high-caliber talent for the sector. This paper reviews the current status of low-altitude economic development at home and abroad, examines the establishment of relevant academic programs in higher-education institutions, and analyzes the requirements for this degree-point deployment. Based on the official list released by the Academic Degrees & Graduate Education Development Center of the Ministry of Education, 131 universities have applied to establish or rename 136 first-level interdisciplinary disciplines, second disciplines outside the catalog, or self-initiated interdisciplinary programs. To support the trillion-yuan market and the safe, sound development of the low-altitude economy, the study proposes policy breakthroughs, disciplinary restructuring, and regional collaboration.

INTRODUCTION

The low-altitude economy, a strategic emerging industry with a strong radiation effect, covers manufacturing, infrastructure, operation, services and support systems in its industrial chain and has entered a rapid development stage. Per China's Civil Aviation Administration, its market size is estimated to hit 1.5 trillion yuan in 2025 and 3.5 trillion yuan by 2035. Currently, over 19,000 Chinese enterprises are engaged in low-altitude economy-related sectors, but the demand for high-quality talents keeps rising – the gap of high-level talents in low-altitude engineering technology is expected to reach 200,000 in 2025 alone.

To address this talent gap, boost talent reserves and enhance organized high-level talent training, China's Office of the Degree Committee of the State Council issued a notice on June 11, 2025, launching a pilot for

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the extraordinary layout of interdisciplinary degree programs in "Low-altitude Technology and Engineering". This pilot innovatively sets up a "green channel" for discipline construction, which fuels the innovative development of the low-altitude economy industrial chain and fosters virtuous interaction between talent training and industrial upgrading. It is China's first extraordinary discipline/major layout for the low-altitude economy field.

CURRENT DEVELOPMENT STATUS IN CHINA

Policy Support

In February 2021, the Central Committee of the Communist Party of China and the State Council issued the "Outline of the National Comprehensive Three-dimensional Transport Network Plan"[1], proposing to "develop platform economy, hub economy, corridor economy, and low-altitude economy in transportation", which was the first time the concept of "low-altitude economy" was written into the national plan. In May 2023, the State Council and the Central Military Commission promulgated the "Interim Regulations on the Management of Unmanned Aircraft Flight"[2], which came into effect on January 1, 2024. In December 2023, the Central Economic Work Conference clearly identified the low-altitude economy as a national strategic emerging industry[3]. In March 2024, the low-altitude economy was written into the "Government Work Report"[4] for the first time, proposing to actively create new growth engines such as the low-altitude economy. In March 2024, the Ministry of Industry and Information Technology, the Ministry of Science and Technology, the Ministry of Finance, and the Civil Aviation Administration of China issued the "Implementation Plan for Innovation and Application of General Aviation Equipment (2024-2030)"[5], proposing to "promote the formation of a trillion-yuan market size of the low-altitude economy by 2030" and "support universities in strengthening the construction of general aviation-related disciplines and majors, and build a number of characteristic colleges. Deepen the integration of industry and education around the cutting-edge emerging interdisciplinary fields of general aviation, and promote joint and precise talent cultivation by universities, research institutions, and enterprises". In July 2024, the Third Plenary Session of the 20th Central Committee of the Party was held in Beijing, and the meeting wrote "developing general aviation and low-altitude economy" into the "Decision of the Central Committee of the Communist Party of China on Further Comprehensively Deepening Reform and Promoting Chinese Modernization"[6]. In December 2024, the National Development and Reform Commission officially established the Department of Low-altitude Economic Development[7], and held a number of meetings such as the "Special Symposium on the Construction of Low-altitude Intelligent Network System"[8], the "Special Meeting on the Safe and Healthy Development of the Low-altitude Economy"[9], and the "Symposium on Promoting the Safe and Standardized Development of the Low-altitude Economy"[10]. In 2025, the low-altitude economy was once again included in the "Government Work Report"[11], proposing to promote the safe and healthy development of emerging industries such as the low-altitude economy.

Major Establishment Situation

In response to the national strategy, the Ministry of Education has seen six "Double First-Class" universities successfully add the major of "Low-altitude Technology and Engineering" in the second half of 2024. The first undergraduate students will be welcomed in September 2025. This major falls under the category of interdisciplinary engineering within the field of engineering, with a four-year duration, and graduates will be awarded a Bachelor of Engineering degree. This move significantly enhances the talent supply to the industry.

Beihang University[12]: Integrates five key disciplines, including aerospace and unmanned systems, and partners with industry to create a multidisciplinary platform for cultivating talent in low-altitude technologies. Beijing Institute of Technology[13]: Enrolls up to 100 students, led by 7 academicians. Focuses on aircraft design and low-altitude traffic control, with strong industry-academia collaboration. Beijing University of Posts and Telecommunications[14]: Combines strengths in ICT, AI, and control to train talent in intelligent low-altitude systems, navigation, and communication. Nanjing University of Aeronautics and Astronautics[15]: Offers a curriculum covering aircraft design, control, and airspace management. Provides drone pilot training, integrating degree education with professional licensing. South China University of Technology[16]: Emphasizes hands-on learning through aircraft and system design projects to cultivate versatile talent for the low-altitude economy. Northwestern Polytechnical University[17]: Focuses on infrastructure, aircraft, and operations to train future engineers for urban air mobility, logistics, and emergency services.

EXTRAORDINARY LAYOUT WORK

Basic Requirements and Suggestions on Disciplinary Directions.

Firstly, the institution must have at least one corresponding degree-granting point in relevant first-level disciplines such as Mechanical Engineering, Electronic Science and Technology, Information and Communication Engineering, Control Science and Engineering, Computer Science and Technology, Transportation Engineering, or Aerospace Science and Technology. Secondly, the institution must have strong faculty in the relevant directions of the above first-level disciplines, possess high-level research platforms, and have sufficient

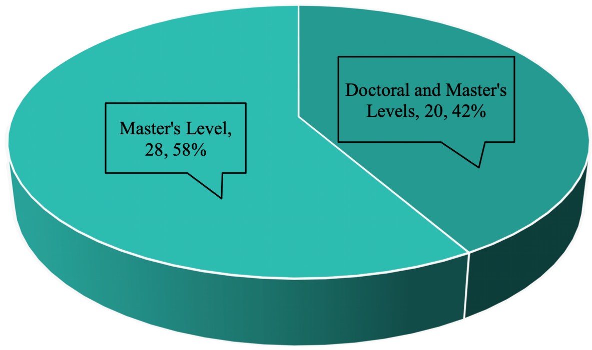

Figure 1 | Distribution of Degree Authorization Point Levels

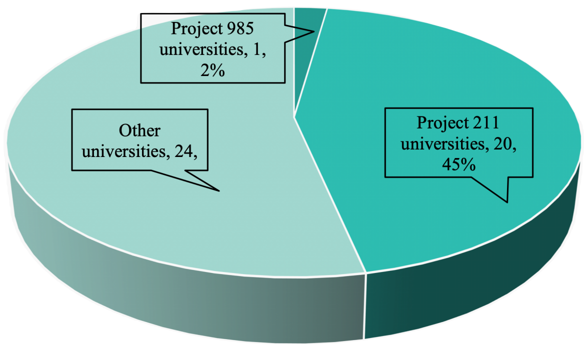

Figure 2 | Distribution of University Categories

research funding and projects as support. Thirdly, the institution must have a certain scale of talent cultivation in the direction of low-altitude technology and engineering, with an average of more than 30 doctoral and master's degrees awarded per year in the past three years.

The "Guidelines for the Setting of Disciplinary Directions in Low-altitude Technology and Engineering" suggest five disciplinary directions: Low-altitude Carrier System Engineering, Low-altitude Intelligent Navigation Technology, Low-altitude Security Assurance Technology, Intelligent Three-dimensional Traffic Engineering, and Low-altitude Airspace Planning and Management. These disciplinary directions are intercrossed, integrated, and supportive of each other.

Suggestions on Disciplinary Directions.

Firstly, universities that meet the pilot conditions and have the authority to independently review degree authorization, in combination with the development needs of the low-altitude economy and their own disciplinary construction plans, may voluntarily argue for the addition of interdisciplinary subjects managed as first-level disciplines, or independently set up second-level disciplines or interdisciplinary subjects outside the directory according to actual conditions. If a new interdisciplinary subject managed as a first-level discipline is added, it will not be subject to the annual limit on the number of new degree-granting points added through independent review. Secondly, universities that meet the pilot conditions but do not have the authority to independently review degree authorization may independently set up second-level disciplines or interdisciplinary subjects outside the directory.

The low-altitude economy industry, from intelligent equipment manufacturing and application scenario design to flight support systems and standard construction, especially in the core technology research and development of low-altitude intelligent networking, and in the construction of security facilities such as surveillance and identification, interception, and countermeasures, urgently needs to accelerate the cultivation of a group of high-level talents with research and development capabilities and innovative spirit to provide talent security for the sustainable development of the low-altitude economy. This layout work is the first extraordinary layout of disciplines and majors in China facing the field of low-altitude economy. Firstly, it opens a "green channel" for the establishment of disciplines. Compared with the traditional process of adding disciplines, which needs to follow a fixed application cycle and go through a lengthy process of multi-layer approval, this work simplifies the approval levels, optimizes the allocation of resources, and significantly shortens the preparation cycle for disciplinary construction. Secondly, it accurately matches industry needs, helping universities to quickly connect with national strategic needs and respond in time to the urgent demands of industry talents and scientific research. This is achieved through building a disciplinary innovation ecosystem, deepening the integration of industry and education, and strengthening policy coordination. Thirdly, it focuses on core technology breakthroughs. Facing the national strategy of the low-altitude economy, it conducts basic theory and key technology research in low-altitude technology and engineering, breaks through the core foundations of low-altitude technology and engineering, and leads the development of the national low-altitude technology and engineering system.

LAYOUT SITUATION

According to the results displayed by the Ministry of Education's Degree and Graduate Education Development Center (as of June 30, 2025), 131 universities plan to add or rename 136 first-level interdisciplinary subjects, second-level subjects outside the directory, and self-established interdisciplinary subjects, including 77 doctoral degree authorization points and 136 master's degree authorization points.

First-Level Disciplinary Doctoral Points.

Tsinghua University, Chongqing University, and Harbin Institute of Technology have already publicized their independent review and addition of doctoral de-

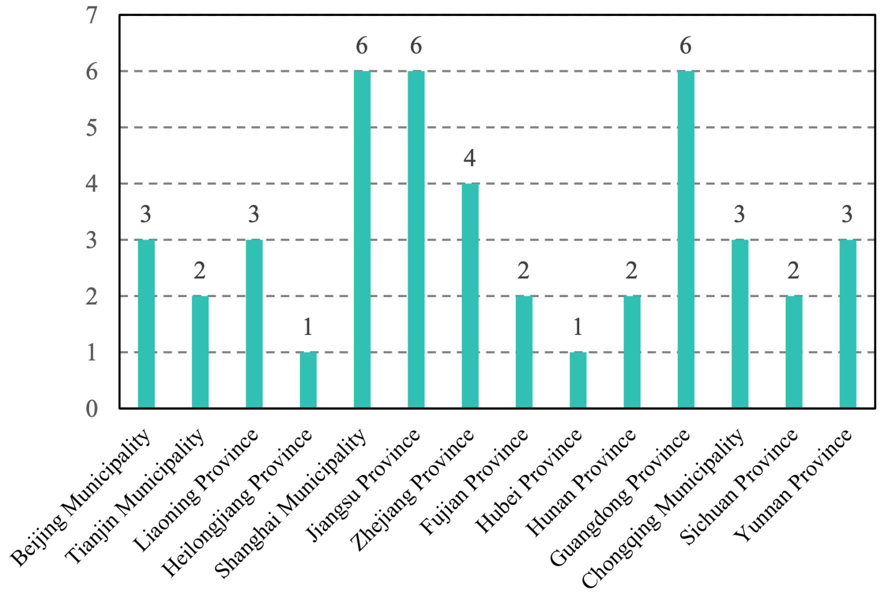

Figure 3 | Distribution of Provinces

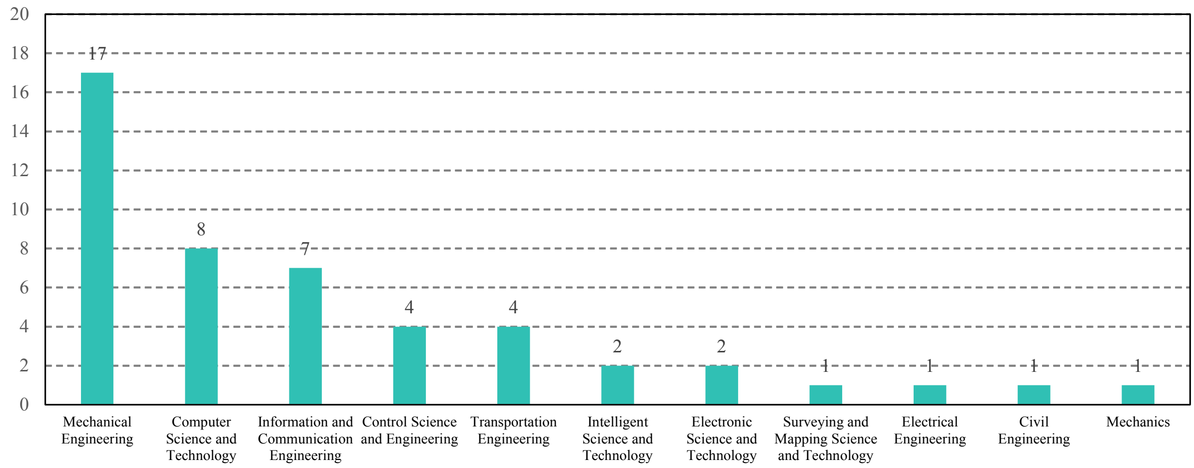

Figure 4 | Distribution of Disciplines

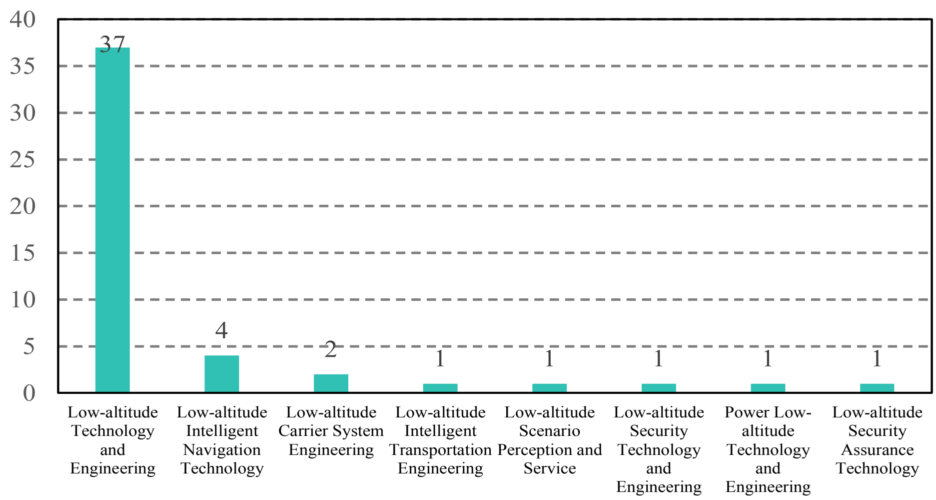

Figure 5 | Names of Second-level Disciplines

gree authorization points for the first-level interdisciplinary subject of Low-altitude Technology and Engineering.

Second-Level Subjects Outside the Directory.

In terms of degree authorization point levels: 48 second-level subjects in low-altitude technology and engineering are planned to be added by universities such as Southwest Jiaotong University and Beijing University of Civil Engineering and Architecture, including 20 doctoral and master's level subject points and 28 master's level points.

In terms of university categories: There is 1 "Project 985" university, which is Nankai University, and 8 "Project 211" universities, including Nankai University, Soochow University, China University of Geosciences (Wuhan), Southwest Jiaotong University, Hunan Normal University, Jinan University, Yunnan University, and Liaoning University.

In terms of provincial distribution: Universities in Shanghai, Jiangsu Province, and Guangdong Province have the highest number at 6 each, accounting for 13.64%.

In terms of disciplinary distribution: Most universities have set up second-level subjects under the recommended 7 first-level disciplines according to the notice. Among them, the number of second-level subjects set up under Mechanical Engineering is the highest at 17, accounting for 35.42%, followed by Computer Science and Technology and Information and Communication Engineering, which account for 16.67% and 14.58% respectively. Control Science and Engineering and Transportation Engineering each account for 8.33%, and Electronic Science and Technology accounts for 4.17%. It is worth noting that currently no university has set up second-level subjects related to the low-altitude field under the first-level discipline of Aerospace Science and Technology. Four universities have set up second-level subjects under the first-level disciplines of Surveying and Mapping Science and Technology (Beijing University of Civil Engineering and Architecture), Electrical Engineering (Shanghai University of Electric Power), Civil Engineering (Suzhou University of Science and Technology), and Mechanics (Southern University of Science and Technology) in combination with their own disciplinary characteristics.

In terms of second-level subject names: 37 subjects use the name of the undergraduate major "Low-altitude Technology and Engineering" as the second-level subject, accounting for 77.08%. Four subjects use the disciplinary direction names suggested in the "Guidelines for the Setting of Disciplinary Directions in Low-altitude Technology and Engineering," namely "Low-altitude Intelligent Navigation Technology" and "Low-altitude Carrier System Engineering." Four universities have set up second-level subject names in combination with their own characteristics: Low-altitude Intelligent Transportation Engineering (Beijing University of Civil Engineering and Architecture), Low-altitude Scenario Perception and Service (Beijing University of Civil Engineering and Architecture), Low-altitude Security Technology and Engineering (Civil Aviation University of China), Power Low-altitude Technology and Engineering (Shanghai University of Electric Power), and Low-altitude Security Assurance Technology (Shanghai Institute of Technology).

Self-Established Interdisciplinary Subjects.

In terms of degree authorization point levels: Universities such as Beijing Jiaotong University and Beijing University of Technology plan to add 85 second-level subjects in low-altitude technology and engineering outside the directory, including 54 doctoral and master's level subject points and 31 master's level points.

In terms of university categories: There are 2 "Project 985" universities, namely Fudan University and East China Normal University, and 17 "Project 211" universities, including Beijing Jiaotong University, Beijing University of Technology, University of Science and Technology Beijing, Beijing University of Posts and Telecommunications, Beijing Forestry University, North China Electric Power University (Beijing), Donghua University, Fudan University, East China Normal University, Nanjing University of Aeronautics and Astronautics, Nanjing University of Science and Technology, Hohai University, Jiangnan University, Nanjing Agricultural University, Wuhan University of Technology, Xidian University, and Chang'an University.

In terms of provincial distribution: Universities in Jiangsu Province have the highest number at 15, accounting for 17.86%, followed by Shaanxi Province and Beijing with 10 (11.90%) and 7 (8.33%) universities respectively.

In terms of disciplinary distribution: Most universities have self-established interdisciplinary subjects in combination with the recommended 7 first-level disciplines according to the notice. Among them, the number of second-level subjects set up under Mechanical Engineering is the highest at 49, accounting for 14.20%, followed by Computer Science and Technology at 13.04%, Control Science and Engineering at 9.86%, Information and Communication Engineering at 8.41%, Transportation Engineering at 4.35%, and Electronic Science and Technology at 3.77%. Aerospace Science and Technology only appears in self-established interdisciplinary subjects, with a total of 5 universities accounting for 1.45%.

More universities have self-established interdisciplinary subjects in combination with their own characteristics under the first-level disciplines of Urban and Rural Planning (Xi'an University of Architecture and Technology), Grassland Science (Beijing Forestry University), and Marine Science (Shanghai Ocean University).

In terms of second-level subject names: 80 subjects use the name of the undergraduate major "Low-altitude Technology and Engineering" as the second-level sub-

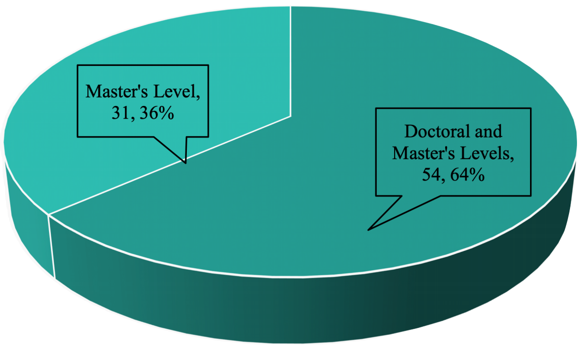

Figure 6 | Distribution of Degree Authorization Point Levels

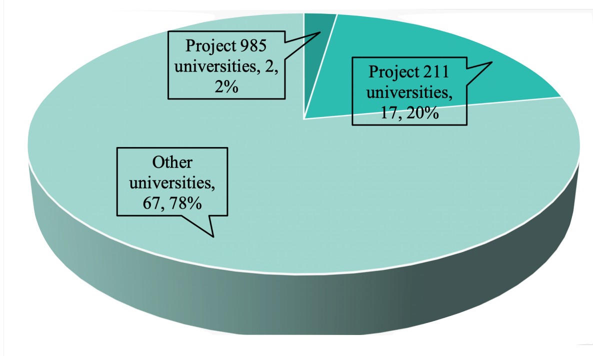

Figure 7 | Distribution of University Categories

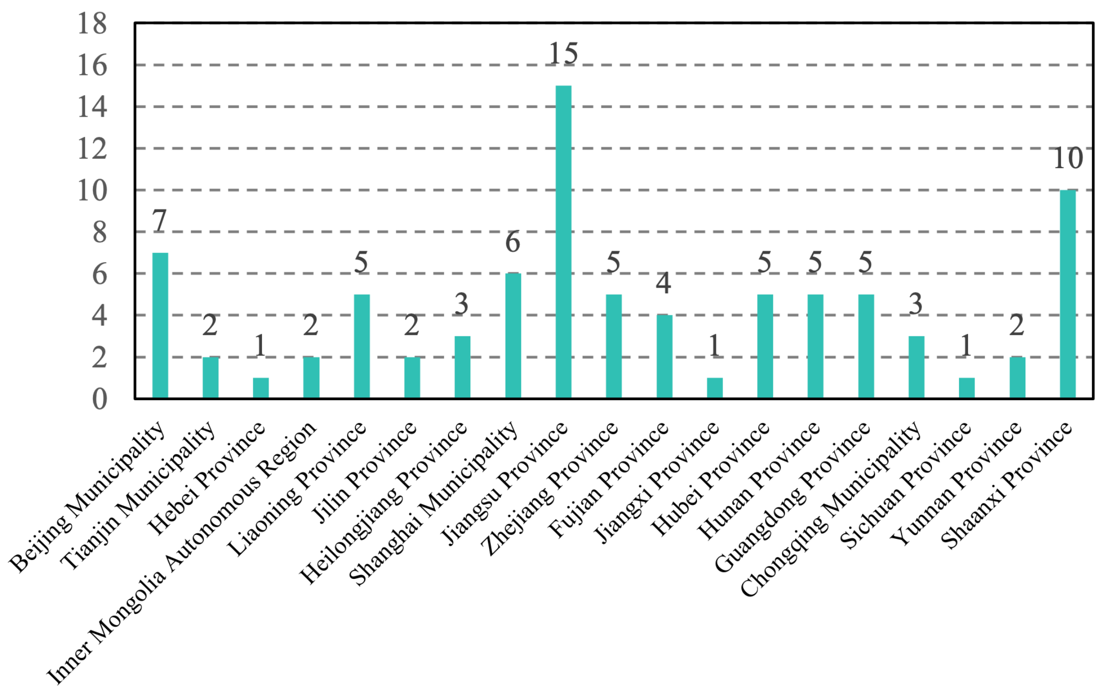

Figure 8 | Distribution of Provinces

ject, accounting for 94.12%. One subject uses the disciplinary direction name "Low-altitude Intelligent Navigation Technology" suggested in the "Guidelines for the Setting of Disciplinary Directions in Low-altitude Technology and Engineering." Four universities have self-established interdisciplinary subject names: Low-altitude Technology and Intelligent Transportation Engineering (Xi'an University of Architecture and Technology), Low-altitude Carrier Technology and Engineering (Ningbo University), Low-altitude Intelligent Technology and Engineering (Chongqing University of Technology), and Low-altitude Intelligence and Safety (East China Normal University).

RELEVANT SUGGESTIONS

Establish a "Region-Industry-Scenario" Three-Dimensional Training System.

Disciplinary construction should be adapted to the development needs of local economic and social development[18]. Disciplines related to low-altitude technology and engineering should be combined with the local low-altitude industry's resource endowment, industrial foundation, and innovation capability to build a talent training system that matches regional characteristics. According to the distribution of provinces, the five provinces of Jiangsu, Guangdong, Beijing, Shaanxi, and Zhejiang account for 47.66% of the second-level disciplines and self-established interdisciplinary subjects. Based on the industrial foundation, policy orientation, and resource characteristics of the low-altitude econo-

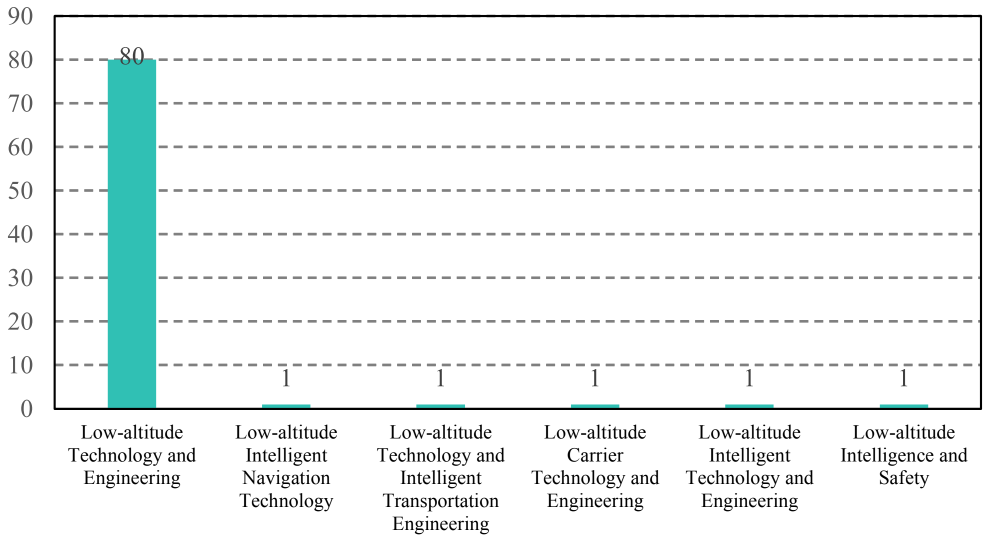

Figure 10 | Names of Second-level Disciplines

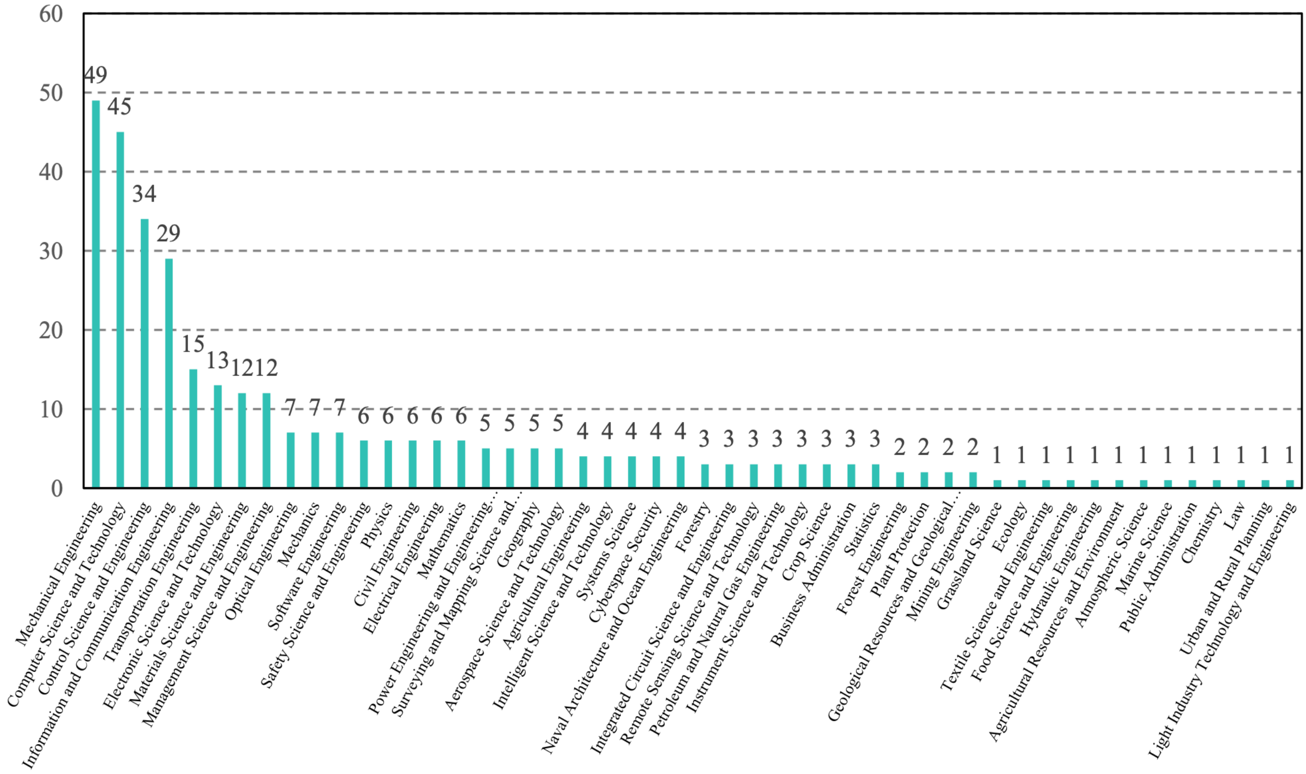

Figure 9 | Distribution of Disciplines

my in the same province, they are divided into three types of regions: industry-leading regions, technology-supporting regions, and scenario-characteristic regions.

Industry-leading regions: Jiangsu Province has a strong manufacturing base and leads in the fields of drone research and development and aerospace parts manufacturing. Guangdong Province is home to a large number of drone companies (such as DJI and EHang). Zhejiang Province has an active private economy and has an urgent need for low-altitude logistics (such as Cainiao Network drone delivery).

Technology-supporting regions: Beijing, as the core of the national strategic scientific and technological forces, gathers scientific research institutes (such as Aviation Industry Corporation of China and China Aerospace Science and Technology Corporation) and leading enterprises in the field of aerospace.

Scenario-characteristic regions: Shaanxi Province has strong aerospace universities such as Northwestern Polytechnical University, and the demand for national defense-related scenarios promotes the deep integration of disciplines with local military industry and manufacturing. The colleges and universities in these provinces have natural advantages in the establishment of disciplines related to low-altitude technology and engineering. The application scenarios of the low-altitude economy have strong industry specificity (such as safety[19], agriculture[20,21], logistics[21], urban governance[22], etc.). It is necessary to take specific applications as the guidance, deeply integrate general technology with industry knowledge, and cultivate compound talents of "low-altitude technology + industry scenario".

Construct a Low-Altitude Characteristic Interdisciplinary Integration Training System.

Building an interdisciplinary integration system with low-altitude characteristics must be guided by the core needs of the low-altitude economy. As analyzed, disciplines related to low-altitude technology and engineering are most closely linked to mechanical engineering, computer science and technology, control science and engineering, information and communication engineering, and transportation engineering. By breaking traditional disciplinary barriers and applying the four-layer structure of "target anchoring - content reconstruction - platform support - mechanism guarantee," cross-domain integration of knowledge, technology, and talents can be achieved.

First, focus on problem-oriented low-altitude scenarios. The low-altitude economy industrial chain includes four links: R&D design, core manufacturing, operation and service, and support systems. For R&D design, disciplines like low-altitude carrier system engineering and intelligent navigation technology cultivate high-end R&D talents For core manufacturing, it connects to first-level disciplines such as mechanical engineering and electronic science and technology to train talents in precision manufacturing, supply chain management, and quality inspection. For operation and service, centering on scenarios like low-altitude logistics and urban air mobility, it cultivates talents in airspace planning, scheduling management, and market operation. For support systems, it corresponds to low-altitude security assurance technology and intelligent 3D traffic engineering to train talents in airworthiness certification, security monitoring, and emergency response.

Second, build a curriculum system with low-altitude characteristics, forming a three-level structure of "basic layer - integration layer - expansion layer." The basic layer, based on core engineering literacy, integrates low-altitude technology logic, core courses, and cutting-edge modules. The integration layer sets interdisciplinary courses, adopts MIT case teaching and project-based experimental models, and requires students to complete practical projects. The expansion layer offers electives, and jointly builds school-enterprise sci-tech and educational platforms with leading enterprises to launch workshops, using real scenarios for teaching and turning corporate pain points into teaching cases.

Improve the Long-Term Operation and Guarantee Mechanism.

First, build an interdisciplinary elite team. As faculty is key for long-term support, integrate multi-disciplinary expert resources to form an interdisciplinary teaching team covering mechanical engineering, computer science and technology, and other core fields. Learn from foreign universities: hire corporate experts as industry mentors and corporate mentors as university technical consultants, and establish a "dual appointment - dual secondment - dual evaluation" mechanism. In-house teachers must hold CAAC or enterprise-recognized UAV/airworthiness qualification certificates to teach, and spend at least 3 months annually working in leading enterprises. Enterprise chief engineers and professor-level senior engineers, after approval by the university's degree evaluation committee, can become part-time professors and must undertake teaching tasks. Establish a "discipline - industry" joint professional title evaluation system, and include corporate project achievements, technical patents, and teaching performance equally in promotion criteria to keep faculty updated on frontline industry technologies.

Second, establish a "diversified investment, open sharing" support system. It is suggested that the State Council Degree Office continue the "extraordinary" layout policy to simplify approval and help universities add discipline programs quickly. The government should set up a "low-altitude education special fund" for school-enterprise co-construction and sharing of integrated experimental-training-flight training platforms, adopting a "school construction, corporate donation, industry co-management" model, with equipment update cycles synchronized with industrial technology iteration. Build a national open low-altitude engineering course cloud, integrate tool chains, and implement credit recognition, faculty exchange, and case sharing to realize cross-school and cross-regional flow of hardware and data resources.

Third, implement a multi-dimensional evaluation system based on industry alignment, international certification, and dynamic feedback. For discipline evaluation, break traditional single academic standards, integrate "low-altitude characteristics" into indicators. Introduce third-party evaluation agencies, cooperate with low-altitude economy industry associations, refer to AABI aviation certification standards to launch international certification for flight technology majors and conduct course quality evaluation. Regularly release reports on the alignment of talent training with industry demand. Establish a dynamic feedback mechanism focusing on quality tracking and risk warning, and include enterprises' evaluation of graduates' skills and the contribution of scientific research results to low-altitude technology breakthroughs in teacher evaluation, forming a "teaching - practice - industry" closed-loop evaluation to ensure talent training meets low-altitude economy development needs.

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Case study

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A Study on the Pathways of Immersive Technology Empowering the Dissemination of China's Red-Culture

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KEYWORDS

Immersive Technology;
Red Cultural Heritage;
Immersive Communication

ABSTRACT

This article analyzes how the immersive technology rejuvenates the dissemination of the revolutionary culture of China, taking the Guizhou Long March Digital Technology Art Museum (Red Ribbon) as an example to follow the dual transformation of the revolutionary culture in terms of narrative approaches and value dimensions in the digital media context. Research shows that the immersive technology transforms static displays into navigable historical sites through virtual scenes and symbolic reconstruction, and transforms the audience from spectators to participants through embodied experiences and interactive narratives. When emotions are triggered by the environment, value cognition crystallizes into self-awareness. This technological intervention does not only innovate dissemination formats, but also creates new trajectories for the reproduction of cultural and social values, providing a reproducible paradigm for sustaining red culture in the new era and crafting its overseas narratives.

INTRODUCTION

Red culture was conceived gradually under the leadership of the Communist Party of China during the revolution, nation-building, reform, and the construction of the new era. It is a value system rooted in Chinese soil, including not only the material traces such as revolutionary sites and archives, but also the spiritual legacies like the spirit of the Red Boat, the Jinggangshan Spirit, and the Yanan Spirit. The red culture has injected vitality into the development of socialist culture and become a key pillar supporting the civilization progress of the country. Following the dissemination of red culture, we can find a track of continuous changes: from the early text records to the later audio-visual transmission, and then to the digital wave, each step forward driven by new media technology. However, the traditional dissemination modes are still plagued by one-way indoctrination, passive acceptance of the audience, and lack of diversity of experience, which leads to a clear gap with the current media consumption habits and aesthetic expectations. How to rebuild the channels of disseminating red culture by means of new tools, new scenarios, and new concepts has become the focus of common concern for both the academic and practitioner circles.

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Immersive media (including virtual reality, augmented reality, mixed reality, holographic imaging, digital twin, etc.) is rapidly maturing and spreading to more scenarios. These media simulate perception and encourage interaction to build layered immersive spaces beyond the traditional limitations of time and space, putting the audience in a narrative setting as if they were there in person. The application of these media to the dissemination of revolutionary culture is not only a format transformation, but also reconstructs the cognitive framework of dissemination methods, the way the audience accepts information, and the identity of the revolutionary culture itself. This article examines three mechanisms scenario immersion, embodied interaction, and emotional resonance and analyzes representative cases to explain how these media assist the digital dissemination of revolutionary culture.

THE CURRENT STATE AND CHALLENGES OF RED CULTURE DISSEMINATION

Limited Dissemination Formats

At present, the spread of red culture mainly depends on physical space such as revolutionary memorial halls, red culture exhibition centers, revolutionary sites, etc. Relevant data show that by 2025, there were more than 1,600 red culture museums and memorial halls in China, holding more than 1.5 million red-themed cultural exhibitions. Nevertheless, the spread of these activities still mainly depends on revolutionary artifacts, event display boards, documentary videos, etc., and the content is often one-way delivered to the audience according to the timelines of history or the biographies of heroes, without sufficient interactivity and motivation. Although this dissemination model can impart knowledge and promote values, it also tends to put the audience in a passive state of watching. It is difficult to really transfer the audience to the historical scenes, and their cognition remains at the superficial level of watching, which greatly restricts the deepening of red cultural memory and the internalization of spirit. At the same time, most red exhibitions use static presentation methods and formulaic narrative methods. The cultural symbol system they build does not have the ability to be recontextualized and renarrated, which restricts the reproduction and social diffusion of red culture.

Disconnect Between Audience and Content

The media ecology is ever-changing, changing audience habits with it. At present, the younger generation, especially Generation Z and Generation Alpha, has become the main target audience who needs to be captured and profoundly influenced in the dissemination of red culture. Red culture itself possesses strong historical, political and value characteristics, often reproducing historical events and heroic deeds in a standardised and formulaic way. In its narrative logic, the dissemination of red culture often unfolds in a linear way along the threads of time and events, highlighting the enumeration of facts and conclusive outputs. Its communication forms depend heavily on the textual, monumental grand narratives. The dissemination process lacks expressions containing physical sensation, emotional tension, daily life scenes and youthful vigour, failing to adapt to the cognitive preferences and aesthetic habits of contemporary youth, who prefer experiential, emotional, digital and interactive participation. This results in a huge generational gap between red narratives and young peoples daily digital lives, making it difficult for the content to resonate emotionally and foster identification among youth. It is often regarded as preachy propaganda, reducing the emotional attractiveness and value guidance that red culture should have innately. (Liang, K. 2020)

Stagnation in Communication Scenarios

The communication context plays a decisive role in the construction of meaning and identity. At present, the dissemination of red culture still mainly depends on physical venues such as museums, memorial halls, and revolutionary education bases to transmit information in the form of carefully arranged exhibitions, lectures, and promotional activities. This process is still one-way, superficial, and mechanical, unable to form a loop of immersion, participation, and recreation. Visitors are still passive receivers, unable to interact in real time with the exhibits and establish emotional ties. This strategy is difficult to attract the younger generation who are used to interactive experience to explore and learn by themselves. At the same time, this rigid single-channel dissemination mode cannot resonate with the current urban public space, online social platform, and immersive digital environment. Therefore, the narrative of red culture is still bound by physical space and traditional cognitive framework, unable to integrate into the daily life of young people. This disconnection results in a gradual weakening of its cultural influence.

In general, the spread of red culture still has many difficulties, such as single formats, mismatched contents and audiences interest, out-of-date scenarios and interaction modes, etc. In this paper, we explore how immersive technologies can be used to enhance the spread of red culture. We discuss several aspects, such as scenario immersion and historical context recreation, embodied interaction and narrative participation, emotional resonance and spiritual internalization, and analyze related cases. We hope to offer suggestions and inspirations for promoting the development and inheritance of red culture in the new era.

THE MECHANISM OF SPATIAL IMMERSION AND HISTORICAL CONTEXTUAL RECONSTRUCTION

The immersive technology empowered red culture dissemination scenarios recreate the historical context and symbolic texts into perceptible virtual scenes. From the remediated point of view, it is a profound rewrite and reshape of legacy media content by new media, which greatly facilitates the audiences understanding of history visibility. (Moschini, I., & Sindoni, M. G.2021) With the production of virtual space and multisensory participation, red historical resources are no longer exhibited artifacts but perceptible real contexts for audience. This approach also brings out red cultural symbols in virtual scenes again, and constantly reinforces and rejuvenates its meaning in the process.

The Integration of Virtual Reenactment and Historical Narrative

Virtual recreation in immersive environments is less a reproduction of history than a re-enactment of history mediated technologically in specific contexts. Bolter and Grusin argue in their theory of remediation that new media do not simply redefine boundaries of the visible and credible, but also absorb and rewrite the ways of presentation of old media (Bolter, J. D., & Grusin, R. 2000). Therefore, the use of immersive technology for disseminating revolutionary culture will inevitably transform traditional historical narratives and their inherent logic, which in turn alters audience perception and understanding of the past. The most fundamental transformation lies in the transfer of discursive power. In traditional exhibitions, text, objects and static images follow a linear path along the wall panels, and visitors assemble history independently through the textual display. In this case, institutions and their docents held the narrative power; history was told instead of entered. With 3D modelling, spatial audio and real-time rendering, immersive technology re-creates historical scenes into navigable environments. Under this dissemination model, the narrative power is co-determined by the narrative script, interactive systems and participants, resulting in a co-authored narrative. (Ryan, M.L. 2015) At the same time, the narrative perspective is transformed: under traditional communication models, the third-person narrative prevails, positioning the audience as outsiders to historical stories participating in textual narratives through an external focus (displaced, over-head perspective). Immersive media, on the other hand, narrates through first- or second-person perspectives. Audiences are situated within historical contexts, becoming witnesses and participants to history. This facilitates more direct affective engagement with revolutionary culture at the cognitive-affective level. The organisational structure of communication content has also been transformed. Traditional historical narratives strictly follow a macro-level timeline, stressing causal logic and authoritative conclusion. Immersive storytelling, on the other hand, generates experiential environments by virtually reconstructing historical contexts and details. Narrative content moves from linear exposition to multi-dimensional, open-ended personal experiential generation.

Symbolic Reconstruction in Immersive Spaces

Famous cultural semiotician, Yuri Mikhailovich Lotman believed that symbols make texts, texts make culture, and culture makes a semiotic circle. This semiotic circle, in his opinion, has synchronous and diachronic connections but is bounded; crossing boundaries requires the constant reconstruction and interpretation of cultural symbols. (Lotman, Y. M. 1990)If we regard red culture as a cultural semicircle, then the application of immersive technology updates the construction of cultural meanings in this semicircle, allowing it to adapt to the rapidly changing media landscape and audience aesthetics. In traditional red culture exhibitions, cultural symbols are often static and captioned, and their meanings are restricted to the exhibited context, without dynamic links to other symbols. However, immersive technology situates them in a multisensory, interactive 3D environment, breaking the static boundaries of meaning production and interpretation for red cultural symbols via spatial narratives and sensorial involvement. This boundary-breaking expression allows red cultural symbols to generate new contextual frames through technological mediation, continuously sustaining their cultural significance and refreshing interpretive dimensions while maintaining their inherent values, thus constantly rejuvenating themselves with new life in the current media.

Virtual recreation and symbolic reconstruction change the representation of historical contexts on different levels. Firstly, the construction of virtual scenarios changes the narrative logic of historical texts, from contexts that are told to contexts that can be lived. Secondly, by means of recontextualisation techniques, red cultural symbols are changed from passive exhibits to interactive, contextualised dynamic signifiers. (Davison, P., & Klinghardt, G. 1997) These components constitute the mechanisms of scene immersion and historical context reconstruction which enable further embodied interaction and narrative participation mechanisms.

THE MECHANISM OF EMBODIED INTERACTION AND NARRATIVE PARTICIPATION

Hypertext is a cultural concept originated by Ted Nelson, who argued that hypertext reading enabled readers to choose and move freely among texts, ideally on interactive screens. The texts are not bound to the authors intended reading order but could be read and experienced in ways chosen by the reader. (Nelson, T.

H. 1965)Although the original notion of hypertext referred to screen-based, visual, non-linear and interactive reading experiences, from the perspective of the theory of embodied cognition, it turns out that the communicative context or mode of reading constructed by immersive technologies is in essence an embodied hypertext reading experience. In this context, users current interactions and narrative participation are the main driving forces for the generation of meaning in red cultural texts.

Embodied Cognition and Experiential Construction

The theory of embodied cognition argues that human cognition is not limited to the brain, but arises from the bodys spatial perception, actions, and interaction with the environment. (Lakoff, G., Johnson, M., & Sowa, J. F. 1999)In technology-built immersive scenarios, the audience places its body into narrative contexts via interactive media. Actions in virtual space build real links to red cultural texts, forming a coupling between body, space, and meaning making that promotes embodied cognition. Posture tracking, motion capture, and real-time rendering are among the mechanisms used by immersive technologies such as VR, AR, and MR to deliver instant feedback on users behaviour in virtual space. Behaviours such as gazing, picking things up, and walking acquire narrative functions and become the driving force of the immersive scenario. At the same time, embodied experience amplifies the perception of meaning. Psychological studies show that bodily involvement greatly increases attention and memory for information received (Malafouris, L., 2004). When historical narratives resonate with physical perception, cognition becomes context-bound. Historical knowledge ceases to be abstract propositions and becomes lived emotional experiences. This cognitive process further consolidates into deep understanding, freeing revolutionary history from abstract, disengaged reception and building it as the lived experience of the audience to be understood and remembered.

Interactive Narrative and Participatory Communication

Unlike traditional linear texts, interactive narratives view meaning as the result of real-time interactions between participants and the system, instead of the pre-determined outcome of a linear text (Mateas, M., & Stern, A., 2005). It frees itself from the shackles of linear causality chains in traditional storytelling; the deeper meanings of the text only appear when the participants actively participate in the narrative system. Therefore, immersive scenarios constructed by immersive technology can be seen as a hypertext reading that transcends conventional methods. That is to say, the use of immersive technology maintains an open narrative structure, granting audiences greater narrative agency; their paths of action directly determine how meaning is realized, transforming the dissemination of red culture from one-way communication to co-creation and participation. The openness is also reflected in the decentralisation of the production of meaning. In traditional linear texts, the text or narrator pre-determines the logic and value trajectory of the story, with audiences able to do no more than receive and re-interpret. However, in interactive narratives, user behaviour and feedback are incorporated into the communication chain, with each choice made within the immersive environment immediately impacting presentation methods and value generation. More importantly, such interaction adds a new social dimension to red culture; individualised experiences and differentiated interpretations resonate even further through social media, propelling red narratives out of isolated sites into wider public spaces.

Immersive technology situates somatic sensation and spatial/temporal action in historical contexts via embodied cognition, allowing people to literally step into events and participate in the continuous discourse with the narrative and co-author the story, shifting them from spectators to co-constructors of meaning. As a result, the spread of revolutionary culture penetrates to deeper psychological transformation and cultural rooting at the deep layers of emotional resonance, value identification, and spiritual inheritance.

THE MECHANISM OF EMOTIONAL RESONANCE AND SPIRITUAL INTERNALIZATION

In his work On Collective Memory, Maurice Halbwachs argues that collective memory is the collective remembrance of events, experiences and values that have certain significance to a particular group. (Halbwachs, M. 1997)Every collective memory needs the support of a community defined by time and space to survive. Hence, the collective memory serves as a symbolic element rooted in the spirit and culture of a nation, which needs the endorsement of the community and remembered to sustain. Scenario immersion and embodied interaction turn red culture from unilateral indoctrination to participatory first-hand experiences. The emotional resonance generated elevates sensory excitement to the identification of values. Immersive technology does not only amplify the textual information of red culture, but also evokes peoples collective memories of it through emotional and psychological resonance, transforming communication from visible to felt. In other words, emotional resonance and spiritual internalization are the essence and final destination of technological empowerment. Therefore, research on how immersive technology can be used to enhance the dissemination of red culture is not just about making visual spectacles, but about seeking narrative strategies and psychological mechanisms to crystallize the essence of red culture from special scenarios into tangible spiritual strength.

Narrative Strategies of Emotional Resonance

Emotion is not a by-product of communication, but an intermediate link in the construction of the meaning of information. Therefore, the emotional response elicited by the audience in immersive scenarios is crucial to the production of meaning and value identification in red culture. In traditional communication models, red culture tends to appear in the form of symbols and concepts. By comparison, communication texts endowed with immersive technology often take emotional nodes as the organizational framework, use emotional cues as the driving force for the advancement of narrative and the transformation of virtual space, and use the physical experience of users to trigger emotional highlights in specific scenarios and amplify the psychological tension of the rhythm of the narrative. This experiential emotional rhythmic narrative transforms history from a topic of narration into a real-life process. At the same time, the first- or second-person role immersion provided by immersive technology gives the audience a sense of agency, synchronizing emotion with narrative. The emotional structure of the revolutionary spirit is reactivated through experience. This is not just a technological innovation, but a strong catalyst for promoting the inheritance of revolutionary culture to shift from superficial symbolic interpretation to deep emotional and neural self-construction.

The Internal Generation of Spiritual Identification

Samuel Huntington once said that when people answer the questions who am I and who are we, they often use the things they think are meaningful, and some symbols become the markers of cultural identity.(Huntington, S. P., & Jervis, R. 1997) Such identity is formed by repeated emotional refinement through cognitive integration and value reflection (Anderson, B. 2020). That is to say, cultural identity is not derived from inherent biological instincts, but a dynamic process of meaning construction based on cultural symbols and emotions. In the context of red culture dissemination, red cultural symbols, as symbols of self-cultural identity, are being transformed into perceptible, interactive emotional symbols by immersive technology. Through participatory immersive interaction mechanism, people participate in red historical scenarios embodied. Their perception intensity towards red cultural symbols is constantly deepened through multi-directional, multi-sensory stimulation and emotional ups and downs from interactive media. These symbols rich in historical memory and cultural sentiment are gradually strengthened through immediate interactive feedback. The audience emotionally elevates these symbols to internal spiritual values, turning them into symbolic answers to the question who are we.

In conclusion, the importance of immersive technology in promoting the spread of revolutionary culture is reflected not only in the innovation of its dissemination forms and contents, but also in the construction of collective memory and cultural identity. With the help of scene immersion and embodied interaction, the revolutionary culture has shifted from passive watching to active experiencing. The strong emotional resonance and association aroused by this builds profound value ties between individuals and revolutionary culture, which ensures that the dissemination of revolutionary culture is constantly rejuvenating its cultural significance.

CASE STUDY AND ANALYSIS

This paper selects the Guizhou Long March Digital Technology Art Museum as a representative case study to analyze the mechanism by which immersive technology empowers the dissemination of revolutionary culture, thereby validating the aforementioned theoretical analysis.

Case Introduction

The Guizhou Long March Digital Technology Art Museum (hereinafter referred to as Red Ribbon) is Chinas first comprehensive cultural venue using a full-immersion digital experience model. With a total construction area of 12,000 square meters, the digital exhibition halls account for more than one third of the total area. Based on Guiyangs unique geographical importance as a major stopover point of the Red Armys Long March route, the museum has systematically integrated red cultural resources within a 300-kilometer radius, such as the Liping Conference Site in southeast Guizhou and the Zunyi Conference Memorial Hall. Since its trial operation began on October 22, 2023, the Red Ribbon has received millions of visitors from both inside and outside the province, becoming a classic tourist attraction and must-see site for red tourism in Guizhou.

Immersive Scenarios and Historical Context Reconstruction

The Red Ribbon project makes use of the latest immersive technologies such as virtual reality, holographic imaging, and motion capture in venue design. Such technologies build up multiple layers of mixed reality experiences in physical space, allowing visitors to relive the Long March in interactive virtual-physical space, thus fully embodying the mechanisms of immersive scenarios and historical reconstruction. For example, in the Digital Long March Panorama Theater part of the project, historical details of significant events such as the Battle of the Xiang River are recreated visually with precision. Hydraulic vibration units are installed in the floor of the venue to simulate explosive impacts of different magnitudes. In terms of acoustics, it adopts the advanced Dolby Atmos technology to accurately locate bullet whistles. A professional climate control system gradually reduces the ambient temperature from 26 degrees Celsius to 18 degrees Celsius during the scenes reenactment to enhance the sense of presence on the battlefield. Similarly, in the Snowy Mountains and Grasslands Physical Challenge part, a special composite material floor is used to simulate the resistance when walking through mud. The environmental control system can instantly reduce the temperature from ambient to minus 15 degrees Celsius, combined with the artificial snow system and a 7.1 channel wind sound simulator to fully reconstruct the extreme conditions of the Jiajin Mountain snowfields. By means of such immersive technologies, visitors can personally enter the corresponding scenarios, turning the narration of history into experience and lived history. They can feel the original historical context physically, while historical memory is recontextualized through technological empowerment to achieve an immersive reproduction.

Embodied Interaction and Narrative Engagement

The Red Ribbon project allows visitors real-life spatial behavior to deeply intersect with true historical events in a virtual dimension, converting the red cultural stories presented on exhibition panels into bodily experiential scenarios. For example, when entering, visitors obtain a special-designed electronic souvenir badge with an NFC chip and motion sensor, which records real-time data such as visitor trajectories and staying time, and generates personalized Long March route maps via the venues central processing system for virtual interaction with authentic historical events. At the same time, the Red Ribbon project employs a modular arrangement, discarding the linear chronological or event-based narratives of traditional red exhibitions, and establishes a multi-threaded, multi-sensory and highly interactive narrative structure. It consists of six chapters: Unnamed Heroes, Baptism by Blood and Fire, Great Turning Point, Forging Ahead, Monument of Victory, and New Long March in the New Era. Red Ribbon: The Great Journey uses the latest technologies such as AI virtual interaction, holographic imaging, multidimensional mechanical motion, virtual reality, and 3D soundscapes to transform historical events into walkable, triggerable and responsive experiential spaces through dynamic spatial and visual transformations to digitally recreate iconic scenes of the Red Armys Long March. When entering the venue, visitors are no longer passive viewers but characters woven into the story. The project densely arranges interactive modules and experience zones throughout the space, fully promoting embodied interaction and participatory engagement. For example, five key zones - Digital Long March Panorama Theater, Interactive Revolutionary Relics Exhibition, Snow Mountain Grassland Physical Challenge, Red Family Letters Creation Station, and Light of Faith Signature Wall - firmly associate individual actions with narrative development, forming a closed loop of user action-system feedback-meaning regeneration, elevating the exhibition from cognitive enlightenment to experiential participation.

Emotional Resonance and Spiritual Internalization

As mentioned above, the final destination of the immersive technologys capability to empower the dissemination of revolutionary culture is to facilitate its penetration into the mind and heart. Red Ribbon project has achieved the audiences emotional resonance and spiritual internalization through a series of immersive technologies. Assisted by those technologies, different areas inside the venue use multi-sensory stimulation such as temperature simulation and control, vibration, simulated wind sound, etc. to enhance the visitors body memory and sense of environment presence so as to achieve emotional immersion and experience uplifting. In addition, the Red Ribbon venue includes ritualized activities that help to internalize emotion and evoke collective resonance through expression, collaboration and commemoration, e.g. Dawn Party Lecture, Starlight Storytelling Session, Red Family Letter Workshop, Light of Faith Signature Wall, etc., which allow participants to establish emotional bond with revolutionary culture through particular ritualized participation. Psychological studies show that repeated validation of beliefs through actions can transform identification from passive conformity to active internalization (Turner, J. C. 2010). Ritualized design does not only extend the duration of individuals emotions, but also helps to socially construct spiritual identification via shared emotional experiences in specific contexts. Moreover, the project uses AI semantic analysis and blockchain technology to statistically process and visualise visitors comments and signature data to generate emotional heat maps. This allows traceability and iterative optimisation of the dissemination route of the revolutionary spirit, and provides quantitative insight for further optimisation.

Case Summary

This project uses immersive technology as a vehicle to reconstruct historical scenes, allowing the audience to engage with the narrative through bodily actions and co-construct textual meanings. The ritualistic components also help internalize and circulate the revolutionary spirit. This shows that immersive technology does not only rethink the communication of revolutionary culture, but also open up new avenues for contemporary articulation and intergenerational transmission of such spirit.

CONCLUSION

This paper discusses how immersive technology empowers the spread of revolutionary culture, and describes the new approaches and models enabled by immersive media. Immersive technology is not just a methodological update, but a paradigm shift: it changes the way audiences accept revolutionary education, transforming external audio-visual stories into internal value recognition, making cultural memory reverberate again in the modern era and continuing its spirit. Through immersive scenarios, revolutionary history breaks away from the physical limitations of traditional displays, transitioning from static texts into real, living, and interactive representational spaces that accomplish narrative re-contextualisation and reproduction. High interactivity enables individuals to step into history as active participants, completing an emotional journey from observing-participating-integrating. Audiences thus become co-producers of meaning, shifting communication from one-way dissemination to multi-party co-production, and transforming transient emotions into lasting value recognition. However, there are still several deficiencies in the implementation of immersive red culture: content homogenisation and overemphasis on technological showmanship favour audio-visual spectacle at the expense of historical context and value orientation; audiences are submerged by entertainment-oriented, ritualistic packaging, weakening the educational essence; and inconsistent evaluation indicators impede cross-comparisons. These problems need to be gradually overcome in future practice.

In general, immersive technology offers a new medium for rebuilding revolutionary memory, allowing Generation Z and even Generation Alpha to approach, acknowledge and sustain revolutionary traditions in a more instinctive way. In the future, with the penetration of artificial intelligence into these endeavors, the promotion of Chinas revolutionary culture will step into an intelligent era, narrating the story of revolutionary legacy in the new era from the perspective of digital civilization.

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Policy–Space Interactions in Urban and Regional Development: A Systematic Review with a Focus on Policy Spatial Footprints

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KEYWORDS

Policy Spatial Footprint;
Spatial Planning;
Land Value Capture;
Network-Time Accessibility;
Urban Governance

ABSTRACT

Abstract Against a backdrop of slowing urbanization, tightening climate constraints, and mounting fiscal pressures, understanding the spatial consequences of public policy is critical. However, empirical research often relies on coarse buffers or administrative units, hindering the isolation of effects from overlapping governance arrangements. This review synthesizes peer-reviewed literature, primarily published between 2020 and 2025, that links public policies—specifically land-use, transport, and environmental regulations—to spatially explicit outcomes such as land values, urban form, and emissions. Based on a systematic search of Web of Science and Scopus, we analyze studies that conceptualize policy as spatially delimited interventions with rigorous exposure metrics. notably, we highlight the Policy Spatial Footprint (PSF) framework. This approach converts regulatory clauses into quantifiable spatiotemporal geometries, facilitating causal identification strategies like staggered difference-in-differences models. Our synthesis reveals persistent sectoral fragmentation and a geographical bias toward major cities in Europe, North America, and China, while the Global South remains underrepresented. Although methodological advances in spatial econometrics and digital twins are evident, open and standardized spatial policy datasets are scarce. We propose a "policy–space–outcome" framework anchored by PSF and advocate for future research integrating resilience and justice to evaluate how policy packages shape spatial development trajectories.

INTRODUCTION

Background: Why Policy–Space Interactions Matter

Over the past decade, debates on urban sustainability have shifted from managing rapid greenfield expansion to governing the reconfiguration of existing built-up areas under climate, demographic and fiscal constraints. Empirical work shows that urban land use and spatial form strongly condition energy demand and car-

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bon emissions, especially through transport and buildings (Creutzig et al., 2015; Ewing & Cervero, 2010; Glaeser & Kahn, 2010; Seto et al., 2012). As the scope for extensive outward expansion diminishes in many regions, the key levers shaping spatial structure have become institutional and policy-based—zoning and building regulations, infrastructure investment, environmental standards and fiscal instruments—rather than simply the availability of developable land (Leibowicz, 2020; Wang & Jin, 2025).

This shift is particularly visible in climate and disaster policy, where spatial planning is framed as a core instrument for mitigation and adaptation. Reviews of land use, spatial planning and carbon outcomes highlight how urban form, land-use mix and development intensity mediate emissions, while disaster-risk and adaptation studies emphasise risk-sensitive planning, zoning of floodplains and coasts, and resilience-oriented infrastructure policies (Creutzig et al., 2015; Menoni, 2025; Nowak et al., 2023, 2024; Seto et al., 2012; Voskamp et al., 2021). In these debates, the central challenge is less whether policy matters and more how different policy mixes translate into measurable changes in land use, morphology, accessibility and ecosystem functions.

Despite a long tradition of research on planning systems, regulatory instruments and governance arrangements, many studies still treat policy as an abstract context or as exogenous control variables, while focusing empirically on spatial patterns and processes. Environmental policy integration (EPI) research, for example, documents the difficulties of aligning sectoral policies with environmental goals but rarely connects these governance dynamics to fine-grained spatial outcomes (Mickwitz, 2003; Runhaar et al., 2014; van Oosten et al., 2018; van den Ende et al., 2025). Work on nature-based solutions and ecosystem-based adaptation similarly examines policy mixes and institutional conditions, yet often stops at programme adoption or project inventories, without tracing how instruments reshape land-use configurations or accessibility landscapes (Kauark-Fontes et al., 2023; van der Jagt et al., 2023; Wamsler, 2015). In land and transport economics, analyses of transit investments and value capture mechanisms demonstrate substantial impacts on land values and development intensity around stations and corridors (Cervero & Kang, 2011; Cervero & Murakami, 2009; Gong et al., 2021; Medda, 2012; Mohammad et al., 2013; van Zoest et al., 2024), but they often rely on generic proximity measures or administrative dummies to represent "policy exposure", only partially capturing the heterogeneous spatial reach of modern instruments such as overlay zones, special assessment districts or hazard-specific regulations.

Defining "Policy" and "Space"

In this review, "policy" is understood not as isolated laws or plans but as configurations of instruments and governance arrangements that shape spatial development over time. Building on work in environmental policy integration and nature-based solutions governance, policy is treated as a multi-dimensional mix of instruments that differ in mode of steering and spatial reach (Dorado-Rubín et al., 2025; Kauark-Fontes et al., 2023; Runhaar et al., 2014; van der Jagt et al., 2023; van den Ende et al., 2025). Four broad categories are distinguished. Regulatory and planning instruments include statutory spatial plans, zoning ordinances, building codes, development control regimes, hazard-zone designations and environmental standards. Fiscal and economic instruments encompass land-value capture mechanisms, impact fees, development charges, property-tax reforms, subsidies and tax incentives linked to spatially targeted objectives (Gong et al., 2021; Medda, 2012; Mohammad et al., 2013; van Zoest et al., 2024; Walters, 2013). Infrastructural and investment policies cover capital expenditure on transport, utilities, green and blue infrastructure and public facilities (Cervero & Kang, 2011; Cervero & Murakami, 2009; Leibowicz, 2020). Organisational and collaborative arrangements include coordination mechanisms between levels of government, inter-municipal agreements, public–private partnerships and participatory planning processes (Masuda et al., 2021; Menoni, 2025; van Oosten et al., 2018).

"Space" is used in a broad sense to encompass physical land-use and morphological patterns, network-based accessibility, ecological and carbon dynamics, and socially differentiated exposure to risks and amenities. Spatial outcomes include land-use type and intensity, urban form and density, and the topology of street and transit networks that underpin multi-scalar accessibility (Cervero & Murakami, 2009; Gong et al., 2021; Leibowicz, 2020; Seto et al., 2012; Wang & Jin, 2025). They also include ecological and ecosystem-service dimensions, where policy decisions about land conversion, conservation and restoration affect carbon stocks, habitat connectivity and ecosystem-service provision, increasingly modelled with spatially explicit tools (Goldstein et al., 2012; Grêt-Regamey et al., 2017; Ronchi, 2018; Voskamp et al., 2021). Spatial structure is inherently temporal and relational: accessibility and exposure depend on network structure, travel times and service frequencies, themselves shaped by policy decisions (Leibowicz, 2020; Medda, 2012). In climate and disaster fields, spatial outcomes include socially differentiated risk exposure and adaptive capacity, for example through settlement patterns in floodplains or heat-prone neighbourhoods that reflect zoning, housing policies and historical discrimination (Menoni, 2025; Nowak et al., 2023, 2024; Wamsler, 2015).

Within this review, "policy–space interactions" therefore refers to the ways in which concrete instruments and governance arrangements produce, stabilise or transform spatial outcomes across these built, ecological, network and social dimensions. The focus is on approaches that treat both policy and space as empirically observable and quantifiable, ideally with explicit geometries, temporal markers and causal identification strategies. The Policy Spatial Footprint (PSF) framework occupies a central position because it operationalises policy as a spatial–temporal footprint that can be intersected with land parcels, networks or ecological units (Xie et al., 2025), but it is viewed as one member of a broader methodological shift towards spatially explicit policy analysis.

Objectives and Research Questions

Against this backdrop, the review aims to systematise recent advances in the study of policy–space interactions, with particular attention to methods that make policy exposure explicit in spatial terms and link it to outcomes using quasi-experimental or otherwise rigorous empirical designs. Between 2020 and 2025, several subfields have produced partial overviews of related topics, including land-use and spatial-planning impacts on carbon emissions (Wang & Jin, 2025), disaster-risk-sensitive urban planning and climate adaptation (Menoni, 2025; Nowak et al., 2023, 2024), tools for planning green infrastructure and nature-based solutions (Kauark-Fontes et al., 2023; Voskamp et al., 2021; Wamsler, 2015), and land-value capture for transport investment (Gong et al., 2021; Medda, 2012; van Zoest et al., 2024). However, there is still no integrative synthesis that compares how different policy domains conceptualise and measure policy exposure, which spatial outcomes they prioritise, and how they address causality, scale and governance complexity.

The first objective is therefore to review empirical and theoretical studies published mainly between 2020 and 2025 that explicitly analyse how policy instruments and mixes affect spatial outcomes across domains such as climate and environmental planning, transport and land-value capture, and ecosystem services and nature-based solutions. The second objective is to compare how these domains define and operationalise the spatial reach of policies, including traditional distance- and buffer-based measures, administrative boundaries and newer approaches such as network-time isochrones and polygon-based policy footprints (Goldstein et al., 2012; Grêt-Regamey et al., 2017; Leibowicz, 2020; Xie et al., 2025). The third objective is to position PSF relative to other spatial policy representations, clarifying its contributions and limitations and exploring how PSF-like ideas could be adapted to sectors beyond transport and land-value capture. Finally, the review aims to propose a synthetic policy–space–outcome framework that can guide future empirical work and support cross-fertilisation between currently fragmented literatures.

These aims translate into four guiding research questions: (1) Which types of policy instruments and policy mixes have been most frequently examined in relation to spatial outcomes, and how does this vary across domains such as climate adaptation and mitigation, transport and nature-based solutions (Kauark-Fontes et al., 2023; Menoni, 2025; Nowak et al., 2023, 2024; van der Jagt et al., 2023)? (2) How is “policy exposure” conceptualised and quantified, and what are the main strengths and weaknesses of approaches ranging from traditional proximity measures and administrative indicators to ecological units and PSF-style network-time and polygonal footprints (Goldstein et al., 2012; Grêt-Regamey et al., 2017; Leibowicz, 2020; Xie et al., 2025)? (3) Which spatial outcomes—such as land values, development density, accessibility, risk exposure or ecosystem services—are prioritised, and at what spatial and temporal scales are these effects evaluated (Cervero & Murakami, 2009; Gong et al., 2021; Masuda et al., 2021; Wang & Jin, 2025)? (4) Where do important gaps remain in terms of geographic coverage, city types and scales of analysis—for example small and medium-sized cities, informal settlements, peri-urban landscapes or cross-jurisdictional governance—and how might PSF-like approaches help address these gaps (Creutzig et al., 2015; Seto et al., 2012; van Oosten et al., 2018; van Zoest et al., 2024)?

Scope and Structure of the Review

The review focuses on peer-reviewed journal articles published between 2020 and 2025 in English-language SCI and SSCI-indexed journals, complemented by earlier theoretical and methodological contributions that remain central to current debates. The disciplinary scope spans land science, urban and regional planning, transport studies, environmental policy and governance, and sustainability science. Studies are included if they (i) analyse at least one identifiable policy instrument or policy mix; (ii) assess spatial outcomes using explicit spatial data, such as land-use maps, parcel records, accessibility measures, ecosystem-service maps or value surfaces; and (iii) provide an empirical link between policy instruments and these outcomes, whether descriptive, correlational or causal. Both single-city and comparative multi-city or multi-country studies are considered, at scales ranging from neighbourhoods and corridors to metropolitan regions and national spatial planning systems.

Within this corpus, particular attention is given to studies that innovate in how policy exposure is conceptualised and measured, including work in ecosystem services and nature-based solutions that maps policy-relevant units and scenarios (Goldstein et al., 2012; Grêt-Regamey et al., 2017; Ronchi, 2018; Voskamp et al., 2021), climate and disaster-risk planning that links regulatory and investment instruments to spatial risk patterns (Menoni, 2025; Nowak et al., 2023, 2024; Wamsler, 2015), and transport–land-value studies that refine notions of accessibility and investment reach (Cervero & Kang, 2011; Cervero & Murakami, 2009; Gong et al., 2021; Medda, 2012; Mohammad et al., 2013; van Zoest et al., 2024). The PSF article is treated as a central exemplar because it formalises policy exposure using network-time and parcel-level geometries that are directly amenable to causal identification (Xie et al., 2025).

The remainder of the article is structured as follows. Section 2 details the systematic search, screening and coding procedures. Section 3 develops a conceptual lens that links policy instruments, multi-level governance and spatial exposure, with PSF presented as one concrete implementation within a wider policy–space–outcome framework. Section 4 summarises the empirical corpus across policy domains, spatial scales and world regions, while Section 5 compares how different studies operationalise policy exposure and identify causal effects. Section 6 discusses governance implications, and Section 7 proposes an integrative framework for future work. Section 8 outlines a forward-looking research agenda, and Section 9 concludes.

METHODS: LITERATURE SEARCH AND REVIEW PROTOCOL

Database Selection and Search Strategy

The review adopts a transparent and replicable search strategy that follows established guidance for systematic and structured literature reviews in the social sciences, planning and environmental policy fields (Moher et al., 2009; Page et al., 2021; Petticrew & Roberts, 2006; Snyder, 2019; Tranfield et al., 2003). The core bibliographic databases are Web of Science Core Collection and Scopus, which jointly provide broad coverage of SCI/SSCI-indexed journals and robust tools for filtering by subject category, document type and publication year (Grant & Booth, 2009; Xiao & Watson, 2019). Using multiple databases reduces the risk of disciplinary blind spots in a field that spans land-system science, urban and regional planning, environmental economics, transport studies and public health (Berrang-Ford et al., 2015; Menoni, 2025; Wang & Jin, 2025).

Searches were restricted to peer-reviewed journal articles published in English between January 2020 and November 2025. This temporal window captures the surge of interest in explicit policy–space modelling and causal identification strategies applied to spatial data, while allowing the inclusion of recent methodological innovations such as the PSF framework and network-time exposure metrics (Page et al., 2021; Snyder, 2019; Wang & Jin, 2025; Xie et al., 2025). Foundational conceptual and methodological works predating 2020, including classic contributions to spatial econometrics and causal inference, are added through backward snowballing to situate recent studies in a longer methodological genealogy (Anselin, 1988; LeSage & Pace, 2009; Moran, 1950; Callaway & Sant'Anna, 2021).

The search strings combine terms for "policy" with terms for "space" using Boolean operators. Policy terms include "policy", "regulation", "zoning", "ordinance", "planning", "governance", "fiscal instrument", "tax", "subsidy", "impact fee", "value capture" and "nature-based solutions". Spatial terms include "spatial", "land use", "land-use change", "built-up area", "urban form", "urban morphology", "spatial structure", "accessibility", "network time", "exposure" and "spatial footprint". In Web of Science, a typical query was: TS = ((policy OR regulation* OR zoning OR "land-use plan*" OR "value capture" OR "impact fee*") AND (spatial OR "land use" OR "urban form" OR "spatial structure" OR "network-time" OR "spatial footprint")), refined by document type (article) and time span (2020–2025). Two focused strings—("policy spatial footprint" OR "PSF") and ("network-time exposure" OR "network travel time" AND policy)—were used to capture PSF-type studies that transform policy texts into machine-readable geometries and network-time buffers (Xie et al., 2025) and related approaches in climate-sensitive spatial policy (Menoni, 2025; Voskamp et al., 2021).

To limit publication bias towards large, well-indexed publishers, database searches were complemented by three forms of snowballing. First, reference lists of key review articles on land-use planning and carbon emissions, disaster-risk-sensitive urban planning and urban climate adaptation tools were screened for additional eligible studies (Berrang-Ford et al., 2015; Menoni, 2025; Voskamp et al., 2021; Wang & Jin, 2025). Second, forward citation searches were conducted on a small set of seminal policy–space studies, including PSF and classic hedonic valuation studies of environmental and land-use regulations (Chay & Greenstone, 2005; Rosen, 1974; Xie et al., 2025). Third, targeted searches in leading field journals (e.g. Land, Sustainability, Journal of the American Planning Association, Regional Environmental Change, Journal of Regional Science) were used to ensure that special issues on zoning, climate policy and spatial planning were not missed because of database indexing idiosyncrasies.

Inclusion and Exclusion Criteria

The inclusion criteria focus the review on studies that (1) analyse an explicit public policy or planning instrument, (2) operationalise spatial exposure or spatial structure in an empirically measurable way and (3) report spatially explicit outcomes. First, studies must examine a public policy broadly defined to include statutory regulations and zoning ordinances, spatial plans and regulatory master plans, fiscal and tax instruments with spatial incidence (e.g. property-tax reforms, land-value capture schemes), transport and infrastructure policies, environmental and climate policies or formalised governance arrangements such as conservation zoning or nature-based solutions programmes (Grant & Booth, 2009; Menoni, 2025; Wang & Jin, 2025). General discussions of "governance" or "institutions" without a

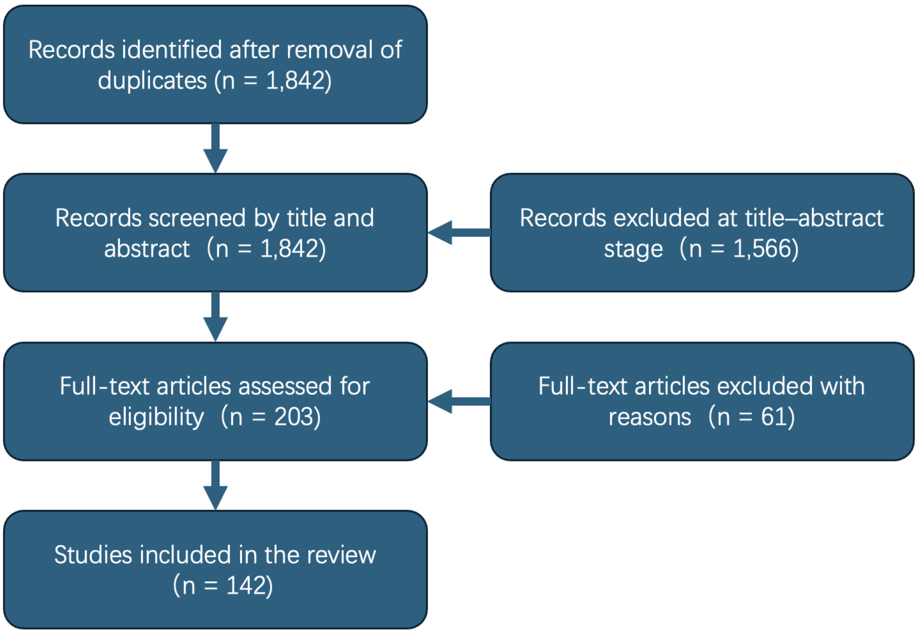

Figure 1 | PRISMA flow diagram for study identification, screening and inclusion

clearly identified instrument, or papers where policy is invoked only as context, are excluded. This reflects the review's aim to map how concrete instruments, rather than abstract governance ideals, translate into spatial footprints and exposures.

Second, eligible studies must contain at least one spatially explicit measure of policy exposure, spatial structure or spatial outcome. Acceptable exposure measures include distance to regulatory boundaries, inclusion within zoning polygons or plan designations, Euclidean or network travel time to new infrastructure, and PSF-type metrics that link legal clauses to network-time buffers or spatial eligibility areas (Kwan, 2012; Xie et al., 2025). Eligible outcomes include land prices or rents, land-use change and built-up expansion, changes in urban form and density, hazard or pollution exposure, ecosystem-service or carbon-emission indicators and distributional outcomes such as segregation or differential environmental risks (Berrang-Ford et al., 2015; Ewing & Cervero, 2010; Seto et al., 2012; Wang & Jin, 2025). Studies that discuss spatial concepts purely qualitatively, or that model hypothetical scenarios without a concrete policy instrument, are excluded.

Third, only peer-reviewed journal articles written in English are included. Conference papers, theses, book chapters, technical reports and policy briefs are excluded, even when they present sophisticated spatial analyses, because their peer-review status and long-term accessibility are harder to verify systematically (Snyder, 2019; Xiao & Watson, 2019). Grey-literature materials, such as early pilots of local PSF-like approaches or internal governmental network-time analyses, are used qualitatively to contextualise gaps but are not coded as part of the formal sample. Studies must provide sufficient methodological detail to identify the policy instrument, exposure metric and spatial outcome. Articles that do not clearly describe their policy intervention, do not specify how spatial units and exposure are defined, or conflate multiple policies without disaggregated analysis are excluded at the full-text stage. Finally, studies whose primary question is why policies are adopted earlier in some places than others, or why their design differs across jurisdictions, are only included if they also analyse spatially disaggregated outcomes of the policies themselves (Angrist & Pischke, 2009; Callaway & Sant'Anna, 2021).

Screening, Coding and Synthesis Procedures

The screening procedure follows PRISMA 2009 and PRISMA 2020 guidelines for transparent reporting of systematic reviews (Moher et al., 2009; Page et al., 2021). After removal of duplicates, the database searches yielded 1,842 records. Title- and abstract-screening reduced this to 276 records, of which 203 articles were retrieved for full-text assessment. Applying the inclusion and exclusion criteria resulted in 142 articles being retained for coding and synthesis. A PRISMA flow diagram (**Figure 1**) documents the number of records at each stage and the main reasons for exclusion.

For each included article, a structured coding framework is applied. Bibliographic fields capture authorship, year, journal and discipline; contextual fields record the country or region, spatial scale (parcel, neighbourhood, city, region, national) and study period. Policy-related fields classify the domain (e.g. land-use and zoning, transport and infrastructure, environmental and climate, social and health, rural and peri-urban), instrument type (regulatory, fiscal/tax, informational or voluntary, organisational and governance, or multi-instrument packages) and whether the policy is primarily enabling, restrictive or redistributive (Berrang-Ford et al., 2015; Grant & Booth, 2009; Menoni, 2025). Spatial-exposure fields record how policy exposure is operationalised: binary inclusion in a zoning or PSF polygon; Euclidean buffers around infrastructure; distance-decay functions; network-based travel time to PSF boundaries, stations or facilities; or composite eligibility indices constructed from multiple criteria (Kwan, 2012; Xie et al., 2025). Outcome-related fields characterise the main spatial outcomes analysed, including land-value or rent capitalisation, land-use conversion or built-up expansion, changes in urban form and density, carbon emissions and energy use, ecosystem-service provision, disaster risk and climate-hazard exposure, and social and health inequalities (Chay & Greenstone, 2005; Ewing & Cervero, 2010; Rosen, 1974; Seto et al., 2012; Voskamp et al., 2021; Wang & Jin, 2025). Methodological fields distinguish between descriptive spatial analysis, spatial econometric models, quasi-experimental designs, simulation models and mixed-methods or qualitative GIS approaches (Abadie et al., 2010; Anselin, 1988; Callaway & Sant'Anna, 2021; Elhorst, 2014; LeSage & Pace, 2009; Snyder, 2019). **Table 1** summarises the coding dimensions and categories.

To enhance reliability, the coding protocol was piloted on a random subset of 20 articles spanning different policy domains, spatial scales and methodological approaches and refined to reduce ambiguity in category boundaries. Two coders then independently coded all articles in the final corpus, with discrepancies discussed and resolved by consensus. Inter-coder agreement, monitored using Cohen's kappa for the main categorical variables (policy domain, instrument type, spatial exposure metric and outcome category), ranged between 0.78 and 0.88, which is commonly interpreted as substantial agreement (Stemler, 2001). A random 10% subsample was re-coded midway through the process as an additional reliability check. Given the heterogeneity of policy instruments, spatial scales, identification strategies and outcome measures, formal meta-analysis of effect sizes is neither feasible nor substantively meaningful. Instead, the synthesis combines descriptive statistics of coded variables with a structured narrative comparison of how studies operationalise policy exposure and address confounding, reporting exact effect sizes only for illustrative cases.

Limitations

The review has several methodological limitations. Restricting the search to English-language, peer-reviewed journal articles indexed in Web of Science and Scopus introduces language and database biases, privileging research produced in and about high-income countries (Berrang-Ford et al., 2015; Snyder, 2019). Empirical work on policy–space interactions in government reports, consultancy documentation or local-language journals is likely under-represented. Focusing on 2020–2025 captures recent methodological innovations but means that earlier generations of policy–space research, such as classic hedonic analyses of environmental regulation or early spatial econometric studies of zoning, are covered only selectively through backward snowballing (Chay & Greenstone, 2005; Rosen, 1974; Tiebout, 1956). Coding of policy instruments, spatial exposure metrics and outcomes inevitably involves judgement, even with a detailed codebook and inter-coder reliability checks (Stemler, 2001); comprehensive spatial plans that embed fiscal instruments and environmental regulations, or hybrid exposure metrics that combine zoning, accessibility and network-time measures, are particularly challenging to classify. Finally, by design the review gives particular attention to studies that explicitly quantify policy spatial footprints, network-time exposure or similar constructs linking legal or policy text to spatial geometries, such as PSF (Xie et al., 2025) and related approaches in climate adaptation and nature-based solutions planning (Menoni, 2025; Voskamp et al., 2021). This emphasis is warranted by the objective of tracing methodological innovation, but it risks biasing the corpus towards data- and method-intensive studies. There is therefore a need for complementary syntheses that connect these advanced methods to more practice-oriented evaluations in low- and middle-income contexts and link simple spatial indicators used in local planning practice to more elaborate exposure metrics.

CONCEPTUAL FOUNDATIONS: POLICY INSTRUMENTS, SPATIAL DIMENSIONS AND PSF

Typologies of Spatial Policy Instruments

Debates on policy instruments provide the first foundation for analysing how public action reshapes space. Classical work distinguishes instruments according to the primary "mode of governing". Bemelmans-Videc et al. (2017) group instruments into "carrots, sticks and sermons," corresponding to economic incentives, regulatory obligations and informational or persuasive tools. Lascoumes and Le Galès (2007) reconceptualise instruments as socio-technical devices that embody particular representations of policy problems and reorder relations between state and society, emphasising that the same broad instrument family can perform very different functions depending on design details. Howlett (2018, 2023) further stresses that instrument choice is constrained both by contextual "selection environments"

Table 1 | Coding framework for policy instruments, spatial exposure and outcomes

Coding dimension	Categories (examples)	Description
Contextual fields	Country or region; city or metropolitan area; spatial scale (parcel, neighbourhood, city, region, national); study period	Records the basic context of each study, including where it is carried out, at which spatial scale the analysis is conducted, and which years or periods are covered by the empirical data.
Policy domain	Land-use and zoning; transport and infrastructure; environmental and climate policy; social and health policy; rural and peri-urban development	Classifies the substantive area of public policy under investigation, recognising that many policies are cross-cutting but typically anchored in one dominant domain.
Instrument type	Regulatory instruments (e.g. zoning ordinances, building codes); fiscal and tax instruments (e.g. taxes, subsidies, development charges, land-value capture schemes); informational or voluntary instruments (e.g. labelling, guidance, awareness campaigns); investment and infrastructure provision; multi-instrument policy packages	Distinguishes the main type of instrument or combination of instruments used to implement the policy, following standard typologies in public policy analysis and urban governance.
Instrument function	Enabling; restrictive; redistributive	Indicates whether the instrument primarily enables and facilitates certain activities, restricts or prohibits them, or redistributes resources and opportunities across groups and places.
Spatial scale	Parcel or neighbourhood; city or municipal; metropolitan or regional; national or multi-level	Records the main spatial decision-making level at which the policy is designed and/or evaluated, recognising that many policies operate across multiple levels but are implemented at a dominant scale.
Spatial exposure metric	Binary inclusion in a zoning district or PSF polygon; Euclidean buffers around infrastructure or facilities; distance-decay functions; administrative-unit assignment; network-based travel time to PSF boundaries, stations or facilities; composite eligibility indices constructed from multiple criteria	Describes how policy exposure is operationalised in spatial terms, ranging from simple inclusion in mapped polygons to more complex measures based on distance, travel time or multi-criteria eligibility indices.
Outcome category	Land values or property prices (including hedonic and repeat-sales models); land-use conversion or built-up expansion; changes in urban form and density; carbon emissions and energy use; ecosystem-service provision; disaster risk and climate-hazard exposure; social and health inequalities	Captures the primary spatial outcomes analysed in the study, with multiple codes assigned where a study reports several outcome types.
Methodological approach	Descriptive spatial analysis; spatial econometric models (e.g. spatial lag, spatial error, spatial Durbin models); quasi-experimental designs (difference-in-differences, staggered adoption, synthetic control, regression discontinuity); simulation models (cellular automata, agent-based models); mixed-methods or qualitative GIS approaches	Classifies the dominant analytical approach used to link policy exposure to spatial outcomes, with attention to whether causal identification strategies are employed.
World region and income group	Europe; North America; East Asia; other high-income regions (e.g. Australia and New Zealand); low- and middle-income regions (e.g. Latin America, Africa, South and Southeast Asia)	Groups countries into broad world regions and income groups, allowing the review to assess geographical and income-related imbalances in the evidence base.

and by policy-makers' capacities, so that the observable mix of instruments is the outcome of incremental layering and past choices rather than technocratic optimisation.

More recent work shifts from single instruments to "policy mixes" and their internal consistency. Capano and Howlett (2020) argue that instrument analysis must move beyond classificatory schemes to examine how combinations of regulatory, economic, informational and organisational tools interact over time. They distinguish between instrument logics (e.g., command-and-control versus market-based) and implementation modalities (e.g., procedural versus substantive tools), showing that certain combinations are prone to conflict or redundancy. Mukherjee et al. (2021) connect policy capacities with instrument effectiveness, highlighting that sophisticated instruments such as dynamic carbon pricing or performance-based planning obligations require analytical and administrative capacities that are unevenly distributed across jurisdictions. Bali et al. (2021) and de Vries (2021) bring procedural tools—participatory processes, consultation requirements, impact assessment, and sequencing rules—into the instrument typology, showing that they shape which spatial options are considered politically and how distributive conflicts are framed.

Within this broader tradition, spatial planning and land-use governance are increasingly analysed through their own instrument palettes. Stead (2021) proposes a typology of spatial planning tools that distinguishes statutory land-use plans and zoning, development control and permits, infrastructure provision, fiscal and financial instruments (e.g., development charges, value capture), information and advisory tools (e.g., design guides), and collaborative or contractual instruments (e.g., public–private partnerships, strategic spatial frameworks). OECD (2017) and Krawchenko and Tomaney (2023) show that countries differ substantially in how they combine these instruments: some rely heavily on hierarchical statutory plans and ex ante zoning, whereas others emphasise negotiated development agreements, performance-based standards, or strategic regional frameworks that guide but do not legally bind local decisions. Restemeyer and Witte (2024) analyse Dutch integrated spatial policies as "instrument palettes" for spatial quality, demonstrating that effective place-based governance requires context-specific blends of permissive zoning, protective designations, targeted subsidies, and participatory design processes rather than any single "best" instrument.

Environmental and climate governance literatures similarly stress instrument diversity but place particular emphasis on environmental policy integration. Kirsop-Taylor et al. (2022) show how nature-based solutions in European cities rely on hybrid mixes of statutory spatial plans, green infrastructure standards, funding programmes, and soft coordination mechanisms that traverse departmental boundaries. Corgo and Freitas (2024) find that climate-adaptation-oriented planning increasingly combines regulatory instruments (e.g., flood zoning), economic incentives (e.g., subsidies for green roofs), and information tools (e.g., hazard maps), but that integration across sectors remains partial. A broader wave of research on policy integration and multi-level policy mixes demonstrates that spatial outcomes emerge from layered, often path-dependent combinations of instruments adopted at different government levels and time periods rather than from isolated planning decisions (Cejudo & Trein, 2023; Dorado-Rubín et al., 2025; Trein et al., 2023).

These developments have important implications for spatial analysis. First, they suggest that any empirical account of “policy–space interactions” must move from single-instrument evaluations (e.g., of a zoning change or a congestion charge) to analysis of how instrument bundles jointly condition land use, accessibility and environmental quality. Second, the growing attention to procedural and organisational tools implies that spatial impacts may arise not only from explicit spatial rules (such as floor-area ratios or building height limits) but also from agenda-setting procedures, consultation mechanisms and cross-sectoral coordination routines that determine which spatial configurations become politically feasible. Finally, typologies that are not spatially explicit need to be complemented by frameworks that map how specific instrument configurations are inscribed into space, which is precisely the gap that the Policy Spatial Footprint (PSF) framework seeks to address.

Spatial Dimensions of Policy Impact

Policy instruments operate across multiple spatial dimensions that are now well characterised in the urban studies and environmental sciences literature. A first dimension concerns land-use intensity, functional mix and built-form characteristics. Ewing and Cervero’s (2010) meta-analysis of the “3D” variables—density, diversity, and design—demonstrates that compact, mixed-use and well-designed neighbourhoods significantly reduce vehicle kilometres travelled, with implications for both congestion and emissions. Glaeser and Kahn (2010) and Danylo et al. (2019) show that variations in land-use patterns and building typologies drive large differences in per-capita carbon emissions across cities and neighbourhoods, while more recent reviews examine how specific urban-form metrics (e.g., building height, floor-area ratio, sky-view factor) affect building operational energy demand (Liu et al., 2025). These findings imply that instruments such as density zoning, plot-ratio controls, and urban growth boundaries have direct implications for emissions and energy use, even when they are not framed as climate policy.

A second dimension relates to the broader urban morphology and the internal spatial structure of metropolitan regions. Work on polycentric mega-city regions highlights how the distribution of employment and services across multiple nodes affects commuting patterns, congestion, and spatial equity in access to opportunities (Hall & Pain, 2006). Morphological measures of centre hierarchy, commuting flows and inter-urban linkages have been used to characterise polycentricity and to evaluate whether strategic spatial plans succeed in rebalancing development away from congested cores. Spatial planning instruments such as transit-oriented development (TOD) zoning, regional strategic plans, and land-value capture mechanisms for station-area development can intentionally steer this internal morphology, although evidence suggests that formal plans and actual development trajectories often diverge under market pressure and fragmented governance (Krawchenko & Tomaney, 2023; Stead, 2021).

Third, policy–space interactions increasingly focus on ecological and carbon spaces. Studies mapping greenhouse-gas emissions at fine spatial resolution show highly uneven emission hotspots across urban fabrics, with detached housing and car-dependent suburbs contributing disproportionately to residential and transport emissions (Danylo et al., 2019; Glaeser & Kahn, 2010). Health impact assessments further demonstrate that urban and transport planning decisions determine exposure to multiple risks, including air pollution, traffic injuries and physical inactivity (Rojas-Rueda et al., 2019). These findings have led to new planning instruments—emission caps for specific zones, low-emission districts, “15-minute city” street reallocation, and nature-based buffers—that are explicitly designed to reshape emission and exposure landscapes rather than simply accommodate growth. Nature-based solutions research shows how zoning for green infrastructure, ecological corridors and blue–green networks can be treated as spatial instruments that manage both ecosystem services and climate risks (Corgo & Freitas, 2024; Qiu et al., 2022; Lai & Zoppi, 2024).

A fourth spatial dimension is socio-spatial and health inequality. Environmental justice studies reveal that low-income and minority communities tend to reside closer to pollution sources and further from high-quality green spaces, even in contexts where aggregate green coverage is high (Twohig-Bennett & Jones, 2018; Wolch et al., 2014). Recent analyses in rapidly urbanising Chinese cities find pronounced socioeconomic inequalities in green-space distribution and access, driven by redevelopment patterns and high-end residential enclaves (Hou et al., 2024; Zhu et al., 2025). Network-based assessments of exposure to green space and other amenities show that using Euclidean buffers underestimates inequalities compared with network-time measures that incorporate actual route options and travel times (Song et al., 2018; Labib et al., 2021). In this context, spatial policy instruments—such as inclusionary zoning, minimum green-space standards per capita, or targeted investment in underserved neighbourhoods—are increasingly assessed in terms of their capacity to reduce spatialised inequalities rather than only to meet aggregate targets.

Taken together, these strands suggest that policy–space interactions must be conceptualised as multi-dimensional: the same instrument can simultaneously affect built-form intensity, metropolitan morphology, emissions and health inequalities. For analytical purposes, the review therefore treats “spatial impact dimensions” as a set of partly overlapping outcome domains—built environment, ecological and carbon spaces, and socio-spatial justice—that provide a common language to compare heterogeneous policy instruments and sectors.

Multi-Level Governance, Policy Space and Spatial Planning

The spatial reach of instruments is mediated by multi-level governance arrangements that allocate planning powers and fiscal resources across scales. Nadin et al. (2021) show that European spatial planning has evolved towards more integrated, adaptive and participatory models, yet strong national frameworks continue to constrain local discretion, particularly in countries with detailed statutory planning hierarchies. Hickmann et al. (2021) locate cities within multi-level climate governance architectures, demonstrating that local climate and land-use plans are nested within international agreements, national mitigation targets and sectoral regulations, creating both opportunities for upward influence and constraints from above. OECD (2017) and Krawchenko and Tomaney (2023) extend this perspective to land-use governance more broadly, proposing conceptual frameworks that distinguish between the formal allocation of competences (e.g., who can zone or levy development charges), fiscal relations (e.g., property-tax assignments, intergovernmental transfers) and informal coordination mechanisms (e.g., metropolitan partnerships).

Within these architectures, “policy space” denotes the discretionary room that sub-national governments have to adapt or combine instruments to local conditions. Banikoi et al. (2024) show that in Sub-Saharan African contexts, local governments’ policy space in land-use and spatial planning is often severely constrained by centralised legal frameworks and donor-driven project logics, which reduces their capacity to address informality and environmental risks. Dorado-Rubín et al. (2025) analyse European urban policies as multi-level policy mixes, arguing that local spatial policies emerge from the interplay of EU directives, national frameworks and municipal initiatives; they stress that genuine integration requires not only horizontal coordination across sectors, but also vertical alignment of objectives and instruments. Cejudo and Trein (2023) and Trein et al. (2023) further highlight that policy integration can follow different pathways—such as layering, displacement or conversion of existing instruments—and that these trajectories are shaped by institutional capacities and political coalitions at each level of government.

Spatial planning is therefore both a distinct policy domain and a site where multi-level policy mixes materialise. National governments typically control high-level instruments such as infrastructure investment programmes, environmental regulations and broad zoning categories, while regional and local governments deploy more fine-grained instruments—detailed land-use plans, development permits, design codes, and municipal taxes or fees. Stead (2021) and Restemeyer and Witte (2024) show that the effectiveness of spatial planning tools depends on how they are embedded in these multi-level regimes: local experiments with nature-based solutions or value-capture instruments are fragile if they are not supported by higher-level frameworks that provide legal certainty and stable revenue streams. At the same time, procedural instruments such as participation requirements, strategic environmental assessment and inter-municipal coordination forums can expand local policy space by enabling municipalities to negotiate exceptions or experiment with novel spatial practices (Bali et al., 2021; de Vries, 2021).

Conceptually, this implies that “policy–space interactions” cannot be reduced to a single regulatory change at one level of government. Instead, spatial outcomes such as transit-oriented development corridors, ecological networks or equitable green-space provision reflect the cumulative and often nonlinear effects of vertical and horizontal instrument combinations. Any attempt to spatialise policy therefore needs to encode not only the location and geometry of specific rules, but also the level of government that owns them, their temporal sequence, and their interaction with broader fiscal and regulatory environments.

Policy Spatial Footprint (PSF) as a Bridge Between Policy Text and Spatial Exposure

Despite the richness of work on instruments, spatial dimensions and multi-level governance, most empirical studies still rely on relatively crude representations of “policy exposure”. A large body of research approximates exposure to transit projects, environmental regulations or amenities using Euclidean buffers (e.g., within 500 m of a new rail station) or administrative units (e.g., within a municipality explicitly targeted by a programme). Built-environment and health studies have progressively adopted more sophisticated network-based and space-time accessibility measures (Kwan, 1998; Fang & Yu, 2010; Song et al., 2018; Labib et al., 2021), but even here exposure is usually defined relative to physical objects (roads, parks, pollution sources) rather than to the legal or fiscal coverage of policy instruments themselves. In parallel, environmental-planning research has developed detailed spatial models of ecosystem services, ecological functional zones and nature-based solutions (Deng et al., 2023; Fistola, 2023; Qiu et al., 2022; Lai & Zoppi, 2024), yet these typically map desired outcomes or biophysical processes rather than the normative reach of specific ordinances, regulations or subsidies.

The Policy Spatial Footprint (PSF) framework proposed by Xie et al. (2025) directly addresses this gap by treating planning and regulatory texts as sources of spatially explicit information. Starting from policy documents—such as station-area development plans, transit-oriented zoning codes and land-value capture ordinances—PSF extracts the clauses that define where, when and how a rule applies. These clauses are translated into georeferenced geometries (points, lines and polygons) that represent the legal coverage of the policy, including inclusion and exclusion areas and multiple intensity levels (e.g., primary vs. secondary impact zones). Each geometry is time-stamped to distinguish between policy announcement, legal enactment and practical implementation, thereby enabling event-study and difference-in-differences designs that account for anticipation effects and implementation lags.

A key innovation of PSF is the explicit use of network-time exposure rather than Euclidean distance. By projecting parcel locations onto multimodal transport networks and calculating shortest travel times to PSF geometries, the framework recognises that accessibility gains and regulatory constraints propagate along actual mobility paths rather than radiating isotropically in space (Xie et al., 2025). This approach builds conceptually on time-geographic accessibility measures (Kwan, 1998) and more recent network-based exposure studies (Song et al., 2018; Labib et al., 2021) but links them directly to the legal geometry of policy instruments. In the Yangtze River Delta case, Xie et al. show that land-value impacts of high-speed rail and associated station-area policies are more sharply defined in network-time space than in straight-line buffers, and that failing to use network-time exposure can lead to underestimation or misidentification of policy effects.

Compared with traditional spatial planning evaluations, PSF offers three further advantages. First, it is explicitly auditable: because PSF geometries are derived from specific textual clauses, they can be traced back to their legal sources and revised when regulations change, aligning with calls in the policy-instrument literature for more transparent and reflexive instrument design (Howlett, 2018; Capano & Howlett, 2020). Second, PSF is compositional: footprints from different instruments (e.g., density bonuses, environmental buffers, affordable-housing requirements) can be overlaid to reveal zones of instrument synergy or conflict, making the notion of a "policy mix" spatially explicit (Restemeyer & Witte, 2024; Kirsop-Taylor et al., 2022). Third, PSF is model-agnostic: once policy exposure has been encoded in network-time space, it can be combined with hedonic pricing models, spatial difference-in-differences, or agent-based simulations, facilitating comparative evaluation across diverse empirical designs.

At the same time, the PSF approach also has limitations that are important for a balanced conceptualisation. Constructing footprints is labour-intensive and requires close collaboration between legal, planning and GIS expertise; ambiguities in policy texts can translate into spatial uncertainty that must be explicitly documented and, where possible, quantified. Moreover, PSF has so far been applied primarily to land-use and transport policies in data-rich settings; extending it to domains such as environmental health, ecosystem services or social policy may require new conventions for coding diffuse or relational obligations (e.g., city-wide emission caps, region-wide ecosystem restoration targets). These challenges, however, are not unique to PSF: they mirror broader difficulties in instrument design and multi-level governance, where overlapping competences and vague mandates are common (OECD, 2017; Nadin et al., 2021; Dorado-Rubín et al., 2025). In this sense, PSF should be viewed not as a fully resolved solution but as a bridge concept that operationalises the links between policy instruments, spatial dimensions of impact, and causal inference tools—providing a common language through which heterogeneous studies on policy–space interactions can be compared and synthesised.

EMPIRICAL EVIDENCE BY POLICY DOMAIN

Across the final sample of 142 articles, most studies focus on land-use regulation, transport and environmental or climate policies, with comparatively fewer contributions on social and health policies or rural and agricultural development. **Table 2** summarises the distribution of studies by policy domain, spatial scale and world region, indicating a marked concentration in higher-income countries and metropolitan regions. **Table 3** cross-tabulates policy domains, spatial exposure metrics and identification strategies, highlighting, for example, the predominance of simple distance- or administrative-unit-based exposure in earlier work and the growing use of network-time and PSF-based measures in more recent studies. These patterns provide the empirical context for the more detailed domain-specific discussions that follow.

Land-Use Regulation, Zoning and Spatial Governance

Land-use intensity, green transition and carbon outcomes

Empirical research increasingly shows that regulation of land-use intensity and functional zoning is closely tied to urban carbon outcomes. Studies using meta-

Table 2 | Distribution of included studies by policy domain, spatial scale and world region

Dimension	Category	Number of studies (n)	Share of sample (%)
Policy domain	Land-use and spatial planning	48	33.8
Policy domain	Transport and infrastructure	36	25.4
Policy domain	Environmental and climate policy	30	21.1
Policy domain	Social and health policy	18	12.7
Policy domain	Rural and peri-urban development	10	7.0
	Subtotal	**142**	**100.0**
Spatial scale	Parcel or neighbourhood	40	28.2
Spatial scale	City or municipal	55	38.7
Spatial scale	Metropolitan or regional	30	21.1
Spatial scale	National or multi-level	17	12.0
	Subtotal	**142**	**100.0**
World region	Europe	52	36.6
World region	North America	38	26.8
World region	East Asia	27	19.0
World region	Other high-income regions	9	6.3
World region	Low- and middle-income regions	16	11.3
	Subtotal	**142**	**100.0**

Table 3 | Cross-tabulation of spatial exposure metrics and methodological approaches

Spatial exposure metric	Descriptive spatial analysis	Spatial econometric models	Quasi-experimental designs	Simulation models	Mixed / qualitative GIS
Binary inclusion in zoning or PSF polygons	●●●	●●●	●●	●	●●
Euclidean buffers or distance-decay functions around infrastructure or facilities	●●●	●●●	●●	●●●	●
Administrative-unit assignment (e.g. census tracts, municipalities)	●●	●●●	●●●	●	●●
Network-based travel time to PSF boundaries, stations or facilities	●●	●●	●●●	●●	●
Composite eligibility indices constructed from multiple criteria	●	●●	●●	●●●	●●●

Note: Cells indicate the relative frequency of combinations in the sample (●●● = common; ●● = occasional; ● = rare; – = not observed).

analytic and multi-city designs demonstrate that higher densities, mixed land uses and transit-supportive built forms reduce vehicle-kilometres travelled and associated emissions, though effects are heterogeneous across contexts (Ewing & Cervero, 2010; Glaeser & Kahn, 2010). Within this broader literature, recent work has turned to explicitly policy-based measures of intensity, such as floor area ratio (FAR) caps, bonus FAR schemes and land-use conversion quotas, to examine how regulatory choices shape both operational and transport-related carbon emissions. For example, Wang and colleagues use panel data for Northeast China to show that cities combining compact, transit-oriented spatial plans with strict controls on low-density expansion achieve significantly lower per-capita emissions than similarly industrialised cities without such planning coherence (Wang et al., 2025). Their difference-in-differences models suggest that up-zoning around transit nodes can reduce transport emissions while only modestly increasing building-related emissions, leading to net carbon benefits when design standards include energy-efficiency requirements.

Another line of work focuses on FAR incentives and development rights as levers for low-carbon urban form. Cheshmehzangi and Dawodu (2021) combine urban form indicators with energy-model scenarios to show that shifting allowable FAR from peripheral to inner-city zones can lower aggregate energy use and emissions, provided that green building codes are enforced in higher-intensity areas. Similarly, transport-oriented spatial planning in Taipei, analysed through a scenario-based spatial model, indicates that concentrating growth within planned high-intensity corridors can cut transport CO_2 emissions by more than 10% relative to business-as-usual, even when overall population and economic activity continue to rise (Wang et al., 2018). These studies collectively suggest that the carbon effects of intensity regulation are highly path-dependent: up-zoning can either lock in high-carbon forms or support green transition, depending on whether regulations

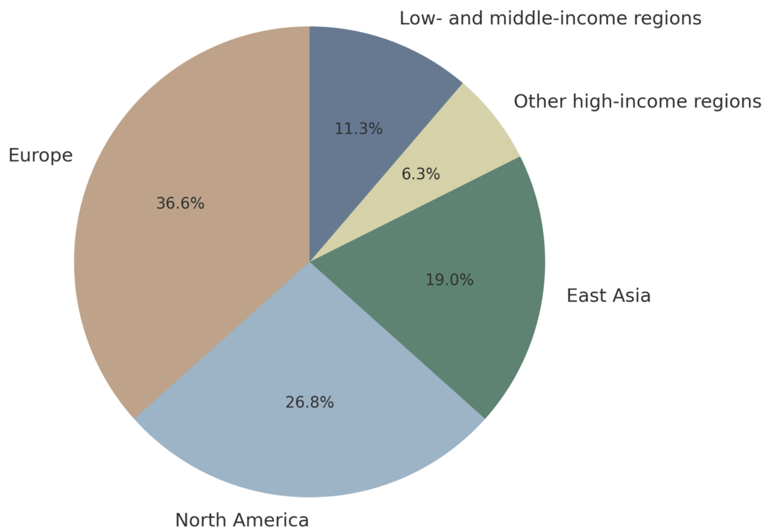

Figure 2 | Regional distribution of included studies by world region

are coordinated with transit investment, building-energy standards and green-space provision.

Beyond aggregate emissions, recent work links land-use intensity policy to spatial patterns of carbon sources and sinks. Remote-sensing based analyses show that enforced minimum plot ratios in central areas often correlate with the loss of small urban green patches, which in turn diminishes local cooling and carbon-sequestration capacity, while strict protection of vegetated areas in peri-urban zones can partially compensate at larger scales (Wang et al., 2025; Xiong & Yao, 2025). These findings underline that FAR and zoning ordinances should be evaluated not only for their influence on trip generation and building energy, but also for their impact on the spatial balance between built surfaces and urban ecosystems.

Urban spatial growth, containment and green belts

Urban containment instruments—urban growth boundaries, green belts, ecological red lines and permanent agricultural protection zones—constitute a second major cluster of spatial policies. Early evaluations of Swiss and other European containment policies found that statutory growth boundaries could substantially reduce leapfrog development and increase infill, though sometimes at the cost of higher land prices and densification pressures inside the boundary (Gennaio et al., 2009). Subsequent comparative work shows that the effectiveness of such instruments depends less on the mere existence of a boundary than on its legal rigidity, enforcement capacity and coordination with transport and housing policies (Kirby et al., 2023).

Recent studies emphasise the multi-functional character of containment instruments. Xiong and Yao (2025) analyse the spatial evolution of metropolitan green belts, showing that belts designated primarily for recreational and landscape purposes may be progressively encroached upon unless backed by strong land-use controls and clear compensation mechanisms for landowners. Where green belts are explicitly integrated into regional ecological networks and climate-adaptation strategies, they appear more resilient against incremental erosion and more effective at steering growth towards transit-served corridors. At the same time, evidence from Chinese and European cases indicates that too rigid containment can displace growth into more distant, poorly served jurisdictions, generating longer commuting distances and increasing regional transport emissions (Gennaio et al., 2009; Kirby et al., 2023).

Methodologically, most evaluations of containment policies rely on spatial metrics of built-up expansion (e.g., edge-expansion indices, leapfrog development rates, infill ratios), combined with land-price or accessibility indicators. More recent work incorporates scenario-based modelling to simulate how alternative boundary locations and accompanying housing policies might alter both land-use efficiency and carbon outcomes (Wang et al., 2018; Xiong & Yao, 2025). However, very few studies explicitly encode the legal geometry and timing of containment provisions—as opposed to simply treating the observed built-up edge as a proxy—leaving scope for more policy-explicit approaches such as PSF to distinguish between de jure and de facto boundaries.

Informality, compliance and implementation gaps

Empirical evidence from the Global South underscores that the spatial impact of land-use regulation is mediated by enforcement capacity and informality. Goytia et al. (2023) exploit parcel-level data from Buenos Aires and find that stringent zoning regulations, when weakly enforced, can unintentionally push low-income households into informal settlements beyond the regulated urban perimeter. Their results suggest that formal regulatory strictness, absent affordable pathways to compliance, may expand rather than shrink informal urban footprints. Complementary studies in African and Asian cities show that informal residential expansion often follows infrastructure corridors and environmentally sensitive areas where formal planning is absent or unenforced, leading to fragmented land-use patterns and ecosystem degradation (Hailu, 2024; Ahmad et al., 2025).

Research using high-resolution imagery and street-scale surveys highlights that planned and unplanned settlements can evolve markedly different spatial morphologies despite similar locational advantages. Mottelson (2023) compares the internal form of planned and unplanned neighbourhoods in Maputo, Mozambique, demonstrating that planned areas have more regular street grids and clearer plot demarcation but not necessarily higher effective densities. In contrast, unplanned zones exhibit organic street patterns and irregular plots, yet may achieve similar or greater residential densities through incremental vertical expansion. These findings challenge simple narratives equating informal with low density, and show that the main spatial efficiency gap often lies in limited access connectivity, lack of public green space and exposure to environmental hazards rather than density per se.

From a policy perspective, recent studies stress the importance of implementation trajectories. Ahmad et al. (2025) analyse Karachi as a “planned city with unplanned land use” and show how decades of ad hoc regularisation and tolerance of informal subdivisions have produced a highly fragmented mosaic of land uses only partially aligned with official land-use plans. Hailu (2024) documents similar dynamics in Addis Ababa, where informal settlements at the urban edge convert agricultural and ecological land without adequate provision of services, undermining ecosystem services and exacerbating spatial inequalities. Together, this literature suggests that the spatial outcomes of land-use regulation result from the interplay of formal instruments, enforcement practices, political economy and everyday coping strategies, and that quantitative evaluation must therefore consider both on-paper regulations and their de facto relaxation, evasion or reinterpretation.

Land value capitalization and PSF: evidence from the Yangtze River Delta

The link between regulatory policies and land values has long been documented in hedonic and quasi-experimental studies, which show that zoning changes, environmental regulations and transport investments are capitalised into land and housing prices (Ewing & Cervero, 2010; Glaeser & Kahn, 2010; Li et al., 2022; Suzuki et al., 2013). However, most empirical work continues to proxy policy exposure using simple distance-to-infrastructure measures, coarse administrative dummies or post-hoc land-use classifications, which obscure the spatial and temporal specificities of policy design and implementation. The Policy Spatial Footprint (PSF) framework proposed by Xie et al. (2025) represents a significant methodological advance by explicitly mapping the spatial geometry, timing and strength of multiple policy instruments and linking them to parcel-level land transactions.

Using approximately 1.10 million land-transaction records from five Yangtze River Delta cities between 2012 and 2024, Xie et al. (2025) construct PSFs for 64 policies spanning planning regulations, transport investments and industrial-land programmes. Policy clauses are parsed and translated into spatial footprints with attributes capturing effective dates, applicable land-use types, intensity thresholds and explicit inclusion or exclusion zones. Network-time buffers based on combined rail-road travel times are then used to define exposure, replacing the conventional Euclidean distance. This enables a staggered multi-period difference-in-differences design in which parcels entering or leaving PSF exposure zones at different times serve as treated and control observations. The results show that direct exposure to PSFs associated with major transport and zoning changes leads to statistically significant increases in land prices over several years, with the magnitude and duration of effects depending on local market depth and pre-existing regulatory “positions” (stringency and credibility of past plans). Spillover effects into adjacent but formally non-covered zones decay rapidly with additional network-travel time, indicating that accessibility and policy credibility interact to shape the spatial decay of capitalisation effects.

When compared with studies that rely on generic zoning or distance measures, PSF-based analysis provides several advantages. First, it allows disentangling overlapping policy effects where multiple regulations coexist in space and time, such as the combination of TOD zoning, industrial-land restrictions and environmental buffers (Li et al., 2022; Wang et al., 2025). Second, the explicit mapping of exclusions and carve-outs clarifies why some parcels close to infrastructure do not experience expected price gains, thereby reducing omitted-policy bias. Third, the network-time exposure metric aligns more closely with actual accessibility and service coverage than straight-line buffers, especially in polycentric regions with complex transport networks. Finally, because PSFs are constructed from auditable legal documents and planning maps, they can be updated and extended across sectors (e.g., environmental, social, fiscal policies), creating a common spatial layer for integrated policy evaluation and comparative studies across cities.

Transport and Mobility Policies With Spatial Effects

Transport and mobility policies modify spatial structure both directly, by reshaping accessibility patterns, and indirectly, by influencing location decisions of households and firms. A large body of empirical work shows that fixed-guideway transit investments and transit-oriented development (TOD) policies are associated with higher densities, greater land-use mixing and reduced car dependence in station areas, although distributive outcomes vary (Ewing & Cervero, 2010; Bertolini, 1999). Cervero and Kang (2011), using a hedonic price model for Seoul, find that bus rapid transit (BRT) corridors with supportive land-use controls generate substantial land-value uplift within walking distance of stations, especially where zoning allows higher intensity and mixed uses. Their results highlight that without explicit land-use reforms, the spatial leverage of transport investments is limited.

Recent studies systematically integrate land value capture (LVC) into evaluations of transport policy. Li et al. (2022) propose a systemic model linking transport investment, accessibility gains and LVC instruments such as betterment levies, joint development and development rights sales, arguing that the spatial distribution of accessibility benefits should guide the design of LVC schemes. Their empirical application shows that station areas with clear, enforceable up-zoning and public land ownership enable more robust LVC than areas where land-use regulations are fragmented. Lin and Wei (2025) examine TOD in metropolitan China and find that rail-served suburbs with strong TOD zoning and inclusionary housing requirements have higher densities and lower car mode shares than similar suburbs without such policies, but may also exhibit rising land prices and socio-spatial sorting.

From a methods perspective, most transport–land-use studies still measure policy exposure via fixed radius buffers around stations or corridors. Network-based accessibility metrics are gaining ground, yet explicit encoding of policy provisions (such as minimum densities, parking maximums or pedestrian-priority zones) remains rare. The PSF approach demonstrates how transport-related policy clauses—such as service coverage guarantees, intermodal transfer requirements or station-area zoning overlays—can be translated into spatial footprints and network-time catchments. By doing so, it becomes possible to estimate not only average station-area effects, but also distributional outcomes across different PSF overlays, such as zones with transit priority plus affordable-housing requirements, versus zones with transit improvements but no land-use reforms (Xie et al., 2025; Li et al., 2022). This integration of transport policy, spatial regulation and land economics is crucial for designing mobility strategies that are both financially and socially sustainable.

Environmental and climate policies in spatial planning

Environmental and climate policies increasingly operate through spatially explicit instruments such as ecological protection zones, low-emission districts, flood risk overlays and carbon-neutral spatial plans. Empirical studies from Europe and East Asia show that integrating climate-mitigation and adaptation objectives into spatial planning can shift development away from high-risk or carbon-intensive locations and foster more compact, transit-supportive patterns (Wang et al., 2018; Menoni & Ferreira, 2025). For instance, Menoni and Ferreira (2025) compare local land-use plans before and after the introduction of national climate-planning guidelines, noting a rise in the designation of flood-resilient zones, compact growth areas and green infrastructure corridors, with measurable changes in subsequent development applications.

In China, Qiu and Xu (2022) review municipal practices and identify several pathways by which climate mitigation is incorporated into urban master plans, including industrial restructuring, transit-oriented intensification and green-space systems designed for both recreation and carbon sequestration. Yet they also point out implementation gaps, as many plans lack clear legal status or enforcement mechanisms. At the micro-scale, studies using building-energy and urban-climate models suggest that environmental regulations targeting building envelopes, street-canyon geometry and urban greenery can produce localised cooling and emissions reductions, but the cumulative effect depends on how these measures are spatially distributed relative to population and activity density (Cheshmehzangi & Dawodu, 2021; Wang et al., 2025).

The PSF logic is readily extendable to environmental and climate policies. Ecological red lines, low-emission zones and hazard-based building restrictions are all defined by legal texts and maps that can be converted into spatial footprints with attributes describing restriction types, enforcement dates and allowable uses. While few studies have fully operationalised such PSFs, early work on ecological zoning and carbon-neutral district planning shows that explicitly mapping protected and regulated areas can clarify trade-offs between development rights and environmental objectives, and can support compensation schemes for landowners in restricted zones (Guo et al., 2023; Hou et al., 2025; Tesfay et al., 2025). Incorporating these environmental PSFs into land-value and development models would allow more systematic evaluation of how climate and biodiversity policies are capitalised into land markets and how they reshape the spatial distribution of risk and opportunity.

Social, Health and Post-Pandemic Policies With Spatial Implications

Social and health policies increasingly operate through spatial rules on service catchments, accessibility standards and quality-of-life indicators. Evidence from public-health and urban-planning research shows that proximity to green spaces, walkable street networks and local services is associated with lower mortality, better mental health and higher levels of physical activity (Twohig-Bennett & Jones, 2018). Despite these findings, many cities still rely on coarse administrative boundaries or simple distance thresholds when defining school catchments, health-service areas or "healthy-city" targets, without fully considering the underlying transport networks and barriers.

The COVID-19 pandemic further highlighted the spatial dimension of social and health policies. While this review focuses primarily on 2020–2025, much of the empirical evidence builds on pre-pandemic work on active travel and greenspace exposure. Studies in European and Asian cities show that neighbourhoods with pre-existing walkability, mixed land uses and accessible green spaces better supported physical activity and social distancing during lockdowns, while car-dependent peripheral areas suffered more severe mobility constraints and mental-health burdens (Ewing & Cervero, 2010; Twohig-Bennett & Jones, 2018). These patterns have motivated proposals for "15-minute city" and "complete neighbourhood" policies, which essentially encode spatial standards for access to daily needs into planning regulations.

From a policy-evaluation perspective, most social and health-related spatial policies are still assessed using proxies: for example, counting facilities within fixed radii or within administrative units. There is substantial scope to apply PSF-style mapping to encode detailed policy clauses—such as maximum walking distances to primary schools, required provision of parks per capita, or eligibility zones for housing vouchers—into spatial footprints aligned with network-time metrics. Doing so would allow more precise estimation of how changes in these policy parameters affect spatial inequalities in access, and how they are capitalised into land and housing prices, particularly in post-pandemic reconfigurations of urban life.

Rural and Peri-Urban Policies and Spatial Restructuring

Finally, rural and peri-urban policies have profound spatial effects, particularly in fast-urbanising regions. Cultivated-land protection policies, rural-revitalisation programmes and land-consolidation schemes reshape settlement patterns, agricultural land-use and ecological networks at the rural–urban interface. Guo et al. (2023) analyse cultivated-land conservation policies in China and show that strict protection quotas can reduce the rate of farmland conversion overall, but may also encourage more intensive land use and construction in unprotected pockets, leading to fragmented landscapes. Hou et al. (2025) examine farmland-protection spatial governance in peri-urban China and find that the spatial configuration of protection zones—continuous belts versus scattered patches—significantly affects both farmland fragmentation and the feasibility of compact urban expansion.

Farmland-consolidation and land-readjustment programmes illustrate how rural policies can function as spatial instruments. Tesfay et al. (2025) use micro-data from Ethiopia to show that consolidation policies can reduce plot fragmentation and improve agricultural productivity, but may simultaneously increase income inequality if better-connected households capture disproportionate gains. In many countries, rural-revitalisation strategies also promote the redevelopment of village centres into compact service hubs and tourism destinations, often combined with the relocation of scattered hamlets. Yet systematic spatial evaluations of these policies remain scarce, especially regarding their long-term effects on ecosystem services and mobility patterns.

The PSF framework offers a way to bring rural and peri-urban policies into the same analytical space as urban regulations. Protection zones, consolidation areas, rural-revitalisation pilot villages and collective-construction land pilot zones are all defined by legal documents that can be mapped as spatial footprints with attributes describing tenure, permitted uses and policy duration (Guo et al., 2023; Hou et al., 2025; Tesfay et al., 2025). Linking these rural PSFs to parcel-level land-use and value data would allow researchers to examine whether rural and peri-urban policies complement or contradict urban containment, TOD and environmental regulations, and how the combined policy mix shapes long-term spatial restructuring across the urban–rural continuum.

METHODOLOGICAL TRENDS IN ASSESSING POLICY–SPACE IMPACTS

The past two decades have seen a rapid convergence between spatial econometrics, quasi-experimental designs, simulation modelling, and data-rich GIS and remote sensing, fundamentally reshaping how policy–space relationships are identified and quantified. Classical spatial regression tools have been refined to better accommodate policy spillovers and multi-scalar dependence, while advances in causal inference have sharpened concerns about treatment definition, interference, and dynamic selection. At the same time, land-use–transport and environmental models have become more behaviourally explicit, and remotely sensed and street-level data now allow fine-grained observation of spatial outcomes. Against this background, the Policy Spatial Footprint (PSF) framework proposed by Xie et al. (2024) is emblematic of a new generation of methods that treat policies themselves as auditable spatio-temporal data objects, closing the long-standing gap between legal text, spatial exposure, and causal identification.

Spatial Econometrics and Quasi-Experimental Designs

Spatial econometrics provides the original toolbox for modelling spatial dependence in policy evaluations. Anselin's (1988) monograph laid the foundations for formal spatial lag, spatial error, and spatial Durbin models, emphasising how regional outcomes are jointly determined by their own covariates and the outcomes or characteristics of neighbouring units. Subsequent contributions by LeSage and Pace (2009) and Elhorst (2014) developed comprehensive treatments of spatial panel models, including fixed-effects specifications suitable for policy interventions that unfold over time. Methodological work on the spatial Durbin model and common-factor tests has clarified when spillovers operate primarily through dependent variables or covariates, with important implications for interpreting policy diffusion and cross-jurisdictional externalities (Mur & Angulo, 2006). Comparative simulations further show that misspecification of spatial weights or functional forms can lead to biased impact estimates, highlighting the need for carefully designed neighbourhood structures in regional policy analysis (Rüttenauer, 2019).

These technical developments have been accompanied by critical reflections on the "value add" of spatial econometrics for policy evaluation. Gibbons and Overman (2012) argue that many applications fail to connect spatial dependence parameters to substantive economic mechanisms, risking "mostly pointless" spatial embellishments when identification remains weak. Corrado and Fingleton (2012) similarly call for stronger theoretical grounding, insisting that spatial specifications should reflect behavioural processes and institutional context rather than merely detecting residual autocorrelation. In the context of land-use regulation, transport infrastructure, and environmental zoning, these debates translate into a demand for treatment variables that reflect the actual geometry and timing of policy exposure. If zoning overlays, corridor plans or ecological red lines are crudely proxied by radial buffers or administrative dummies, then even sophisticated spatial regressions remain vulnerable to misclassification and omitted mechanism bias.

In parallel, quasi-experimental designs have become the dominant standard for causal claims in applied policy evaluation. Difference-in-differences (DiD) and related designs provide transparent estimators of average treatment effects under parallel trend assumptions, extending earlier instrumental-variable traditions emphasised by Angrist and Pischke (2009). Synthetic control methods allow credible counterfactual trajectories for treated units, especially in small-N, staggered-adoption settings typical of institutional or planning reforms (Abadie, Diamond, & Hainmueller, 2010; Abadie, 2021). Recent advances explicitly address heterogeneous treatment timing and effects: Callaway and Sant'Anna (2021) propose group-time average treatment effects for multi-period DiD designs, while Sun and Abraham (2021) show that conventional two-way fixed-effects event-study estimators can be severely biased when effects vary across cohorts. De Chaisemartin and D'Haultfoeuille (2020) further demonstrate that two-way fixed-effects estimators can produce weighted averages with negative weights under heterogeneity, motivating alternative estimators that preserve causal interpretability. Athey and Imbens (2022) formalise these concerns in a design-based framework and advocate estimators that explicitly reflect the assignment process and timing of policy adoption.

When these causal tools are combined with explicitly spatial outcomes—such as property prices, land-use change, or exposure to infrastructure—the key methodological bottleneck shifts to the definition of "treatment" and "control" in space. Spatial spillovers violate the stable unit treatment value assumption, as policies implemented in one jurisdiction may affect neighbouring units through migration, investment, and network effects. Spatial econometric models can partially address such interference by modeling lagged outcomes and covariates (Elhorst, 2014; Mur & Angulo, 2006), but they do not in themselves solve the problem of assigning exposure status. In many empirical studies, treatment is defined by simple Euclidean distance thresholds from a policy boundary or facility, or by coarse administrative membership. This creates sensitivity of DiD and event-study estimates to arbitrary buffer choices and ignores the network-time structure of accessibility. The emerging PSF approach directly targets this gap by translating detailed legal and planning texts into spatio-temporal treatment indicators that can be interfaced with staggered-adoption DiD and spatial panels, thereby aligning econometric design with the actual geometry and timing of policy implementation (Xie et al., 2024).

Land-Use, Transport and Environmental Modelling

A second major methodological strand concerns ex-ante simulation of policy impacts through land-use–transport interaction (LUTI) and environmental models. Wegener (2014) provides a comprehensive review of LUTI models that couple transport networks, location choice, and land-use change, tracing their evolution from early aggregate gravity-based systems to disaggregate and activity-based formulations. Acheampong and Silva (2015) synthesise more recent LUTI applications and highlight how they are increasingly used to test planning scenarios, such as transit-oriented development (TOD), congestion pricing, and growth boundaries, under varying behavioural and policy assumptions. In these models, spatial policy interventions are usually encoded as changes in zoning capacity, transport costs, or development constraints, which in turn drive simulated locational responses.

Multi-agent and agent-based approaches provide finer representations of decision making and heterogeneous actors. Crooks, Patel, and Wise (2014) discuss how multi-agent systems can represent residents, firms, and planners with distinct objectives and information sets in urban planning scenarios, allowing exploration of complex feedbacks between regulations, market dynamics, and built form. Parker and Filatova (2008) propose a conceptual design for bilateral agent-based land markets with heterogeneous agents, in which prices, development patterns, and land-use change emerge from decentralised bargaining rather than imposed equilibrium conditions. Wahyudi, Liu, and Corcoran (2019) extend this logic to developing-country contexts, simulating how heterogeneous private developers generate divergent urban land configurations under different policy constraints. Dai et al. (2020) review agent-based models of land systems and outline key design issues, including representation of planning rules, enforcement regimes, and environmental externalities. At the same time, Grimm et al. (2006) argue for standardised protocols (ODD) to improve the transparency and reproducibility of agent-based and individual-based models, which is particularly important when they are used to inform real-world policy debates.

Despite their sophistication, LUTI and agent-based models often treat policies as scenario parameters rather than as objects derived from actual legal and regulatory texts. For example, a greenbelt may be represented as a simple radial constraint, and a TOD policy as a density bonus within an arbitrary distance of a station (Acheampong & Silva, 2015; Wegener, 2014). Few models explicitly encode the multi-layered nature of real-world policy packages—where floor-area ratios, building height limits, parking standards, and inclusionary zoning requirements interact—and even fewer tie these representations to verifiable policy documents. As a result, while simulation models are powerful for exploring “what-if” trajectories and system dynamics, their policy levers are often stylised and difficult to align with the exact boundaries, exemptions, and phasing of enacted regulations. PSF-type methods can provide a bridge by offering empirically derived, geometry-rich representations of existing policy regimes that can be imported as model inputs, reducing the gap between scenario design and legal reality.

GIS, Remote Sensing and Big Data Analytics

Advances in GIS and remote sensing have dramatically improved the measurement of spatial outcomes, thereby strengthening the evaluation side of policy–space research. Seto, Fragkias, Güneralp, and Reilly (2011) conduct a meta-analysis of global urban land expansion and document systematic variation in growth rates by region, income level, and governance context, using consistent remote sensing products to harmonise land-cover change across hundreds of cities. Building on this, Seto, Güneralp, and Hutyra (2012) generate global forecasts of urban expansion to 2030 and quantify direct impacts on biodiversity and carbon pools, illustrating how large-scale land-change data can be overlaid with ecological layers to evaluate future planning risks. Bren d’Amour et al. (2017) similarly combine global urban expansion projections with high-resolution cropland maps to estimate the potential loss of prime agricultural land, underlining the importance of integrating land-use dynamics into food-security and climate policies. More recently, Gao et al. (2021) compare the spatiotemporal trajectories of global population growth and built-up land expansion, revealing mismatches that inform debates on urban form and infrastructure efficiency. Angel (2023) synthesises these strands to propose an “urbanization science” agenda, arguing that observed patterns of urban expansion can guide normative policy choices on containment, densification, and infrastructure investment.

At finer scales, street-level imagery and other “Big Geo-Data” sources are increasingly used to characterise neighbourhood form and environmental quality. Li et al. (2015) develop a modified green-view index based on Google Street View to measure street-level greenery, providing an accessible indicator for urban design and health studies. Similar pipelines have been adapted to estimate building heights, façade transparency, and pedestrian-scale enclosure, feeding into assessments of walkability and micro-climate. Remotely sensed products with high spatial and temporal resolution are also being mobilised for policy monitoring: Whitcraft, Becker-Reshef, and Killough (2015) evaluate the revisit capabilities of current and planned optical satellite missions for global agricultural monitoring, while Lancheros et al. (2018) assess the Copernicus system’s ability to support polar region monitoring, both explicitly framed around observational requirements for policy and sustainable development. These developments are part of a broader “Big Data (R)evolution” in geography, which Pérez and colleagues (2024) describe as simultaneously expanding the empirical scope of spatial analysis and posing new challenges of data integration, governance, and ethics.

However, the overwhelming focus of GIS, remote sensing, and big-data work has been on measuring outcomes and exposures—such as built-up land, vegetation, population density, or pollution—rather than on spatialising the policies that shape those outcomes. Land-use plans, zoning ordinances, and sectoral regulations are often represented in empirical work only indirectly, for example through treatment indicators defined by arbitrary buffers around infrastructure or administrative boundaries (Seto et al., 2012; Angel, 2023). This asymmetry means that highly detailed spatial outcome data are frequently paired with coarse or ad hoc policy proxies, limiting the interpretability of causal results and complicating meta-analysis across studies. The PSF framework can be seen as a response to this imbalance, proposing to treat policy instruments themselves as spatial datasets that can be versioned, audited, and combined with the rich observational layers produced by modern GIS and remote sensing.

Policy Quantification, PSF and Network-Time Exposure

Quantifying the content of policy texts has a long history in political science and policy studies, but only recently has it become central to spatial policy evaluation. Early text-as-data methods such as Wordscores and related scaling models aimed to recover latent policy positions from party manifestos and legislative speeches (Laver, Benoit, & Garry, 2003; Slapin & Proksch, 2008). Grimmer and Stewart (2013) survey a wide range of automated content-analysis techniques and emphasise both their promise and pitfalls for drawing inferences from large corpora of political texts. Lucas et al. (2015) demonstrate how supervised and unsupervised machine-learning methods can be used to classify documents, detect topics, and extract covariates for comparative politics, while warning that measurement error and construct validity remain major concerns. In the climate and environmental domain, Geese, Ganseforth, and Kern (2024) apply text-as-data tools to systematically measure the content and ambition of climate policies across countries, illustrating how large textual corpora can be converted into structured indicators for subsequent statistical analysis. Sewerin et al. (2023) go further by introducing the POLIANNA dataset, in which policy documents are manually annotated along multiple design dimensions to support the training and validation of automated classifiers.

These approaches, however, primarily generate **scores** rather than **shapes**: they quantify what policies say, but not where they apply. For spatial planning and land-use governance, the missing link is a systematic way to translate textual provisions—such as zoning categories, overlay districts, buffer requirements, and exemption clauses—into geometries on the ground. Xie et al. (2024) address this gap by proposing the Policy Spatial Footprint (PSF) framework, which defines policies as spatio-temporal objects derived directly from legal and planning documents. Their four-stage workflow begins with the collection and semantic parsing of policy texts, identifying relevant clauses and associating them with spatial referents (e.g., specific corridors, station areas, ecological zones). In the second stage, these referents are converted into vector geometries—points, lines, and polygons—using cadastral, transport, and administrative base layers, while explicit exclusion rules (such as de-listed parcels or overlapping regimes) are encoded as negative geometries. Third, each footprint is assigned time stamps corresponding to announcement, legal effect, and implementation phases, and categorised into intensity levels reflecting regulatory stringency or fiscal generosity. Finally, exposure metrics are computed for parcels or other spatial units, including Euclidean buffers, network-time isochrones, and multi-policy overlap indicators, with explicit treatment of uncertainty arising from ambiguous or incomplete clauses.

A defining feature of PSF is its use of network-time rather than simple distance as the primary measure of policy exposure. In their Yangtze River Delta application, Xie et al. (2024) compute shortest travel times along combined road–rail networks from each land-transaction parcel to the nearest PSF geometries, arguing that accessibility to policy-defined zones, rather than proximity per se, drives the capitalisation of regulatory and infrastructure benefits into land prices. This network-time exposure is then embedded in a staggered-adoption DiD framework that distinguishes direct footprint effects from diffuse spillovers, while spatial panel specifications allow for cross-parcel dependence. Conceptually, this design brings together the strengths of spatial econometrics and modern DiD: treatment is defined at the level of observable legal geometry and network-time reach, while interference is modelled through both explicit PSF overlaps and residual spatial lags.

Relative to conventional policy quantification, PSF offers several advantages. First, the processing chain from legal text to spatial exposure is fully auditable and reproducible: each policy's geometry can be visualised, checked against original maps or statutory descriptions, and updated as amendments occur. Second, policy exposure becomes a continuous, multi-dimensional construct rather than a binary buffer membership, facilitating nuanced analyses of threshold effects, decay functions, and interactions between overlapping instruments—for example, where density bonuses, infrastructure subsidies, and environmental constraints co-exist (Xie et al., 2024). Third, by anchoring treatment variables in policy texts rather than outcomes, PSF reduces endogeneity concerns arising from ad hoc buffer choice or reverse-engineered treatment definitions. The approach is also inherently scalable: new policy domains (e.g., health, education, or climate resilience) can be incorporated by adding further semantic categories and geometry-construction rules, and aspects of the workflow can be automated using the text-as-data and annotation techniques developed in the broader policy-measurement literature (Grimmer & Stewart, 2013; Sewerin et al., 2023).

At the same time, PSF raises practical and methodological challenges. Constructing high-quality policy footprints requires access to complete legislative and planning archives, including historical versions, as well as substantial domain expertise to interpret cross-referenced clauses and implicit spatial references. The GIS work needed to reconcile legal descriptions with real-world geometries—such as resolving ambiguities in corridor widths or station-area radii—can be resource-intensive, particularly when extended to multiple jurisdictions. Moreover, as PSF datasets become more complex, researchers must carefully manage multicollinearity between overlapping policies and ensure that network-time metrics do not simply proxy for broader urban hierarchy or market thickness. Addressing these issues will likely require closer integration of PSF workflows with both automated text-as-data pipelines and principled causal-inference designs, including sensitivity analyses that explicitly test alternative exposure definitions and lag structures.

Comparative and Cross-Case Frameworks

Finally, methodological advances in policy–space research increasingly emphasise comparative and cross-case designs, seeking to move beyond single-city case studies towards generalisable insights. Comparative LUTI and simulation studies already use shared model structures to explore how different metropolitan areas respond to identical policy shocks, yet they often rely on locally tailored representations of zoning and governance (Wegener, 2014; Acheampong & Silva, 2015). Global urban-expansion analyses similarly adopt common land-change datasets and metrics, but treat planning and regulation only as background context or coarse categorical variables (Seto et al., 2011, 2012; Bren d'Amour et al., 2017; Angel, 2023). Without harmonised measures of policy exposure, it remains difficult to compare, for example, the effect of urban containment in one country with transit-oriented zoning in another, even when outcomes are measured with similar satellite or cadastral data.

PSF-type frameworks open the possibility of genuinely cross-national and cross-institutional comparisons of spatial policy effects. If different cities and countries adopt a shared protocol for translating planning statutes, infrastructure plans, and environmental regulations into spatio-temporal footprints, researchers can apply common causal designs—such as staggered-adoption DiD with network-time exposure—to evaluate heterogeneous treatment effects across institutional settings (Athey & Imbens, 2022; Callaway & Sant'Anna, 2021; Xie et al., 2024). Such a standard would also facilitate meta-analysis: instead of comparing studies that use different buffer distances, administrative units, or ad hoc zoning categories, analysts could pool PSF-based exposure metrics and estimate how the effectiveness of similar policy instruments varies with governance capacity, market structure, or urban morphology. In this sense, PSF does not compete with spatial econometrics, simulation modelling, or remote-sensing analytics; rather, it provides a common, geometry-rich policy layer that can be combined with these methods to produce more transparent, comparable, and policy-relevant evidence on how public interventions reshape space.

CROSS-CUTTING THEMES AND KNOWLEDGE GAPS

Sectoral Fragmentation Versus Integrated Spatial Governance

Across most planning systems, land-use regulation, transport investment, environmental protection, housing, and public health are still largely organised as separate policy sectors with their own legal bases, budgeting streams, and professional communities. Comparative work on land-use governance shows that responsibilities for zoning, infrastructure, and environmental regulation are often distributed across several ministries and levels of government, with only weak mechanisms for coordination (Krawchenko & Tomaney, 2023; Nadin et al., 2021). Studies of policy integration similarly argue that, although "joined-up" government has become a ubiquitous slogan, substantive integration of objectives, instruments, and implementation routines remains the exception rather than the rule (Howlett et al., 2017; Trein et al., 2023). Mechanism-focused analyses find that fragmentation is reproduced by sectoral mandates, path-dependent routines, and institutionalised veto points, which make it difficult to align, for instance, climate mitigation with agricultural, housing, and transport policies at the same time (Biesbroek & Candel, 2020; Eckhardt et al., 2020).

Recent systematic reviews of land-use governance confirm that social norms, market dynamics, and policy interventions interact in complex ways, and that the institutional architecture of the state often fails to provide a coherent spatial strategy that joins these forces (Dingkuhn et al., 2025). While national climate strategies and net-zero roadmaps increasingly acknowledge the importance of compact, transit-oriented urban forms, implementation frequently remains siloed at the level of sectoral ministries or projects (Lwasa et al., 2022; Seto et al., 2012). Global evidence on urban expansion and densification suggests that without integrated governance, containment policies, greenbelts, transit investments, and housing programmes can easily pull urban development in different directions, reproducing low-density growth and car dependence (Angel et al., 2021; Seto et al., 2011).

In this context, digitalisation has been presented as a possible remedy for fragmentation by enabling shared spatial data infrastructures and integrated decision-support tools. However, reviews of urban digital twins show that governance ambitions often outstrip institutional capacity: many projects remain confined to specific sectors (energy, mobility, flood risk) and rarely engage with statutory planning processes or cross-sectoral prioritisation (Azadi et al., 2025; Deng et al., 2021; Deren et al., 2021). Technical work on nationally connected digital twins and geospatial infrastructures stresses the need for common data models and governance arrangements if spatial data are to support integrated policy packages rather than isolated pilots (D'Hauwers et al., 2021; Ellul et al., 2024). Yet even in advanced cases of dynamic digital twins for city development, questions remain about how far these tools actually reshape organisational routines and sectoral power relations (Batty, 2018, 2024; Ferré-Bigorra & Neumann, 2022; Hämäläinen et al., 2021; Campos et al., 2025; Sánchez-Vaquerizo et al., 2025). The emerging policy spatial footprint (PSF) approach adds a different but complementary perspective: by encoding multiple sectoral policies in a common spatial framework, PSF can reveal overlaps, gaps, and conflicts in the actual geographic reach of land-use, transport, environmental, and fiscal instruments, thus making fragmentation empirically visible rather than treating it as an abstract governance problem (Xie et al., 2025; Dingkuhn et al., 2025).

Temporal Dynamics, Path Dependency and Lock-in

A second cross-cutting theme concerns the temporal structure of policy–space interactions. Classic work on carbon lock-in argued that energy and transport systems become entrenched through mutually reinforcing technological, institutional, and behavioural feedbacks, making them resistant to change even when low-carbon alternatives are available (Unruh, 2000). More recent reviews extend the lock-in lens to the built environment, arguing that urban form, housing stocks, and infrastructure networks create long-lived path dependencies that constrain future mitigation and adaptation options (Buzási & Csizovszky, 2023; Seto et al., 2012). Meta-analyses of urban expansion show that once low-density, leapfrog patterns are established, subsequent densification policies must contend with entrenched property rights, infrastructure layouts, and expectations of car-based mobility (Seto et al., 2011; Angel et al., 2021).

Despite this recognition, empirical policy evaluations still tend to focus on short-term effects of single instruments. Many studies examine land price changes in the years immediately following a zoning reform, transit project, or greenbelt designation, without tracing how multiple waves of policy adjustments and market responses accumulate over one or two decades (Eckhardt et al., 2020; Krawchenko & Tomaney, 2023). Climate policy assessments underline that achieving deep decarbonisation requires sequences of interventions that purposefully shift infrastructures, technologies, and spatial practices over time, yet robust empirical evidence on such sequences remains limited (Lwasa et al., 2022; Seto et al., 2021; Biesbroek & Candel, 2020).

The PSF approach provides an example of how temporal dynamics can be incorporated more systematically. In the Yangtze River Delta case, the PSF database captures the announcement, legal enactment, and operationalisation of 64 land-use, transport, and industrial policies over 2012–2024, and links each temporal layer to observed changes in land prices within and around the affected areas (Xie et al., 2025). By constructing staggered treatment cohorts for successive policy waves and estimating dynamic effects over multiple post-treatment years, the study traces how capitalization effects build up, taper off, or reverse, and how they interact with broader market cycles. Similar dynamic designs are beginning to appear in access-based hedonic models of transport project benefits (Wang & Levinson, 2023) and in evaluations of bus rapid transit (BRT) corridors that consider both initial and delayed land development responses (Cervero & Kang, 2011; Mehmood et al., 2024). However, such temporally explicit analyses are still rare. Existing evidence therefore provides only partial insight into how early policy choices constrain or enable later interventions, and how lock-ins can be deliberately dismantled.

Policy–Space–Economy Coupling and Unintended Consequences

A third cross-cutting theme is the tight but often under-analysed coupling between policy, spatial structure, and economic outcomes. Land-use and transport policies alter accessibility patterns, development rights, and risk profiles, which in turn shape land values, investment decisions, and fiscal capacities. Hedonic and accessibility-based models show that improvements in network connectivity and regulatory relaxations tend to be capitalised into higher land prices, with magnitudes varying by market thickness, baseline accessibility, and complementary policies (Wang & Levinson, 2023; Cervero & Kang, 2011). Work on land value capture (LVC) highlights that capturing part of this uplift through taxes, fees, or joint development can help finance infrastructure but also risks regressive impacts if not carefully designed (Botticini & Auzins, 2022; Echevarría et al., 2025). Reviews of land-use governance underline that the distribution of development rights and fiscal instruments is central to explaining why some jurisdictions see speculative booms, spatial exclusion, or fiscal crises after major infrastructure projects, while others achieve more balanced development (Dingkuhn et al., 2025; Krawchenko & Tomaney, 2023).

The PSF contribution is to create a more explicit bridge between policy text, spatial exposure, and economic outcomes. By mapping regulatory and infrastructure policies into auditable geometries with time stamps and intensity levels, PSF allows researchers to define treatment not simply as “within x km of a station” but as “within the legally defined area of a particular policy at a particular time” (Xie et al., 2025). In the Yangtze River Delta application, network-time exposure measures distinguish parcels that are inside a policy footprint and closely connected via road–rail networks from those that are spatially adjacent but poorly connected, revealing steep decay of capitalization effects in network-time rather than in Euclidean distance. This approach clarifies how specific combinations of zoning rules, infrastructure commitments, and industrial designations shape land price trajectories, instead of attributing all effects to a generic “transit impact.” Evidence from BRT corridors and associated land development confirms that land markets respond to both spatial design and the credibility of long-term service provision (Cervero & Kang, 2011; Mehmood et al., 2024). At the same time, digital twin experiments show that economic and land market impacts are rarely integrated into governance dashboards, which often focus on traffic flows or energy use (Batty, 2018, 2024; Azadi et al., 2025;

Hämäläinen et al., 2021). Overall, there is still limited causal evidence on unintended consequences such as speculative bubbles, displacement, or fiscal over-reliance on land revenues, even though conceptual work clearly identifies these risks.

Uneven Geography of Evidence

The existing body of work on policy–space interactions is marked by a pronounced geographical skew. Systematic reviews of land-use governance and climate policy integration find that most empirical studies focus on Europe, North America, and a small number of large Chinese cities, while evidence from small cities, secondary regions, and the Global South remains sparse (Dingkuhn et al., 2025; Eckhardt et al., 2020; Krawchenko & Tomaney, 2023). Meta-analyses of global urban expansion and densification identify strong regional contrasts in growth patterns but note that detailed policy histories are rarely available outside a limited set of cases, making it difficult to attribute observed trajectories to specific instruments or governance arrangements (Seto et al., 2011, 2012; Angel et al., 2021). Even in rapidly urbanising regions where infrastructure rollout and land reform are proceeding at pace, empirical work often treats policy as a coarse dummy (e.g., “post-reform period”) rather than reconstructing the fine-grained spatial reach of different measures.

The digital governance literature exhibits a similar concentration. Systematic reviews of urban digital twins report that most documented projects are located in North America, Western Europe, China, and a few high-income Asian countries, with city-scale implementations often concentrated in capital regions or global hubs (Deng et al., 2021; Azadi et al., 2025). Case studies of smart-city digital twins from Helsinki, Shanghai, and other major cities push the methodological frontier but do little to illuminate how such tools might support governance in small municipalities with limited data and capacity (Deren et al., 2021; Hämäläinen et al., 2021; Campos et al., 2025; Sánchez-Vaquerizo et al., 2025). Work on nationally connected digital twin infrastructures further reinforces a focus on countries with strong geospatial agencies and substantial public investment in data infrastructures (D’Hauwers et al., 2021; Ellul et al., 2024; Abdelrahman et al., 2025). Against this backdrop, the PSF application to Chinese county-level cities is one of the few examples of a high-resolution, policy-explicit spatial dataset outside core OECD contexts (Xie et al., 2025). However, comparable PSF-style reconstructions for African, South Asian, Latin American, or Eastern European cities are still missing, which limits our ability to draw robust conclusions about how institutional variation shapes policy–space relationships globally.

Under-Researched Policy Instruments and Outcomes

Finally, there are notable gaps in the types of instruments and outcomes examined. Most empirical work still centres on land-use regulation, transport infrastructure, and, to a lesser extent, environmental zoning and hazard regulation (Dingkuhn et al., 2025; Nadin et al., 2021). By contrast, fiscal and tax instruments—such as land value taxation, tax increment financing, betterment levies, and impact fees—receive far less attention in spatially explicit evaluations, despite their centrality for funding infrastructure and shaping development incentives. Recent conceptual and empirical contributions on land value capture underline both the potential and the pitfalls of these instruments: while well-designed schemes can align private gains with public infrastructure costs, poorly designed ones may entrench inequalities or incentivise speculative up-zoning (Botticini & Auzins, 2022; Echevarría et al., 2025; Wang & Levinson, 2023). Yet most of this work either uses coarse spatial proxies for policy (for example, buffers around stations assumed to be subject to LVC) or focuses on financial and legal design without reconstructing the actual spatial reach of the instruments.

Digital and information-based tools represent another under-researched frontier. While digital twins, smart-city platforms, and open data portals are increasingly deployed with the stated aim of improving spatial governance, few studies systematically track how they alter decision-making, participation, or outcomes on the ground (Batty, 2018, 2024; Ferré-Bigorra & Neumann, 2022; Abdelrahman et al., 2025; Campos et al., 2025). Existing evaluations typically measure technical performance rather than policy change, leaving unanswered whether such tools reinforce existing sectoral silos or help to integrate policy mixes. Similarly, outcome variables remain skewed towards land prices, development densities, and carbon emissions, with far fewer studies examining distributional justice, public health, or subjective wellbeing as spatially structured outcomes (Lwasa et al., 2022; Buzási & Csizovszky, 2023). The PSF framework, by making policy exposure explicit and auditable, offers a platform for extending analyses beyond land markets to social and health indicators, but this potential has not yet been realised in empirical work (Xie et al., 2025; Krawchenko & Tomaney, 2023). Addressing these gaps will require closer collaboration between fiscal scholars, public health researchers, and spatial analysts, as well as investment in longitudinal, multi-sector datasets that link policy, space, and diverse outcomes in a comparable way.

TOWARDS AN INTEGRATED ANALYTICAL FRAMEWORK

A Policy–Space–Outcome Framework Anchored by PSF

An integrated analytical framework for policy–space interactions needs to connect three elements that are often studied in isolation: the formal design of policy instruments, the spatial structure of exposure and mediation, and the multidimensional outcomes that emerge over time. Comparative research on urban expansion, climate mitigation and land-use governance shows that spatial outcomes are driven by overlapping regulatory, infrastructural and fiscal choices, rather than by any single instrument (Seto et al., 2011, 2012, 2021; Angel et al., 2021; Dingkuhn et al., 2025; Eckhardt et al., 2020; Krawchenko & Tomaney, 2023; Nadin et al., 2021). The Policy Spatial Footprint (PSF) concept proposed by Xie et al. (2025) offers a way to anchor these elements in a single workflow by treating policy itself as an auditable spatio-temporal data object. In this framework, the inputs are legal and planning texts, which are parsed and converted into spatial footprints with attributes for timing and intensity; these footprints are then used to compute exposure metrics in network-time space, which feed into models of land, transport, environmental and social processes, and ultimately into environmental, economic, social and health outcomes.

On the input side, the PSF stage translates heterogeneous policies—zoning ordinances, infrastructure plans, ecological red lines, industrial designations and fiscal instruments—into a harmonised layer of geometries tagged with dates and intensity levels (Xie et al., 2025). This responds directly to the longstanding observation that spatial governance is fragmented across sectors and levels, with poorly aligned policy mixes for land, transport, environment and social provision (Biesbroek & Candel, 2020; Dingkuhn et al., 2025; Howlett et al., 2017; Krawchenko & Tomaney, 2023; Nadin et al., 2021; Trein et al., 2023). Instead of representing planning as a single boundary or dummy variable, PSF allows each instrument to be represented explicitly and combined into additive or conflicting packages. For example, a station area may simultaneously fall under transit-oriented up-zoning, flood-risk building restrictions and inclusionary housing requirements; each of these can be encoded as a separate footprint, with overlaps indicating where trade-offs and synergies must be analysed (Cervero & Kang, 2011; Menoni & Ferreira, 2025; Qiu & Xu, 2022; Wang S. et al., 2018; Wang Y. et al., 2025; Xiong & Yao, 2025).

The second layer of the framework concerns spatial exposure and mediation. Network-time accessibility is a central element here, because the benefits and burdens of policies are transmitted along transport and service networks rather than purely through straight-line distance (Angel et al., 2021; Ewing & Cervero, 2010; Glaeser & Kahn, 2010; Wang & Levinson, 2023; Xie et al., 2025). PSF-based exposure metrics therefore measure how quickly parcels, neighbourhoods or villages can “reach” policy-defined areas, and vice versa, using multimodal travel-time surfaces derived from road–rail networks (Abdelrahman et al., 2025; Angel et al., 2021; Deren et al., 2021; Wang & Levinson, 2023). These exposure fields then interact with mediating subsystems: land and housing markets (Li et al., 2022; Suzuki et al., 2013; Xie et al., 2025), transport networks and mode choice (Bertolini, 1999; Cervero & Kang, 2011; Mehmood et al., 2024), environmental processes such as emissions and ecosystem services (Guo et al., 2023; Hou et al., 2025; Menoni & Ferreira, 2025; Seto et al., 2012; Twohig-Bennett & Jones, 2018), and social structures including informality, segregation and access to services (Ahmad et al., 2025; Goytia et al., 2023; Hailu, 2024; Lin & Wei, 2025; Mottelson, 2023; Tesfay et al., 2025).

The final layer captures outcomes and feedbacks. Environmental outcomes include direct impacts on land-cover change, carbon emissions and climate risk, which can be measured with remote sensing and environmental models (Angel et al., 2021; Buzási & Csizovszky, 2023; Guo et al., 2023; Hou et al., 2025; Seto et al., 2011, 2012, 2021; Wang S. et al., 2018; Wang Y. et al., 2025). Economic outcomes include land and housing price capitalisation, investment patterns and fiscal positions, which are shaped by both policy exposure and market conditions (Botticini & Auzins, 2022; Echevarría et al., 2025; Li et al., 2022; Suzuki et al., 2013; Wang & Levinson, 2023; Xie et al., 2025). Social outcomes encompass spatial inequality in access to jobs, education, health and green space, as well as the expansion or regularisation of informal settlements (Ahmad et al., 2025; Goytia et al., 2023; Hailu, 2024; Lin & Wei, 2025; Mottelson, 2023; Tesfay et al., 2025; Twohig-Bennett & Jones, 2018). Health outcomes are increasingly recognised as spatially mediated, reflecting exposure to pollution, heat, green space and active travel opportunities (Buzási & Csizovszky, 2023; Lwasa et al., 2022; Seto et al., 2021; Twohig-Bennett & Jones, 2018). The framework also recognises feedback loops: spatial outcomes affect future policy choices and market expectations, reinforcing or eroding carbon and spatial lock-in (Angel et al., 2021; Buzási & Csizovszky, 2023; Seto et al., 2012; Unruh, 2000).

In operational terms, the proposed policy–space–outcome framework can be seen as a modular architecture. PSF provides the input layer of policy footprints and exposure metrics. Spatial econometrics and quasi-experimental designs link these exposures to outcome data, while simulation models and digital twins can be placed in the mediation layer to explore dynamic scenarios (Abdelrahman et al., 2025; Azadi et al., 2025; Batty, 2018, 2024; Campos et al., 2025; D’Hauwers et al., 2021; Ellul et al., 2024; Hämäläinen et al., 2021). Remote sensing, GIS and administrative microdata populate the outcome layer with high-resolution indicators (Angel et al., 2021; Guo et al., 2023; Hou et al., 2025; Seto et al., 2011, 2012; Xie et al., 2025). Governance analyses of policy integration and land-use institutions provide the interpretive context, clarifying why similar policy mixes have different effects across jurisdictions (Biesbroek & Candel, 2020; Dingkuhn et al., 2025; Eckhardt et al., 2020; Howlett et al., 2017; Krawchenko & Tomaney, 2023; Nadin et al., 2021; Trein et al., 2023).

Application to Ex-Ante and Ex-Post Assessment

Anchoring evaluation in PSF also enables a clearer distinction and linkage between ex-ante and ex-post assessment. Ex-ante, planners and policymakers increasingly use scenario models to explore the implications of different spatial strategies for emissions, congestion, ecosystem services or housing affordability. Yet many land-use–transport and environmental models still encode policies in stylised ways, such as simple density changes, generic growth boundaries or uniform green-space targets (Angel et al., 2021; Ewing & Cervero, 2010; Menoni & Ferreira, 2025; Seto et al., 2012; Wang S. et al., 2018). Integrating PSF into these models would allow scenarios to be defined directly in terms of alternative policy footprints and timings: for example, comparing a compact transit-corridor PSF package with an edge-expansion package, holding demographic and macroeconomic assumptions constant (Bertolini, 1999; Guo et al., 2023; Hou et al., 2025; Qiu & Xu, 2022; Wang Y. et al., 2025; Xiong & Yao, 2025). The resulting forecasts of land-use change, emissions, and accessibility can then be attributed to specific policy configurations rather than to generic “smart growth” or “business-as-usual” labels.

Digital twins and related geospatial infrastructures provide a complementary ex-ante environment. Many city and national digital-twin initiatives already integrate 3D built-form representations, real-time traffic data and environmental sensors (Abdelrahman et al., 2025; Azadi et al., 2025; Batty, 2018, 2024; Campos et al., 2025; Deren et al., 2021; Hämäläinen et al., 2021). Yet these platforms often lack explicit encodings of planning rules, fiscal instruments and sectoral regulations, limiting their value for testing governance options (Deng et al., 2021; D’Hauwers et al., 2021; Ellul et al., 2024; Ferré-Bigorra & Neumann, 2022; Sánchez-Vaquerizo et al., 2025). Embedding PSF layers into digital twins would allow users to visualise where and when different policies apply, test alternative footprints, and immediately see how they interact with predicted flows and risks, for example by overlaying alternative flood-risk building regulations with projected climate hazards and transport access (Eckhardt et al., 2020; Lwasa et al., 2022; Menoni & Ferreira, 2025; Seto et al., 2021).

Ex-post, PSF-based treatment definitions can be combined with econometric and quasi-experimental designs to estimate realised impacts. Xie et al. (2025) show how staggered difference-in-differences models with network-time exposure and parcel fixed effects can identify the timing and magnitude of land price capitalisation for overlapping waves of zoning, infrastructure and industrial policies. Their approach can be generalised to other outcomes, such as built-up expansion, densification, mode share, emissions or health indicators (Angel et al., 2021; Buzási & Csizovszky, 2023; Guo et al., 2023; Hou et al., 2025; Seto et al., 2011, 2012; Twohig-Bennett & Jones, 2018). Accessible land-market models and LVC evaluations already provide templates for linking accessibility changes to price trajectories (Botticini & Auzins, 2022; Cervero & Kang, 2011; Echevarría et al., 2025; Li et al., 2022; Mehmood et al., 2024; Wang & Levinson, 2023), but in most cases the causal variable is a coarse distance buffer or project dummy. Replacing these proxies with PSF-based indicators can sharpen identification and reveal heterogeneity across policy packages.

Remote sensing and administrative microdata are equally central to ex-post analysis. Global urban-expansion datasets and high-resolution built-up maps can be used to observe land-cover and density changes in and around PSF footprints over time (Angel et al., 2021; Seto et al., 2011, 2012, 2021; Wang S. et al., 2018; Wang Y. et al., 2025). Parcel and address registers allow fine-grained tracking of development and tenure changes, while social registries and health records can provide outcome indicators for distributional and wellbeing analyses (Ahmad et al., 2025; Goytia et al., 2023; Hailu, 2024; Lin & Wei, 2025; Tesfay et al., 2025; Twohig-Bennett & Jones, 2018). When combined with PSF-based treatment, these datasets make it possible to test, for example, whether TOD and containment policies jointly produce compact, low-carbon and equitable outcomes, or whether they mainly deliver price gains near high-access areas alongside displacement into informal or peripheral zones. The same framework can quantify the extent to which climate and ecological regulations shift risk exposure or concentrate development in residual high-risk pockets (Buzási & Csizovszky, 2023; Eckhardt et al., 2020; Guo et al., 2023; Hou et al., 2025; Lwasa et al., 2022; Seto et al., 2021).

Implications for Policy Design and Spatial Planning Practice

The analytical framework outlined above has several implications for how policies and plans are written, negotiated and implemented. First, if PSF-style evaluation is to be possible, policy documents need to be drafted in ways that make spatial and temporal coverage unambiguous. Reviews of land-use governance and climate policy integration repeatedly point to vague formulations, overlapping jurisdictions and ambiguous exemptions as sources of implementation gaps and policy conflicts (Biesbroek & Candel, 2020; Dingkuhn et al., 2025; Eckhardt et al., 2020; Howlett et al., 2017; Krawchenko & Tomaney, 2023; Nadin et al., 2021; Trein et al., 2023). From a PSF perspective, these ambiguities directly translate into uncertainty about footprint geometry and timing. Planners and legislators can therefore increase evaluability by specifying clear geographic boundaries (preferably tied to cadastral or network features), explicit activation and sunset dates, and transparent hierarchy rules for overlapping regulations.

Second, planning practice needs to shift from instrument-by-instrument design towards explicit policy-mix configuration in space. The evidence reviewed in earlier chapters shows that transport, land-use, environmental and fiscal instruments interact strongly, sometimes reinforcing and sometimes offsetting each other (Angel et al., 2021; Echevarría et al., 2025; Krawchenko & Tomaney, 2023; Li et al., 2022; Nadin et al., 2021; Wang & Levinson, 2023; Xie et al., 2025). PSF makes these interactions visible by revealing where TOD zoning coexists with strict parking minimums, where ecological buffers overlap with planned growth areas, or where industrial designations and residential up-zoning collide. This information can feed back into plan-making: planners can use PSF overlays in digital twins and GIS environments to identify conflict zones, test alternative package geometries, and adjust compensation and mitigation measures (Abdelrahman et al., 2025; Azadi et al., 2025; Batty, 2018, 2024; Campos et al., 2025; Deren et al., 2021; Ellul et al., 2024; Hämäläinen et al., 2021; Sánchez-Vaquerizo et al., 2025).

Third, integrating network-time exposure and equity analysis into fiscal instruments is essential. LVC tools such as betterment levies, development charges and joint development are increasingly advocated to finance infrastructure, but their design often ignores the distribution of accessibility gains and burdens across different groups and places (Botticini & Auzins, 2022; Cervero & Kang, 2011; Echevarría et al., 2025; Li et al., 2022; Suzuki et al., 2013; Wang & Levinson, 2023). By combining PSF-based exposure metrics with land-price and socio-demographic data, planners can identify who benefits and who pays under different LVC schemes, and adjust parameters accordingly—for example, by calibrating rates to network-time gains or earmarking revenue for affordable housing in high-exposure zones (Ahmad et al., 2025; Goytia et al., 2023; Lin & Wei, 2025; Mehmood et al., 2024; Tesfay et al., 2025). Similar reasoning applies to climate and environmental regulations: PSF layers for heat-risk overlays, flood zones or air-pollution controls can be combined with health and income data to assess whether protective measures disproportionately favour already advantaged areas (Buzási & Csizovszky, 2023; Lwasa et al., 2022; Seto et al., 2021; Twohig-Bennett & Jones, 2018).

Finally, the framework suggests new roles for spatial planners and geospatial professionals in policy design. Instead of being consulted only after broad policy choices have been made, they can contribute to drafting PSF-ready clauses, building and maintaining policy footprint repositories, and mediating between sectoral agencies with different objectives (Dingkuhn et al., 2025; Krawchenko & Tomaney, 2023; Nadin et al., 2021). Integrating PSF into urban digital twins and national spatial-data infrastructures can help move spatial planning from a largely static, document-centred practice towards a more iterative and evidence-based process, in which policy proposals are routinely stress-tested in space and time before adoption (Abdelrahman et al., 2025; Azadi et al., 2025; Batty, 2018, 2024; Campos et al., 2025; D'Hauwers et al., 2021; Ellul et al., 2024; Ferré-Bigorra & Neumann, 2022; Sánchez-Vaquerizo et al., 2025).

FUTURE RESEARCH AGENDA

Advancing Causal and Multi-Scale Methods

Future research on policy–space interactions needs to move beyond single-scale, single-instrument evaluations towards designs that can credibly identify the effects of complex policy packages across multiple spatial and temporal scales. Existing work has demonstrated the value of quasi-experimental approaches such as difference-in-differences, event studies and access-based hedonic models in isolating the impacts of transport projects, zoning changes and growth boundaries, but these studies typically rely on coarse distance buffers or administrative boundaries to define treatment (Cervero & Kang, 2011; Echevarría et al., 2025; Kirby et al., 2023; Li et al., 2022; Mehmood et al., 2024; Wang & Levinson, 2023). Global analyses of urban expansion and densification similarly operate at city or metropolitan scales, leaving the micro-spatial pathways through which policy affects land markets, emissions and social outcomes only loosely specified (Angel et al., 2021; Seto et al., 2011, 2012, 2021; Wang S. et al., 2018; Wang Y. et al., 2025). There is therefore a clear need to integrate PSF-based treatment definitions with multi-scale spatial econometric models that explicitly represent parcel, neighbourhood, city and regional processes, and to exploit recent advances in staggered difference-in-differences and event-study estimators for heterogeneous and overlapping treatments.

The PSF application in the Yangtze River Delta provides a template for such work by combining detailed, policy-derived exposure metrics with dynamic panel models of land value capitalisation (Xie et al., 2025). Extending this approach to other outcomes and contexts would require careful consideration of spatial dependence, network spillovers and scale interactions. For example, future studies could use PSF-based treatment at parcel or grid level, while simultaneously modelling higher-level feedbacks in infrastructure provision or fiscal capacity using hierarchical or multilevel models (Abdelrahman et al., 2025; Campos et al., 2025; Dingkuhn et al., 2025; Krawchenko & Tomaney, 2023; Nadin et al., 2021). Integrating PSF with spatial Durbin or network autoregressive models would allow researchers to distinguish between direct effects within policy footprints and indirect effects transmitted through transport and development networks (Angel et al., 2021; Ewing & Cervero, 2010; Glaeser & Kahn, 2010; Wang & Levinson, 2023). Similarly, combining PSF with remote-sensing-based land-cover trajectories and dynamic climate-risk indicators could underpin event-study designs that capture both immediate and lagged responses of built-up expansion, emissions and exposure to hazards (Buzási & Csizovszky, 2023; Guo et al., 2023; Hou et al., 2025; Menoni & Ferreira, 2025; Seto et al., 2011, 2012, 2021).

Another methodological frontier lies in bridging causal inference with exploratory simulation. Land-use–transport and environmental models already incorporate detailed representations of behaviour and feedbacks but often rely on stylised scenarios rather than actual policy histories (Bertolini, 1999; Cheshmehzangi & Dawodu, 2021; Guo et al., 2023; Menoni & Ferreira, 2025; Suzuki et al., 2013; Wang S. et al., 2018). PSF can provide empirically grounded inputs for these models, enabling ex-post replication of historical policy sequences and ex-ante prototyping of alternative policy mixes. Future work could combine PSF-derived policy sequences with agent-based or cellular automata models to explore how different timing, intensity and spatial targeting of policies affect long-term urban form and lock-in, subject to empirical calibration using quasi-experimental estimates (Angel et al., 2021; Buzási & Csizovszky, 2023; Echevarría et al., 2025; Seto et al., 2012, 2021; Unruh, 2000). This would support a more iterative dialogue between theory, empirical identification and scenario analysis than is currently common in the literature.

Building Open Spatial Policy Datasets and PSF Repositories

A second priority is the systematic construction and sharing of open spatial policy datasets. At present, most PSF-style datasets are bespoke and confined to single projects or regions, limiting comparability and reuse (Dingkuhn et al., 2025; Eckhardt et al., 2020; Krawchenko & Tomaney, 2023; Xie et al., 2025). By contrast, there has been significant progress towards open, standardised datasets for land cover, urban expansion, emissions and exposure, which have enabled global meta-analyses of urbanisation and climate risk (Angel et al., 2021; Buzási & Csizovszky, 2023; Guo et al., 2023; Hou et al., 2025; Seto et al., 2011, 2012, 2021; Wang Y. et al., 2025). The asymmetry between rich outcome data and sparse, non-standard policy data hampers both replication and cross-city comparison. Future research agendas should therefore prioritise the development of PSF repositories that store ordinance texts, machine-readable clauses, geometry files, time stamps and uncertainty annotations under open licences and with clear documentation.

Digital-twin and national geospatial infrastructure initiatives offer a natural institutional home for such repositories. Many current digital twins already integrate high-resolution 3D building models, transport networks and sensor data but lack explicit layers for planning rules and fiscal instruments (Abdelrahman et al., 2025; Azadi et al., 2025; Batty, 2018, 2024; Campos et al., 2025; Deren et al., 2021; Hämäläinen et al., 2021; Sánchez-Vaquerizo et al., 2025). Embedding PSF repositories into these platforms would enable both analysts and practitioners to visualise policy coverage and to query the regulatory and fiscal status of any location. Nationally connected digital twins and spatial data infrastructures, as currently being piloted in several countries, could adopt common PSF schemas to facilitate cross-regional benchmarking and multi-level governance analysis (D'Hauwers et al., 2021; Ellul et al., 2024; Lwasa et al., 2022; Menoni & Ferreira, 2025).

Building such repositories will require methodological and institutional innovation. From a methodological standpoint, research is needed on semi-automated text parsing, ontology design for policy clauses, and reproducible pipelines linking legal sources to spatial geometries and version control (Biesbroek & Candel, 2020; Dingkuhn et al., 2025; Ferré-Bigorra & Neumann, 2022; Howlett et al., 2017; Trein et al., 2023). From an institutional standpoint, questions of data governance, confidentiality and political sensitivity must be addressed, particularly for fiscal instruments and socially contested policies (Botticini & Auzins, 2022; Echevarría et al., 2025; Goytia et al., 2023; Lin & Wei, 2025; Tesfay et al., 2025). Adopting FAIR (findable, accessible, interoperable, reusable) principles and interoperable licensing frameworks can help foster trust and reuse, while pilot PSF repositories in willing cities or regions can demonstrate feasibility and benefits. Over time, such efforts could support meta-analyses that compare policy packages and outcomes across hundreds of jurisdictions, thereby addressing the current geographical and sectoral biases in the evidence base (Angel et al., 2021; Dingkuhn et al., 2025; Krawchenko & Tomaney, 2023; Seto et al., 2011, 2012, 2021).

Deepening Comparative Governance Studies

A third avenue for future research concerns comparative governance. Existing conceptual frameworks emphasise that land-use and spatial planning systems vary widely in their allocation of powers, fiscal capacities and enforcement mechanisms, which shapes the feasible "policy space" for local governments (Krawchenko & Tomaney, 2023; Nadin et al., 2021; Trein et al., 2023). Empirical work on climate policy integration and land-use governance similarly shows that coordination problems, path dependencies and sectoral veto points differ across centralised and decentralised regimes, but these analyses rarely link institutional variation to fine-grained spatial outcomes (Biesbroek & Candel, 2020; Dingkuhn et al., 2025; Eckhardt et al., 2020; Lwasa et al., 2022; Seto et al., 2021). Applying PSF in different governance contexts would create a basis for systematically comparing how similar policy instruments are deployed spatially and how their impacts on land markets, emissions and equity differ.

For example, comparative PSF studies could analyse how transit-oriented development, growth boundaries and greenbelts are defined and enforced in metropolitan regions under varying degrees of planning autonomy and fiscal dependence, building on existing work on transport-oriented development, growth boundaries and resilience (Angel et al., 2021; Bertolini, 1999; Cheshmehzangi & Dawodu, 2021; Kirby et al., 2023; Lin & Wei, 2025; Suzuki et al., 2013). Similarly, cross-national PSF analyses of land value capture schemes and development charges could examine how policy footprints, network-time exposure and capitalisation patterns differ between, for example, North American, European and Asian metropolitan regions (Botticini & Auzins, 2022; Echevarría et al., 2025; Li et al., 2022; Wang & Levinson, 2023; Xie et al., 2025). In decentralised systems, PSF could help to trace the proliferation of local zoning overlays and fiscal incentives, shedding light on inter-jurisdictional competition and regional spatial inequalities (Ahmad et al., 2025; Goytia et al., 2023; Hailu, 2024; Tesfay et al., 2025).

Such comparative work would also benefit from the integration of qualitative governance analysis with quantitative PSF datasets. Case studies of policy design, negotiation and implementation can help interpret why similar footprints arise under different institutional constraints, or why formally similar policies are applied in very different places (Dingkuhn et al., 2025; Krawchenko & Tomaney, 2023; Menoni & Ferreira, 2025; Nadin et al., 2021; Qiu & Xu, 2022; Trein et al., 2023). Conversely, PSF maps can guide qualitative inquiry by revealing unexpected patterns of overlap, gaps or exemptions that merit closer investigation. Over time, this dialogue between governance research and PSF-based spatial analysis could yield a richer understanding of how formal rules, informal practices and market forces jointly shape policy–space–outcome relations.

Integrating Resilience, Justice and Digitalisation

Finally, future research should integrate urban resilience, spatial justice and digitalisation into a unified policy–space research agenda. Studies of carbon and spatial lock-in stress that resilience depends on both the flexibility of physical infrastructures and the adaptability of institutional arrangements, yet few empirical evaluations explicitly measure how policy-induced changes in spatial structure affect exposure and vulnerability of different groups (Buzási & Csizovszky, 2023; Lwasa et al., 2022; Menoni & Ferreira, 2025; Seto et al., 2021; Unruh, 2000). At the same time, growing literatures on informality, land regularisation and peri-urban transformation show that zoning and infrastructure policies frequently produce or reinforce socio-spatial inequalities, including the expansion of informal settlements in residual or risk-prone spaces (Ahmad et al., 2025; Goytia et al., 2023; Hailu, 2024; Mottelson, 2023; Tesfay et al., 2025). PSF, combined with network-time exposure metrics and socio-demographic data, could provide a framework for systematically measuring which groups are included or excluded from the benefits and burdens of policy packages, and how these distributions evolve over time.

Digitalisation adds another layer of complexity and opportunity. Urban digital twins and smart-city platforms promise to provide real-time situational awareness and decision support, but empirical reviews highlight substantial gaps between these ambitions and actual governance practices (Abdelrahman et al., 2025; Azadi et al., 2025; Batty, 2018, 2024; Campos et al., 2025; Deng et al., 2021; Deren et al., 2021; Hämäläinen et al., 2021; Sánchez-Vaquerizo et al., 2025). Few implementations incorporate explicit justice or resilience metrics, and even fewer embed policy footprints in ways that allow users to understand the spatial distribution of regulatory and fiscal regimes. Future research should therefore explore how PSF layers can be integrated into digital twins to enable interactive analysis of resilience and justice—for example, by overlaying policy footprints with flood-risk maps, accessibility surfaces and indicators of deprivation or health vulnerability (Guo et al., 2023; Hou et al., 2025; Lin & Wei, 2025; Twohig-Bennett & Jones, 2018).

A justice-oriented PSF research agenda would also examine how policies governing digital infrastructures themselves—such as broadband roll-out, sensor deployment and data governance—shape spatial inequalities in access to digital services and data-driven governance (Campos et al., 2025; Ferré-Bigorra & Neumann, 2022; Sánchez-Vaquerizo et al., 2025). Encoding such policies as PSFs would allow analysts to measure which neighbourhoods are included in digital initiatives and how this interacts with existing inequalities in physical infrastructure and services. Ultimately, integrating resilience, justice and digitalisation within a PSF-anchored framework can support the design of policy packages that are not only efficient and low-carbon but also socially inclusive and robust to shocks.

CONCLUSIONS

This review has argued that understanding how policies shape space—and how spatial structures in turn mediate environmental, economic, social and health outcomes—requires an explicit representation of policy as a spatial and temporal object. Traditional approaches to policy evaluation in urban and regional studies have relied heavily on distance buffers, administrative units and stylised scenarios to approximate policy exposure, which obscures the complexity of overlapping instruments and institutional arrangements (Angel et al., 2021; Cervero & Kang, 2011; Echevarría et al., 2025; Kirby et al., 2023; Li et al., 2022; Wang & Levinson, 2023). By contrast, the Policy Spatial Footprint framework formalised by Xie et al. (2025) represents a qualitative shift: it treats policy clauses as the primary data source, translates them into auditable geometries with time stamps and intensity levels, and computes network-time exposure measures that can be directly linked to observed trajectories in land prices, urban form, emissions and social outcomes.

The evidence reviewed across land-use, transport, environmental and social policy domains shows that spatial outcomes emerge from complex policy mixes, mediated by land and housing markets, transport networks, environmental processes and social structures (Ahmad et al., 2025; Angel et al., 2021; Buzási & Csizovszky, 2023; Dingkuhn et al., 2025; Goytia et al., 2023; Guo et al., 2023; Hou et al., 2025; Lwasa et al., 2022; Menoni & Ferreira, 2025; Nadin et al., 2021; Qiu & Xu, 2022; Seto et al., 2011, 2012, 2021; Tesfay et al., 2025). The PSF case from the Yangtze River Delta demonstrates how a multi-policy, multi-period dataset can be used to identify direct and spillover effects of overlapping zoning, infrastructure and industrial policies on land value capitalisation in network-time space (Xie et al., 2025). Similar principles can be extended to study emissions, risk exposure, accessibility and wellbeing, particularly when combined with advances in spatial econometrics, quasi-experimental designs, remote sensing and digital twins (Abdelrahman et al., 2025; Azadi et al., 2025; Batty, 2018, 2024; Campos et al., 2025; Deren et al., 2021; Ewing & Cervero, 2010; Guo et al., 2023; Hou et al., 2025; Sánchez-Vaquerizo et al., 2025).

At the same time, the review has highlighted significant gaps. Geographically, the evidence base is heavily skewed towards large cities in Europe, North America and China, with limited PSF-style work in small cities, peri-urban regions and the Global South (Ahmad et al., 2025; Dingkuhn et al., 2025; Goytia et al., 2023; Hailu, 2024; Mottelson, 2023; Tesfay et al., 2025). Sectorally, fiscal and tax instruments, digital-governance policies and health-related regulations remain under-researched from a spatial perspective, despite their centrality for financing infrastructure, managing risk and delivering equitable services (Botticini & Auzins, 2022; Echevarría et al., 2025; Lin & Wei, 2025; Twohig-Bennett & Jones, 2018; Wang & Levinson, 2023). Methodologically, there is a need for multi-scale, dynamic designs that integrate PSF with hierarchical models, simulation and digital twins, and for open PSF repositories that enable replication and comparative research (Abdelrahman et al., 2025; Campos et al., 2025; D'Hauwers et al., 2021; Ellul et al., 2024; Ferré-Bigorra & Neumann, 2022; Trein et al., 2023).

Overall, PSF should not be seen as a standalone technique but as a central component of a broader policy–space–outcome framework. Its main contribution is to align policy semantics, spatial networks and causal identification in a way that is transparent, auditable and extensible across contexts. Realising this potential will require closer collaboration between legal scholars, planners, economists, data scientists and communities, as well as institutional reforms that encourage clear, PSF-ready policy drafting and open sharing of spatial policy data (Biesbroek & Candel, 2020; Dingkuhn et al., 2025; Howlett et al., 2017; Krawchenko & Tomaney, 2023; Nadin et al., 2021; Qiu & Xu, 2022; Trein et al., 2023). The work of Xie et al. (2025) marks an important step in this direction, but much remains to be done to generalise PSF to other regions, policy domains and outcome dimensions. Advancing this agenda offers a promising route towards more rigorous, transparent and just evaluations of how policies shape the spaces in which people live, work and adapt to a changing climate.

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