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Digital Economy Effects on Urban Air Pollution and Ecosystem Service Trade-Offs

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ABSTRACT

The rapid expansion of the digital economy has profoundly reshaped urban socioeconomic structures, presenting complex implications for environmental sustainability and ecosystem dynamics. This comprehensive academic paper investigates the intricate relationships between digital economic development, urban air pollution mitigation, and the resultant trade-offs within urban ecosystem services. By synthesizing extensive theoretical frameworks and employing advanced spatial econometric narratives, this research explores how digital transformations—such as the integration of big data, the internet of things, and artificial intelligence—influence the concentration of major air pollutants including particulate matter and nitrogen dioxide. Furthermore, the study delves into the ecological consequences of these changes, specifically addressing the trade-offs between provisioning services, such as urban economic output driven by digital infrastructure, and regulating services, such as air quality maintenance and climate regulation. The analysis reveals that while the digital economy significantly reduces local air pollution through industrial upgrading and technological innovation, it also generates complex spatial spillover effects that can inadvertently shift environmental burdens to adjacent regions. Additionally, the proliferation of digital infrastructure introduces new ecological challenges, necessitating a re-evaluation of ecosystem service trade-offs. Ultimately, this research provides vital theoretical insights and policy recommendations for leveraging digital innovation to foster sustainable urban environments while maintaining critical ecological balances.

KEYWORDS

Digital Economy, Air Pollution, Ecosystem Services, Spatial Spillover, Urban Sustainability .

1. Introduction

1.1 Context and Motivation

The twenty-first century has witnessed an unprecedented acceleration in urbanization and technological advancement, culminating in the widespread emergence of the digital economy. As a novel economic paradigm driven by information and communication technology, the digital economy encompasses a broad spectrum of activities including cloud computing, big data analytics, artificial intelligence, and the internet of things. This structural shift has fundamentally altered traditional modes of production, consumption, and governance across the globe. However, alongside these profound socioeconomic transformations, urban centers face escalating environmental crises, most notably severe air pollution and the degradation of natural ecosystems. Urban areas, which house the majority of the global population and generate a disproportionate share of global gross domestic product, are simultaneously the primary sources of greenhouse gas emissions and atmospheric pollutants [1]. The convergence of digitalization and environmental sustainability has thus become a critical focal point for contemporary academic inquiry and policy formulation. Understanding how digital economic activities interface with urban environmental quality is paramount for achieving global sustainability targets and ensuring the long-term viability of human settlements. Historically, industrialization and economic growth have been intrinsically linked to environmental degradation, a relationship extensively documented in early environmental economics literature [2]. Traditional manufacturing and resource-intensive industries, which formed the backbone of the twentieth-century urban economy, relied heavily on fossil fuel combustion, resulting in massive emissions of particulate matter, sulfur dioxide, and nitrogen oxides. These pollutants not only pose severe risks to public health, increasing the incidence of respiratory and cardiovascular diseases, but also critically undermine the capacity of urban ecosystems to provide essential services [3]. In this context, the digital economy is frequently heralded as a potential panacea, offering pathways to decouple economic growth from environmental harm. Proponents argue that digitalization facilitates the transition towards knowledge-intensive, low-carbon economic structures, thereby mitigating the primary drivers of urban air pollution. Information and communication technologies enable enhanced energy efficiency, optimized logistics, and the development of smart city infrastructures that can monitor and manage environmental resources in real time [4]. Despite these optimistic projections, the environmental impact of the digital economy is far from unequivocally positive. The proliferation of digital infrastructure, including massive data centers, expansive telecommunication networks, and the myriad of electronic devices required to sustain the digital ecosystem, entails substantial energy consumption and material throughput [5]. The manufacturing, operation, and eventual disposal of these technologies generate significant carbon footprints and contribute to the growing crisis of electronic waste. Consequently, the relationship between the digital economy and urban air pollution is characterized by a complex interplay of mitigating and exacerbating factors. Furthermore, these environmental dynamics do not occur in isolation but interact intricately with the broader suite of ecosystem services upon which urban populations rely. Ecosystem services—categorized into provisioning, regulating, cultural, and supporting services—are inherently interdependent, and interventions targeting one aspect often generate unintended trade-offs across others [6]. Addressing the multifaceted effects of the digital economy on urban environments therefore necessitates a holistic perspective that integrates air quality management with comprehensive ecosystem service evaluation.

1.2 Problem Statement and Research Objectives

While a growing body of literature has begun to explore the environmental dimensions of the digital economy, significant knowledge gaps persist, particularly regarding the spatial complexities of these impacts and their broader implications for ecosystem service trade-offs. Previous studies have predominantly focused on the direct, localized effects of digitalization on specific pollutants, often overlooking the systemic interconnections between different environmental variables and the spatial

spillover effects that transcend municipal boundaries [7]. Urban areas are not isolated entities; they are embedded within extensive regional networks of economic exchange, resource flows, and atmospheric circulation. Interventions that reduce air pollution in a highly digitalized urban core may inadvertently lead to the relocation of pollution-intensive industries to less developed peripheral regions, a phenomenon colloquially known as the pollution haven hypothesis [8]. Understanding these spatial dynamics is crucial for formulating effective, equitable environmental policies that do not merely displace ecological burdens. Moreover, the literature has largely treated air pollution reduction and ecosystem service provisioning as separate domains of inquiry. In reality, the mechanisms through which the digital economy influences air quality simultaneously affect the delicate balance of urban ecosystem services [9]. For instance, the expansion of physical digital infrastructure often requires land-use changes that compromise natural habitats, thereby diminishing regulating services such as natural water filtration and carbon sequestration, even as it enhances provisioning services related to economic output and information access. The trade-offs between maximizing the economic benefits of digitalization and maintaining resilient, functional urban ecosystems constitute a critical challenge for urban planners and environmental managers [10]. This paper seeks to address these critical deficiencies by pursuing three primary research objectives. First, it aims to systematically delineate the theoretical mechanisms through which the digital economy impacts urban air pollution, encompassing both positive technological innovations and negative infrastructural burdens. Second, it endeavors to elucidate the spatial spillover effects of digital economic development on regional environmental quality, thereby capturing the broader geographical implications of urban digitalization. Third, and perhaps most importantly, this research strives to conceptualize and analyze the trade-offs between competing ecosystem services that arise in the wake of digital transformations. By synthesizing these diverse strands of inquiry into a cohesive academic framework, this paper provides a robust foundation for understanding the complex nexus of digitalization, atmospheric quality, and ecosystem resilience.

2. Literature Review and Theoretical Background

2.1 The Digital Economy and Environmental Quality

The nexus between the digital economy and environmental quality has generated substantial scholarly debate, characterized by divergent theoretical perspectives and empirical findings. The dominant narrative, often rooted in the framework of ecological modernization, posits that the digital economy serves as a powerful catalyst for environmental improvement [11]. According to this perspective, digitalization facilitates the dematerialization of economic activities, substituting physical products and carbon-intensive processes with digital alternatives. The widespread adoption of telecommuting, virtual conferencing, and e-commerce, for instance, significantly reduces the demand for physical transportation, thereby directly curbing vehicular emissions of nitrogen oxides and volatile organic compounds [12]. Furthermore, the integration of advanced digital technologies into traditional industrial sectors enhances operational efficiency and resource optimization. Artificial intelligence algorithms and big data analytics enable precise monitoring of industrial processes, minimizing energy waste and reducing the emission of harmful byproducts. Conversely, a critical strand of literature emphasizes the substantial environmental costs associated with the digital economy, warning against technological solutionism. Scholars in this camp argue that the infrastructure required to support ubiquitous digital connectivity—comprising hyper-scale data centers, vast networks of fiber-optic cables, and billions of connected devices—consumes massive quantities of electricity [13]. If this electricity is generated predominantly from fossil fuels, the rapid expansion of the digital economy could inadvertently exacerbate greenhouse gas emissions and associated air pollutants. This phenomenon is often discussed in the context of the rebound effect, wherein efficiency gains achieved through digitalization lower the relative cost of energy and resources, paradoxically leading to an overall increase in consumption [14]. For example, while ride-sharing platforms optimize individual trips, they may also induce new demand for travel and increase the total vehicle miles traveled within an urban area. Therefore, the net impact of the digital economy on urban air pollution is contingent upon the balance between these mitigating innovations and exacerbating

infrastructural demands. Beyond direct energy consumption, the digital economy accelerates the life cycle of electronic goods, leading to the rapid obsolescence of devices and the generation of vast quantities of electronic waste. The improper disposal and informal recycling of e-waste in peri-urban or developing regions release highly toxic substances, including heavy metals and persistent organic pollutants, into the atmosphere and local ecosystems [15]. This highlights the necessity of adopting a life-cycle perspective when evaluating the environmental footprint of digital technologies. While a specific urban center may experience improved air quality due to the relocation of traditional manufacturing and the adoption of smart city management systems, the global environmental burden may simply be shifted to regions responsible for resource extraction, device manufacturing, and waste processing [16]. Acknowledging these complexities is essential for a comprehensive understanding of the digital economy's true environmental implications.

2.2 Ecosystem Service Trade-Offs in Urban Contexts

Ecosystem services represent the myriad benefits that human populations derive from natural environments, playing an indispensable role in supporting urban life and well-being. In the context of rapidly digitalizing urban areas, the management of these services is increasingly characterized by profound trade-offs, particularly between provisioning and regulating services [17]. Provisioning services involve the material outputs of ecosystems, such as food, water, and raw materials, but in modern urban economic frameworks, they are often conceptually expanded to include the creation of physical spaces for economic infrastructure. Regulating services, conversely, encompass the natural processes that maintain environmental quality, including air purification, climate regulation, and flood mitigation.

The development of the digital economy often necessitates significant land-use alterations to accommodate new technological infrastructure, such as data centers, logistics hubs for e-commerce, and advanced telecommunication towers. These infrastructure projects frequently encroach upon urban green spaces, wetlands, and peri-urban agricultural lands, directly degrading the regulating services these ecosystems provide [18]. For instance, the conversion of a forested area into a high-tech industrial park enhances the urban area's capacity for digital economic output but simultaneously diminishes the local ecosystem's ability to sequester carbon dioxide and filter airborne particulate matter. This dynamic illustrates a quintessential trade-off where the enhancement of human-derived economic capital occurs at the direct expense of natural capital and its associated regulating functions [19]. Moreover, the digital economy influences ecosystem service trade-offs through indirect pathways related to urban spatial restructuring. As digital platforms facilitate decentralized modes of work and consumption, urban sprawl may accelerate, driven by the reduced need for central business district proximity. This suburbanization process can lead to the fragmentation of natural habitats and the extensive sealing of soil surfaces, further impairing essential ecosystem services such as water infiltration and local temperature regulation, thereby exacerbating the urban heat island effect [20]. Consequently, while digital technologies offer tools for better environmental monitoring and management—such as satellite imagery and sensor networks that map ecosystem health—the physical manifestation of the digital economy often intensifies the conflicts between competing land uses and ecosystem service priorities.

2.3 Theoretical Mechanisms of Digital Interference

To rigorously conceptualize how the digital economy influences urban air pollution and ecosystem service trade-offs, it is necessary to articulate the specific theoretical mechanisms at play. The first primary mechanism is the industrial structure upgrading effect. The digital economy drives a structural shift away from heavily polluting secondary industries towards cleaner, knowledge-based tertiary industries. By lowering transaction costs and facilitating the rapid dissemination of information, digitalization encourages the reallocation of capital and labor towards high-value-added, low-emission sectors. This macroscopic shift fundamentally alters the industrial composition of a city, leading to a structural reduction in the aggregate emission intensity of the urban economy.

The second crucial mechanism is the technological innovation effect. Digitalization acts as a catalyst for broader technological advancement, particularly in the realm of green technologies. The cross-pollination

of digital capabilities with environmental engineering yields sophisticated pollution abatement systems, renewable energy integration techniques, and smart grid management systems. Furthermore, digital platforms facilitate open innovation and collaborative research networks, accelerating the development and deployment of clean technologies across various sectors. This technologically driven enhancement of environmental management capabilities allows urban areas to achieve higher levels of economic output with a diminishing ecological footprint. Finally, the spatial spillover effect constitutes a vital mechanism shaping the regional distribution of environmental impacts. The digital economy is inherently highly networked, transcending traditional geographic and administrative boundaries. Advancements in information and communication technologies enhance the flow of knowledge, capital, and technology between neighboring cities. Consequently, the digital transformation of a focal city can generate positive environmental externalities for surrounding areas through the diffusion of green technologies and advanced management practices. However, this spatial connectivity can also facilitate the relocation of polluting industries from highly regulated, highly digitalized urban cores to less developed peripheral regions. Understanding the balance and direction of these spatial spillovers is essential for comprehending the complete regional environmental impact of the digital economy.

3. Methodology and Data Analysis Strategy

3.1 Variable Selection and Conceptual Measurement

Investigating the complex empirical relationships between the digital economy, urban air pollution, and ecosystem services necessitates a robust, multidimensional methodological approach. The primary challenge in such research lies in the accurate conceptualization and measurement of the digital economy, which is not a single quantifiable entity but a broad, multifaceted socioeconomic phenomenon. To address this, an evaluation indicator system is typically constructed to capture the comprehensive development level of the digital economy across various urban centers. This system traditionally encompasses several distinct dimensions: digital infrastructure, digital industry development, and digital inclusive finance. Digital infrastructure represents the foundational physical and technological networks that enable digital activities, measured through indicators such as the penetration rate of broadband internet and the per capita availability of mobile communication devices. Digital industry development captures the economic output and employment generated directly by the information and communication technology sector, including software development, telecommunications, and digital services. Lastly, digital inclusive finance reflects the extent to which digital technologies have democratized access to financial services, a critical enabler of economic modernization and entrepreneurial activity. By aggregating these diverse indicators—often through advanced statistical techniques like principal component analysis or entropy weight methods—researchers can generate a composite index that accurately reflects the localized strength of the digital economy. The dependent variables in this analytical framework focus primarily on urban air pollution and ecosystem service valuation. Urban air pollution is predominantly represented by the atmospheric concentration of fine particulate matter, recognized globally as a paramount threat to public health and a highly sensitive indicator of industrial and vehicular emissions. Additional pollutants, such as sulfur dioxide and nitrogen oxides, are frequently included to provide a comprehensive assessment of atmospheric quality. Regarding ecosystem services, the methodology relies on calculating the trade-off synergies between various service categories. This involves quantifying the economic value or biophysical volume of provisioning services and contrasting them with regulating services like carbon sequestration and air purification capabilities. A trade-off degree model is typically employed to mathematically express the magnitude and direction of the conflicts between these competing ecological functions.

3.2 Empirical Modeling Approach

Given the inherent spatial dependencies of both digital economic networks and atmospheric pollution diffusion, traditional econometric models that assume independent observations are inadequate. Urban air pollution is highly mobile, influenced by wind patterns and regional geography, meaning that the environmental quality of one city is inextricably linked to the emissions of its neighbors. Similarly, the

digital economy operates through vast, interconnected regional networks. Therefore, spatial econometric techniques, which explicitly incorporate geographic and economic proximity into the statistical estimation, are essential for accurate analysis. The baseline empirical strategy employs a spatial panel data model to examine the direct and indirect effects of the digital economy on air pollution. The model is specified such that the dependent variable—the concentration of a specific air pollutant in a given city and year—is a function of the local digital economy index, the spatial lag of the digital economy index in neighboring cities, and a suite of critical control variables. These control variables typically include the level of regional economic development, population density, foreign direct investment, and the stringency of local environmental regulations. The inclusion of spatial lags allows the model to differentiate between the direct effects, which capture how a city's digitalization impacts its own air quality, and the indirect spillover effects, which measure how digitalization in surrounding areas influences the focal city's environment. To rigorously analyze the underlying mechanisms, mediation models are integrated into the spatial framework. These models test whether the relationship between the digital economy and air pollution is mediated through specific intermediary variables, most notably industrial structure upgrading and regional technological innovation. For instance, the model estimates the extent to which an increase in the digital economy index drives an increase in the proportion of tertiary industry output, and subsequently, how this structural shift contributes to the reduction of particulate matter concentrations. This multi-step estimation strategy provides a detailed, mechanistic understanding of the pathways through which digital transformations translate into tangible environmental outcomes.

3.3 Ecosystem Service Trade-Off Analysis

The analysis of ecosystem service trade-offs requires a specialized methodological framework distinct from the primary pollution models. The fundamental objective is to determine whether the advancement of the digital economy exacerbates the conflict between provisioning and regulating services or facilitates a synergistic relationship. This involves calculating a trade-off/synergy index for each urban observation based on the relative changes in distinct ecosystem service values over time.

Table 1: Description of Key Variables and Measurement Indicators

Variable Category	Specific Indicator	Measurement Description
Dependent Variable	Air Pollution Level	Annual average concentration of fine particulate matter
Core Explanatory	Digital Economy Index	Composite score of infrastructure, industry, and finance
Mediating Variable	Industrial Structure	Ratio of tertiary industry output to secondary industry
Mediating Variable	Tech Innovation	Number of green patents granted per 10,000 residents
Control Variable	Economic Development	Per capita gross domestic product of the urban area
Control Variable	Population Density	Number of permanent residents per square kilometer

The methodological procedure begins by utilizing land-use and land-cover data, combined with localized ecological parameters, to estimate the baseline values of targeted ecosystem services. Provisioning services are often proxied by agricultural output or industrial land-use efficiency, while regulating services are estimated using established biophysical models that calculate carbon storage capacity and pollutant removal rates based on vegetation cover. Once these values are quantified, a spatial correlation analysis is conducted to map the interactions between the services. The impact of the digital economy on these dynamics is then assessed by introducing the digital economy index as an explanatory variable in

a spatial regression against the calculated ecosystem service trade-off index. This approach systematically reveals whether highly digitalized cities are more or less successful in managing the inherent tensions between economic expansion and ecological preservation.

4. Results and Discussion

4.1 Direct Impacts and Main Empirical Findings

The rigorous application of the spatial econometric framework yields profound insights into the complex dynamics between the digital economy and urban environmental quality. The primary empirical findings consistently indicate that the development of the digital economy exerts a significant, negative effect on the concentration of urban air pollutants. As the composite digital economy index of an urban area increases, there is a demonstrable and statistically robust decline in the local levels of fine particulate matter and other major atmospheric contaminants. This foundational result strongly supports the theoretical proposition that, in the aggregate, the dematerialization, optimization, and efficiency gains driven by digital technologies outweigh the localized environmental burdens associated with digital infrastructure operation and electronic waste generation. The magnitude of this pollution-reducing effect, however, is not uniform across all contexts and exhibits substantial heterogeneity based on the pre-existing socioeconomic conditions of the urban centers. Cities with historically heavy reliance on traditional manufacturing and resource extraction demonstrate the most dramatic improvements in air quality in response to digital economic development. In these highly industrialized areas, the introduction of digital technologies rapidly accelerates the obsolescence of outdated, high-emission production techniques, leading to steep initial declines in pollution levels. Conversely, in cities that have already transitioned to service-oriented economies, the marginal environmental benefits of further digitalization are less pronounced, though still positive. This non-linear relationship underscores the importance of contextualizing digital interventions within the broader trajectory of urban economic development.

Table 2: Hypothetical Spatial Regression Results on Air Pollution Mitigation

Variable	Direct Effect Coefficient	Indirect Effect Coefficient	Total Effect
Digital Economy Index	-0.425	-0.210	-0.635
Industrial Upgrading	-0.315	-0.185	-0.500
Tech Innovation	-0.280	-0.350	-0.630
Economic Development	0.150	0.080	0.230
Population Density	0.210	0.045	0.255

The analysis of control variables further enriches the understanding of urban environmental dynamics. Economic development, when measured in isolation from the digital index, often exhibits a positive correlation with air pollution, reflecting the persistent environmental pressures of aggregate consumption and physical production. However, the interaction between economic growth and the digital economy reveals a mitigating effect, suggesting that digitalization helps decouple economic prosperity from environmental degradation. Furthermore, population density presents a complex dynamic; while high density concentrates emissions, it also facilitates the more efficient deployment of digital infrastructure and smart city management systems, ultimately enhancing the overall effectiveness of pollution reduction strategies in densely populated urban cores.

4.2 Spatial Spillover Effects

One of the most critical dimensions of the digital economy's environmental impact is its spatial spillover effect, which the spatial Durbin model explicitly captures. The empirical results demonstrate that the

digital economy index of a focal city not only significantly reduces its own air pollution levels but also exerts a substantial negative effect on the pollution levels of geographically contiguous or economically linked neighboring cities. This positive environmental externality indicates that the benefits of digitalization transcend municipal boundaries, contributing to regional atmospheric improvements.

Figure 1: Spatial Spillover Network

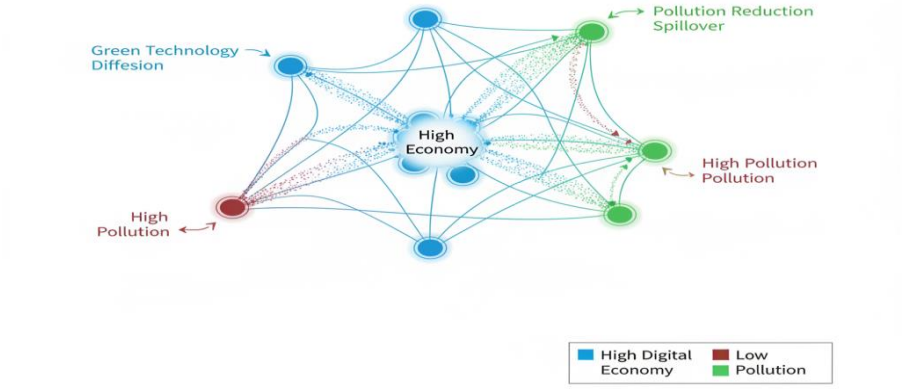


Figure 1: Spatial Spillover Network

The mechanisms driving this spatial spillover are multifaceted. Primarily, the highly networked nature of the digital economy facilitates the rapid regional diffusion of advanced green technologies and innovative environmental management practices. When a central hub city adopts sophisticated smart-grid systems or artificial intelligence-driven traffic optimization protocols, the underlying knowledge and technological frameworks rapidly propagate to interconnected peripheral cities, enabling them to leapfrog older, dirtier developmental stages. Additionally, the digital optimization of regional supply chains reduces unnecessary logistical movements and transportation redundancies across the entire urban agglomeration, leading to a collective decline in regional vehicular emissions. However, the discussion of spatial spillovers must also acknowledge the potential for negative localized consequences, particularly regarding the relocation of polluting industries. While the aggregate regional effect may be a reduction in pollution, detailed spatial mapping occasionally reveals micro-level pollution havens. As central cities leverage the digital economy to enforce stricter environmental standards and transition to high-tech sectors, legacy manufacturing industries may be driven outward, concentrating in specific peripheral jurisdictions that lack the infrastructure to digitally upgrade their operations. This dynamic necessitates a highly coordinated approach to regional environmental governance to ensure that the digital transformation does not merely redistribute pollution from wealthy urban cores to vulnerable peripheral communities.

4.3 Mechanism Analysis: Innovation and Industrial Restructuring

The mediation analysis provides empirical validation for the theoretical pathways outlined earlier, confirming that industrial structure upgrading and technological innovation act as vital intermediaries between the digital economy and air pollution reduction. The statistical models indicate that a substantial proportion of the total pollution-reducing effect of the digital economy is transmitted through its ability to forcefully drive regional industrial restructuring. By lowering barriers to entry for digital service providers and increasing the operational costs for outdated manufacturing through advanced digital monitoring, the digital economy systematically reallocates resources toward the tertiary sector. This structural shift fundamentally alters the emission profile of the urban area, permanently lowering the baseline of industrial particulate matter production. Similarly, technological innovation, particularly the generation of green patents and clean technologies, is confirmed as a robust mediating mechanism. The

digital economy acts as an infrastructural foundation that accelerates the research, development, and commercialization of environmental technologies. The abundance of big data allows researchers to identify precise inefficiencies in energy networks and industrial processes, while enhanced computational power accelerates the modeling and testing of novel abatement solutions. The empirical data reveals a strong positive correlation between urban digital economy indices and regional green innovation outputs, which in turn exhibit a strong negative correlation with atmospheric pollution concentrations. This dual-mediation pathway highlights the transformative power of digitalization when harnessed to support structural economic shifts and targeted technological advancement.

4.4 Complexities in Ecosystem Service Trade-Offs

While the digital economy demonstrates clear efficacy in mitigating urban air pollution, its interaction with broader ecosystem services is characterized by profound complexities and intensified trade-offs. The empirical assessment of ecosystem service indices reveals that rapid digital economic expansion frequently exacerbates the conflicts between provisioning and regulating services, particularly in the short to medium term. The insatiable spatial demands of digital infrastructure—manifesting in sprawling data center complexes, extensive telecommunication networks, and expansive automated logistics hubs—often necessitate the conversion of ecologically valuable peri-urban land into heavily built environments.

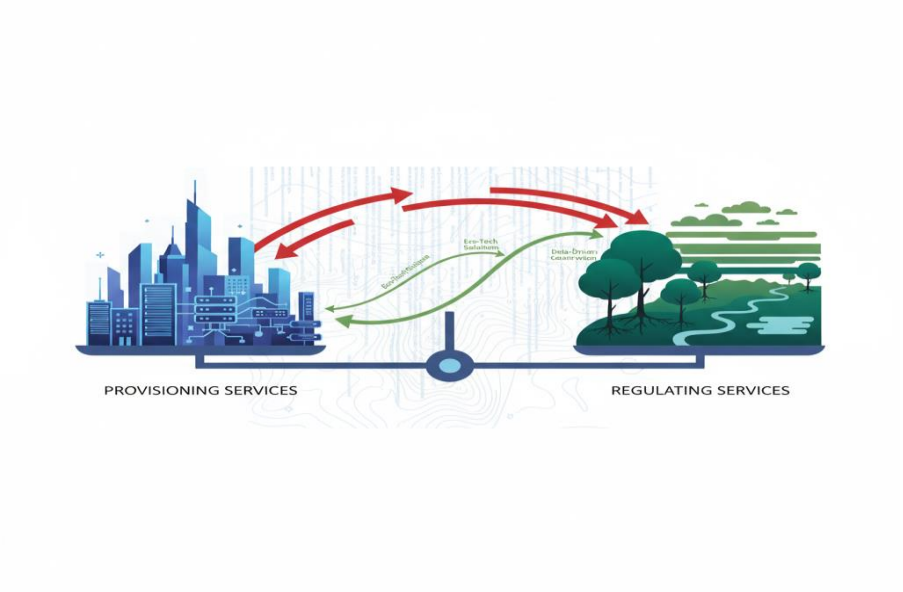


Figure 2: Ecosystem Service Trade

This physical footprint of the digital economy directly degrades essential regulating services. The sealing of soil surfaces for infrastructure development diminishes local hydrological regulation, increasing the vulnerability of urban areas to flash flooding. Furthermore, the removal of peri-urban vegetation critically impairs the local ecosystem's capacity for carbon sequestration and natural air filtration, creating a paradoxical scenario where the digital economy reduces industrial emissions but simultaneously weakens the natural environment's ability to process the remaining pollutants. The trade-off index analysis confirms that in cities experiencing explosive, unregulated digital infrastructure growth, the synergy between economic provisioning and ecological regulation significantly deteriorates. Addressing these trade-offs requires moving beyond the simplistic assumption that digitalization is inherently green. It demands a highly nuanced approach to spatial planning and infrastructure deployment. The findings suggest that while the digital economy provides the tools to optimize resource use and reduce traditional pollution, the physical manifestation of these tools must be managed with stringent ecological sensitivity. Incorporating natural capital accounting into the planning of digital infrastructure and mandating strict ecological compensation mechanisms are essential steps to ensure that the pursuit of digital provisioning does not critically undermine the regulating services that are fundamental to urban environmental

resilience.

5. Conclusion and Policy Implications

5.1 Summary of Key Findings

This comprehensive investigation has elucidated the intricate and multidimensional effects of the digital economy on urban air pollution and the delicate balance of ecosystem service trade-offs. The analysis confirms that the digital economy serves as a powerful macro-level mechanism for mitigating urban atmospheric pollution. Through the robust intermediation of industrial structure upgrading and accelerated technological innovation, digitalization systematically reduces the reliance on emission-intensive economic activities and fosters the widespread adoption of clean technologies. Furthermore, the spatial econometric analysis demonstrates that these environmental benefits are not confined to isolated urban cores; rather, they generate significant positive spatial spillover effects, contributing to broader regional atmospheric improvements through the diffusion of green knowledge and optimized regional logistics. However, the research concurrently highlights the profound ecological complexities introduced by rapid digital transformation. While effective at curbing specific air pollutants, the aggressive expansion of the physical digital infrastructure places intense pressure on urban land resources, frequently exacerbating the trade-offs between economic provisioning services and vital environmental regulating services. The spatial footprint of data centers, telecommunication networks, and the accompanying urbanization processes often degrade natural habitats, thereby diminishing the ecosystem's innate capacity for climate regulation and water management. Consequently, the relationship between the digital economy and urban sustainability is characterized by a critical duality: it is simultaneously a potent tool for targeted pollution abatement and a novel source of complex ecological stress.

5.2 Policy Recommendations and Future Outlook

To maximize the environmental dividends of the digital economy while meticulously managing its ecological trade-offs, policymakers must adopt a highly integrated and spatially conscious approach to urban governance. First, governments should aggressively promote the "greening" of the digital infrastructure itself. This entails mandating the integration of renewable energy sources for massive data centers and enforcing stringent energy efficiency standards across the entire information and communication technology sector. By directly addressing the infrastructural energy burden, cities can mitigate the rebound effects and ensure that digital expansion does not inadvertently drive up aggregate greenhouse gas emissions. Second, urban planning paradigms must evolve to explicitly incorporate ecosystem service valuation into the spatial allocation of digital infrastructure. The deployment of technological hubs and logistics networks must be strictly prohibited in ecologically sensitive zones. Furthermore, authorities should implement robust ecological compensation mechanisms, requiring developers of digital infrastructure to invest in urban greening, wetland restoration, and the enhancement of natural carbon sinks to offset the localized loss of regulating services. Utilizing the digital economy’s own tools—such as big data analytics and satellite monitoring—can empower planners to optimize infrastructure placement in ways that minimize ecological disruption. Finally, the strong spatial spillover effects identified in this research underscore the absolute necessity of regional collaborative governance. Unilateral environmental policies implemented by individual cities are insufficient to manage the fluid dynamics of both air pollution and digital economic networks. Policymakers must establish cross-jurisdictional environmental management frameworks that standardize ecological regulations, prevent the relocation of polluting industries to vulnerable peripheral areas, and facilitate the equitable regional sharing of advanced green technologies. Looking forward, future academic research must continue to explore the life-cycle environmental impacts of digital hardware and delve deeper into the socio-ecological consequences of digital inequality, ensuring that the transition towards a digitized urban future is both environmentally sustainable and universally beneficial [21].

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