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RESEARCH ARTICLE

Assessment of Spatiotemporal Evolution of Ecological Security in Urban Agglomerations of China: A PSR Model Approach

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ABSTRACT

This study focuses on the spatiotemporal evolution of ecological security in the fast-growing megacity of Beijing using the PSR framework. Within the last three decades, Beijing has been under considerable stress due to rapid urbanization and industrialization. Over the past three decades, Beijing has experienced significant transformations in land use, biodiversity, air quality, and water resources, driven by urban expansion and industrial growth. The findings reveal extensive habitat fragmentation, biodiversity homogenization, and the encroachment of built-up areas on green spaces, highlighting critical ecological challenges. Restoration projects, such as those in the Yongding River Wetland Park, have improved vegetation health and biodiversity, but invasive species and uneven recovery remain concerns. The improvements in air quality due to strict policies still show prevailing ozone pollution. In general, water withdrawals have stabilized consequent to conservation, whereas hydrological disruptions due to diversion projects underpin demands for sustainable use of this resource. This research underlines how integrated and data-driven approaches to urban planning have become indispensable in providing a rich context of the interplay between urbanization and ecological security in megacities.

1. INTRODUCTION

Urban agglomerations have emerged as focal points for economic development and human activity. Among these, Beijing, the capital of China, stands as a prime example of a megacity grappling with the dual challenges of rapid urbanization and ecological degradation. Over the past three decades, Beijing has experienced unprecedented urban sprawl, industrial expansion, and demographic growth. These changes have intensified pressures on its ecological systems, leading to critical issues such as air pollution, loss of biodiversity, and wetland degradation (Li et al., 2020a; Xiao et al., 2023). The city's environmental challenges are further compounded by its role as a political and cultural hub, making the sustainability of its urban ecosystem a pressing concern. Balancing the competing demands of economic development and ecological preservation requires an integrated, data-driven approach to assess and mitigate risks (UN-Habitat, 2022). Beijing's ecological systems have been subjected to significant transformations, driven by factors such as land-use changes, increased urban density, and industrial emissions. These transformations have led to elevated landscape ecological risks and deteriorating ecosystem services (Li et al., 2020a; Peng et al., 2021). This study aims to assess the spatiotemporal evolution of ecological security in Beijing using the PSR model framework. By systematically analyzing the pressures exerted by urbanization, the state of the urban ecosystem, and the responses initiated to mitigate ecological risks, this research seeks to provide actionable insights into Beijing's ecological challenges. The objectives of this paper include identifying key ecological loss due to rapid urbanization, industrialization, and land-use changes in Beijing and examining urban ecosystems' health and spatiotemporal trends in ecological security over the last 30 years.

2. LITERATURE

Ecological security assessment in urban regions, especially megacities like Beijing, has become a growing area of research due to the urgent challenges brought forth by urbanization and environmental degradation. The reviewed studies address several dimensions of ecological security, such as landscape changes, biodiversity, environmental resilience, and the application of assessment frameworks like the PSR model. Li et al. (2020) conducted a study on the multifunctional landscape and LER of Beijing between 2000 and 2010. These results indicated that the process of multifunctionality, according to obvious spatial differences, went toward expansion from the northwest through high multifunctionality areas in many directions to the southwest during the research period, but conversely, low multifunctionality congregates in the southeast. With geographically weighted regression, there is a negative correlation between multifunctionality and ecological risk, which indicates increasing ecological function lowers ecological risks. This work underpins the importance of spatial planning in an effort to reduce ecological hazards. Xiao et al. (2023) investigated what effects urbanization has on Beijing's biodiversity, considering plant communities of parks, residential areas, and along roads. In total, it identified 536 plant species; significant differences in both richness and diversity of species were visible within the urbanization gradient. The distribution of native and imported species underpinned the role of local ecosystem development. This research, therefore, evidences the need for a differential approach to conservation, through planning strategies such as green corridors, which will guarantee at least a portion of urban biodiversity in the face of increased urbanization.

Peng et al. (2021) used the DPSIR-DEA model to assess ecological security in the Beijing-Tianjin-Hebei urban agglomeration. It was indicated by the result that there exist spatial differences; northern counties are ecologically safer than southern ones. Among such security factors, the main influence was found to include population density, the proportion of construction land, and PM2.5 levels. The emphasis here is on taking policies very seriously regarding regional coordination to narrow disparities in ecosystems and uplifting general security. Liu et al. (2022) illustrated the application of the PSR model in identifying ecological source areas in Tianjin and gave substantial methodological insight for Beijing. In this study, the inclusion of landscape connectivity indices and morphological spatial pattern analysis revealed a decline in ecological connectivity despite restoration. Their findings emphasize the need to maintain ecological corridors for sustainable urban development. Dai and Khan (2023) extended the PSR model to include an ecological carrying capacity index and coupling coordination models. Their study in Nanchang showed temporal improvements in ecological security due to policy interventions and improved resource management. This gives a clear framework to understand the dynamic interplay of pressures, states, and responses within urban ecosystems.

Zhang et al. (2023) have estimated the UER in the Pearl River Delta based on the PSR framework; the results indicated that most of the resilience indicators displayed obvious spatial differences and were offset by high-value central areas with low resilience areas. This paper is very crucial as it emphasizes incorporating a resilience-based approach into the assessment of ecological security and transferable insights for Beijing. Spatiotemporal evolution analyses of ecological land in BTH were done by Wang et al. (2024). In that study, they used remote sensing and landscape indices to detect notable changes in land use, including conversions between cropland and construction land. The method adopted for the current study is very robust in analyzing land use pressure on ecological security and therefore should have relevance to the assessment of the urban landscape in Beijing.

Guo et al. (2021) analyzed land ecological security in the BTH region and indicated that industrial emissions and accelerated urban growth are the significant factors responsible for this concern. According to their result, it was observed that LES experienced an uptrend from 2007 to 2018, though the regional gap still exists. An obstacle degree model proposed by this paper is a useful diagnosis tool that can be used for the ecology of Beijing, which then can be used in specific areas for intervention. Yu et al. (2011) suggested the "negative approach" to the planning of city growth in Beijing with ecological infrastructure (EI) serving as a framing mechanism where sustainable development could be envisioned. By identifying those critical areas of landscape elements for their strategic protection as such, the negative approach effectively balances urban growth with ecological concerns. This study shows the potential of EI which would offset the adverse effects of conventional urban planning practices as far as ecology was concerned. Li et al. (2021) proposed an ecological security evaluation algorithm based on the PSR model for resource-exhausted cities. They identified the top indicators in industrial sulfur dioxide emissions and forest cover, thus showing the usefulness of using computational tools to enhance ecological assessments. The results could serve as a good reference to apply similar methodologies to ecological issues in Beijing.

Gaps

These reviewed studies put together a complex knowledge of ecological security challenges across urban areas: the identification of spatial and temporal dynamics in landscape change, the important role of biodiversity conservation, and the applicability of the PSR framework in structuring ecological assessments. While significant advances underpin this progress, substantial gaps persist in effectively incorporating resilience and connectivity analyses with actionable policy recommendations tailored to the unique urban ecosystem that Beijing represents. This literature review lays the foundation for a spatiotemporal analysis of Beijing's ecological security, with a focus on holistic approaches combining ecological and technological solutions driven by policies.

3. METHODS AND STUDY AREA

3.1. Methods

This study uses the spatiotemporal approach in assessing ecological security in Beijing, focusing on green space and urban space. In general, the methodology integrates the Pressure-State-Response (PSR) framework with spatial analysis tools to evaluate and map the ecological dynamics. The land use, green space, and urban space data from secondary sources were obtained from the Sentinel-2, Google Earth Pro and other sources.

PSR model framework

- Pressure: The trends in urbanization, industrial activities, and land-use change were assessed in terms of population density, urban expansion metrics, and construction land ratios.
- Status: Indicators assessing air quality, biodiversity, and the coverage of green space were considered.
- Response: The review of existing policies and restoration measures was done to determine the effectiveness of ecological recovery efforts.

Figure 1: Study area

3.2 Study area

Beijing is located at 39°54′24″N 116°23′51″E covering an area of approximately 16,410 square kilometres including urban districts, suburban areas, and mountainous regions. Beijing is a megacity, and its population fluctuates between 700,000 and 1,200,000 as it is a political, cultural, and economic hub (Britannica, n.d). The rapid urbanization of Beijing has greatly changed its landscape, with habitat fragmentation, loss of biodiversity, and declining air quality. It contains a variety of green spaces, from large parks like the Olympic Forest Park to urban forests, and peripheral wetlands. These areas are important to mitigate the heat island effect of the city, improve air quality, and maintain biodiversity. In recent times, urban sprawl and sprawling industrial development have diminished the greenspace, hence raising avid demands for ecological planning capable of sustainability.

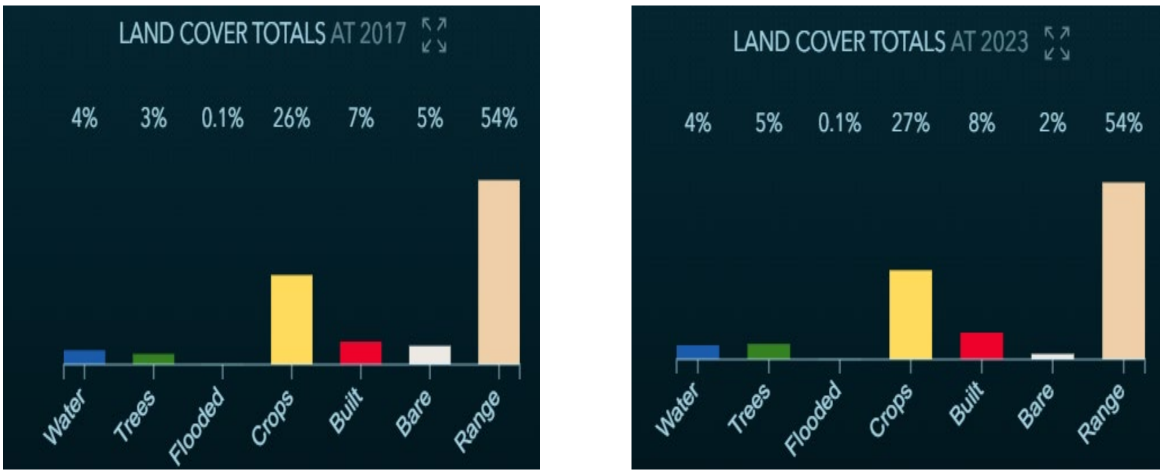
3.3 Ethical issues

No primary data collection has been undertaken in this research. The use of secondary data complies with ethical standards, and all data sources are cited appropriately.

4. RESULT

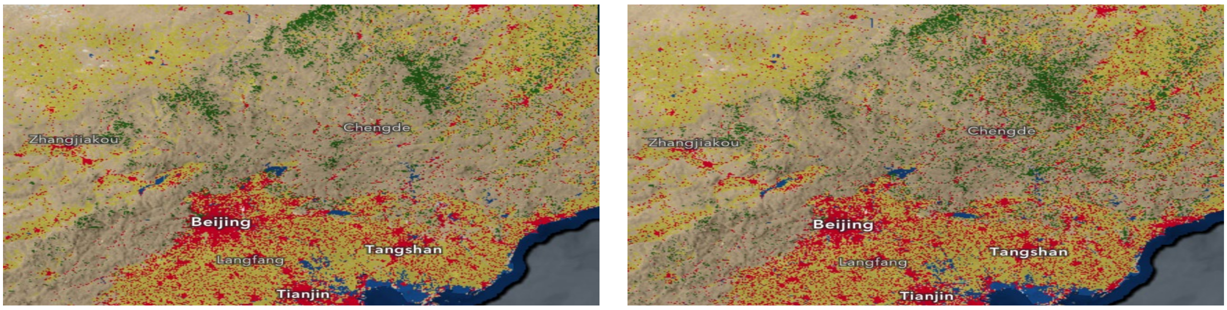
Spatio-temporal changes

China has witnessed substantial transformations in land use and land cover (LULC) over recent decades, driven by rapid urbanization, industrial expansion, and large-scale agricultural development. The country's efforts to balance economic growth with ecological sustainability have led to significant shifts in green spaces, cropland, and urban built-up areas. Between 2017 and 2023, data from Sentinel-2 land cover maps (Fig. 1a and 1b) reveal a steady expansion in built-up areas across major regions, while rangelands and croplands remain the dominant land cover types. The proportion of built-up areas has increased from 7% in 2017 to 8% in 2023, reflecting intensified urban development. Tree cover shows marginal improvement, from 3% to 5%, suggesting reforestation or afforestation efforts, while croplands display minor adjustments as urban expansion encroaches on agricultural zones. The northern and southeastern regions, including Beijing, demonstrate significant urban growth patterns, aligning with national trends of industrial clustering and population concentration.



a. 2017 Land Cover **b. 2023 Land Cover**

Figure 2: Comparison of land cover in 2017 and 2023

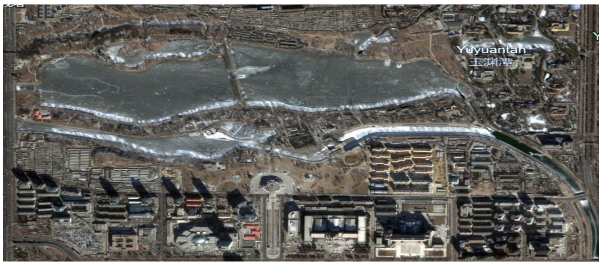


a. 2017 land cover map **b. 2023 land cover map**

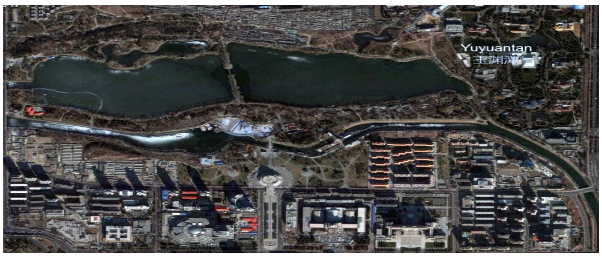
Figure 3: Esri Sentinel-2 land cover of Beijing of 2017 and 2023 (Source: Sentinel-2)

Beijing, as the capital city and a megacity of China, has undergone extensive land-use transformations. Rapid urbanization has led to a reduction in natural habitats, replaced by urban infrastructure, industrial zones, and residential developments. The Sentinel-2 maps for Beijing (Fig. 1c and 1d) from 2017 to 2023 indicate noticeable changes. Built-up areas in Beijing have increased, particularly in suburban districts, reducing cropland and open spaces. The city's focus on ecological restoration, particularly in greenbelt projects and urban forestry, has slightly improved tree cover and green spaces. Despite these efforts, urban heat island effects and air quality concerns remain pressing issues due to the loss of green spaces and vegetation.

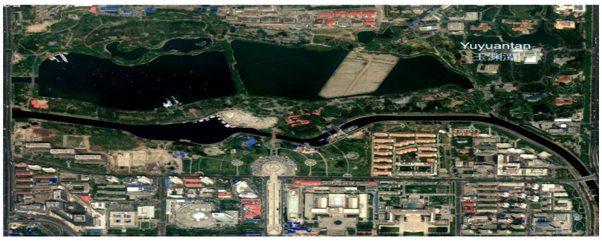
For the purpose of showing a closer view of the spatio-temporal transformations of Beijing to understand its impact on ecological security, an area of Yongding River Wetland Park is represented below (Refer to Fig 2).



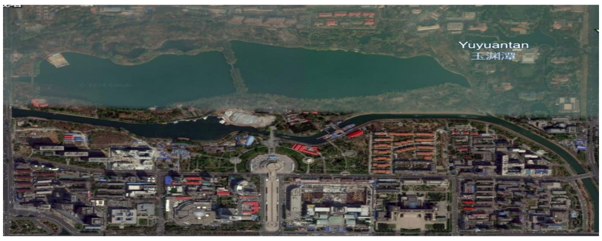
a. 2001



b. 2005

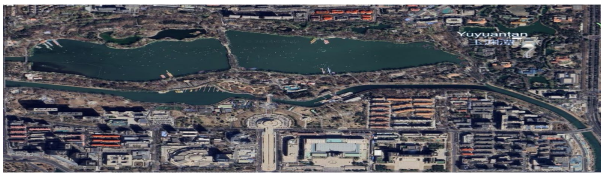


c. 2010



d. 2015

e. 2020



f. 2024

Figure 4: Spatio-temporal changes of a small block of Yongding River Wetland Park, Beijing from 2001 to 2024 (Source: Google Earth Pro)

In western Beijing, the Yongding River Wetland Park has gone through a significant ecological change in the last decades, under both rapid urbanization and targeted ecological restoration. Rapid urbanization and industrial processes led to environmental destruction that minimized vegetation cover and disrupted hydrological systems in the catchment area (Refer to Fig 2 a to f). Focused restoration processes, however, have reduced these adversities and created considerable ecological improvement. A study on the vegetation greenness of the Yongding River Basin between 2002 and 2022 showed that the overall trend in vegetation health was increasing. The average growth season and maximum annual NDVI growth rates were 0.006/10a and 0.008/10a, respectively, while about 90% of the area showed increased vegetation greenness (Zhang, 2024). This is a positive trend that incorporates good land management and restoration projects, which have enhanced vegetation cover and ecosystem vitality.

Field surveys before and after water replenishment in 2022 indicated an increase in plant species richness from 69 to 96 species and a compositional shift toward more hydrophytic plants. It has also pointed out the increase of invasive species, for example, Bidens frondosa and Xanthium italicum, after the supplement of water, which indicated that effective care has to be exercised regarding restoration activities to prevent inadvertent ecological consequences (Guo, 2024). These findings underline the reciprocal relationships among urbanization, ecological degradation, and restoration within the Yongding River Wetland Park: initial urbanization has caused heavy vegetation loss and fragmentation of habitat; on the other hand, restoration projects afterwards have assisted in ecological recovery by enhancing vegetation greenness and biodiversity. However, invasive species development has raised an alert for an integrated approach toward sustainable restoration.

Urban ecosystems health

The health of urban ecosystems in Beijing and across China reflects the intricate balance between rapid urbanization and efforts toward environmental restoration. Over the decades, multiple indicators highlight the interplay between anthropogenic pressures and ecological responses, as shown in Figs. 3 through 6. These provide a comprehensive picture of the evolving state of urban ecosystems in China.

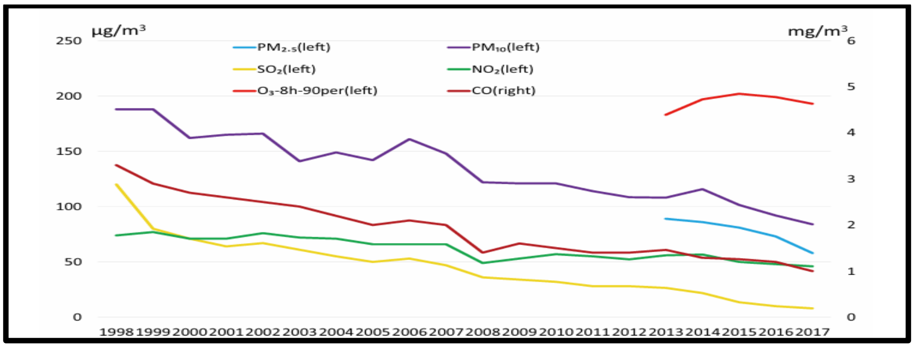


Figure 5: Changes in annual average concentrations of air pollutants in Beijing, 1998-2017 (Source: UN Environment, 2019)

The air quality in Beijing from 1998 to 2017 demonstrates significant fluctuations influenced by industrialization, vehicular emissions, and targeted air quality control measures. The concentrations of key pollutants, including PM2.5, PM10, SO_2, NO_2, and CO, showed a downward trend during this period. PM10 experienced a substantial decline, indicating the success of dust control and road cleaning measures (Refer to Fig 3). SO_2 levels dropped sharply, reflecting a reduction in coal usage and improvements in industrial emission standards. PM2.5, which poses severe health risks, also showed a marked decline after 2013, correlating with the implementation of stringent air pollution control policies, including the "Action Plan for Air Pollution Prevention and Control." Despite these improvements, the presence of O_3 (ozone) remains a challenge. While other pollutants decreased, ozone concentrations exhibited fluctuating trends, suggesting the need for more targeted efforts to address secondary pollutants formed through complex chemical reactions.

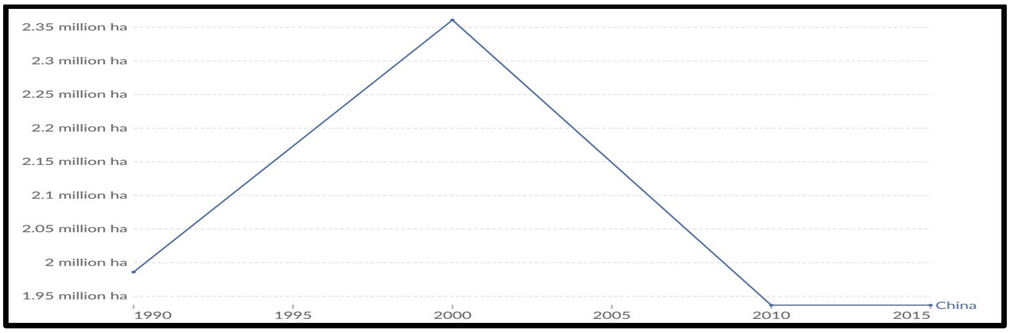


Figure 6: Forest loss in China from 1990 to 2015 (Source: Our World Data)

From 1990 to 2015, major changes have taken place in the forest area of China as well as Beijing. In the first phase, starting in 1990 and lasting until the early 2000s, the annual increase in forest area rose steadily due to afforestation efforts and natural regeneration. However, the latter part of this period 2005 saw a sudden reverse in that growth rate. The annual increment in forest area basically stagnated at zero by 2010 due to increasing pressures on land from urbanization and industrial use (Refer to Fig 4). This trend serves to underline the competition between ecological conservation and land development in a rapidly urbanizing region like Beijing. As much as national afforestation programs have increased forest coverage, pressures from urban sprawl and agricultural needs have impinged on available land, which limits further reforestation.

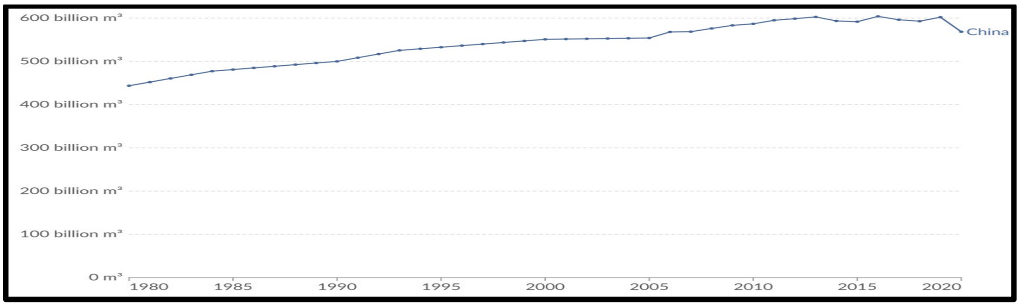


Figure 7: Water Loss in China from 1980 to 2020 (Source: Our World Data)

China's freshwater withdrawals have increased significantly, particularly from 1980 to 2010, driven by industrial, agricultural, and domestic demands. Total annual water withdrawals surpassed 600 billion cubic meters in the early 2010s before levelling off. The plateauing trend after 2015 reflects improved water conservation measures and more efficient usage in response to mounting water scarcity. In urban ecosystems like Beijing, water stress is exacerbated by high population density and industrial activities. The diversion of water resources to urban centres has strained natural aquatic ecosystems, further complicating the balance between urban growth and ecological sustainability.

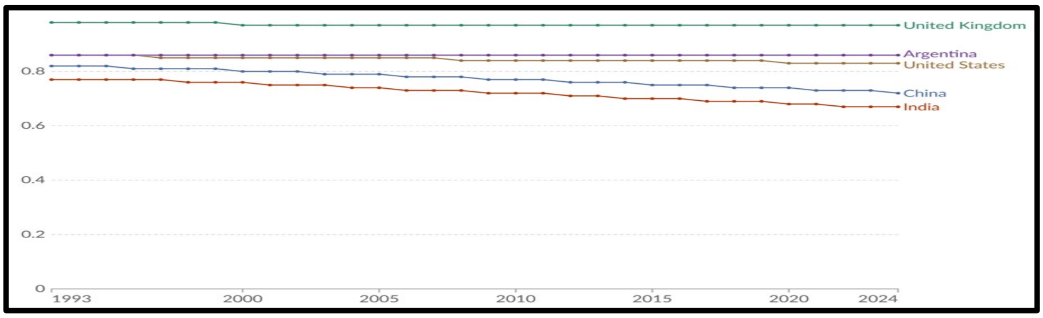


Figure 8: Red List Index of China from 1993 to 2024 (Source: Our World Data)

The Red List Index for China from 1993 to 2024 illustrates the declining health of biodiversity within the country. The Index, which measures extinction risk, indicates a steady deterioration of species populations due to habitat destruction, pollution, and climate change. This trend reflects the broader impact of urban expansion and industrialization on biodiversity. In urban settings like Beijing, habitat fragmentation and loss have significantly impacted local biodiversity. Efforts to mitigate these effects include creating green corridors, implementing urban forestry projects, and restoring degraded habitats. However, the Red List data represent the need for intensified conservation measures to reverse these trends and protect threatened species.

PSR Model

Table 1: PSR model in assessing urban ecosystems in Beijing

PSR Component	Description	Key Findings	Figures/Data
Pressure	Anthropogenic drivers cause ecological stress.	**Urbanization and Industrialization**: Increased built-up areas and reduced green spaces due to rapid urban expansion. **Air Pollution**: High levels of PM2.5, PM10, SO_2, and NO_2 before 2013. **Water Demand**: Rising freshwater withdrawals due to industrial and domestic usage. **Deforestation**: Decline in forest area expansion after 2005.	Figs. 1, 2, 3, 4, 5
State	Current ecological conditions resulting from pressures.	**Air Quality**: Improvements in PM2.5 and SO_2, but challenges with O_3 (Fig. 3). **Biodiversity**: Declining Red List Index, showing increasing extinction risks for species (Fig. 6). **Vegetation**: Reduction in green spaces due to urban sprawl (Figs. 1 and 2). **Water Stress**: Plateau in water availability despite high demand (Fig. 5).	Figs. 3, 5, 6
Response	Actions and strategies to mitigate ecological impacts and improve sustainability.	**Restoration**: Successful transformation of degraded land into wetlands at Yongding River Wetland Park. **Policy**: Implementation of air quality improvement measures, such as the "Action Plan for Air Pollution Prevention and Control." **Afforestation**: National reforestation programs increasing forest cover before 2005. **Water Conservation**: Policies leading to efficient water use and stabilization of withdrawals post-2015.	Figs. 1, 4, 5

The table above applies the PSR model to assess ecological challenges and interventions in Beijing's urban ecosystem. The Pressure component gives the anthropogenic factors driving ecological stress, such as rapid urbanization, industrialization, deforestation, and increasing water demand. These pressures have brought about significant land-use changes, with green spaces and croplands giving way to urban infrastructure. High concentrations of PM2.5, PM10, and SO_2 before 2013 indicate air pollution, further underlining the impact of industrial and vehicular emissions on Beijing's environment.

The State component is a representation of the current ecological condition resulting from these pressures. While the reduction in PM2.5 and SO_2 has indeed improved air quality, the increased level of ozone still presents a challenge. On biodiversity health, the continuous downward trend of the Red List Index, as used for measurement, reflected increased risks of species extirpation. For water resources, high demand stressed out the available supply. Urban sprawl contributes to reduced green spaces, hence further compromising ecosystem health.

The Response part captures Beijing's mitigation strategies involving wetland restoration processes, afforestation, and water conservation policies. This encompasses prominent successes, such as the ecological transformation of Yongding River Wetland Park, improvements in air quality, and other aspects reflecting the city's commitment to striking a balance between urban growth and ecological sustainability. These fall into broader national efforts in terms of enhancing ecological resilience.

5. DISCUSSION

5.1. Key ecological Loss due to urban agglomerations in Beijing

As one of the most rapidly urbanizing cities in the world, the urban agglomeration of Beijing is a highly complex ecosystem that has incurred tremendous ecological losses. The assessment of such losses through the Pressure-State-Response model offers a logical sequence through which anthropogenic pressures, ecosystem health, and mitigation efforts can be assessed.

Reduction in biodiversity

As urbanization in Beijing proceeded rapidly, the natural habitat was changed and new pressures were imposed on the ecosystem, seriously affecting its biodiversity. Xiao et al., (2023) recorded rich biodiversity in Beijing, with a record of 536 plant species within the city limits; among them, 361 species were native and 175 species were introduced. However, the introduction of alien species, 95 domestically introduced and 80 foreign contributed to the homogenization of urban plant communities, the most current common trend within rapidly urbanizing regions (Xiao et al., 2023). Habitat fragmentation has been one of the primary causes of loss in biodiversity. The extension of urban infrastructure brought about isolation among green spaces, decreasing their ecological connectivity. As Xiao et al. (2023) stated green spaces have a generally low plant diversity with higher invasive species frequency. Losses in native species owing to such compositional changes negatively impact overall urban biodiversity and have further cascading effects on various ecosystem functions such as pollination, soil stabilization, and carbon sequestration.

Losses in vegetation cover are one of the most salient ecological losses caused by urban sprawl and industrial expansion in Beijing. Historical data on Yongding River Wetland Park (Refer to Figure 2). Between 2001 and 2005, this area had very serious vegetation loss due to the activities of construction and hydrological disruption. This trend reflects a wider pattern throughout Beijing, with areas in built-up locations reaching from 7% of all land in 2017 to 8% this year, while the surface taken by croplands and green spaces has been lost to that growth. The restoration does not work well in terms of vegetation recovery, and invasive species bring about new challenges. Guo et al. (2024) recorded a number of invasive plant species like Bidens frondosa and Xanthium italicum that had grown in the Yongding River Wetland after replenishment projects. Such a project enhances vegetation greenness and biodiversity, but integrated management is needed to avoid unanticipated ecological consequences.

Air quality degradation

Air pollution has been one of the most visible and damaging ecological losses in Beijing. As shown in Fig. 3, the early 2000s also saw the peak of the concentration of key pollutants because of industrial emissions, vehicle exhaust, and coal use. For example, the PM10 exceeded 150 μg/m^3 in 2000, which seriously threatened the health and environment. While Beijing has made huge strides in reducing air pollution PM10 and SO_2 levels dropped precipitously after 2013 -ozone pollution remains obdurate. Fluctuating trends of O_3 concentrations underpin the complexity of atmospheric chemical reactions and underline the need for targeted interventions in terms of secondary pollutants (UN Environment (2019).

Water resource stress

The over-exploitation and depletion of water resources is another critical ecological issue in Beijing. Fig. 5 illustrates that the trend of water withdrawals kept going up from 1980 to 2010, and the total annual amount has reached over 600 billion cubic meters. Along with population growth, increasing industrial demands, and enlarged agriculture, it has caused a very high demand for Beijing's hydrological systems. Water withdrawals have stabilized since 2015, reflecting the efficiency of water conservation policies; however, the over-extraction legacy remains and imparts continuing impacts on aquatic ecosystems. The diversion of water resources toward urban centres has reduced the supply to natural habitats, furthering ecological imbalances and contributing to wetland degradation.

Habitat fragmentation

A high pace of urbanization results in habitat fragmentation into pieces, with the loss of ecological connectivity among those pieces of green. Through analyses, Xiao et al. (2023) indicate a high similarity index for different zones within the green areas, implying the homogenization of plant communities in urban Beijing. For example, the similarity index between the 3rd-4th and 4th-5th rings for street green spaces is 0.50, reflecting the uniformity of species composition. Besides the fact that fragmentation reduces viability in native species, it also restricts the adaptability of native species in response to environmental changes. This is more evident in small-sized green spaces like residential and street gardens, where ecological functions are confined by space and human interference.

Based on the above discussion, Beijing is highly obliged to have integrated urban planning with the conservation strategy. A reduction in biodiversity loss will take appropriate priority for native species to be preserved and ecological corridors enhanced, adding to the connectivity of green spaces. Such an approach can help preserve the ecological identities of the region by ensuring inclusive, biodiversity-sufficient coverage in every single form of urban landscaping, using native plants that thrive in the area. The holistic approach that a restoration project needs to consider ecological sustainability, especially for vegetation loss, starts with reevaluation. By contrast, urban wetlands represent a category that can form part of ecological buffers when the right mechanisms and measures exist, thereby serving critical ecosystem services in improving the resiliency of urban settings, as shown by the successful development of Yongding River Wetland Park. While this would help improve air quality, there should also be an effort to reduce ozone precursors through the imposition of stricter emission standards and the encouragement of cleaner energy technologies.

5.2. Urban ecosystem health of Beijing

The urban ecosystem health of Beijing reflects the interplay between rapid urbanization and ecological restoration efforts, along with the persistent challenges of maintaining sustainability. The Pressure-State-Response (PSR) framework serves as a comprehensive tool to assess these dynamics by analyzing anthropogenic pressures, ecological conditions, and the responses implemented to address environmental challenges.

Air quality: progress and remaining challenges

Air quality is one of the critical indicators for urban ecosystem health. Beijing has suffered from industrialization, vehicle emissions, and coal consumption for quite some time. Because of strict regulatory measures and urban policies, the concentration of major air pollutants such as PM2.5, PM10, SO_2, and NO_2 decreased noticeably from 1998 to 2017 (Refer to Fig. 3) For example, the concentrations of PM10 decreased from over 150 μg/m^3 in the early 2000s to less than 50 μg/m^3 by 2017, indicating successful dust suppression and road cleaning. Similarly, the emissions of SO_2 fell steeply with decreases in the use of coal and with enhancements in industrial emission standards. While these improvements underpin the effectiveness of Beijing's air pollution control policies, challenges are far from over. The secondary pollutant ozone, O_3, due to complex photochemical processes that occur in the atmosphere by precursors such as nitrogen oxides and volatile organic compounds, presented fluctuation trends during this period. However, with such a reduction of these primary pollutants, there is no clear downward trend of the concentration of O_3, which is supposed to happen; it therefore shows how complicated air quality management in megacities could be.

Biodiversity under urban stress

Habitat fragmentation, the proliferation of invasive species, and biodiversity homogenization are among the profound effects that urban expansion causes on the biodiversity of Beijing. This generally means that while the populations of native species constantly decrease, those of introduced species continuously increase. For example, it is estimated that over 500 plant species are hosted by Beijing, with almost one-third being introduced species (Guo, 2024). This pattern of species homogenization, driven by urban landscaping and the introduction of ornamental plants, represents the antagonism between urban development and ecological preservation. These urban green spaces, such as parks and residential areas, provide essential refuges for biodiversity. However, the biodiversity of Beijing's urban zones differs significantly in spatial distribution.

Dynamics of green space: transformation and challenges

Green spaces have very important functions in maintaining urban ecosystem health through the control of microclimates, air quality, and supporting biodiversity. However, the process of urbanization has brought changes in Beijing's green space dynamics. From 2017 to 2023, the built-up area in Beijing has grown from 7% to 8%, mainly converted from cropland and other natural habitats (Refer to Fig. 1). Although tree cover increased from 3% to 5%, this has been inadequate to balance the overall loss of green space following urban sprawl. One such important case can be identified with Yongding River Wetland Park, which recently has been extensively restored within these twenty years. The industrial activities in the previous history and vast urban growth made this particular park badly degraded; now, the vegetation cover has considerably improved here with a substantial increase in water flow and the frequency of recreation events. Restoration efforts have been targeted at the recovery of hydrological balance, vegetation health, and integration into urban infrastructure. Yet, invasive species and uneven recovery indicate that adaptive management strategies will be necessary.

Management of water resources

The management of water resources in Beijing can be used to illustrate the complicated relationships that exist between the growth of cities and ecological sustainability. In China, freshwater withdrawals have been increasing rapidly from 1980 to 2010 due to increasing demands from industries, agriculture, and the domestic sector (Refer to Fig. 5). Beijing's reliance on external water sources, such as the South-to-North Water Diversion Project, underlines the city's water stress and its impact on aquatic ecosystems. More recent policies to improve water use efficiency have stabilized the withdrawals after 2015. It included policy measures regarding the adoption of water-saving technologies, further restriction of industrial water use, and increasing public awareness about water saving (Shi et al., 2022). Major ecological effects due to the diversion of water include disrupting hydrological processes and degrading the ecosystem downstream. The Yongding River Wetland Park represents both the challenges and opportunities in water resource management in Beijing. Ecological restoration has recovered the wetland water flow, improving the ecological functions and biodiversity. Meanwhile, with the water replenishment, invasive species have been introduced, indicating the necessity of comprehensive monitoring and management to ensure sustainability. Integrated Management Approaches to Beijing's urban ecosystem health both reflect the achievements and ongoing challenges in ecological management. The PSR framework, while useful for understanding these dynamics, underlines the need for integrated strategies that tackle anthropogenic pressures, improve ecological conditions, and sustain restoration efforts.

5.3. Overall spatiotemporal trends of Beijing

The spatiotemporal trend in Beijing over the last three decades shows the huge impact that rapid urbanization and industrial extension have on the ecological landscape of the metropolis. Having been developed into a megacity, dramatic changes in land-use patterns in Beijing are characterized by the steady growth of built-up areas and the corresponding reduction of natural habitats and cropland. Between 1990 and 2020, the country saw rapid urban sprawl, especially in the northern and southeastern parts, impelled by population growth and economic development. Such changes have accentuated the urban heat island effect, disrupted hydrological systems, and fragmented habitats, creating ecological challenges that require sustainable urban planning. Proliferation has placed increasing pressure on the green open spaces that are so important both for mitigating urban heat and supporting biodiversity. Although restoration efforts-regarded as the Beijing greenbelt projects have regained tree cover from 3% to 5% between 2017 and 2023, these are highly insufficient to balance the critical loss of green spaces due to rapid urbanization. Indeed, such processes have been occurring in the Yongding River Wetland Park, a place which has undergone much-needed restoration to improve vegetation health and its ecological functions.

Rapid urbanization and industrial demands continued to drive water withdrawals upward through 2015, at which time a suite of conservation policies was initiated to stabilize the total quantities withdrawn. Yet, even more ambitious engineering feats, such as the South-to-North Water Diversion, have interfered with natural hydrological regimes and thus altered downstream ecosystems and compromised long-term sustainability. Such patterns illustrate the need for integrative management of water resources to balance urban needs against ecosystem stability. Correspondingly, there is a loss of habitat and homogenization of species, which has been a dilemma for biodiversity in Beijing.

6. CONCLUSION

Spatiotemporal evolution in Beijing underlines the challenge of balancing rapid urbanization with ecological sustainability. During the last three decades, dramatic changes have taken place in land use, biodiversity, air quality, and water resource management in the city, reflecting the profound pressures of population growth and industrial expansion. Urban development has resulted in habitat fragmentation, biodiversity loss, and ecological degradation, especially in central areas. Although focused restorations have indeed borne fruit in some areas, like the Yongding River Wetland Park, many others face problems with invasive species and habitat fragmentation, hence there is a dire need for integrated management. The application of the PSR model has enabled an evaluation of such changes in depth, from success stories to areas that require further attention. The improvements in air quality due to stringent policies and water conservation measures prove that good governance can work effectively. However, the continued problems with ozone pollution, urban heat islands, and water stress highlight the need for sustained efforts and new approaches.

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