Ecosystem Health and Sustainability
A SCIENCE PARTNER JOURNAL

RESEARCH ARTICLE

Rapid Urbanization Reduces Biodiversity and Degrades Wetland Ecosystems in Kunshan, China: Implications for Restoration

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Rapid urbanization negatively affects landscape, ecological connectivity, and biodiversity of wetland ecosystems worldwide, and the specific effect mechanisms need to be deeply explored. In the present study, we aimed to determine if and how rapid urbanization has affected the biodiversity and ecosystems of wetlands in Kunshan, which has ranked first among China's top 100 counties and cities in comprehensive strength for 20 years. We conducted field investigations in 11 towns of Kunshan, where we determined different water parameters and biodiversity indices in the wetlands of urban, middle, and natural regions as well as several urbanization indices. The results indicated an upward trend for the biodiversity indices, including density, biomass, species number, Shannon diversity, and Margalef richness of the aquatic plants and macrobenthos from the urban to middle to natural regions. Furthermore, the results indicated a downward trend for the water parameters, including salinity, total dissolved solids, pH, total phosphorus content, ammonia nitrogen content, and permanganate index from the urban to middle to natural regions. Overall, the biodiversity indices of aquatic organisms were negatively correlated with water parameters and urbanization indices, including population density, gross domestic product, number of industrial enterprises above the designated size, industrial energy consumption, and building construction area. Thus, the results demonstrate that rapid urbanization leads to habitat destruction and biodiversity reduction in aquatic plants and macrobenthos. This study provides scientific implications for management and restoration of urban wetlands during rapid urbanization, including water pollution control, ecological shoreline protection, ecological connectivity optimization, aquatic plants, and macrobenthos restoration.

Citation: Qiu D, Xu Z, Ren Y, Zhang H, Zhu Y. Rapid Urbanization Reduces Biodiversity and Degrades Wetland Ecosystems in Kunshan, China: Implications for Restoration. *Ecosyst. Health Sustain.* 2025;11:Article 0450. https://doi.org/10.34133/ehs.0450

Submitted 17 July 2025
Revised 22 October 2025
Accepted 8 November 2025
Published 26 November 2025

Introduction

Urbanization is an inevitable process in the development of human society; however, its rapid progress has caused a series of negative impacts on natural ecosystems and biodiversity [1,2]. Urban sprawl and frequent human disturbances have caused landscape destruction, ecological connectivity disruption, environmental pollution, carbon emission intensification, habitat fragmentation, biodiversity loss, ecological function decline, and ecosystem degradation around and inside cities [3–5], which seriously affect their sustainable development.

Wetlands are one of the most important ecosystems worldwide because they perform important ecosystem service functions, such as landscape beautification, water conservation [6,7], biodiversity maintenance [8,9], carbon sequestration [10,11], and nutrient regulation [12,13]. However, wetlands are vulnerable and easily influenced by urbanization [14], which decreases their ecosystem service functions. Urbanization has caused wetland areas reduction and ecological connectivity disruption via population expansion and the filling, occupation, and modification of wetlands to provide for urban construction and transportation needs [15–17]. Furthermore, urbanization has caused nutrient and heavy metal pollution of water and soil in urban wetlands via discharge of domestic and livestock sewage, and that of industrial wastewater [18–21]. Additionally, the decrease in environmental quality, habitat fragmentation, and ecological connectivity disruption induced by urbanization has resulted in the reduction and loss of biodiversity of aquatic organisms, which has decreased the stability and sustainability of wetland ecosystems [22–24]. The destruction of urban wetlands can ultimately affect the ecological security and sustainable development of humans [17,25]. Thus, studying the effects of urbanization on wetlands and improving the management and restoration of wetlands degraded by urbanization are becoming increasingly important.

Kunshan city, located in the Taihu Plain of the Yangtze River Delta of China, is densely covered with river and lake wetlands inhabited by various aquatic plants, macrobenthos, fish, and water birds. These aquatic organisms have often been used as biological indicators of wetland status [26–28]. Kunshan is a typical city with rapid urbanization, having ranked first among China's top 100 counties and cities in comprehensive strength for 20 consecutive years [29]. With rapid economic development, the urban space in Kunshan city continues to expand. A recent study shows that the urban land of Kunshan increased by 19% from 2006 to 2016, and will continue to expand by 15% from 2016 to 2030 under the Business-As-Usual scenario [30]. This rapid urbanization has negatively affected wetland environments and hydrological and biological connectivity, and has significantly decreased the biodiversity of aquatic organisms in Kunshan. Consequently, the specific mechanisms by which rapid urbanization influences these urban river and lake wetlands in Kunshan need to be studied, and scientific and efficient measures need to be taken to protect and restore the biodiversity and ecosystems of these urban wetlands.

In the present study, we aimed to examine the effects of rapid urbanization on the biodiversity of plants, macrobenthos, and wetland ecosystems in Kunshan, Jiangsu, China via field investigations. Specifically, we tested the following hypotheses: (a) the biodiversity indices of the aquatic plants and macrobenthos in the urban regions are significantly lower than those in the natural regions; (b) the water salinity, total dissolved solids (TDS), pH, total phosphorus content (TP), ammonia nitrogen content (NH_3-N), and permanganate index (CODMn) in the urban regions are significantly higher than those in the natural regions; (c) the biodiversity indices of the aquatic plants and macrobenthos are negatively related to the water salinity, TDS, pH, TP, NH_3-N, and CODMn; and (d) the biodiversity indices of the aquatic plants and macrobenthos are negatively related to several urbanization indices, including population density (PD), gross domestic product (GDP), number of industrial enterprises above designated size (NIEADS), industrial energy consumption (IEC), and building construction area (BCA). This study underscores the importance of strategic wetland ecosystem management and restoration amid rapid urbanization, and provides scientific implications and policies for ecosystem management and restoration of urban wetlands in the process of rapid urbanization.

Materials and Methods

Study site and species

Field work was conducted in 11 towns (Zhoushi, Bacheng, Yushan, Kaifaqu, Lujia, Qiandeng, Huaqiao, Zhangpu, Jinxi, Zhouzhuang, and Dianshanhu) of Kunshan city, Jiangsu Province (31°06′ to 31°32′ N, 120°48′ to 121°09′ E; Fig. 1), located in the Taihu Plain of the Yangtze River Delta, east China. Kunshan is densely covered with river and lake wetlands, such as the Wusong, Lou, and Xiajia rivers, and the Dianshan, Yangcheng, and Kuilei lakes, all of which support varieties of aquatic organisms and provide many ecosystem service functions. The area has a subtropical monsoon climate, which is mild and humid, with 4 distinct seasons, and plenty of sunlight and rainfall. Kunshan has ranked first among China's top 100 counties and

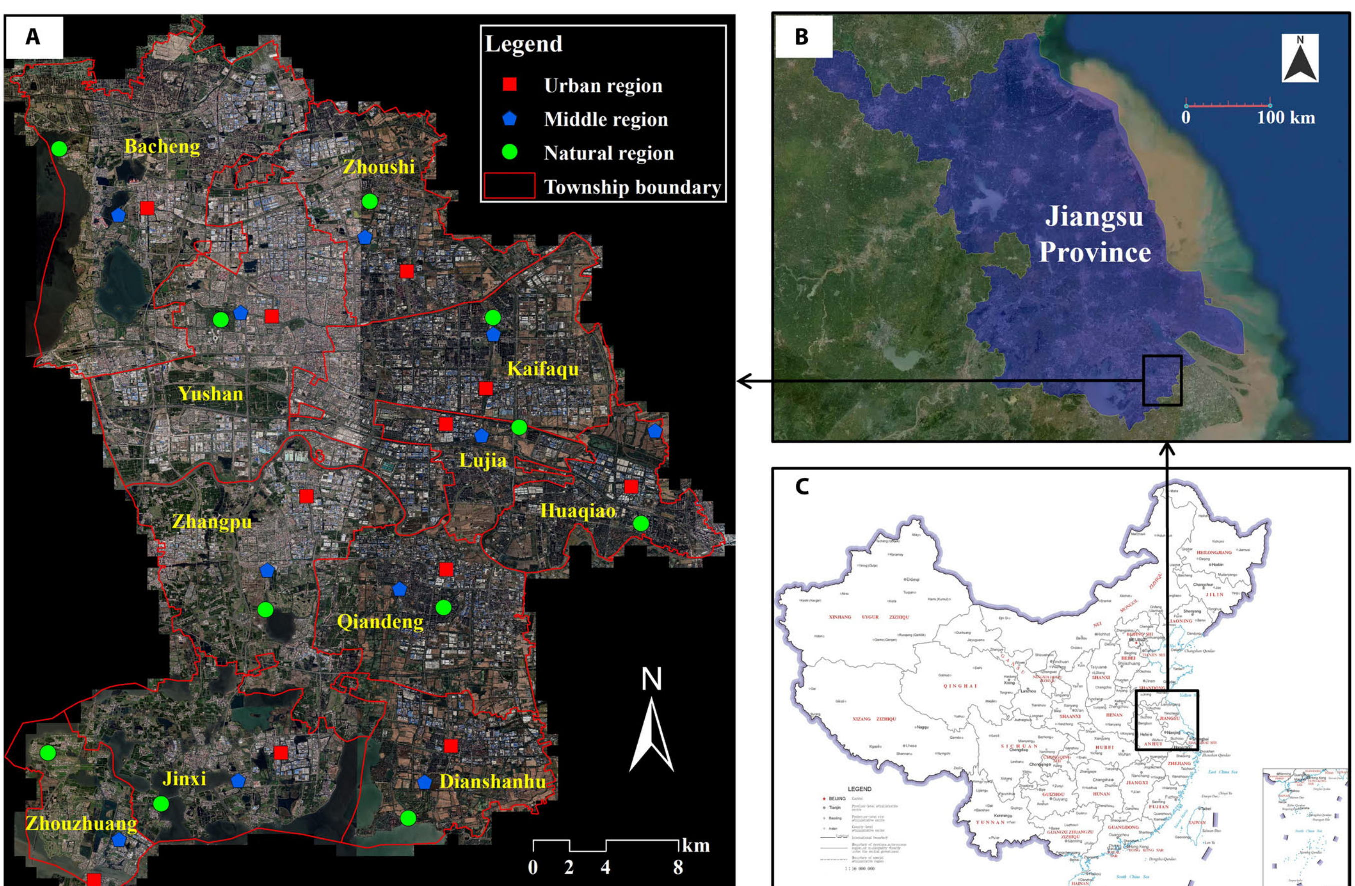

Fig. 1. Maps showing the locations of study sites in 11 towns of (A) Kunshan city, (B) Jiangsu Province, (C) China.

cities in terms of comprehensive strength for 20 consecutive years. With rapid economic development, the urban space in Kunshan city continues to expand.

Many kinds of aquatic macrobenthos and plants live in the river and lake wetlands in Kunshan. The species of aquatic plants include *Hydrocharis dubia*, *Zizania latifolia*, *Azolla imbricata*, *Trapa natans*, and *Alternanthera sessilis*. The macrobenthos species include *Bellamya aeruginosa*, *Cipangopaludina cathayensis*, *Whitmania pigra*, *Grandidierella taihuensis*, and *Anodonta woodiana*.

In the present study, 3 representative river or lake wetland regions (urban, middle, and natural) in the 11 towns of Kunshan were selected to study the effects of urbanization on the biodiversity of plants, macrobenthos, and wetland ecosystems (Fig. 1C). Urban regions were located in the center of towns, surrounded by residential buildings and factories. Natural regions were far away from the center of towns, residential buildings, and factories, almost in the outer suburbs, where the environment is approaching the natural state. The position of the middle regions, their environment, and the degree of human interference were intermediate between the urban and natural regions.

Field investigations

We conducted field investigations in July 2022 in the 11 towns in Kunshan. We randomly established 3 replicated plots of area 0.5 m × 0.5 m each in the urban (Fig. S1A to C), middle (Fig. S1D to F), and natural (Fig. S1G to I) regions, thus amounting to a total of 99 plots.

All aquatic plants within each plot were identified to species level and counted in the field and then transported to the laboratory. We transferred the plant samples to a paper envelope and placed them in a drying oven set at 60 °C for more than 72 h. An analytical balance was used to weigh the dried plant samples and get the dry biomass.

From each plot, a Petersen grab dredge (1/16 m^2) was used to collect sediment samples 4 times. The sediment samples were put in and passed through a 0.45-mm sieve, and the macrobenthos retained in the sieve were fixed in 75% alcohol solution. All macrobenthos were identified to species level and counted under a microscope, and the biomass was weighed using an electronic balance.

A multiparameter (HANNA HI98194, Italy) was used to measure the water salinity, TDS, and pH of each plot. Additionally, the measured data of water parameters, including TP, NH_3-N, and CODMn, in the 3 types of regions (urban, middle, and natural) of 5 towns (Bacheng, Dianshanhu, Jinxi, Kaifaqu, and Zhouzhuang) were obtained from the nearest government monitoring stations to our sampling plots, with measurements taken concurrently in July 2022, ensuring temporal and spatial relevance (Table S1). The data for the urbanization indices, including PD, GDP, NIEADS, IEC, and BCA for all 11 towns (Table S2), were obtained from the 2022 Kunshan statistical yearbook [31].

Statistical analyses

The Shannon diversity (H') and Margalef richness (D) of the aquatic plants and macrobenthos were calculated using the following formulas:

$$H' = -\sum_{i=1}^{S} \frac{Ni}{N} \ln \frac{Ni}{N} \tag{1}$$

$$D = \frac{S-1}{\ln(N)} \tag{2}$$

where S is the total number of species in a plot and Ni and N are the number of individuals of species i and all species in the plot, respectively.

$\mathrm{Log}_{10}(x+1)$ transformation was applied to some of the variables to improve variance homogeneity and the normal distribution of the residuals. For the normalized data, randomized-block analysis of variance (ANOVA) followed by Tukey's HSD (Honestly Significant Difference) multiple comparisons tests were used to compare the different biodiversity indices of aquatic plants and macrobenthos in the urban, middle, and natural regions in the 11 towns; nonparametric Kruskal–Wallis tests were used to analyze the data that did not meet the assumptions of ANOVA even after application of transformations. SPSS version 22.0 was used to conduct all statistical analyses. R (v4.0.5) was used to perform the redundancy analysis (RDA) to analyze the correlation of the aquatic biodiversity indices and water indices. The average of each type of aquatic biodiversity indices in 9 plots (including 3 replicated plots in urban, middle, and natural regions) of each town was regarded as the aquatic biodiversity indices of that town, and which was then used to conduct RDA with the urbanization indices of each town. The correlation of the aquatic biodiversity indices and urbanization indices of the 11 towns was analyzed.

Results

Effects of urbanization on aquatic plants

A total of 25 aquatic plant species were recorded in 11 towns of Kunshan (Table S3), which belonged to 3 phyla (Angiospermae, Pteridophyta, and Chlorophyta), 4 classes (Dicotyledoneae, Monocotyledoneae, Leptosporangiopsida, and Charophyceae), and 15 orders (Alismatales, Myrtales, Centrospermae, Apiales, Ranunculales, Apiales, Tubiflorae, Najadales, Poales, Farinosae, Arales, Typhales, Cyperales, Salviniales, and Zygnematales).

Overall, the results indicated an upward trend in the density, dry biomass, Shannon diversity, species number, and Margalef richness of aquatic plants from the urban to the middle to natural regions. Except for that in the towns of Dianshanhu, Huaqiao, and Jinxi, the aquatic plant density in the urban regions of all towns was significantly lower than that in the natural regions (Fig. 2). Except for that in the towns of Kaifaqu and Lujia, the dry biomass of aquatic plants in the urban regions of all towns was significantly lower than that in the natural regions (Fig. 3). Except for that in the towns of Dianshanhu, Huaqiao, Kaifaqu, and Qiandeng, the Shannon diversity of aquatic plants in the urban regions of all towns was significantly lower than that in the natural regions (Fig. 4). Except for that in the towns of Dianshanhu, Huaqiao, and Qiandeng towns, the species number of aquatic plants in the urban regions of all towns was significantly lower than that in the natural regions (Fig. S2). Except for that in the towns of Dianshanhu, Huaqiao, Kaifaqu, Lujia, Qiandeng, and Zhangpu, the Margalef richness of aquatic plants in the urban regions of all towns was significantly lower than that in the natural regions (Fig. S3).

Effects of urbanization on macrobenthos

A total of 56 species of macrobenthos were recorded in the 11 towns of Kunshan (Table S4), which belonged to 4 phyla (Mollusca, Annelida, Chordata, and Arthropoda), 7 classes (Gastropoda, Bivalvia, Oligochaeta, Hirudinea, Osteichthyes, Malacostraca, and Insecta), and 17 orders (Mesogastropoda,

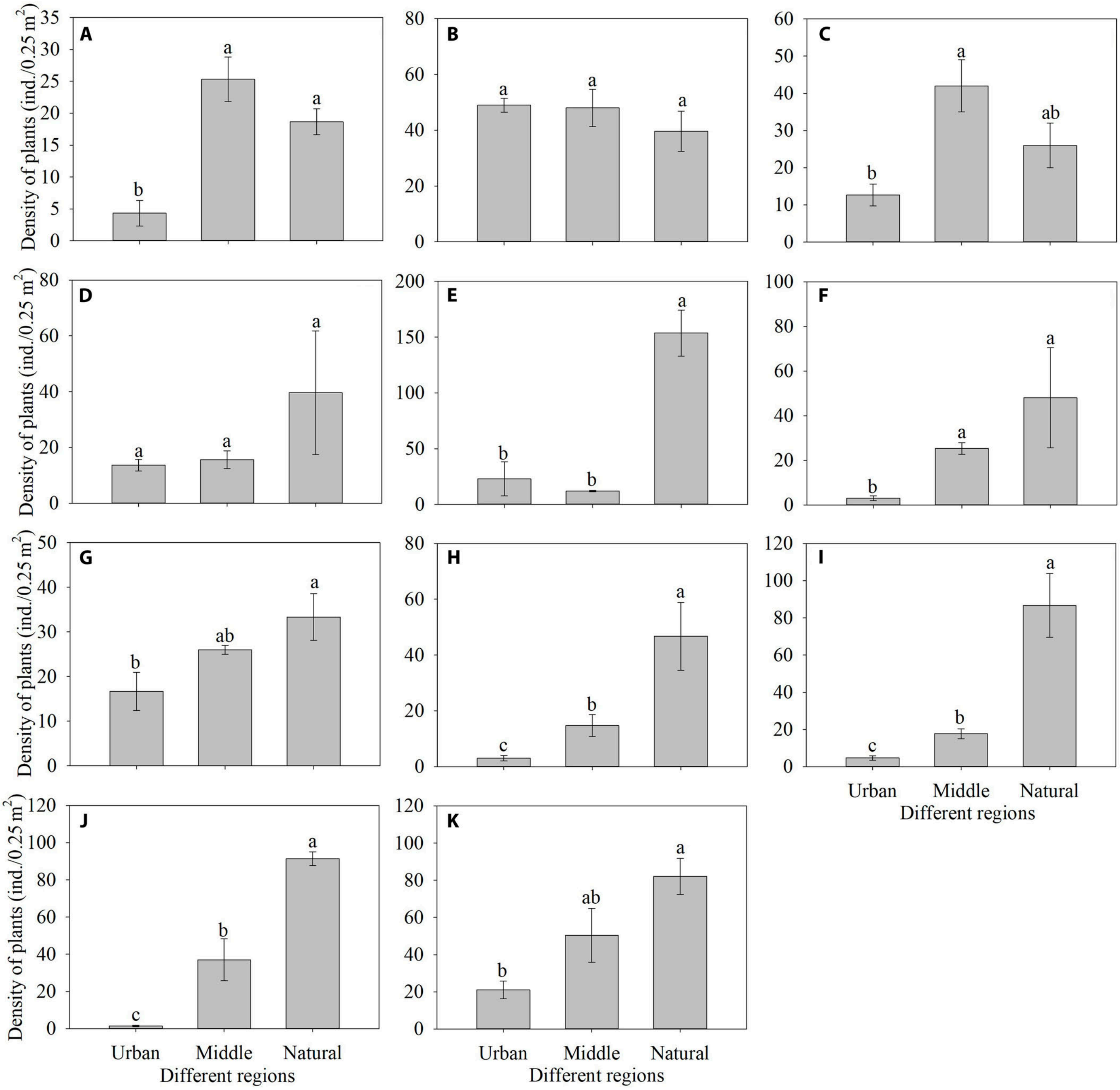

Fig. 2. Comparison of the aquatic plant density in the urban, middle, and natural regions of 11 towns in Kunshan, including (A) Bacheng, (B) Dianshanhu, (C) Huaqiao, (D) Jinxi, (E) Kaifaqu, (F) Lujia, (G) Qiandeng, (H) Yushan, (I) Zhangpu, (J) Zhoushi, and (K) Zhouzhuang. Data are shown as means ± SE ($n = 3$), and the means with the same letter are not significantly different from one another ($P > 0.05$; Tukey's HSD multiple comparisons or nonparametric Kruskal–Wallis tests); the same goes for the succeeding figures.

Basommatophora, Unionoida, Veneroida, Mytiloida, Tubificida, Arhynchobdellida, Rhynchobdellida, Perciformes, Amphipoda, Isopoda, Decapoda, Diptera, Coleoptera, Hemiptera, Odonata, and Lepidoptera).

Overall, the results indicated an upward trend in the density, dry biomass, Shannon diversity, species number, and Margalef richness of macrobenthos from the urban to the middle to natural regions. Except for that in the towns of Bacheng, Huaqiao, Kaifaqu, Yushan, and Zhoushi, the density of macrobenthos in the urban regions of all towns was significantly lower than that in the natural regions (Fig. 5). Except for that in the towns of Bacheng, Huaqiao, Kaifaqu, Yushan, and Zhangpu, the macrobenthos biomass in the urban regions of all towns was significantly lower than that in the natural regions (Fig. 6). Except for that in the towns of Bacheng, Dianshanhu, Jinxi, Kaifaqu, Qiandeng, and Zhangpu, the Shannon diversity of macrobenthos in the urban regions of all towns was significantly lower than that in the natural regions (Fig. 7). Except for that in the towns of Bacheng, Dianshanhu, and Kaifaqu, the species number of macrobenthos in the urban regions of all towns was significantly lower than that in the natural regions (Fig. S4). Except for that in the towns of Bacheng, Dianshanhu, Huaqiao, Kaifaqu, Qiandeng, and Zhangpu, the Margalef richness of macrobenthos in the

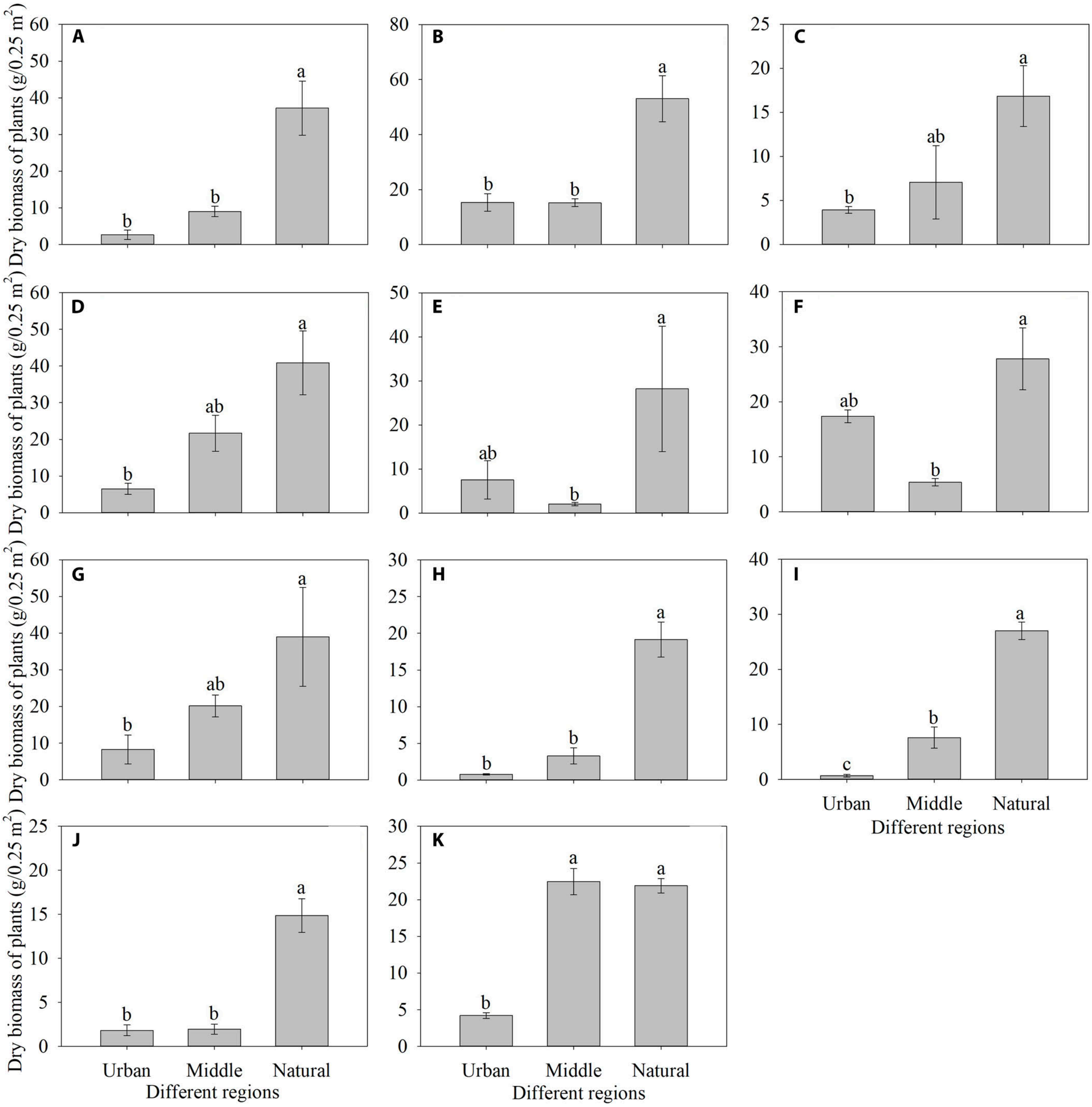

Fig. 3. Comparison of the dry biomass of aquatic plants in the urban, middle, and natural regions of the 11 towns of Kunshan, including (A) Bacheng, (B) Dianshanhu, (C) Huaqiao, (D) Jinxi, (E) Kaifaqu, (F) Lujia, (G) Qiandeng, (H) Yushan, (I) Zhangpu, (J) Zhoushi, and (K) Zhouzhuang.

urban regions of all towns was significantly lower than that in the natural regions (Fig. S5).

Effects of the urbanization on water quality

Overall, the results indicated a downward trend in the TDS, pH, and salinity of water from urban to middle to natural regions. The TDS and salinity in the natural regions were significantly lower than those in the urban regions for all 11 towns (Figs. S6 and S7). Except for that in the towns of Kaifaqu and Zhouzhuang, the pH in the natural regions of all towns was significantly lower than that in the urban regions (Fig. S8).

Overall, the results indicate a downward trend for TP, CODMn, and NH_3-N in the water from the urban to the middle to natural regions. The TP and CODMn of water in the urban regions were higher than those in the natural regions in 5 towns (Bacheng, Dianshanhu, Jinxi, Kaifaqu, and Zhouzhuang). Except for that in the towns of Jinxi and Zhouzhuang, the NH_3-N of water in the urban regions of all other towns was higher than that in the natural regions (Table S1).

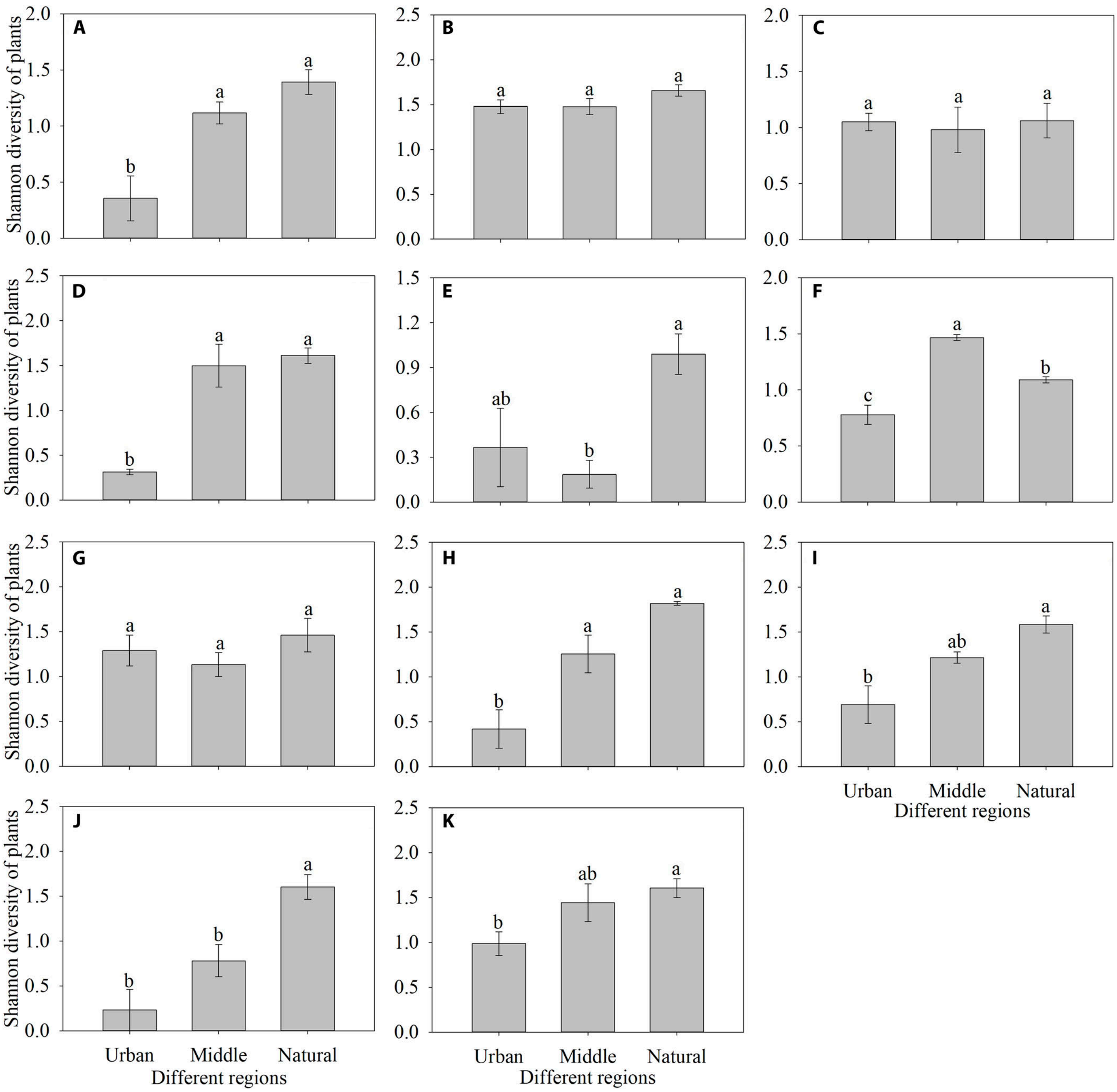

Fig. 4. Comparison of Shannon diversity of aquatic plants in the urban, middle, and natural regions of the 11 towns in Kunshan, including (A) Bacheng, (B) Dianshanhu, (C) Huaqiao, (D) Jinxi, (E) Kaifaqu, (F) Lujia, (G) Qiandeng, (H) Yushan, (I) Zhangpu, (J) Zhoushi, and (K) Zhouzhuang.

Correlation of the aquatic biodiversity indices and water indices

The RDA showed that different water indices influenced the aquatic biodiversity indices to varying degrees. For all 11 towns, all the biodiversity indices of aquatic plants and macrobenthos were negatively related to water salinity, TDS, and pH. Additionally, all the biodiversity indices of macrobenthos were positively related to those of aquatic plants (Fig. 8).

For 5 towns (Bacheng, Dianshanhu, Jinxi, Kaifaqu, and Zhouzhuang), the biomass, Shannon diversity, species number, and Margalef richness of the aquatic plants and macrobenthos were negatively related to TP, NH_3-N, and CODMn. However, the density of aquatic plants was positively related to the TP whereas that of macrobenthos was negatively related to the TP, NH_3-N, and CODMn (Fig. 9).

Correlation of the aquatic biodiversity indices and urbanization indices

The RDA showed that different urbanization indices influenced the aquatic biodiversity indices to varying degrees. For all 11 towns, the biomass, Shannon diversity, species number, and Margalef richness of the aquatic macrobenthos and plants were negatively related to urbanization indices, including PD, GDP,

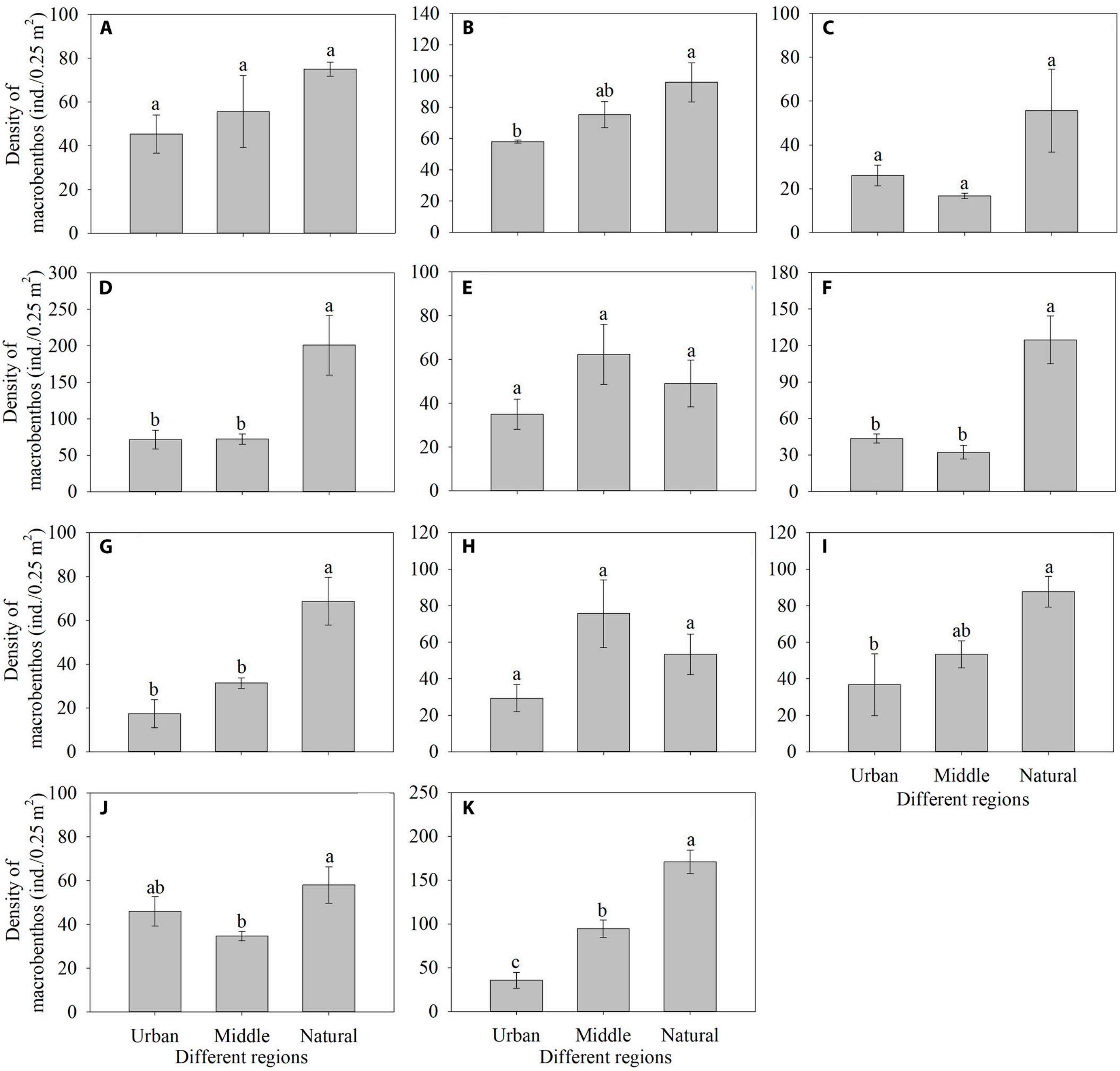

Fig. 5. Comparison of the density of macrobenthos in the urban, middle, and natural regions of 11 towns in Kunshan, including (A) Bacheng, (B) Dianshanhu, (C) Huaqiao, (D) Jinxi, (E) Kaifaqu, (F) Lujia, (G) Qiandeng, (H) Yushan, (I) Zhangpu, (J) Zhoushi, and (K) Zhouzhuang.

NIEADS, IEC, and BCA. However, the density of aquatic plants was positively correlated with the IEC whereas that of macrobenthos was negatively correlated with PD, GDP, NIEADS, IEC, and BCA (Fig. 10).

Discussion

Negative effects of rapid urbanization on biodiversity and ecosystem of urban wetlands

The results of this study showed that rapid urbanization has negatively affected the aquatic environment and resulted in a biodiversity decrease of aquatic organisms in the urban wetlands of Kunshan, which has dramatically reduced ecosystem functions. Different biodiversity indices of all aquatic plants and macrobenthos in the urban regions were significantly lower than those in the natural regions of Kunshan.

Urbanization causes a reduction of biodiversity of aquatic organisms by reducing the wetland area, fragmenting the habitat, decreasing environmental quality, and disrupting hydrological and biological connectivity, which then decreases the stability and sustainability of wetland ecosystems [15,17,22–24]. For instance, Dar et al. [24] found that urbanization increased the loss of native species in Atlantic *Chamaecyparis thyoides* wetlands. Liao et al. [23] found that urbanization decreased the richness of diving beetle species (*Dytiscidae*), which indicated that some diving beetle species had a negative reaction to urbanization. Johnson et al. [22] found that urban wetlands supported a 33% lower richness of aquatic insects, mollusks,

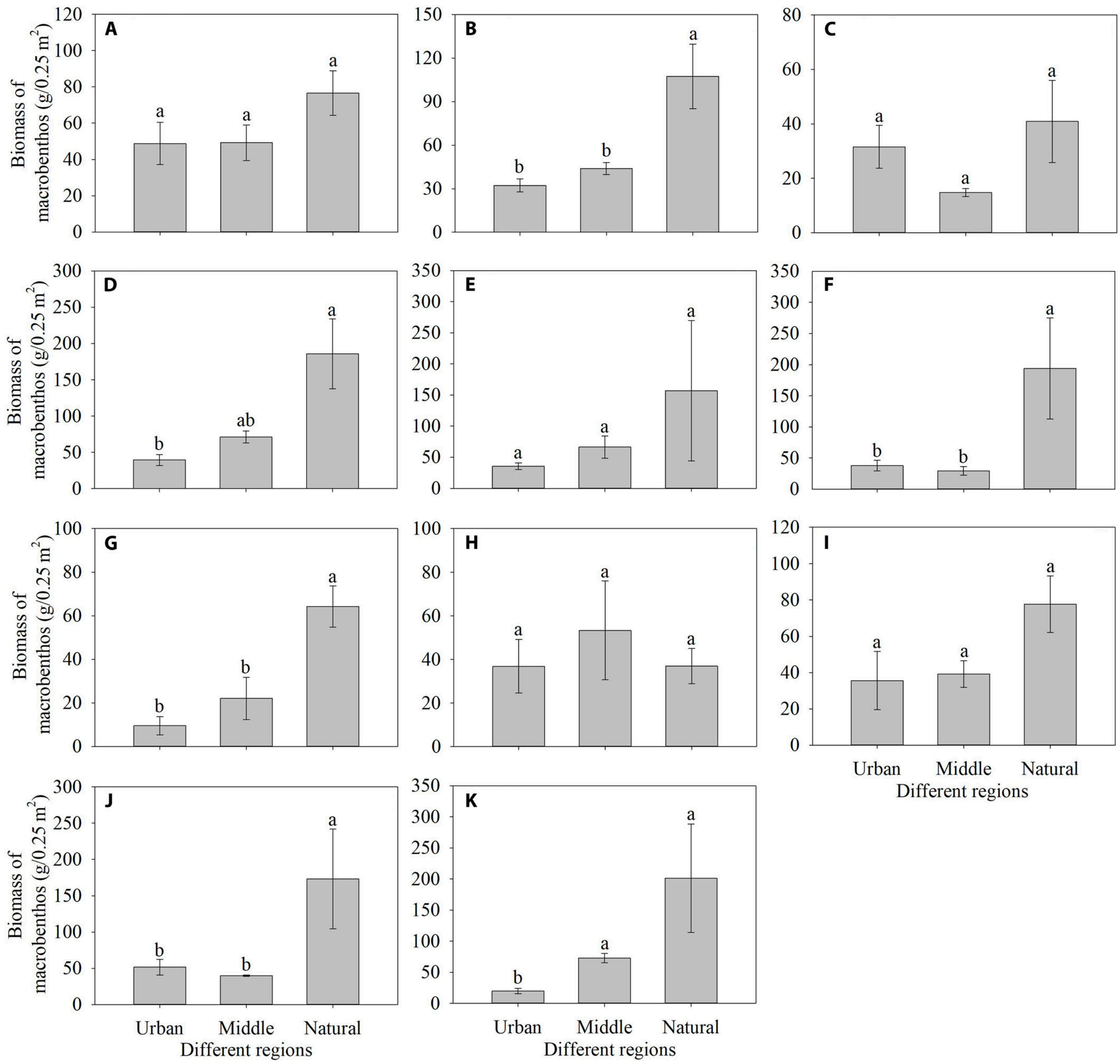

Fig. 6. Comparison of the biomass of macrobenthos in the urban, middle, and natural regions of the 11 towns in Kunshan, including (A) Bacheng, (B) Dianshanhu, (C) Huaqiao, (D) Jinxi, (E) Kaifaqu, (F) Lujia, (G) Qiandeng, (H) Yushan, (I) Zhangpu, (J) Zhoushi, and (K) Zhouzhuang.

and crayfish than grassland wetlands because of changes in biotic and abiotic factors and in landscape characteristics of the urban wetlands.

The present study showed that water salinity, TDS, pH, TP, NH_3-N, and CODMn in the natural regions were significantly lower than those in the urban regions of Kunshan. These findings are similar to those reported by previous studies, which showed that urbanization could cause nutrient and heavy metal pollution of water and soil in urban wetlands due to discharge of domestic and livestock sewage, and that of industrial wastewater [18–21]. Fang et al. [18] found that urbanization caused nutrient and heavy metal pollution in the Napahai wetland, China; most of the water nutrients and heavy metals originated from municipal sewage. Zhao et al. [21] found that rapid urbanization led to severe nutrient pollution and eutrophication of surface water in Xin'an River and Qiandaohu Reservoir, China; the TP content and NH_3-N increased by 77.7% and 164.4%, respectively, after the river flowed through areas with high population concentration and high degree of urbanization.

The results of the present study showed that most of the biodiversity indices, including the biomass, Shannon diversity, species number, and Margalef richness of the aquatic plants, and the biomass, density, Shannon diversity, species number, and Margalef richness of the macrobenthos, were negatively correlated with the measured water parameters (salinity, TDS, pH, TP, NH_3-N, and CODMn) and urbanization indices (PD, GDP, NIEADS, IEC, and BCA) in Kunshan. Rapid urbanization

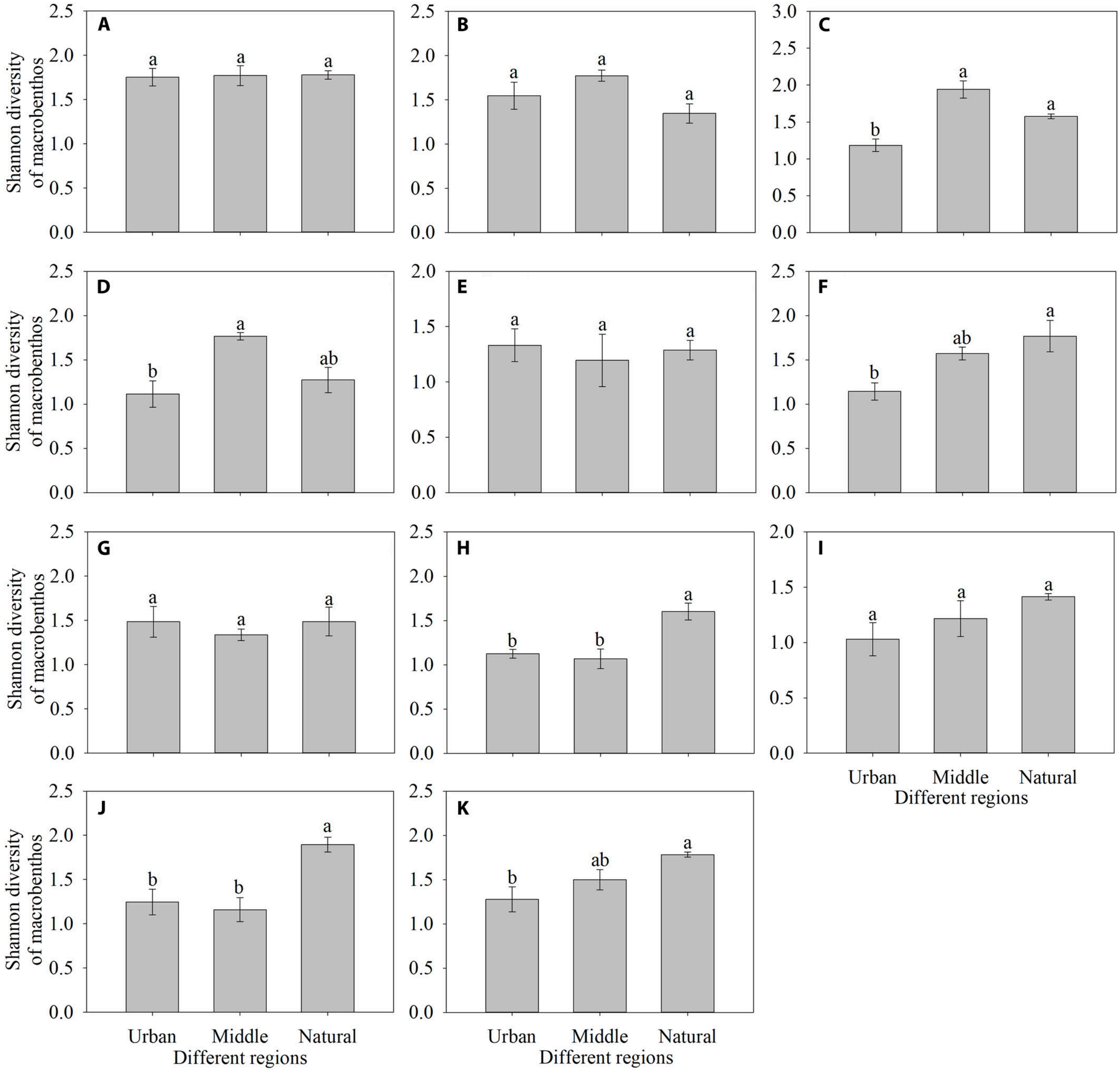

Fig. 7. Comparison of the Shannon diversity of macrobenthos in the urban, middle, and natural regions of 11 towns in Kunshan, including (A) Bacheng, (B) Dianshanhu, (C) Huaqiao, (D) Jinxi, (E) Kaifaqu, (F) Lujia, (G) Qiandeng, (H) Yushan, (I) Zhangpu, (J) Zhoushi, and (K) Zhouzhuang.

has altered the aquatic environment and has negatively affected aquatic organisms. Aquatic plants are influenced by water environmental conditions of wetlands, such as salinity [32], pollutants [33], and nutrients [34]. The distribution and survival of macrobenthos are also influenced by the environmental conditions of wetlands, including pH [35], salinity [36], and organic matter content [37].

Furthermore, our field observations indicated that some wetland restoration and construction projects in Kunshan employ highly engineered approaches (e.g., extensive use of concrete revetments), which further reduces wetland biodiversity. Only a few rivers and lakes in the urban areas of Kunshan have natural revetments with mudflats, with most having hard cement revetments (personal observation), such as the Dianshan Lake and Xiajia River, which has damaged the landscape, disrupted hydrological and biological connectivity, polluted the water and sediment environment, caused substrate heterogeneity loss, deprived habitat space, and reduced the biodiversity of aquatic organisms on the shore of the wetland [38,39].

The results of the present study also revealed a confusing and special index—the density of aquatic plants—which was positively correlated with TP and IEC. This anomaly is likely attributable to the extremely high density of floating plants (e.g., *Salvinia natans* and *Spirodela polyrrhiza*) in the natural region plots of Kaifaqu, which coincided with high IEC and TP levels. Furthermore, the present study showed that the biodiversity indices of macrobenthos were positively related to those of aquatic plants in Kunshan, possibly because aquatic plants can

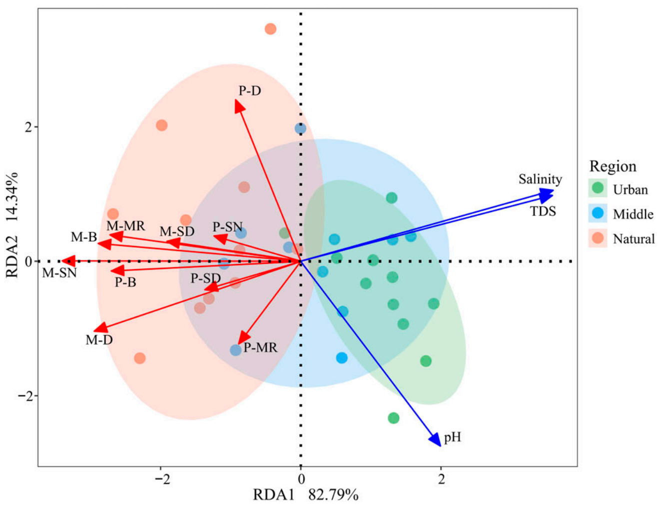

Fig. 8. RDA results of the correlation of the aquatic biodiversity indices and water parameters for all 11 towns. P-SN, P-D, P-B, P-SD, and P-MR respectively represent the species number, density, biomass, Shannon diversity, and Margalef richness of plants; M-SN, M-D, M-B, M-SD, and M-MR respectively represent the species number, density, biomass, Shannon diversity, and Margalef richness of macrobenthos; the same goes for the succeeding figures. The water parameters included the water salinity, total dissolved solids (TDS), and pH. Small dots represent different samples from the urban, middle, and natural regions of the 11 towns of Kunshan.

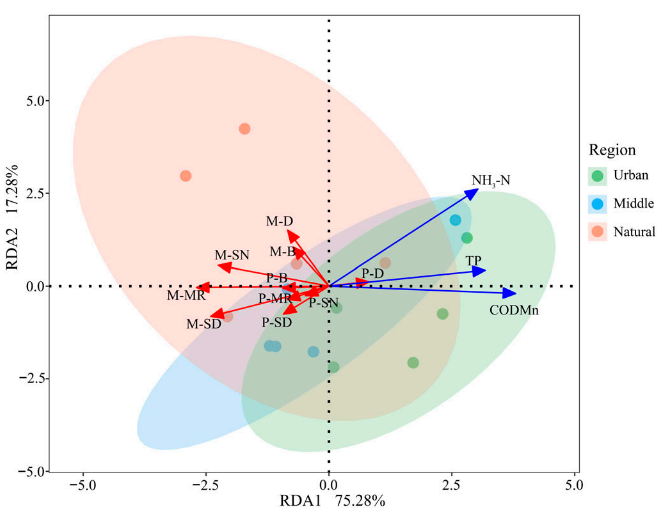

Fig. 9. RDA results of the correlation of the aquatic biodiversity indices and water parameters for 5 towns (Bacheng, Dianshanhu, Jinxi, Kaifaqu, and Zhouzhuang). The water parameters include the ammonia nitrogen content (NH_3-N), total phosphorus content (TP), and permanganate index (CODMn).

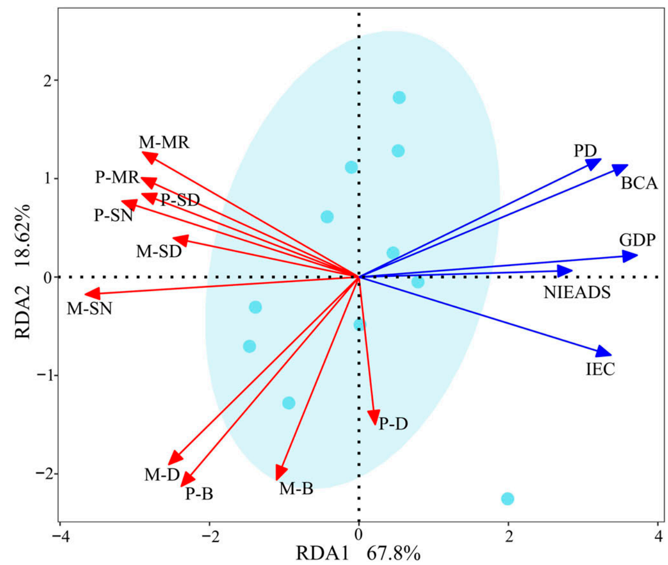

Fig. 10. RDA results of the correlation of the aquatic biodiversity indices and urbanization indices for all 11 towns. The urbanization indices include the population density (PD), number of industrial enterprises above designated size (NIEADS), industrial energy consumption (IEC), gross domestic product (GDP), and building construction area (BCA).

benefit macrobenthos by supplying food and refuge and reducing environmental stress [40,41].

Implications and policies for management and restoration of urban wetlands

River and lake wetlands are widespread in Kunshan city, and they perform important ecosystem service functions such as water conservation, biodiversity maintenance, carbon sequestration, nutrient regulation, and landscape beautification [7,8,11,12]. However, rapid urbanization in Kunshan has negatively affected the landscape, ecological connectivity, biodiversity, and ecosystems of the urban wetlands. Thus, scientific and efficient measures are imminently needed to maintain the biodiversity and restore and improve the health and stability of urban wetland ecosystems. Given the impact of urbanization on the biodiversity and ecosystems of urban wetlands in Kunshan, we propose some suggestions and policies to support urban wetland management and restoration. We call on community residents and the general public to jointly participate in the conservation and management of urban wetlands.

The first step is the management and restoration of the aquatic environment. Kunshan has many factories, and it is necessary to strictly control the discharge of pollutants into rivers and lakes. Industrial wastewater should be discharged after the treatment based on the Wastewater Treatment Standards, and domestic sewage should be collected and discharged after treatment by urban sewage treatment plants. Aquatic plants with the ability to purify water must be planted in polluted urban wetlands to directly absorb or degrade polluted substances. Additionally, ecological floating island technology, which is a new and popular restoration method for urban wetlands, should be employed to reduce the pollution load in water bodies and beautify the landscape [42].

Shore zones of lakes and river wetlands, which are transitional zones between aquatic and terrestrial ecosystems, possess a rich biodiversity and have high ecological value [43]. However, many rivers and lakes in Kunshan have adopted hard cement revetments, which greatly disrupted hydrological and biological connectivity and reduce the aquatic biodiversity, particularly aquatic plants and macrobenthos, on the shores of wetlands. Therefore, we recommend replacing hard cement revetments with gently sloped natural shorelines or employing eco-engineering techniques such as wooden pile or ecological bag revetments [44,45], which would optimize the ecological connectivity and promote the restoration of shoreline biodiversity.

The healthy and unimpeded hydrological and biological connectivity is essential for maintaining and promoting biodiversity of wetland ecosystems. Besides protecting and restoring the ecological shoreline, some other measures, such as constructing an ecological corridor and connecting fragmented wetlands, carrying out a project for water system connectivity, and removing water-blocking structures (abandoned dams and illegal embankments), could also optimize ecological connectivity and restore biodiversity.

Aquatic plants form the basis for wetland ecosystem restoration [46]. The positive role of native aquatic plant species in the ecosystem should be acknowledged, and native wetland vegetation species should be adopted to restore multilevel plant communities from the shore to the water body in wetlands. For example, various aquatic plants, such as emergent, floating, and submerged plants, should be planted in wetlands to enhance their biodiversity and increase the stability of plant communities in wetlands.

Macrobenthos are a crucial component of wetland ecosystems and have important ecosystem functions. Macrobenthos play an important role in energy flow and material circulation in wetland ecosystems [47]. Additionally, many macrobenthos have strong pollution resistance, enrichment capacity, and decomposition capacity, and can effectively absorb and transform water pollutants [48,49]. Thus, appropriate measures should be conducted to conserve and restore the macrobenthos diversity in the wetlands of Kunshan, which lack adequate macrobenthos. Habitat improvement is an important prerequisite for macrobenthos restoration. Aquatic plants provide safe shelter and nutrients to macrobenthos [41,50]. Therefore, the restoration of wetland aquatic plant communities can directly restore the habitat of macrobenthos, thereby effectively promoting their diversity. In addition, in degraded wetlands where macrobenthos are scarce, especially in river and lake wetlands near highly urbanized residential and industrial areas, the diversity of macrobenthos can be restored by the artificial propagation and release of native macrobenthos species.

This study systematically combines biodiversity and urbanization indicators to investigate the impacts of rapid urbanization on wetland ecosystems across various towns in a typical rapidly urbanizing Chinese city, and provides scientific implications and policies for management and restoration of urban wetlands. Thus, this study possesses significant scientific value and several innovative aspects, including the use of multiple indicators, multi-regional comparisons, strong interdisciplinary relevance, and strong policy orientation. In addition, based on our findings, we also propose some recommendations and directions for future research. These include establishing a long-term monitoring and assessment mechanism to track the sustained effects of urbanization on wetlands, developing early risk identification and warning technologies for wetland ecosystem degradation caused by urban expansion, and advancing research and development on ecological restoration techniques for urban wetlands.

Acknowledgments

Funding: This study was supported by the National Natural Science Foundation of China (Grant No. 42407617).
Author contributions: D.Q.: Conceptualization, statistical analysis, investigation, methodology, writing—original draft, and writing—review and editing. Z.X.: Investigation, methodology, statistical analysis, and writing—review and editing. Y.R.: Investigation, methodology, and writing—review and editing. H.Z.: Investigation, methodology, and writing—review and editing. Y.Z.: Conceptualization, methodology, writing—review and editing, and supervision.
Competing interests: The authors declare that they have no competing interests.

Data Availability

Data will be made available on request.

Supplementary Materials

Figs. S1 to S8
Tables S1 to S4

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Ecosystem Health and Sustainability
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Rapid Urbanization Reduces Biodiversity and Degrades Wetland Ecosystems in Kunshan, China: Implications for Restoration

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Citation: Qiu D, Xu Z, Ren Y, Zhang H, Zhu Y. Rapid Urbanization Reduces Biodiversity and Degrades Wetland Ecosystems in Kunshan, China: Implications for Restoration. *Ecosyst Health Sustain*. 2025;**11**:0450. DOI: 10.34133/ehs.0450

Rapid urbanization negatively affects landscape, ecological connectivity, and biodiversity of wetland ecosystems worldwide, and the specific effect mechanisms need to be deeply explored. In the present study, we aimed to determine if and how rapid urbanization has affected the biodiversity and ecosystems of wetlands in Kunshan, which has ranked first among China's top 100 counties and cities in comprehensive strength for 20 years. We conducted field investigations in 11 towns of Kunshan, where we determined different water parameters and biodiversity indices in the wetlands of urban, middle, and natural regions as well as several urbanization indices. The results indicated an upward trend for the biodiversity indices, including density, biomass, species number, Shannon diversity, and Margalef richness of the aquatic plants and macrobenthos from the urban to middle to natural regions. Furthermore, the results indicated a downward trend for the water parameters, including salinity, total dissolved solids, pH, total phosphorus content, ammonia nitrogen content, and permanganate index from the urban to middle to natural regions. Overall, the biodiversity indices of aquatic organisms were negatively correlated with water parameters and urbanization indices, including population density, gross domestic product, number of industrial enterprises above the designated size, industrial energy consumption, and building construction area. Thus, the results demonstrate that rapid urbanization leads to habitat destruction and biodiversity reduction in aquatic plants and macrobenthos. This study provides scientific implications for management and restoration of urban wetlands during rapid urbanization, including water pollution control, ecological shoreline protection, ecological connectivity optimization, aquatic plants, and macrobenthos restoration.
Image

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https://spj.science.org/doi/10.34133/ehs.0450

Ecosystem Health and Sustainability (ISSN 2332-8878) is published by the American Association for the Advancement of Science. 1200 New York Avenue NW, Washington, DC 20005.