RESEARCH ARTICLE

Effects of soil properties and urbanization on the trait variations of riparian species: Evidence from central Japan

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Riparian habitats have been significantly affected by both natural and anthropogenic disturbances, leading to various ecological issues. However, the case studies focusing on urban ecosystems remain insufficient. As a basic element of riparian areas, it is essential to figure out how aquatic species respond to urbanization for their acclimation to the external environment. This study examined the variations in species diversity and characteristics of *Phragmites australis*, and their correlation with environmental factors in urban ecosystems in central Japan. The investigation results revealed that increased urbanization intensity was associated with the diminishing dominance of *P. australis*. Consistent with previous studies, the results showed that soil moisture was identified as the major influencing factor for the traits of *P. australis*. Interestingly, we found that land-cover types and soil chemical properties also played crucial roles in the traits of *P. australis*. The results further confirmed the ecological characteristics of *P. australis*, serving as a guide for conserving the native aquatic plants inhabiting urban areas. Our findings are believed to provide insights into the impact of urbanization on the traits of riparian plants and biodiversity conservation in urban areas. Tightening regulations and restricting human activities near riversides may be conducive to maintaining the biodiversity and resilience of urban ecosystems in the face of urbanization pressures.

Keywords: *Phragmites australis*; riparian vegetation; urbanization; plant trait; soil properties.

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Introduction

Despite accounting for a relatively small proportion of the landscape, riparian ecosystems play a vitally important role in maintaining biodiversity [1]. However, riparian habitats conservation is increasingly threatened by urbanization and human activities. Urban development, industry, and agriculture activities are causing the degradation and loss of riparian ecosystems globally due to alterations in flooding protection and conversion of riparian areas [2, 3].

Human disturbance can affect riparian habitats in several ways. The initial factor is the alteration of the land cover. The significant human-induced alterations in the land cover of riparian areas might result in riparian degradation, potentially affecting the hydrological and sediment patterns [3]. Consequently, riparian plant and animal groups may experience significant population decreases due to their incapacity to adjust to disruptions in their natural riparian habitat [4]. Besides, the changes in land cover associated with the development of infrastructure and urban spaces can result in the fragmentation of riparian vegetation communities [5]. Under such circumstances, human activities can unintentionally aid in the spread and growth of invasive plant species, potentially leading to a temporary increase in plant diversity in riparian habitats [6-8]. Moreover, pollution caused by human activity poses a significant risk to the well-being of riparian ecosystems. In the urban settings, runoff and industrial and domestic waste increased loads of pollutants, which is a major contributing factor for the deteriorating quality of soil and water [9]. The main pollutants from urban areas primarily involve increasing nitrogen, phosphorus, and inorganic nutrients as documented in previous studies [10, 11].

To maintain biodiversity and ecosystem services in riparian habitats, it is crucial to enhance our comprehension of how plants respond to urbanization facing growing disturbances. Plant traits offer an opportunity to do this. Plants grow in constant-changing environments, leading to plant traits that can be regarded as the measurable indices that determine how plants interact with the external environment [12]. Especially in riparian areas, vegetation is exposed to the impact of various disturbances. Riparian areas encompass the space between the running water and the floodplain, where vegetation is subject to natural disturbances, such as flooding, sediment, and inundation [13, 14]. However, riparian areas and plant assemblages are also affected by artificial disruptions due to urbanization and human activity [15]. Despite a number of studies that have examined how riparian vegetation responds to environmental changes, most of them concentrate on changes in plant community structure and diversity, or the influence of a specific environmental factor [16, 17]. Therefore, riparian plant characteristics respond to multiple disturbances that remain largely unexplored in urban contexts.

Riparian species are specialized to inhabiting riparian areas, and their response to the environment could serve as an indicator of the health of riparian habitats. Representing one of the dominant plant species in riparian areas [18], *Phragmites australis*, generally known as common reed, is a prevalent plant species in riparian habitats due to its capacity to adapt to many environmental circumstances [19]. Although *P. australis* is not currently threatened in Asia, this species plays crucial roles in riparian ecosystems by creating dense monospecific communities and providing habitats for biodiversity conservation [20, 21]. Moreover, various biological features of *P. australis* can serve as a biological filter for pollution. However, due to the impact of multiple disturbances such as hydrological regulation, unreasonable drainage, land use conversion, and pollution, the riparian areas are at the risk of severe degradation and the gradual decline of *P. australis* [18, 22]. With a view to the decline of *P. australis*, declining and contraction ecological condition of reed beds has been widely discussed in recent decades [23-25].

Although there has been considerable progress in our knowledge regarding *P. australis* worldwide, including in regions where it has been introduced and in its native range, research on its characteristics has primarily focused on natural habitats including grasslands, marshes, and wetland areas [26, 27]. Furthermore, previous studies have predominantly focused on ecological aspects of *P. australis* that are influenced by natural factors including the impact of hydrology, alterations in topographical gradient, and fluctuations in substratum condition and salinity level [28, 29]. However, there has been a lack of comprehensive research examining the impact of anthropogenic factors on the traits of *P. australis* in riparian regions. This dearth of research hinders our understanding of the ecological characteristics of *P. australis*, particularly in densely populated urban areas that are characterized by significant human activities. For a sustainable urban riparian ecosystem, therefore, understanding the ecology and management strategies for riparian plant species are indispensable. Given the limitations of existing vegetation-environment relationship studies in urban riparian settings, this study

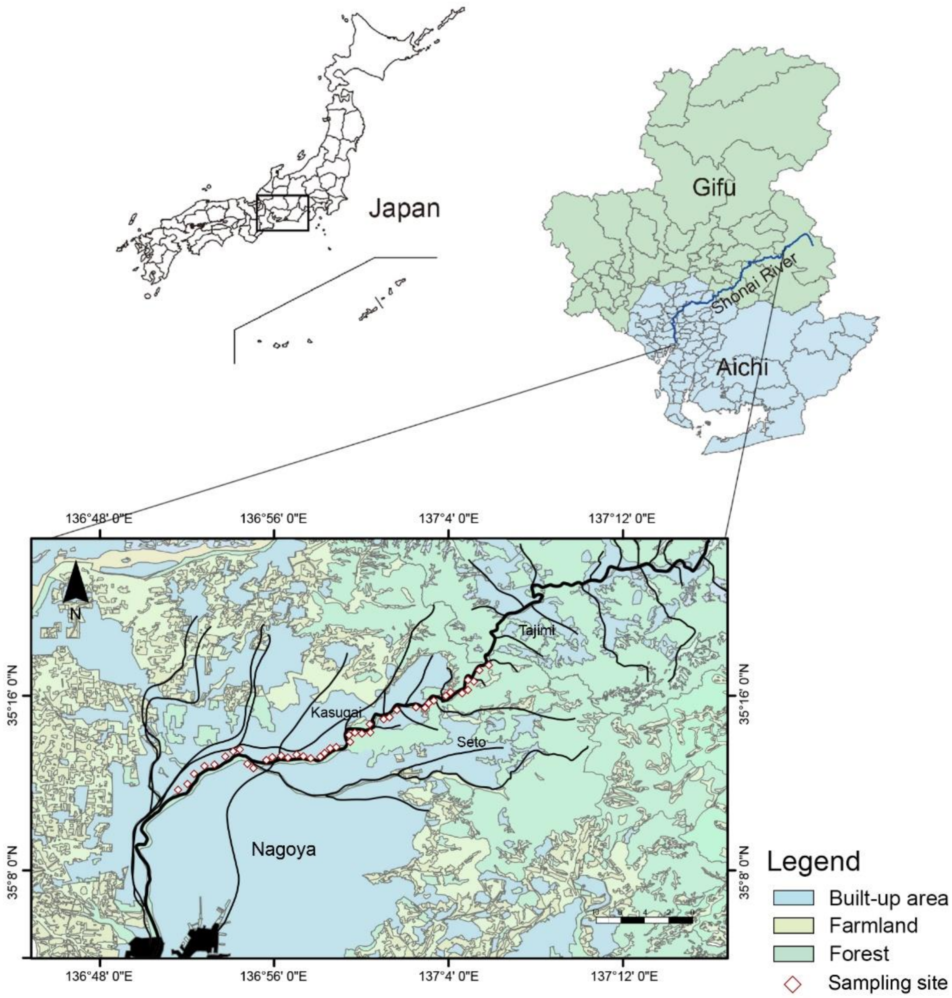

Figure 1. Locations of the study sites and an overview of the Shonai River system in Japan.

aimed to evaluate how urbanization impacted the ecological characteristics of *P. australis*. The study focused on the primary environmental factors that might affect the characteristics of plant growth at both individual and community levels. Furthermore, several management measures were suggested to enhance the management of the *P. australis* community in the urban ecosystem. The study examined the ecological traits of *P. australis* at varying levels of urbanization and analyzed how soil attributed and urbanization impacted the ecological traits of *P. australis*. The findings of this study could shed light on riparian plant survival strategies and provide a theoretical foundation for urban riparian area conservation and management.

Materials and methods

Study area and site selection

The study was conducted in the riparian areas of the Shonai River (35°04′-35°24′ N, 136°49′-137°20′ E) in the Aichi and Gifu prefectures in the central region of Japan (Figure 1). The Shonai River flows through Nagoya City from a 1,010 km^2 basin and a 96-km-long mainstream. The topography of the Shonai River basin is inclined from the northeast to the southwest with an altitude ranging from 0 to 843 m. The region features a typical warm temperate climate with the maximum and minimum monthly temperatures of 27.8°C (August) and 4.5°C (January), respectively. In the river's riparian area, the land use is divided into three categories including urban zones (52.9%), agricultural fields (11.1%), and forest (36.0%) according to the Ministry of Land, Infrastructure, Transport and Tourism, Japan (2018). Since the 1870s, the basin of the Shonai River has grown into the core area of Nagoya city, making it one of the most urbanized rivers in Japan. At present, it is experiencing significant urbanization, which has resulted in the degradation of riparian vegetation. Currently, the density of the population is approximately 2,400 persons per km^2 according to the 2018 report of the Ministry of Land, Infrastructure, Transport and Tourism, Japan.

The *P. australis* communities were sampled using Google Earth's Digital Globe satellite imagery (1:5000) and a 1/25,000 vegetation map downloaded from Japan Integrated Biodiversity Information System (J-IBIS, 2013) (http://www.biodic.go.jp/J-IBIS). To cover the whole river basin, we selected sampling sites from the lower to upper reaches of the Shonai River, following an urbanization gradient. Moreover, the sampling sites were determined according to the following criteria of (1) the presence of *P. australis* and (2) the land condition is riparian lowland. Meanwhile, to mitigate the influence of the mismatch between actual and satellite imaging, as well as major variances in environmental conditions, we conducted a field survey to ensure the applicability of potential sites that met the previous criteria. Overall, 40 sampling sites were selected along the Shonai River (Figure 1).

Field sampling

The field research was conducted from April to July 2019. In each sampling site, a transect was established perpendicularly to the river shore, and two 10 m × 10 m plots were established along the transects for the sampling of trees and shrubs. To include two cases of wetlands and transition areas, the two plots were separated by 20-30 m. In addition, we excluded the area less than two meters from the shore to eliminate the marginal effects. In each plot, five 1 m × 1 m small plots located in the center and at the four corners of each plot were established for the sampling of herbs. In each plot, we measured several variables describing the characteristics of *P. australis* communities including (1) the name, density, and coverage of all present plant species, and (2) the height, stem diameter, and leaf area of *P. australis*. The density of each species was measured by recording the number of plants in a 1 m × 1 m range, and the coverage of each species was measured visually [30]. The height and stem diameter were obtained from the mean values of 10 random *P. australis* individuals, and the leaf area was obtained from the mean values of 10 randomly selected *P. australis* leaves. After the collection of leaves, they were transferred to the laboratory, and Win SEEDLE image analysis software (Regent Instruments Inc., Québec City, Quebec, Canada) was applied to measure the leaf area. From each plot, soil samples were collected from the five small plots at depths of 20 - 40 cm to determine the physical and chemical properties of the soil. Leaf litter was cleared before the sampling of soil samples. All samples were removed with a corer and stored in labeled plastic Ziplock bags immediately. The images for each plant community were captured using a Canon EOS 5D camera (Canon U.S.A., Inc., Melville, New York, USA).

Table 1. Number of sampling sites and surrounding impervious surface for each urbanization level.

	Urbanization intensity		
	Low	Moderate	High
Number of site	13	15	12
Range of IMP	[0.00-23.4]	[23.4-47.2]	[47.2-79.1]
Mean IMP (%)	9.82	29.28	64.14

Urbanization intensity

The 40 sampling sites were classified into different urbanization intensities determined by estimating the proportion of impervious surface at each sampling location within a 500-m buffer zone. It is known that the expansion of impervious surfaces (IMP) is an inevitable consequence of the urbanization process, thus,

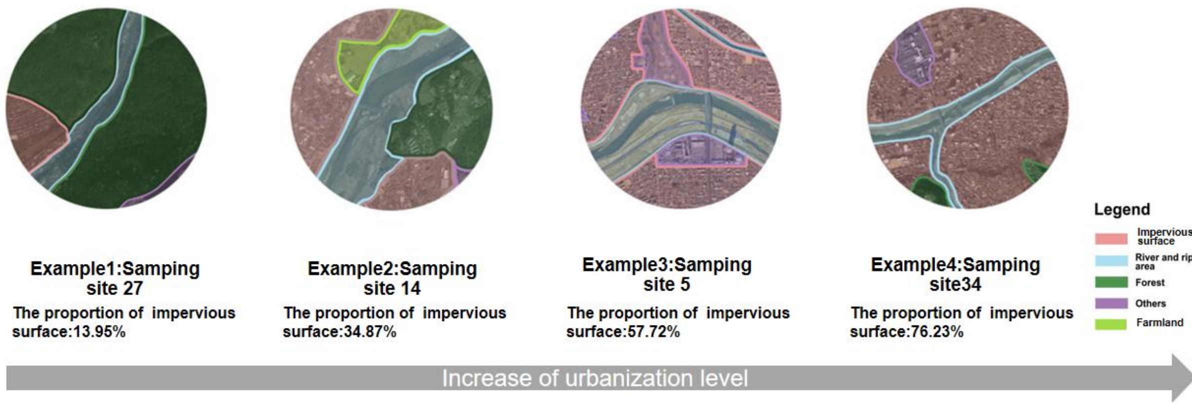

Figure 2. The land use map around the sampling section of example sampling sites. **Note:** The map shows the areas of impervious surface (roads and constructions), forest, farmland, and waterbody within 500-m far from the rivers.

the IMP is usually used as a proxy for urbanization. The sampling sites were then classified into three levels of urbanization intensity using k-means clustering based on the percentage of impervious surfaces on each of the 40 sampling sites (Table 1).

Environmental data

Environmental factors were primarily involved in land cover types, soil physical and chemical properties, and soil moisture that shaped the riparian habitat of the Shonai River. Land cover data was classified into several categories including IMP, forest, farmlands, river and riparian areas, and other land cover types (Figure 2). IMP, which includes roads, pavement, rooftops, and other land cover types, is characterized by permeable ground such as bare ground, footpaths, and baseball fields. The land cover classification was conducted using Landsat 7 remote sensing images, which were retrieved from United States Geological Survey (USGS) website (https://www.usgs.gov/). ArcGIS 9.3 (ESRI, Redlands, California, USA) was employed to estimate the percentage of land cover within a 500-m radius of the quadrat center.

We measured the riparian soils in terms of their chemical and physical properties. Electrical conductivity (EC) and pH were obtained using a CO 3100 H Conductivity meter (VWR International, Chicago, Illinois, US) and an electric A121 Portable pH Meter (ThermoFisher Scientific, Waltham, Massachusetts, USA), respectively. In addition, soil organic matter (SOM), total nitrogen (TN), and total sulfur (TS) were also measured. The carbon, hydrogen, nitrogen, and sulfur elements (CHNS) analysis were conducted using Flash 2000 organic elemental analyzer (ThermoFisher Scientific, Waltham, Massachusetts, USA) to measure the SOM, TN, and TS. Each sample was weighed in the range of 10 - 40 mg, and the induction furnace of the organic elemental analyzer was maintained at 950°C [31]. S induction furnace oil moisture was measured by its water content and texture. To evaluate soil water content (SWC), fresh soil samples were oven-dried at 105°C for 48 hours to a consistent mass [32]. The soil texture was classified as silt (< 0.05 mm), sand (0.05 - 2 mm), and gravel (> 2 mm) using a Malvern 3000 Mastersizer (Malvern Panalytical Ltd., Great Malvern, West Midlands, United Kingdom).

Data analysis

R (version 3.2.2) (https://www.r-project.org/) was employed for statistical analysis of this study, and involved several steps as follows:

(1) The species diversity of *P. australis* communities was determined using Shannon-Wiener index [33], which was calculated using the R package "vegan":

$$H = -\sum_{i=1}^{s}(P_i \ln P_i) \quad (1)$$

where P_i indicated the relative importance value of species *i*, and S referred to the total number of species in the *i*th site.

(2) One-way analysis of variance (ANOVA) was used to assess the differences between dependent variables (e.g., plant traits, biodiversity indices) and environmental variables (e.g., soil properties). The plant traits, biodiversity indices, and environmental variables for the different sites were compared using post-hoc multiple comparisons with the Tukey test. The multiple comparisons were performed using "multcomp" package in R.

(3) Principal Components Analysis (PCA) was used to reduce the large number of highly correlated variables to a smaller set of uncorrelated variables. As the multicollinearity test conducted among the land-cover types and soil moisture factors indicated a strong negative correlation between the proportion of impervious surfaces and open green space (Spearman rank coefficient r = -0.70, $P < 0.001$) and a negative correlation between the content of gravel and SWC (Spearman rank coefficient r = -0.75, $P < 0.001$), a PCA was used to create independent explanatory variables. The PCA was computed using the “vegan” packages.

(4) Variations in traits and diversity of *P. australis* communities were modeled using stepwise linear regressions that combined land cover types and soil properties. Backward selection was used to select significant environmental factors until the maximum value of the coefficient of determination (R^2) was obtained. The statistical significance (*P* value) of each model that was less than 0.05 (after 999 random permutations) was considered in this study.

(5) To further explore the relative and unique significance of soil physical and chemical properties, soil moisture, and land-cover types in the variation of plant traits, the variation was assessed by partitioning the variation explained by each subset using redundancy analysis (RDA). The variation partitioning was performed using the “vegan” packages.

Results

Variation in the traits of *P. australis* in different level of urbanization intensity

The coverage and traits of *P. australis* differed significantly across different levels of urbanization intensity, implying that riparian area development had inhibited *P. australis* colonization and expansion. In low urbanized areas, the coverage, height, and stem diameter of *P. australis* were significantly higher than that in other degrees of urbanization intensity ($P < 0.01$) (Figure 3 a-c). The leaf area was significantly higher in plots with low urbanization intensity and reached its lowest value in high urbanized area ($P < 0.05$) (Figure 3 d). Unlike the traits of *P. australis*, the Shannon-Wiener diversity index exhibited higher values in moderately urbanized areas compared to that in other levels of urbanization intensity (Figure 3 e). The most common accompanying species was *Solidago altissima*, which was distributed across the three levels of urbanization intensity (Table 2). In highly urbanized areas, alien species such as *Iris pseudacorus*, *Festuca arundinacea*, *Ambrosia trifida*, and *Coreopsis lanceolate* coexistent with *P. australis*. Distinct from highly urbanized areas, the most frequent and abundant plants accompanying *P. australis* in less urbanized areas were native species, for example, *Rosa multiflora Thunb*., *Iris japonica*, and *Phalaris arundinacea*. The number of total species varied across different levels of urbanization intensity with moderate urbanized areas (12.5 ± 0.85) showing the highest values (Table 2). The proportion of alien species, which represents the percentage of alien species in total species number, reached its maximum value in highly urbanized areas (35.1%).

Variation of environmental variables in *P. australis*’ habitat

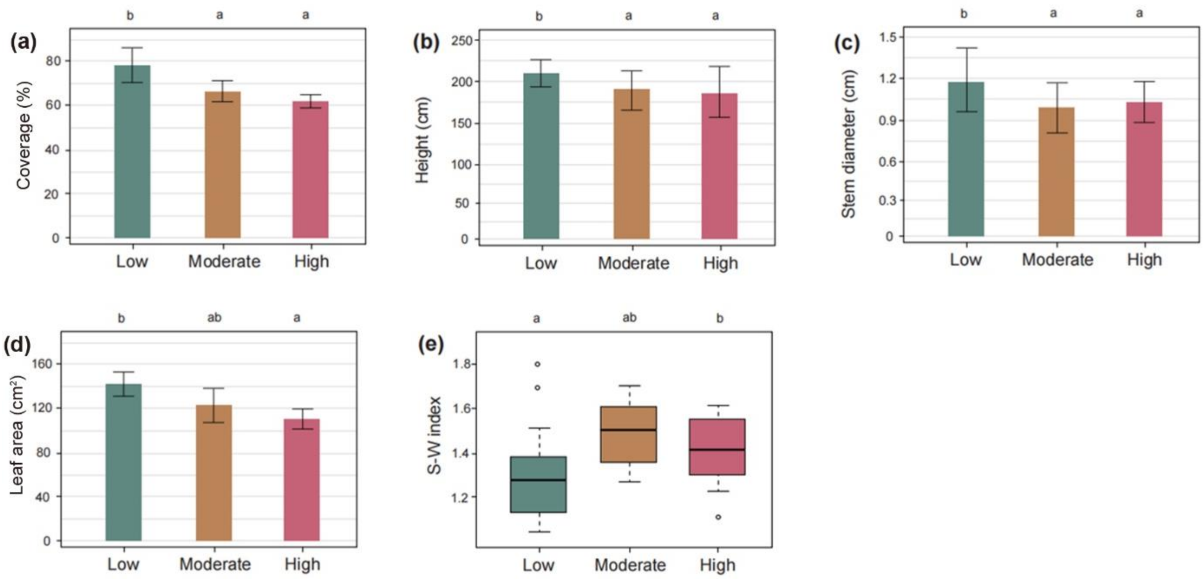

Figure 3. Differences in the coverage (a), height (b), stem diameter (c), and leaf area (d) of *P. australis* and diversity index (e) in different levels of urbanization intensity. The values were represented as means ± SE. The values with the same letter were insignificantly different at the 0.05 significance level.

Table 2. Accompanying species and species richness among three levels of urbanization intensity.

Urbanization intensity level	Accompanying species	Species richness	The proportion of alien species
Low	*Phalaris arundinacea, Iris japonica, Miscanthus sacchariflorus, Artemisia indica var. maximowiczii,* ***Solidago altissima.***	9.8 ± 0.69[a]	14.7%
Moderate	*Miscanthus sacchariflorus, Poa annua,* ***Solidago altissima****, Rosa multiflora Thunb,* ***Coreopsis lanceolate****.*	12.5 ± 0.85[b]	19.8%
High	***Solidago altissima, Iris pseudacorus,*** *Miscanthus sinensis,* ***Coreopsis lanceolate,*** *Artemisia indica var. maximowiczii*	10.1 ± 0.56[a]	35.1%

Note: Only the top five accompanying species were listed in order of importance value. Alien species were shown in bold. Values with the same letter were not significantly different at the 0.05 significance level.

Among environmental parameters, pH and electrical conductivity values differed considerably with urbanization intensity (Table 3). The mean salinity of the soil (as measured by EC in μS/cm) reached its maximum values in highly urbanized areas. Furthermore, soil collected from less urbanized areas was more acidic than soil collected from highly urbanized areas (mean vales 5.81 vs. 6.40). The other local factors indicated no significant variations across urbanization groups.

Relationship between the characteristics of *P. australis* and environmental factors

The results of PCA in land-cover types showed that the first two principal components accounted for 83.1% of the total variance. The first principal-component axis (LAND1) described a gradient from a large proportion of impervious surfaces (positive values) to a large proportion of open green space (negative values), whereas in the second principal axis (LAND2), open green spaces showed a negative value while water bodies had a positive value. On the other hand,

Table 3. One-way analysis of variance (ANOVA) and significance results comparing local factors of soil samples collected in different levels of urbanized area.

	Low	Moderate	High	Df	X2	*P*-value
Gravel (%)	16.45 ± 3.93	15.98 ± 5.58	17.45 ± 6.42	2	1.422	ns
Sand (%)	36.35 ± 4.88	37.25 ± 6.12	41.02 ± 4.81	2	1.131	ns
Silt (%)	47.19 ± 4.97	46.77 ± 5.32	41.53 ± 6.38	2	3.246	ns
pH	5.81 ± 0.13	6.11 ± 0.22	6.40 ± 0.19	2	20.122	< 0.001**
EC (μS/cm)	55.58 ± 6.79	71.55 ± 12.23	89.37 ± 19.44	2	21.524	< 0.001**
SWC (g/g)	0.22 ± 0.03	0.24 ± 0.02	0.21 ± 0.02	2	2.098	ns
TN (%)	0.19 ± 0.04	0.18 ± 0.02	0.16 ± 0.03	2	1.583	ns
SOC (%)	1.98 ± 0.38	2.07 ± 0.15	1.57 ± 0.32	2	1.978	ns
TS (%)	0.04 ± 0.01	0.03 ± 0.02	0.05 ± 0.02	2	0.681	ns

Notes: Values were represented means ± SE. SWC: soil water content. TN: total nitrogen. TS: total sulfur. SOC: soil organic carbon. EC: electrical conductivity. ns: no significant difference.

the results of PCA showed that the first two principal components accounted for 90.3% of the total variance in the soil moisture variables. The first principal-component axis (SM1) was positively associated with the soil water content and the content of silt. However, on the second principal axis (SM2), sand had a positive value while silt showed a negative value.

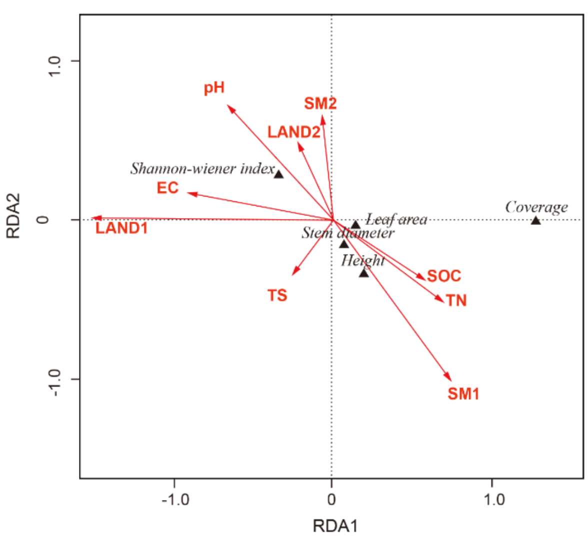

Figure 4. RDA ordination diagram between vegetation traits of P. australis and environmental variables. LAND1: the first principal axis in Principal Components Analysis (PCA) of land-cover variables. LAND2: the second principal axis in PCA of land-cover variables. SM1: the first principal axis in PCA of soil moisture variables. SM2: the second principal axis in PCA of soil moisture variables. TN: total nitrogen. TS: total sulfur. SOC: soil organic carbon. EC: electrical conductivity.

Figure 4 depicted the results of the RDA ordination of environmental variables and the traits of *P. australis*. The coverage of *P. australis* was distributed closely with the percentage of greenspace and soil organic carbon (SOC), while situated opposite to the land-cover-related factors (LAND1). The height of *P. australis* showed a close relationship with SM1. The stem diameter and leaf area were combined in the RDA diagram, which revealed a strong correlation with total nitrogen (TN), soil water content, and soil particle composition. Similarly, the stem diameter, leaf area, and height were all inversely correlated with land-cover-related parameters (LAND1), soil electrical conductivity (EC), pH, and the percentage of gravel. The Shannon-Wiener index was positioned on the left side of the ordination diagram and had a positive association with the land-cover-related factors (LAND1 and LAND2), soil electrical conductivity (EC), pH, and SM2.

To establish how environmental factors could affect the characteristics of *P. australis*, a regression analysis was conducted, and the best explanatory factor and model with the highest adjusted R^2 value were selected as listed in Table 4. According to the regression analysis, the land-cover-related-factors could be used as predictors for the coverage of *P. australis* and the Shannon-Wiener index, explaining 15.1 - 43.2% of the variation in the characteristics. Soil moisture

Table 4. Step multiple linear regression of the characteristics of *P. australis* with environmental factors.

	Predictor	Adjusted R^2	*P* value
Coverage	LAND1	0.432	< 0.001
	SM1 + EC + LAND1	0.591	< 0.001
Leaf area	TN	0.149	< 0.05
	SM1 + TN + SOC + EC	0.185	< 0.05
Height	SM1	0.411	< 0.001
	SM1 + TN	0.489	< 0.001
Stem diameter	SM1	0.342	< 0.001
	pH + EC + SM1 + LAND2	0.554	< 0.001
Shannon-Wiener index	LAND1	0.151	< 0.05
	SM2 + pH + LAND1	0.294	< 0.05

Notes: LAND1: the first principal axis in Principal Components Analysis (PCA) of land-cover variables. LAND2: the second principal axis in PCA of land-cover variables. SM1: the first principal axis in PCA of soil moisture variables. SM2: the second principal axis in PCA of soil moisture variables. TN: total nitrogen. TS: total sulfur. SOC: soil organic carbon. EC: electrical conductivity.

variables explained 34.2 - 41.1% of the variation, which was closely associated with the variation in the height and stem diameter of *P. australis*. Soil physical and chemical properties (TN) were primarily affected by the leaf area of *P. australis*, which explained 14.9% of the variation in the characteristics. The explanatory model with the highest adjusted R^2 value for each characteristic was the combination of soil properties, soil moisture, and land cover types, which explained 18.5 - 59.1% of the variation.

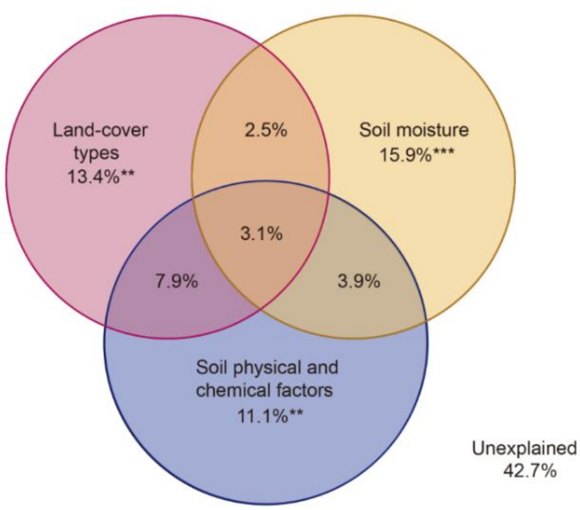

Figure 5. Variation partitioning for the relative importances of land-cover types, soil moisture, and soil physical and chemical properties in the characteristics of *P. australis*. ***: $P < 0.001$. **: $P < 0.01$.

Relative importance of land-cover types, soil moisture, soil physical and chemical properties in the characteristics of *P. australis*

Variation partitioning analysis revealed the relative importance of land cover types, soil moisture, and soil physical and chemical properties in the characteristics of *P. australis*. All the environmental factors accounted for 57.3% of the overall variance (Figure 5). The soil moisture had a higher explanatory ability (15.9%) than that in other factor groups. Land cover types, as well as soil physical and chemical properties had a significant impact on variation of *P. australis*, accounting for 13.4% and 11.1% of the total variance, respectively.

Discussion

The variation of *P. australis* in different levels of urbanization intensity

Urban development, the most significant change in land use in recent decades, is defined by urban, suburban, and rural areas with distinct biophysical and social environments, such as soil qualities, land use and land cover, population density, and air temperature [34]. As expected, several significant trait-environment associations were found in this study as plant traits shifted in response to the changes in urbanization level. The coverage of *P. australis* decreased with increasing urbanization intensity implying that the riparian environment was affected by intensive human disturbance, hence altering the dominance of *P. australis*. Similarly, Sciance *et al*. found that the construction of wetlands reduced the abundance of *P. australis* [35]. On the other hand, the decreasing coverage of *P. australis* could be related to the invasions of alien plants. Human disturbance has long been considered to promote the spread of alien species [36, 37]. Our findings indicated that there were more alien plant species in *P. australis* communities observed in highly urban areas than in other areas along the Shonai River. It is thought that the construction and alteration of riparian habitats give alien species a competitive advantage over native species [38], thus causing the dominance of *P. australis* to diminish. Plant traits represent the plant strategy for adapting to environmental change [39]. The *P. australis* in highly urbanized riparian areas showed a decrease in height, stem diameter, and leaf area. The height and stem diameter are considered indicators for the plant's abilities in resource acquisition and nutrition supply and delivery [40, 41]. In addition, the leaf area is also a significant trait for plant growth [42]. According to our results, there was a decrease in the competitiveness of *P. australis* with the increase in the urbanization intensity in riparian areas. Moreover, as evidenced by differences in the plant traits among the *P. australis* communities in the areas with different urbanization levels, the dominance of *P. australis* was positively associated with their morphological traits [43]. Our results indicated that, in riparian plant communities, *P. australis* with higher coverage was more capable of taking advantage of environmental resources than those with its lower coverage, resulting a positive correlation between plant coverage and their traits. Species diversity is commonly used to characterize the relationship between vegetation and the environment [44]. In this study, we found that the diversity of *P. australis* communities was the highest in moderately urbanized areas, which was consistent with the findings that the diversity index was higher in urban than suburban areas as a result of the increasing diversity due to intermediate disturbance [45]. Furthermore, the dominance of *P. australis* was thought to contribute to the variability of diversity indices across different levels of urbanization intensity. It is well understood that the diversity of local species in plant communities with a high level of dominance by the target species is usually lower than that in communities with a low level of dominance. The results of species diversity in this study coincided with the previous research results, indicating that the dominance of *P. australis* was negatively associated with the diversity index of the plant communities [46].

Anthropogenic disturbance play an important role on *P. australis*

Plant characteristics play a role in determining how plants respond to environmental variables [12]. This study found that urbanization and elevated soil pH and electrical conductivity were the significant influencing factors for the variance in the traits of *P. australis* in the urban ecosystem. Compared with suburban areas, urban areas harbor a significantly larger proportion of impervious surfaces. Consistent with earlier research, the higher IMP and lower percentage of open green space may result in a reduction in *P. australis* coverage [4]. This tendency could be explained by the sharp increase in IMP having the potential to degrade riparian habitats due to the concentration of human activities and the increase in surface runoff. Additionally, impervious surfaces can disrupt the exchange of gas, water, and minerals between the soil and the atmosphere, impacting the soil ecosystem [47]. On the other hand, human disturbance increased the chance of survival and growth for invasive plant species [48], which might also be attributed to the fact that the riparian soils surrounded by the impervious surface create adverse environmental conditions for *P. australis*. Our study has similar findings to those of Grella *et al*., who found that there were positive correlations between the proportion of imperviousness and the species richness of invasive species [11]. In our study area, the soils in highly urbanized areas were more alkaline than those in less urbanized areas, which might be attributed to the runoff from calcium carbonate-containing urban materials. In this study, it was revealed that the elevation of soil pH might contribute to the growth inhibition of *P. australis* by affecting their stem diameter. Plant stem diameter is commonly used as a measure of plant performance when evaluating competitive ability and resource availability [49]. Our findings suggested that relatively high pH levels could lead to a competitive disadvantage in obtaining resources. In this study, it was noted that *P. australis* performed well in stem diameter when the pH was below 6.0, suggesting that it could thrive in slightly acidic conditions, despite previous reports of its ability to grow on various substrates and tolerate pH levels ranging from 2.5 to 9.8 [22, 50]. Additionally, soil pH significantly influences soil fertility. Mildly acid soil (i.e., pH 5.5 – 6.0) is usually considered the optimal pH condition as most micronutrients are more available to plants than those in neutral-alkaline soils, which is generally conductive to plant growth [51, 52]. Increased electrical conductivity in urban areas can be attained through thorough irrigation in highly urbanized riparian areas. The riparian area of the Shonai River was occupied by parks, golf courses, and fields, which gave rise to the need for a considerable amount of irrigation water for the purpose of landscape management [53]. A strong negative association was discovered in the current study between the stem diameter of *P. australis* and the electrical conductivity (EC) of the soil, which aligned with previous research indicating that salinity could harm the structure of *P. australis* [54, 55]. It is worth noting that, being a salt-tolerant plant, *P. australis* is capable of adjusting its function depending on the salinity of the surrounding environment [56]. Therefore, the lower stem diameter of *P. australis* might also result from its self-adjustment to the relatively high level of EC in urban areas.

Applications for management

The population and diversity of native species have gradually declined in riparian areas around the world [57, 58]. These tendencies may be accelerated by anthropogenic disturbance, resulting in a gradual loss of natural resilience in urban ecosystems [16]. As expected, urbanization effects played a crucial role in the dominance of *P. australis* in the current study. Thus, in riparian areas, restrictive approaches such as restricting the construction of public space in riverside, implementing legislation to prevent human activities within a certain area of riversides, and establishing protective zones for *P. australis* are recommended for ecological restoration in urban areas in the future. Urbanization-induced increases in soil pH and EC also have a considerable influence on the traits of *P. australis*. Therefore, controlling urban runoff by strengthening supervision and rationally planning urban and river junction zones are suggested through this study [59]. Furthermore, it was noticed that riparian habitat in urban areas included many golf courses and parks, and these public spaces were characterized by high water consumption. A large amount of irrigation might be related to the higher conductivity assumed in this study. Thus, to maintain the resilience of riparian areas and prevent the decrease in native species diversity, management approaches such as regulating golf course construction and implementing water-saving irrigation for the urban ecology are advised.

Conclusion

This study investigated the ecology of *P. australis* at various degrees urbanization intensity and found environmental elements that influenced *P. australis* colonization and growth. The traits of *P. australis* were associated with its ability to adapt to changing environments. The traits of *P. australis* mainly included the most effective utilization of nutrients, light, and water resource dispersal strategies. Environmental factors would cause the traits of *P. australis* to vary. However, there was an array of other environmental influencing factors in the traits of *P. australis* such as flooding frequency, chemical, and physical water characteristics. These factors, as potential co-variates, might affect the variation of *P. australis* in the urban ecosystem. Future research is needed to disentangle the effect of artificial disturbance and urbanization from hydrological conditions on plant traits.

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