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Land cover and plant diversity in tropical coastal urban Haikou, China

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ABSTRACT

Urban development proceeds rapidly, so understanding the mechanisms underpinning this process is critical to urban planning. One way to accomplish this is by measuring and comparing mosaics in urban ecosystems across space and time, and relating these to ecosystem processes. In this study, we examined 190 Urban Functional Units (UFUs) within urbanized areas in the tropical city of Haikou in China, and we assigned each to a UFU type. We assessed land cover as well as plant taxonomic and phylogenetic diversity within each UFU using field investigations and by interpreting imagery from remote sensing. Additionally, we quantified several relevant factors that may influence plant diversity. Using these data, we built general linear models to test how UFU types, as well as relevant biophysical, socioeconomic, and management factors, predict variation in urban plant diversity. We found that the 190 UFUs examined in Haikou belong to 6 primary and 16 secondary UFUs. We observed that land cover varied strongly among secondary UFUs and that species richness and diversity differed significantly across the 6 primary UFUs. Most land cover and plant diversity variables were significantly positively correlated with total land area, the age of the UFU, and average housing prices. Tree species richness, phylogenetic distance, and the mean nearest taxon distance were positively correlated with maintenance times and watering frequency per year (green management variables). Our study indicated that socioeconomic variables help predict the percentage of green space and plant taxonomic and phylogenetic diversity differences among Haikou urban ecosystems.

1. Introduction

Urbanization is frequently linked to rapid changes in Land Use and Land Cover (LULC), urban natural environments, and socioeconomics. Land cover reflects what currently covers a portion of the landscape (e.g., grass, asphalt, bare ground, etc.) while land use reflects how the land is used by people (e.g., urban, agricultural). Studies suggest that 70% of the world's population will be living in urban areas by 2050 (Grimm et al., 2008). To address sustainability challenges in growing cities, urban ecology research has emerged as a prominent field (Alberti and Marzluff, 2004; Grimm et al., 2008, 2000; Pickett et al., 2001). Urban landscapes are highly dynamic and are comprised of heterogeneous patches influenced by both human society and the natural environment (Alberti, 2005). By measuring and comparing spatial and temporal variation among patches within a city, and by linking them with LULC changes, we are able to identify and describe spatial patterns, understand the causes and consequences of those patterns in urban environments, and therefore enhance urban ecosystem functions and services to improve the lives of urban residents (Dunn et al., 1991; Gustafson, 1998; Li and Wu, 2007). Buyantuyev (2008) has examined these patterns elsewhere and assumed that land cover and land use in each urban patch are relatively homogeneous. However, the patterns of land cover in each urban patch that Buyantuyev (2008) examined were not based on Urban Functional Units (i.e. UFU, e.g. hospitals, universities etc.). That is, Buyantuyev (2008) examined land cover and land use based on remote sensing images for the whole region – this approach cannot identify specific land cover details for a particular UFU (e.g. for our Hainan University campus). However, we divided our remote sensing image into hundreds of equal-sized grid cells, selected UFUs (i.e. Urban Functional Units, UFUs, e.g. schools, hospitals etc)

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within the grid, and then interpreted the land cover and land use within each UFU. Thus far, researchers have integrated land use and coverage maps to describe mosaic patch features; however, additional research is needed to more clearly understand how different land cover and land use patterns are related to plant diversity and how these patterns develop within urbanized areas.

Urban green infrastructure and plant diversity are crucial to the well-being of urban dwellers; they reduce dust (Nowak et al., 2006), sequester carbon (Nowak and Crane, 2002), help cool Urban Heat Islands (UHI) (Yuan and Bauer, 2007), and enhance both aesthetics and culture (Smardon, 1988). It has been suggested that plant diversity and the extent of urban forests are closely linked to socioeconomic factors. For example, research conducted in Phoenix (Arizona, USA), found a relationship between wealth and plant diversity (i.e. a luxury effect: high-priced housing was positively associated with higher surrounding plant diversity (Hope et al., 2003). The preference of urban dwellers for higher plant diversity provides sufficient financial incentive for urban planners to preserve and augment diversity. In Baltimore (Maryland, USA), Grove et al. (2006) explored the relationship between vegetation cover and local population density, lifestyle and social status, and found that the lifestyle of residents on private land reflected the area's vegetation cover. They also observed that income and education were related to urban vegetation changes. Luck et al. (2009) found that plant diversity and the percentage of green space were both negatively correlated with community housing density and the area dedicated to medium density housing, and positively correlated with the education level of those living there, the proportion of the population previously aggregated in Census Collection Districts, and the age of the development. Johnson et al. (2015) surveyed herb species and abundance in Baltimore (Maryland, USA), and their findings suggest that human land-use legacies had impacts on the processes and patterns observed across the urban landscape. Wang et al. (2016) investigated the interrelationships among geographical and socioeconomic variables across 328 different Urban Functional Units (UFUs, e.g. universities, parks, residential areas) in Beijing, China, and found that geographical, social, and economic factors were closely related in urban ecological systems.

Asian cities have different development patterns and drivers compared to western cities. For example, the Beijing urban development pattern proceeds from a central point outward, like a pie. At present, China is experiencing unprecedented urbanization rates. In just 38 years, its population has increased from 0.17 billion in 1978 to 0.77 billion in 2016 (Anonymous, 2019a). By the year 2050, China's total urban population is expected to reach 1.2 billion (Anonymous, 2019b). Thus far, few studies have examined urban vegetation and plant diversity in Chinese cities with most studies having concentrated on more developed western cities (Botzat et al., 2016). Additionally, most studies have focused on temperate regions and few have explored relationships among land cover, plant diversity, and socioeconomic factors in tropical urban ecosystems where urbanization is increasing and presumably exerts even more pronounced effects due to high regional biodiversity. Furthermore, previous research has focused on protected urban forests and parks; however, important marginal urban green spaces such as university campuses and residential areas have been neglected.

An additional gap in the existing literature is related to understanding patterns of phylogenetic diversity in China's tropical, urban, coastal cities. Understanding patterns in urban phylogenetic diversity (PD) may suggest management practices that could improve vegetation survival and performance in stressful environments (e.g., areas with short growing seasons). There are many potential benefits of considering the phylogenetic relationships among plant species when developing urban green infrastructure (e.g. supporting biodiversity conservation, promoting the persistence of plants, and enhancing the ecological and aesthetic features). MacIvor et al. (2016), for example, recommend the use of phylogenies to help achieve desirable outcomes for urban green infrastructure. Furthermore, efforts to increase PD in urban environments could also improve overall habitat diversity, aesthetics, and provide other direct human benefits (Macivor et al., 2016) (e.g. faster recovery from illness through establishment of a tranquil and healthy environment (Kuo and Sullivan, 2001). Most urban biodiversity studies have been conducted at the ecosystem scale (e.g., habitat or land-use) or focus only on taxonomic diversity, while other dimensions of biodiversity (e.g., phylogenetic diversity and functional diversity) have received considerably less attention (Botzat et al., 2016).

In this study, we extend previous research to examine patterns in Haikou, one of the fastest growing tropical cities in China, and examine multiple aspects of plant diversity. We selected 190 UFUs using a stratified random procedure following Wang et al. (2016). We interpreted 2010 SPOT imagery to obtain LULC information and conducted field investigations to assess patterns of plant diversity and abundance. We then compiled socioeconomic data (e.g. housing price, UFU age, and population density), and determined the phylogenetic diversity of each UFU to explore the interrelationships among these biophysical, socioeconomic and management variables. Specifically, we focused on addressing the following two questions: 1) how do land-use, plant taxonomic diversity and phylogenetic diversity differ among UFUs; and 2) what factors explain observed spatial variation in plant taxonomic and phylogenetic diversity?

2. Methods

2.1. Study area

Haikou is the capital city of Hainan province, a southern island 18 km off the coast of mainland China (Fig. 1). The northern and eastern borders of Haikou City are delineated by water. The city's total area is 11,960 ha in Haikou, 5023 ha of which is forested land, accounting for 42% of the total land area. Haikou's central urbanized areas have a 2000-year history that stretches back to the Han dynasty (200 BCE); this area is representative of a typical tropical urban ecosystem.

Haikou has a tropical island climate free from frost or snow; it experiences fog in spring, thunderstorms in summer, typhoons in the autumn, and cold and drought in winter. The average annual temperature is 23.8 °C, and the city receives 1639 mm of precipitation annually. Tropical biological resources are abundant in Haikou. There are 1980 terrestrial plant species, of which more than 40 species are endemic to Hainan Province. Several species, including *Cycas revolute* Thunb., *Hopea hainanensis* Merr. et Chun and *Dalbergia odorifera* T. Chen, are listed as having first-level protection nationally, while several others, including *Dalbergia hupeana* Hance, *Cephalotaxus sinensis* (Rehd. et Wils.) Li, *Aquilaria sinensis* (Lour.) Spreng. and *Antiaris toxicaria* Lesch. have second-level protection. More than 80 tree and shrub species are found in this area; several of these, including *Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg. and *Cocos nucifera* Linn., are economically valuable (Mapping, 2015).

Haikou has undergone increasingly rapid urbanization in recent years; the permanent resident population has grown from 1.4 million in 2005 to 2.2 million in 2014, while the total fixed annual investment in this area by either business or China's government, rose from 13.7 billion Yuan (ca. 2.05 billion US dollars) to 82.14 billion Yuan (12.28 billion US dollars) over the same period (HMBS (Haikou Municipal Bureau of Statistics, 2014). Rapid human population growth and economic investment makes Haikou an ideal city to explore plant diversity changes under rapid urbanization.

2.2. Sampling design

We employed a grid-based stratified sampling method in this study. First, we used a cloud-free SPOT 5 image (Satellite Pour l'Observation de la Terre) with a spatial resolution of 10 m (accessed in October 2010) for Haikou. This image was geometrically rectified using ground control

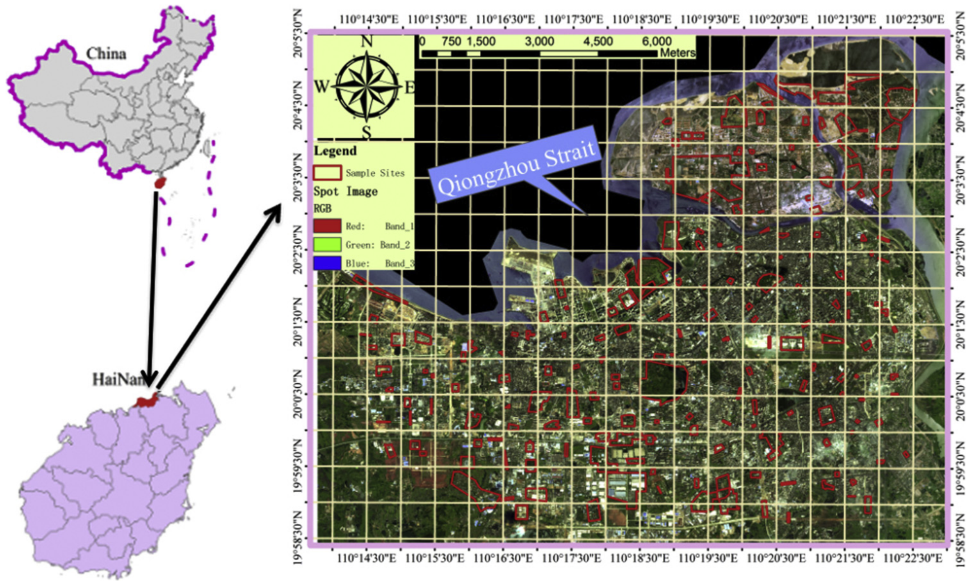

Fig. 1. Urban Functional Units (190) are identified within the urbanized tropical areas of Haikou, China. From left to right are A to O, from top to bottom is 1 to 14. Fig. 1 was created by authors using ArcGIS 10 based on the SPOT 5 images. SPOT-5 images were purchased from the God's eye website (version: SPOT-5, resolution 2.5 m, URL: http://www.godeyes.cn/satellite-168-1-1.html).

Table 1
A summary of the prevalence of urban functional districts in urbanized areas within Haikou.

Primary Urban Functional Units	Secondary Urban Functional Units	Number	Percentage (%)
Public affairs service districts	Governmental Agencies	18	9.57
	Colleges/Universities	7	3.68
	Primary/Middle Schools	18	9.47
	Research Institutes	4	2.11
	Hospitals	12	6.32
Industry and business districts	Industry	12	6.32
	Hotels	11	5.79
	Industrial Offices	9	4.74
	Supermarkets	3	1.58
Residential districts	Low-Density Residential Areas (lower than 6 storeys)	5	2.63
	High-Density Residential Areas (higher than 6 storeys)	43	22.63
Recreation and leisure districts	Parks	7	5.79
	Museums	5	2.63
Transportation	Main/Secondary Roads	28	14.73
	Bus Parking	5	2.63
Undeveloped land	Wasteland	3	1.58
Total	16	190	100

points from orthorectified images and then mosaiced using ERDAS Imagine TM software. Portions of the image within the urbanized areas of Haikou were extracted and form a layer containing 192 1 × 1 km grid cells (Fig. 1, some UFUs with very few plant species were excluded). Then, one UFU was selected randomly in each grid cell. The boundary of each UFU was determined using Google Earth (accessed from Oct. to Nov. in 2015), the Haikou City tourism Atlas (scale 1:50,000), and in situ surveys (including interviews with local people at UFU boundaries). Finally, using the SPOT 5 images, the boundaries were drawn by on-screen digitization of the images with ArcGIS 10 (Fig. 1). We adopted a stratified random sampling approach following Wang et al. (2016) to span the geographic extent of the city while also spanning the diverse UFUs (6 Primary Urban Functional Units and 16 secondary UFUs, Table 1), especially for UFUs that were spatially underrepresented. Random sampling was not feasible given that we did not know where the sampling sites would be and random selection would have frequently resulted in sites in water or other inaccessible locations. Consequently, we adopted the following two measures to decrease sampling bias. First, our grid sampling covered all urbanized areas of Haikou, ensuring that our sampling covered as many of these areas as possible. Second, we randomly selected one UFU (UFUs) in each 1 × 1 km grid to avoid repetition (Fig. 1).

2.3. Land cover classification and interpretation

We adopted the land cover classification system used by Cadenasso et al (2007), which is called High Ecological Resolution Classification for Urban Landscapes and Environmental Systems (HERCULES). The system not only has greater spatial resolution, but also refines urban landscape characterization of ecological features. We used an Object-Based Image Analysis (OBIA) approach to interpret the Land-Use/Land-Cover (LULC) map in Haikou; this approach includes segmentation and classification. OBIA groups the pixels into homogeneous objects with different shapes and sizes, which are used to classify objects. Consequently, the statistics include context, geometry and texture of image objects. The analyst defines statistics in the classification process to determine land cover. We used one SPOT 5 image (four color banded; 10 m resolution) from October 2010 as the main source for LULC classification. We used methods and procedures for interpretation that have been employed in previous studies (Congalton, 1991; Walker and Blaschke, 2008; Wang et al., 2013, 2016), following three established steps. First, we used the outcome of the segmentation process to identify objects for classification (Walker and Blaschke, 2008). Second, we used fuzzy rules and the standard nearest neighbor (SNN) algorithm to identify objects. We then used digital topographic maps, field work, Quick Bird imagery and Google Earth to classify all different LULC types. Third, we manually improved the quality of classification by adjusting the image-based classification based on our field observations and experience/knowledge. In this study, we identified the area for five kinds of land cover types: Trees and shrubs, herbs, water, sand, and Built-up areas. The percentage of samples falling within each LULC type in every UFU was calculated using ArcGIS 10 (ESRI). We compared the reference collection with classified imagery (Congalton, 1991) to evaluate classification accuracy. The overall accuracy of land cover classification using the confusion matrix was 93.37% and the Kappa coefficient was 0.93 (ca. Wang et al., 2013, 2016). We calculated the percentage of each LULC type within every UFU using ArcGIS 10 (ESRI) based on the derived LULC map.

Among the 190 UFUs examined in Haikou, Public Affairs Service Districts made up the most common primary UFU (59, 31.15%) while

Undeveloped Land was the least common primary UFU (3, 1.58%). High-Density Residential Areas were the most common secondary UFU (43, 22.63%), while Supermarkets (or Wastelands) were the least common secondary UFU (3, 1.58%) (Table 1).

2.4. Vegetation surveys

We conducted vegetation surveys using a stratified sampling method for the 190 UFUs examined (Fig. 1). We investigated the urban vegetation within each UFU, examining tree, shrub, and herb layers. A tree was recorded when its diameter at breast height (DBH) was larger than 2 cm. We examined at least three 20 × 20 m tree sampling plots within each UFU, with five 2 × 2 m shrub sample plots and five 1 × 1 m herb plots within the same 20 × 20 m tree plot. The locations of the 20 × 20 m plots within the UFU were determined to capture the highest representative plant species richness and diversity. After surveying each UFU, we selected a 20 × 20 m plot with high representative plant diversity richness and plant cover (i.e., tree, shrub, herb, liana/vine) to conduct our field work. We recorded species identity, DBH (for trees), height, crown width (for trees) and cover (for shrubs and herbs) estimated in square metres. We determined Tree/shrub abundance using the average number of individuals of each tree or shrub species in each plot. The abundance of each herb species was estimated as the cover of herbs in each plot.

2.5. Phylogenetic data

Phylogenetic diversity represents an additional component of diversity that provides valuable information beyond that provided by taxonomic diversity and is important for conservation efforts (Kirkpatrick et al., 2007). As such, we created one phylogenetic tree for our entire species list. First, we used Phylomatic and Phylocom to generate our phylogenetic tree, estimate branch lengths, and calculate phylogenetic metrics (details below). The phylogeny was generated based on the Angiosperm Phylogeny Website (mobot.org/MOBOT/research/apweb/), and the angiosperm phylogeny at mobot.org resolved to family. Phylocom was used to assign ages to each clade based on fossil records (Kirkpatrick et al., 2007). Based on the age of known nodes, the bladj function was used to match the branch length for the entire tree with topological structure.

2.6. Functional data

We collected functional trait data (plant height, wood density, specific leaf area (SLA) from the TRY database (https://www.try-db.org/TryWeb/Home.php). The mean trait value for each species was used when multiple samples existed for a given species. These commonly examined functional traits are considered important traits designating plant function, and consequently have received much general attention, including within urban plant community research (Benson et al., 2012; Knapp et al., 2008) (Table S2).

2.7. Socioeconomic and geographic variables

Socioeconomic variables examined include secondary UFU types: UFU age, housing price, population density, and traffic flow (Table 2). The Secondary UFU type classification was modified from the Urban Forest Effects (UFORE) Model: Field Data Collection Manual. Primary UFUs (6 types) include Public affairs service districts, Industry and Business Districts, Residential Districts, Recreation/Leisure Districts, Transportation, and Undeveloped Land. Secondary Urban Functional Units (16 types) include Governmental Agencies, Colleges/Universities, Primary/Middle Schools, Research Institutes, Hospitals, Industry, Hotels, Industrial Offices, Supermarkets, Low-Density (lower than 6 storeys) Residential Areas, High-Density (higher than 6 storeys) Residential Areas, Parks, Museums, Main/Secondary Roads, Bus Parking, and Wasteland (Table 1).

Table 2
Variables used in this study, $y_{1\text{-}11}$, $x_{1\text{-}12}$ are codes applied in the General Linear Model analyses.

Variables	Secondary variables	Code
Land cover	Trees and shrubs area	y1
	Herb area	y2
	Watery area	y3
	Built-up area	y4
	Sand land	y5
Plant diversity	Tree species	y6
	Shrub species	y7
	Herb species	y8
Phylogenetic diversity	PD	y9
	mpd.obs	y10
	mntd.obs	y11
Socioeconomic variables	Secondary UFU types	x1
	UFU age	x2
	Housing Price	x3
	Population Density	x4
	Traffic flow	x5
Biophysical variables	Longitude	x6
	Latitude	x7
	Area of detail UFU	x8
	Distance from main road (m)	x9
Green management variables	Maintenance times per year	x10
	Fertilizing times/year	x11
	Watering frequency/year	x12

To determine the age of the UFU (in years), first, the year each UFU was established or brought into service/function was obtained using the city portal website or through interviews with people who live or work in specific UFUs. We then subtracted the year of establishment from 2016 to obtain the UFU age that reflected the total length of the UFU's existence. Housing price (Yuan/m^2) was determined using a well-used real estate website for Haikou (http://haikou.anjuke.com/sale/) from October to November in 2015; from this website, we determined the average second-hand housing price for each nearby UFU. Only a few UFUs had no housing price information, and for these we referred to the local housing value evaluation center (i.e., http://www.zplh.net/) and interviewed more than 30 residents to estimate the average and limit bias (Wang et al., 2016). We counted the number of buildings (B), the number of storeys for each building (S) and the number of apartments on each storey (A) within each UFU by visiting each UFU or using Google Earth (http://earth.google.com/). We determined the average family size (M) by referring to the Haikou Statistics Yearbook (HMBS, Haikou Municipal Bureau of Statistics, 2014), and the population (P) of each UFU was determined using the formula: $P = B \times S \times A \times M$. Permanent population density (person/km^2) was determined as P/Ar where Ar is the area of each UFU. Traffic flow was measured as the traffic volume observed each minute on the nearest main road near the UFUs (Wang et al., 2016).

Biophysical variables include latitude, longitude, and area of each specific UFU, as well as the distance from a main road. Latitude and longitude identify the central point of the tree plot in each UFU; area of each specific UFU was determined as the total area taken up by the various categories of land use (Trees and shrubs, Herbs, Water/wetland, Built-up area and Sandy land/beach). Distance from a main road (m) was measured from the tree plot central point to the main road edge.

Green management variables included maintenance times per year, fertilization frequency (per year) and watering frequency (per year); these were determined by interviewing residents. We conducted the survey of socioeconomic and green management variables as follows: first, we asked the property management department of each UFU for the relevant green management variables after explaining that the information (data) they provide will be used for research only and would not be shared. If the UFU did not have a property management department or if the existing one refused our requests, we surveyed residents using questionnaires to gain the required information. Specifically, we designed a questionnaire that included questions about local socioeconomics as well as green management variables adapted from Harlan et al. (2006). We placed these questionnaires in each UFU and promised to reward residents who completed them. We obtained these data from residents who are responsible for determining green management plans, including maintenance frequency, watering times, etc. We interviewed these individuals in the field and adjusted the data according to their responses.

2.8. Data analysis

We calculated Simpson, Shannon and Pielou indices to assess the diversity of plants in each UFU. We calculated these indices using the following formulas:

1 We calculated Species richness (S) as the number of tree or shrub or herb species in each UFU；
2 Simpson diversity index (*D*) (Simpson, 1949):

$$D = 1 - \sum_{i=1}^{S} p_i^2 \quad p_i^2 = \frac{ni(ni-1)}{N(N-1)}$$

3 Shannon diversity index (e-base) *He′* (Shannon, 1948):

$$He' = -\sum_{i=1}^{S} p_i lnPi$$

4 Pielou evenness index (*Je*) (Pielou, 1966):

$$Je = \frac{He'}{H\max'}$$

In the above formulae, S refers to the number of species in each UFU; $P_i = n_i/N$, where n_i refers to the number of an individual species I, N is the total number of species, while $H'_{\max}$ refers to the maximum Shannon diversity. When $D = 0$, it means there were no species in the sampling plot. To estimate local functional diversity, we selected height, wood density, and specific leaf area (SLA) as functional traits. Then, we range-standardized these traits (standardizing to mean zero and unit variance), and calculated functional dispersion (FDis), which assesses functional trait diversity within a plant community using different species abundances (Pielou, 1966). To determine local phylogenetic diversity for each UFU, we calculated abundance-weighted MPD (Mean Phylogenetic Distance) and the abundance-weighted MNTD (Mean Nearest Taxon Distance). MPD refers to the mean distance between all plant species within the same community. MNTD refers to the mean distance between every species and its closest relative in the same community, and it measures phylogenetic similarity between co-occurring species. The number of species varies between communities, affecting the value of MPD and MNTD. In this study, we report both MNTD and MPD results. Phylogenetic diversity is lower than expected (underdispersion/clustering) when $p < 0.025$, and phylogenetic diversity is considered greater than expected when $p > 0.975$. Importantly, research has indicated that ecosystems characterized by higher phylogenetic diversity (i.e., overdispersed), are more stable (Cadotte et al., 2012).

The Simpson, Shannon and Pielou indices for tree, shrub, and herb species were compared among the 16 secondary UFU types. We compiled plant traits and socioeconomic variables for each UFU. Using Minitab 16 (Minitab, Inc.), we tested all the residuals of a model for all variables with a D-test (Kolmogorov-Smirnov test) and a W-test (Shapiro-Wilk test) to determine whether or not they were normally distributed. If the variables were not normally distributed, a Johnson transformation was applied to ensure that variables approached a normal distribution. These transformations were required for the following biological variables: total species richness, tree species richness, shrub species richness, herb species richness. Transformations were also necessary for the following socioeconomic variables: UFU age, housing price, population density, traffic flow, longitude, latitude, area of secondary UFU, distance from main road (m), maintenance times per year, fertilization frequency per year, watering frequency per year. A Pearson's correlation was used to test for highly correlated explanatory variables; if a pair of variables were correlated with $R > 0.5$ (R is the correlation coefficient), we excluded one of the variables. We use the Duncan multiple comparisons test In SPSS Statistics software (ver. 17.0, IBM Corporation, New York, USA, Aug., 2008) to make sure there was a significant difference between average land cover and plant diversity among different UFUs.

The relationships between land cover, species diversity, phylogenetic diversity, and socioeconomic variables were analyzed using a multiple General Linear Model (GLM) with stepwise selection in R (Posada, 2008). First, we constructed simple GLMs with one explanatory variable and one response variable. Then, we conducted a multiple GLM, including all explanatory variables that tended towards significance (*p*-values < 0.1) in the simple GLMs. For cases where no explanatory variables had $p < 0.1$, no multiple GLM was conducted. Finally, we conducted stepwise selection for each multiple GLM. For each multiple GLM, the model with the lowest Akaike Information Criterion (AIC) was adopted.

3. Results

3.1. Land cover in different secondary urban functional units

Areas of barren land (e.g. beach) are strongly influenced by human activities (e.g. reclamation for real estate development in Haikou) and can therefore change rapidly over time. Consequently, we did not consider these lands in our study. Parks have the largest Trees and shrubs area (28.03 ± 33.04 ha, n = 7), significantly higher than the forest area of the other 14 secondary UFUs. The area with Trees and shrubs in Parks is also significantly higher in Low-Density Residential Areas. The difference in Sand land area between Main/Secondary Roads, High-Density Residential Areas, and Parks is not significant (Table 3). Among secondary UFU types, Hotels had the lowest area covered by trees and shrubs (0.04 ± 0.09 ha, n = 11). The secondary UFUs with the greatest coverage of herbs was Colleges/Universities (1.33 ± 1.37 ha, n = 7) while those with the lowest coverage of herbs were Bus Parking Lots (0 ha) and Supermarkets (0 ha). Among secondary UFUs, Parks contained the largest area with water 3.27 ± 7.98 ha, n = 7, while Supermarkets, Bus Parking, Main/Secondary Roads, Hotels, Research Institutes, as well as Primary/Middle Schools contained no areas with water. The most Built-up areas were Low-Density Residential Areas (22.68 ± 10.43 ha, n = 5), and the least Built-up areas were Research Institutes (0.39 ± 0.50 ha, n = 4) (Table 3, Fig. 2).

3.2. Plant taxonomic diversity

There was no significant difference in tree species richness and taxonomic diversity indices among UFUs in Haikou. The highest tree species richness was found in Colleges/Universities (5.29 ± 2.06, n = 7) while the lowest was found in UFUs classified as Main/Secondary Roads (2.85 ± 1.28, n = 28). The highest and lowest Simpson index values were found in Bus Parking (0.37 ± 0.12, n = 5) and Parks (0.27 ± 0.04, n = 7) respectively and the highest and lowest Shannon indices for trees were in Colleges/Universities (1.35 ± 0.29, n = 7) and Parks (0.98 ± 0.19, n = 7), respectively. Based on the Pielou index, the highest tree evenness was observed in Parks (0.93 ± 0.05, n = 7) while the lowest was in Colleges/Universities (0.80 ± 0.08, n = 7). Shrub species richness was highest in Parks (2.26 ± 0.46, n = 7) and lowest in UFUs classified under Industry (1.04 ± 0.50, n = 12) (Table 4).

Table 3
The average land cover (i.e. Trees and shrubs area, Herb area, Water area, Built-up area and Sand land,) in each Urban Functional Units (area in hectares).

Secondary UMT	Trees and shrubs area (ha)	Herb area (ha)	Water area (ha)	Built-up area (ha)	Sand land (ha)
Industry	2.94 ^{a} ± 3.21	0.15 ^{a} ± 0.41	0.02 ^{a} ± 0.04	8.51 ^{a} ± 19.14	0
Low-Density Residential Areas	8.24 ^{ab} ± 5.61	0.12 ^{a} ± 0.12	2.28 ^{bc} ± 2.49	22.68 ^{b} ± 10.43	0
Main/Secondary Roads	0.05 ^{a} ± 0.15	0.01 ^{a} ± 0.04	0	1.11 ^{a} ± 1.05	0.04 ^{a} ± 0.21
Industrial offices	0.89 ^{a} ± 1.01	0.01 ^{a} ± 0.02	0.02 ^{a} ± 0.03	2.23 ^{a} ± 2.61	0
Supermarkets	0.33 ^{a} ± 0.57	0	0	0.93 ^{a} ± 0.98	0
Research Institutes	0.40 ^{a} ± 0. 25	0.25 ^{a} ± 0.50	0	0.39 ^{a} ± 0.50	0
Bus Parking	0.66 ^{a} ± 1.30	0	0	1.91 ^{a} ± 0.88	0
High-Density Residential Areas	1.34 ^{a} ± 2.07	0.04 ^{a} ± 0.10	0.11 ^{a} ± 0.42	3.30 ^{a} ± 3.24	0.13 ^{a} ± 0.61
Governmental Agencies	1.42 ^{a} ± 3.34	0.10 ^{a} ± 0.36	0.03 ^{a} ± 0.10	2.87 ^{a} ± 4.32	0
Colleges/Universities	16.90 ^{b} ± 29.59	1.33 ^{b} ± 1.37	1.27 ^{ab} ± 3.21	20.49 ^{b} ± 27.11	0
Primary/Middle Schools	1.60 ^{a} ± 2.95	0.42 ^{a} ± 0.73	0	3.18 ^{a} ± 3.39	0
Hotels	0.04 ^{a} ± 0.09	0.03 a ± 0.08	0	1.15 ^{a} ± 1.12	0
Hospitals	0.85 ^{a} ± 1.59	0.02 ^{a} ± 0.06	0.02 ^{a} ± 0.04	3.73 ^{a} ± 4.92	0
Museums	1.70 ^{a} ± 2.60	0.03 ^{a} ± 0.03	0.04 ^{a} ± 0.05	4.34 ^{a} ± 6.87	0
Parks	28.03 ^{c} ± 33.04	0.23 ^{a} ± 0.53	3.27 ^{c} ± 7.98	7.32 ^{a} ± 14.51	0.45 ^{a} ± 0.99

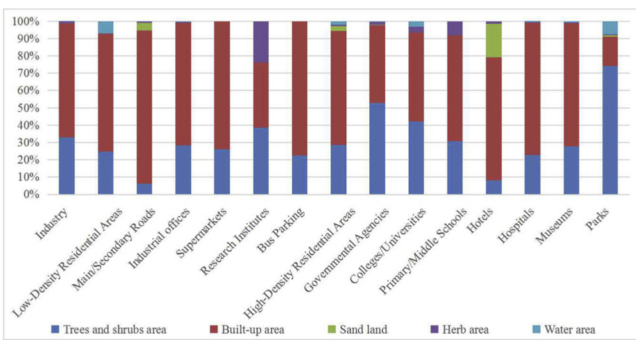

Fig. 2. Land cover of each secondary Urban Functional Unit in urbanized areas of Haikou, China.

There was no significant difference in shrub species richness and taxonomic diversity indices among UFUs in Haikou. Based on the Simpson index, shrub diversity was also highest in Parks (0.39 ± 0.02, n = 7) and was lowest at Research Institutes (0.17 ± 0.14, n = 4). Shannon diversity for shrubs was highest at Hospitals (0.92 ± 0.16, n = 12) and lowest in Low-Density Residential Areas (0.61 ± 0.36, n = 5). The evenness of shrub cover among species (Pielou index) was highest at Bus Parking (0.99 ± 0.02, n = 5) and lowest in Low-Density Residential Areas (0.79 ± 0.44, n = 5) (Table 4).

There was no significant difference in herb species richness and taxonomic diversity indices among UFUs in Haikou. For herb species, different patterns emerged for the different indices. Herb richness was highest in Parks (4.68 ± 1.63, n = 5) and lowest in Hotels (1.40 ± 0.52, n = 11) while the Simpson Index for herbs was highest for Hotels (0.45 ± 0.04, n = 11) and lowest for Supermarkets (0.26 ± 0.23, n = 3). Herb diversity assessed using the Shannon index was highest at Museums (1.08 ± 0.29, n = 5) and lowest at Supermarkets (0.67 ± 0.58, n = 3) while evenness for herbs was highest in Hotel UFUs (0.95 ± 0.06, n = 11) and lowest at Supermarkets (0.56 ± 0.49, n = 3) (Table 4, Fig. 3).

3.3. Plant phylogenetic diversity

There was no significant difference in phylogenetic diversity indices among UFUs in Haikou. Phylogenetic diversity did not peak in the same UFUs as taxonomic diversity indexes. Phylogenetic diversity was the highest at Hospitals (1309.77 ± 447.31, n = 12) and lowest at Main/Secondary Roads (993.42 ± 211.77, n = 28) and the greatest MPD was associated with Colleges/Universities (237.63 ± 38.86, n = 7) while the lowest was associated with Parks (140.08 ± 66.21, n = 7). The highest MNTD values were associated with Primary/Middle Schools (232.50 ± 40.53, n = 18) while the lowest values were found at Supermarkets (151.23 ± 58.04, n = 3) (Table 4).

In the MPD analyses, phylogenetic diversity was significantly greater than expected by chance in Low-density Residential Areas, Museums, Main/Secondary Roads, Governmental Agencies and High-Density Residential Areas (i.e. P2, N11, L1, G14, K5, O5) (mpd.obs. $p >$ 0.975). Conversely, phylogenetic diversity was lower than expected by chance (i.e., underdispersed) in Industrial Offices and Supermarkets (i.e. G11, O8, N9) (mpd.obs.$p < 0.025$) (Figs. 4, S4). Aside from these examples, no significant patterns of phylogenetic over- or underdispersion (i.e. clustering) were observed (Table 4).

3.4. Phylogenetic signal in traits

No obvious evidence of phylogenetic signal was found for our four functional traits (i.e. maximum height, photosynthetic pathway (C3, C4, CAM), wood density and specific leave area). Therefore, phylogenetic and functional trait diversity are not clearly correlated for the species in this study and therefore represent complementary measures of diversity (Appendix S6, S7 and S8).

3.5. Relationships between land cover or plant diversity and its driving forces

Secondary UFU types differed significantly with respect to several vegetation attributes; for example, Low-Density Residential Areas differed significantly from Parks in the area of trees and shrubs; the area of trees and shrubs in D16 (Low-Density Residential Area) extended up to a maximum of 15.12 ha. Coverage of herbs also differed significantly between some secondary UFU types; for example, between Colleges/Universities and Primary/Middle Schools, the area covered by herbs in K16 (Colleges/Universities) was up to 3.74 ha. Finally, the amount of Built-up area significantly differed among secondary UFU types, e.g., Low-Density Residential Areas and in Parks (Table 4).The Built-up area in D16 (Low-Density Residential Area) was as high as 36.34 ha.

The number of tree species significantly differed among several Secondary UFU types, although they did not significant differ among Colleges/Universities, Low-Density Residential Areas, and Museums. Shrub species richness was significantly different among parks. Herb species richness was significantly different among Secondary UFU types (e.g. Parks, Colleges/Universities and Low-Density Residential Areas). Phylogenetic diversity was significantly different among secondary UFU types (e.g., Colleges/Universities, Hospitals, and Low-Density Residential Areas; Table 5).

Most land cover and plant diversity variables were significantly correlated with the area of the specific secondary UFU, including UFU age and housing price. Only a few variables (e.g. tree species MPD and PD) were correlated with maintenance times or watering frequency per

Table 4
The average Plant richness, Simpson, Shannon, Pielou, phylogenetic diversity, MPD and MNTD in each Urban Functional Units.

Secondary UMT	Tree species	Simpson index of tree	Shannon index(e-base) of tree	Pielou eveness(J)of tree	Shrub species	Simpson index of shrub	Shannon index(e-base) of shrub	Pielou eveness(J) of shrub	Herb species	Simpson index of Herb	Shannon index(e-base) of herb	Pielou eveness(J) of herb	PD	mpd.obs	mntd.obs
Industry	3.50 ^{a} ± 2.47	0.36 ^{b} ± 0.08	1.12 ^{ab} ± 0.33	0.85 ^{ab} ± 0.11	1.04 ^{a} ± 0.50	0.19 ^{a} ± 0.14	0.67 ^{ab} ± 0.26	0.87 ^{ab} ± 0.33	1.46 ^{a} ± 0.70	0.38 ^{ab} ± 0.15	0.77 ^{ab} ± 0.31	0.82 ^{ab} ± 0.31	1109.21 ^{a} ± 425.25	185.43 ^{ab} ± 67.61	208.30 ^{abc} ± 51.28
Low-Density Residential Areas	3.60 ^{a} ± 2.30	0.27 ^{a} ± 0.13	1.17 ^{ab} ± 0.36	0.90 ^{ab} ± 0.10	1.33 ^{abc} ± 1.38	0.24 ^{ab} ± 0.17	0.61 ^{a} ± 0.36	0.79 ^{a} ± 0.44	2.33 ^{a} ± 1.20	0.39 ^{ab} ± 0.07	1.01 ^{ab} ± 0.25	0.90 ^{b} ± 0.08	1026.71 ^{a} ± 288.11	186.78 ^{ab} ± 49.36	192.98 ^{abc} ± 49.33
Main/Secondary Roads	2.85 ^{a} ± 1.28	0.36 ^{b} ± 0.06	1.09 ^{ab} ± 0.23	0.87 ^{ab} ± 0.08	1.26 ^{abc} ± 0.45	0.27 ^{ab} ± 0.16	0.77 ^{abc} ± 0.19	0.92 ^{ab} ± 0.20	1.49 ^{a} ± 0.94	0.38 ^{ab} ± 0.16	0.75 ^{ab} ± 0.32	0.80 ^{ab} ± 0.32	993.42 ^{a} ± 211.77	211.09 ^{ab} ± 77.90	214.46 ^{bc} ± 47.52
Industrial offices	3.50 ^{a} ± 1.41	0.33 ^{ab} ± 0.06	1.22 ^{ab} ± 0.25	0.87 ^{ab} ± 0.07	1.41 ^{abc} ± 0.39	0.38 ^{b} ± 0.05	0.82 ^{bc} ± 0.15	0.96 ^{ab} ± 0.05	1.94 ^{a} ± 0.83	0.39 ^{ab} ± 0.04	0.97 ^{ab} ± 0.11	0.89 ^{b} ± 0.07	1165.13 ^{a} ± 256.39	179.95 ^{ab} ± 43.38	168.39 ^{ab} ± 42.68
Supermarkets	3.67 ^{a} ± 0.58	0.34 ^{ab} ± 0.02	1.16 ^{ab} ± 0.16	0.86 ^{ab} ± 0.05	2.06 ^{cd} ± 0.82	0.36 ^{b} ± 0.06	0.92 ^{c} ± 0.11	0.89 ^{ab} ± 0.10	1.67 ^{a} ± 1.53	0.26 ^{a} ± 0.23	0.67 ^{a} ± 0.58	0.56 ^{a} ± 0.49	1023.16 ^{a} ± 322.58	163.27 ^{ab} ± 53.85	151.23 ^{a} ± 58.04
Research Institutes	4.00 ^{a} ± 1.15	0.31 ^{ab} ± 0.03	1.29 ^{ab} ± 0.16	0.82 ^{a} ± 0.04	1.40 ^{abc} ± 0.43	0.17 ^{a} ± 0.14	0.83 ^{bc} ± 0.15	0.98 ^{b} ± 0.03	1.83 ^{a} ± 1.31	0.45 ^{b} ± 0.06	0.84 ^{ab} ± 0.22	0.87 ^{b} ± 0.16	1170.84 ^{a} ± 221.43	142.82 ^{a} ± 70.67	211.32 ^{bc} ± 55.96
Bus Parking	4.50 ^{a} ± 2.65	0.37 ^{b} ± 0.12	1.14 ^{ab} ± 0.52	0.90 ^{ab} ± 0.12	1.18 ^{ab} ± 0.24	0.33 ^{ab} ± 0.14	0.74 ^{abc} ± 0.06	0.99 ^{b} ± 0.02	1.50 ^{a} ± 0.79	0.45 ^{b} ± 0.06	0.82 ^{ab} ± 0.15	0.88 ^{b} ± 0.14	1036.45 ^{a} ± 173.15	180.53 ^{ab} ± 64.83	171.11 ^{ab} ± 19.33
High-Density Residential Areas	4.58 ^{a} ± 2.71	0.32 ^{ab} ± 0.05	1.28 ^{ab} ± 0.29	0.83 ^{ab} ± 0.08	1.44 ^{abcd} ± 0.35	0.29 ^{ab} ± 0.10	0.82 ^{bc} ± 0.09	0.96 ^{ab} ± 0.03	2.04 ^{a} ± 1.15	0.39 ^{ab} ± 0.08	0.95 ^{ab} ± 0.28	0.87 ^{b} ± 0.16	1213.44 ^{a} ± 305.83	224.72 ^{ab} ± 73.94	203.14 ^{abc} ± 40.01
Governmental Agencies	3.50 ^{a} ± 1.83	0.34 ^{ab} ± 0.06	1.18 ^{ab} ± 0.25	0.84 ^{ab} ± 0.07	1.58 ^{abcd} ± 1.07	0.29 ^{ab} ± 0.12	0.77 ^{abc} ± 0.11	0.96 ^{b} ± 0.05	1.64 ^{a} ± 1.20	0.39 ^{ab} ± 0.13	0.82 ^{ab} ± 0.32	0.87 ^{b} ± 0.26	1054.89 ^{a} ± 267.87	217.97 ^{ab} ± 89.78	206.96 ^{abc} ± 46.95
Colleges/ Universities	5.29 ^{a} ± 2.06	0.32 ^{ab} ± 0.05	1.35 ^{b} ± 0.29	0.80 ^{a} ± 0.08	1.31 ^{abc} ± 0.34	0.29 ^{ab} ± 0.10	0.79 ^{abc} ± 0.11	0.97 ^{b} ± 0.03	2.05 ^{a} ± 0.96	0.41 ^{b} ± 0.06	0.95 ^{ab} ± 0.20	0.92 ^{b} ± 0.07	1279.80 ^{a} ± 347.88	237.63 ^{b} ± 38.86	209.44 ^{bc} ± 63.80
Primary/Middle Schools	3.28 ^{a} ± 1.67	0.35 ^{ab} ± 0.05	1.13 ^{ab} ± 0.23	0.85 ^{ab} ± 0.08	1.34 ^{abc} ± 0.44	0.31 ^{ab} ± 0.12	0.74 ^{abc} ± 0.11	0.96 ^{ab} ± 0.07	1.64 ^{a} ± 0.96	0.38 ^{ab} ± 0.15	0.78 ^{ab} ± 0.32	0.81 ^{ab} ± 0.30	1075.06 ^{a} ± 269.87	195.17 ^{ab} ± 57.41	232.50 ^{c} ± 40.53
Hotels	4.00 ^{a} ± 2.35	0.32 ^{ab} ± 0.05	1.21 ^{ab} ± 0.26	0.85 ^{ab} ± 0.10	1.39 ^{abc} ± 0.48	0.29 ^{ab} ± 0.14	0.80 ^{bc} ± 0.13	0.97 ^{b} ± 0.04	1.40 ^{a} ± 0.52	0.45 ^{b} ± 0.04	0.79 ^{ab} ± 0.12	0.95 ^{b} ± 0.06	1076.52 ^{a} ± 238.73	178.74 ^{ab} ± 25.84	226.13 ^{bc} ± 49.99
Hospitals	4.40 ^{a} ± 2.37	0.33 ^{ab} ± 0.06	1.24 ^{ab} ± 0.31	0.81 ^{a} ± 0.08	1.85 ^{abcd} ± 0.83	0.28 ^{ab} ± 0.10	0.92 ^{c} ± 0.16	0.93 ^{ab} ± 0.05	1.83 ^{a} ± 0.69	0.42 ^{b} ± 0.04	0.90 ^{ab} ± 0.13	0.90 ^{b} ± 0.07	1309.77 ^{a} ± 447.31	197.45 ^{ab} ± 86.53	195.10 ^{abc} ± 36.21
Museums	3.52 ^{a} ± 2.12	0.34 ^{ab} ± 0.09	1.09 ^{ab} ± 0.28	0.83 ^{ab} ± 0.14	1.92 ^{bcd} ± 2.24	0.31 ^{ab} ± 0.14	0.73 ^{abc} ± 0.09	0.96 ^{ab} ± 0.09	3.70 ^{b} ± 3.47	0.39 ^{ab} ± 0.07	1.08 ^{b} ± 0.29	0.82 ^{ab} ± 0.13	1053.16 ^{a} ± 348.99	212.51 ^{ab} ± 132.49	193.40 ^{abc} ± 62.09
Parks	4.01 ^{a} ± 0.80	0.27 a ± 0.04	0.98 ^{a} ± 0.19	0.93 ^{b} ± 0.05	2.26 ^{d} ± 0.46	0.39 ^{b} ± 0.02	0.91 ^{c} ± 0.06	0.87 ^{ab} ± 0.03	4.68 ^{b} ± 1.63	0.39 ^{ab} ± 0.02	1.07 ^{b} ± 0.11	0.71 ^{ab} ± 0.09	1006.73 ^{a} ± 289.23	140.08 ^{a} ± 66.21	190.67 ^{abc} ± 41.91

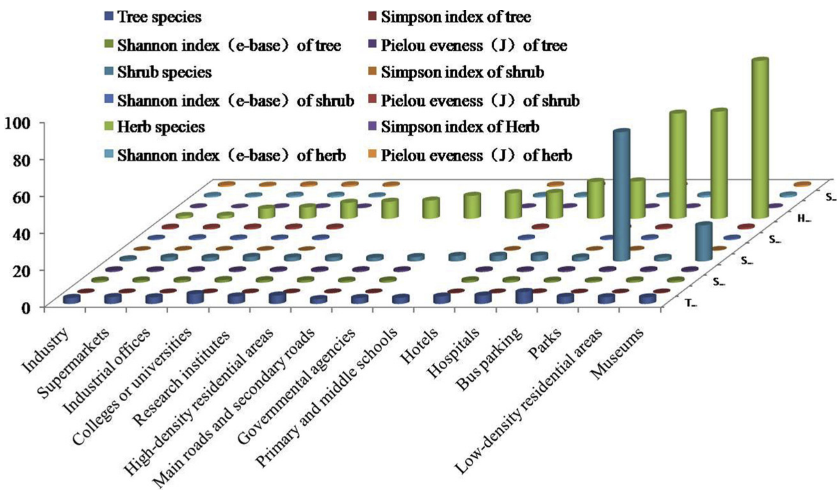

Fig. 3. Tree, shrub, and herb species richness, diversity (Simpson, Shannon) and evenness (Pielou) for the 16 different secondary Urban Functional Units in Haikou, China. Wastelands are not shown.

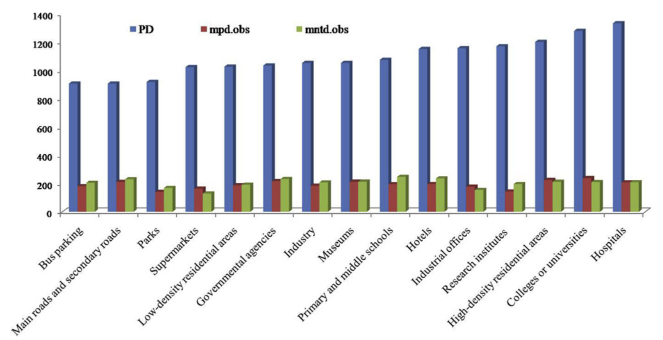

Fig. 4. Phylogenetic diversity (PD), mean phylogenetic distance (MPD) and the abundance-weighted mean nearest taxon distance (MNTD) for the 16 different secondary Urban Functional Units in Haikou, China. Wastelands are not shown.

year (Greening management variables) (Table 5).

The coverage of trees and shrubs, and herbs was strongly positively correlated with house price and population density, while tree/shrub and herb species richness is strongly correlated to fertilization frequency and maintenance frequency, while PD, MPD and MNTD were correlated to other variables (such as watering frequency, traffic flow etc.) (Figs. 5, S9)

4. Discussion

4.1. Pattern of land cover within urban functional units in Haikou

This study indicates that the land area covered by trees and shrubs is highest in Parks and lowest in UFUs designated as Main/Secondary Roads; this finding reflects the simply reality that Parks are planted with trees for tourism and/or shade, while trees and shrubs are mainly distributed at the sides of roadways. In Haikou, the percentage of Built-up areas was highest in Low-Density Residential Areas and lowest at Research Institutes (Table 3, Fig. 2). This, however, is different from the Built-up areas in the UFUs in urbanized areas of Beijing. Wang et al. (2013) found that the percentage of Built-up areas is highest in UFUs designated as Hotels in Beijing, most likely to maximize profit through reduced spending on green management practices compared to an increased area for hotel rooms. This study indicated that cities differ in land cover even within equivalent UFUs. Inevitably, this results from different regional priorities. For example, local context will determine the extent to which greening is used to develop tourism in more Built-up areas.

4.2. Driver of urban land cover changes in Haikou

Using quantitative data to understand how vegetation patterns change with land-use variation can help us understand what drives urban structure and functional evolution (Pickett et al., 2001). Zhang (2010) applied an Analytic Hierarchy Process (AHP) to determine what factors drive domestic urban vegetation patterns and found that socioeconomic factors are the primary drivers of these patterns (54%), while natural factors play a secondary role (28%), and stress on vegetation from human interference plays a less prominent but still significant role (18%). In the context of China's urban construction, macroeconomic policies play an important role in driving patterns in urban vegetation. For example, the Urban Gardening and Greening Bureau regulates the percentage of urban green space, which has resulted in recent increases in green space. However, at the UFU scale within a city (e.g. Chicago, USA), the habits of urban dwellers, education levels, income, and other socioeconomic factors influence the prevalence of green space and species diversity significantly (Hope et al., 2003; Zhang, 2010; Wang et al., 2013, 2016; Zhu et al., 2019). In this study, we found that the housing prices associated with different UFUs were strongly associated with the amount of green space and plant diversity in UFUs (Table 5). This link highlights socioeconomic influences on urban land cover and plant diversity in Haikou tropical urban ecosystems. Our study determined that land cover and plant diversity variables were positively correlated with the area of UFUs, UFU age, and housing prices in most UFUs. Only a few variables (e.g. tree species richness, MPD and PD) were positively correlated with maintenance times or watering frequency per year (green management measures) (Table 5), which echoes the results of Zhang (2010). In Haikou, socioeconomics appear to play more important roles in affecting the prevalence of green space and plant diversity than do human greening management measures.

4.3. Drivers of urban plant taxonomic diversity in Haikou

There are great differences between American and Chinese studies on cities. There are several researchers conducting urban ecology studies on American cities (Harlan et al., 2006, https://shesc.asu.edu/research/research-topic/phoenix-area-social-survey). Those studies have access to reliable socioeconomic data (e.g. income, population, education level) collected at a finer scale [e.g. Data from the National Aeronautics and Space Administration (NASA), Fink et al., 2003, or companies such as Nielsen and its PRIZM geo-demographic segments for the United States (Grove et al., 2006)]. These are important variables that affect urban plant diversity (Grove et al., 2006). Researchers

Table 5
Relationships between variables and its potential affecting factors based on General Linear Models (GLMs), nm = not in the model.

		Trees and shrubs area	Herb area	Water area	Built-up area	Sand land	Tree species	Shrub species	Herb species	PD	mpd.obs	mntd.obs
Socioeconomic variables	Secondary UFU types	0.006897 ** in Low-Density Residential Areas, 0.000209 *** in parks	3.68e-08 *** in Colleges/ Universities, 0.02252 * in Primary/Middle Schools	nm	0.00883 ** in Low-Density Residential Areas, 0.00202 ** in parks	0.02245 * in parks	At least significant except Colleges/ Universities, Low-Density Residential Areas and Museums	< 2e-16 *** in parks	4.20e-15 *** in parks, * in Colleges/ Universities and Low-Density Residential Areas	0.00882 ** in Colleges/ Universities, * in Hospitals and Low-Density Residential Areas	0.08778. in Colleges/ Universities	nm
	UFU age	0.182891	0.12233	nm	0.12997	nm	0.117114	0.00971 **	nm	0.05992.	0.11146	nm
	Housing Price	nm	0.00063 ***	0.00229 **	0.05061.	0.00528 **	nm	nm	6.27e-10 ***	nm	0.14499	nm
	Population Density	nm	0.01920 *	nm	nm	nm	nm	nm	nm	nm	nm	0.1302
	Traffic flow	nm	nm	nm	nm	0.13072	nm	nm	nm	nm	nm	nm
Biophysical variables	Longitude	0.148879	0.04309 *	nm	nm	nm	nm	nm	nm	nm	nm	nm
	Latitude	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm
	Area of detail UMT	< 2e-16 ***	8.94e-08 ***	< 2e-16 ***	< 2e-16 ***	0.07154.	0.086883.	nm	5.19e-15 ***	0.00249 **	0.05767.	0.0322 *
	Distance from main road(m)	nm	nm	nm	nm	nm	0.072760.	nm	nm	nm	nm	nm
Greening management variables	Maintenance times per year	nm	nm	nm	nm	nm	3.47e-07 ***	0.05820.	nm	1.16e-06 ***	nm	0.0942.
	Fertilizing times/year	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm
	Watering frequency/year	nm	nm	nm	nm	nm	nm	nm	nm	nm	0.00540 **	0.0559.
GLM features	Minimum Akaike information criterion	4524.4	3600.9	4044.7	4568.4	3646.1	804.56	1437.1	2151.3	2644.1	2052.5	2061.5
	Estimate	−2.35E+03	3.72E+03	1.97E+03	−1.11E+04	−3.83E+02	6.16E+00	−3.15191	8.65E+01	7.43E+02	1.22E+02	2.04E+02
	Std. Error	1.87E+04	1.67E+03	1.67E+03	2.23E+04	2.08E+03	1.10E+00	5.12369	3.43E+01	1.34E+02	4.09E+01	1.52E+01
	t -value	−0.125	2.229	1.176	−0.497	−0.185	5.576	−0.615	2.527	5.548	2.988	13.42
	$Pr(>\|t\|)$	0.900431	0.02713 *	0.24125	0.62011	0.85377	9.65e-08 ***	0.53927	0.0124 *	1.10e-07 ***	0.00325 **	< 2e-16 ***

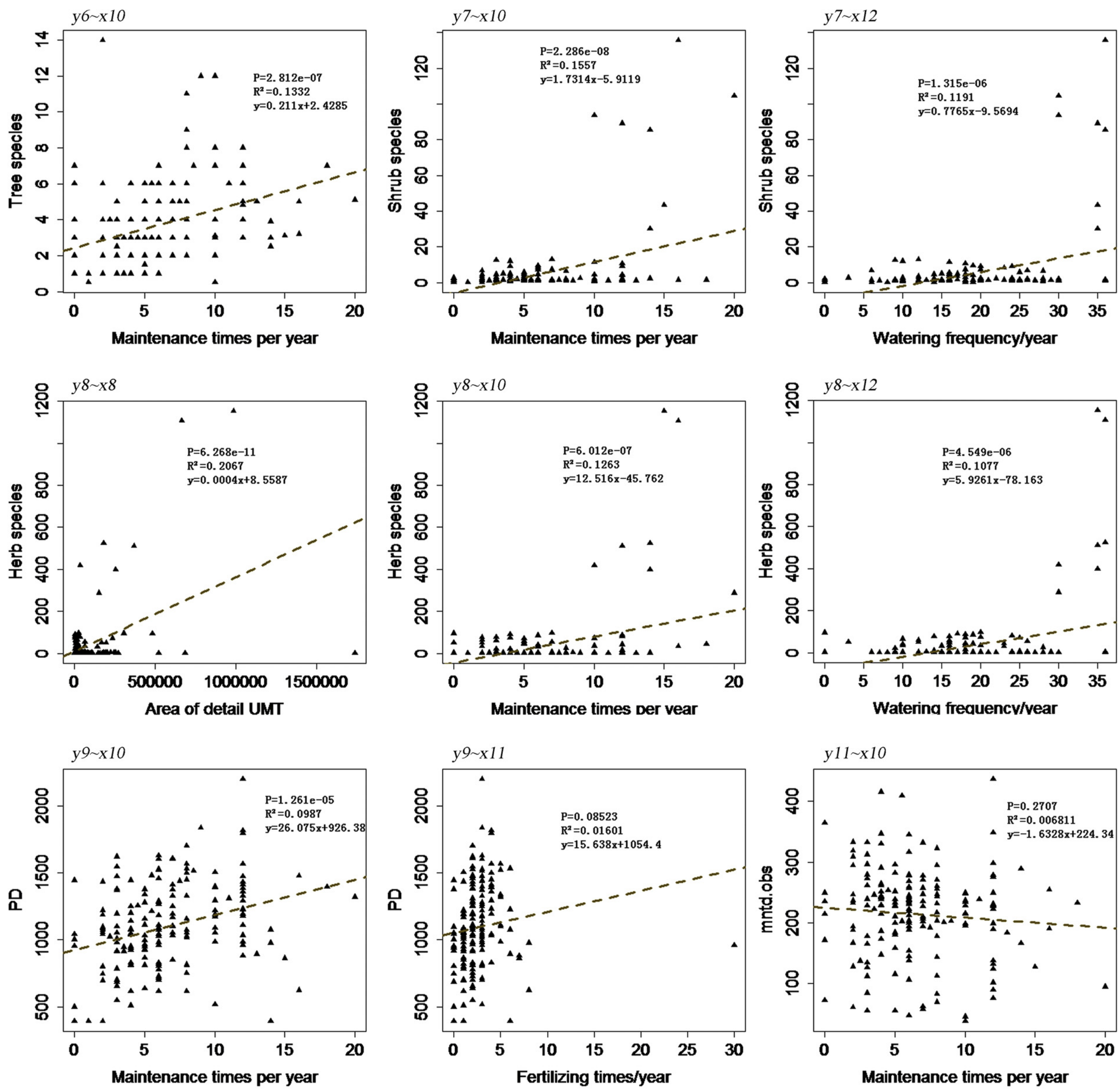

Fig. 5. Linear correlations between tree/shrub areas, herb areas, tree/shrub, herb species richness, phylogenetic diversity (PD), mean phylogenetic distance (MPD), the abundance-weighted mean nearest taxon distance (MNTD), and housing price, population density, fertilization frequency, and maintenance frequency.

currently do not have access to similar high-resolution socioeconomic data for Chinese cities. This is due to a series of shortcomings related to the relative infrequency of censuses (every ten years at best), the quality of statistics collected by government agencies, and the reliability of official statistics. For example, we can acquire basic data, such as information about the population of each district in Beijing from the Beijing Statistic Yearbook series. However, we cannot get finer scale statistics that are more useful. There is currently no way, for example, to know how many people are living in a given community, how many of them are foreigners, how old they are, what their education level is, what their income is, and so on. For now, we must instead rely on public data such as housing price to indicate income levels for a particular UFU (Wang et al., 2013; Wang and López-pujol, 2015).

Housing price-to-income ratio refers to the ratio of housing prices to the annual income of urban households and it is an internationally recognized national housing index (Iverson and Cook, 2000). House prices generally reflect the residents' income. In the United States, Iverson and Cook (2000) found that the prevalence of green space was correlated with household density and the family income; they demonstrated that in urban vegetation areas, land cover was significantly correlated with median household income and housing densities. Furthermore, the positive relationships between property status and vegetation or plant diversity have been reported in some other studies (Hope et al., 2003; Guo et al., 2007; Troy et al., 2007; Cook et al., 2012; Wang et al., 2015, 2016; Zhu et al., 2017, 2019). These studies suggest that wealthier residential neighborhoods or communities have more plants species and residents provide more resources and have more time to maintain the vegetation. Wealthy communities may be self-reinforcing, because they attract additional affluent residents. Increasingly affluent residents result in a larger tax base that can be allocated to the planning and maintenance of public green space, and may be more attractive to other high-income buyers. In this study, we found analogous patterns; housing prices were positively correlated with the area within a UFU that was covered by trees and shrubs, as well as the diversity of trees, shrubs, and herbs (Table 5). Our results support a consistent association between housing prices and green space that spans both temperate and tropical cities (Wang et al., 2013, 2016), while climate appears to be of little influence (Tables 5, S9).

These patterns are in line with predictions related to the luxury effect; however, it is useful to note that such broad patterns can have complex underlying causes reflecting other influences including educational, cultural, and gender-based preferences in addition to economic ones (Escobedo et al., 2006; Conway and Hackworth, 2007).

4.4. Drivers of Urban plant phylogenetic diversity in Haikou

Given the potential benefits of considering phylogenetic relationships in urban plant communities, MacIvor et al. (2016) recommended that ecologists work with landscape architects and other design professionals to test how ecophylogenetics – the application of phylogenies in ecology – might aid in achieving desirable outcomes for green infrastructure. In this study, we found that MPD and PD are positively correlated with maintenance times or watering frequency per year (Green management variables) (Table 5). The number of maintenance times per year is strongly positively associated with PD in this study. Phylogenetic diversity was not significantly higher or lower than expected by chance, except in some UFUs (e.g., Low-Density Residential Areas, Museums, Main/Secondary Roads, Governmental Agencies and High-Density Residential Areas; i.e. P2, N11, L1, G14, K5, O5). Phylogenetic diversity was positively associated with green management practices, which reflected social processes. Would-be residents who are looking for an area to live, are clearly aware that a greater diversity in vegetative form and function is frequently found in locations with more active management, and are seeking such locations out. Greater phylogenetic diversity may simply require greater management; a wide spectrum of different growth forms related to phylogenetic differences may reasonably be expected to require a similar diversity of management practices, and therefore increased management time. However, it is also possible that locations with greater phylogenetic diversity will be more resilient to pests and climatic variation, reducing some long-term management costs (Johnson et al., 2015; MacIvor et al., 2016; Zhu et al., 2019).

5. Conclusions

Our findings highlight significant patterns in the urban distribution of plant diversity in the tropical city of Haiku, China. The patterns observed may indicate long-term urban legacy effects and plant adaptations to specific disturbances over the course of centuries such as those observed in other regions of the world with a long history of urbanization. This study's approach can be used to prescriptively design appropriate urban plant community assemblages as part of green infrastructure practices. Phylogenies of existing urban plants could be used to assess the suitability of proposed urban plant species as part of landscape designs. Species from the same genus or its relatives have the same or similar characteristics (e.g. attractive flowers and long flowering periods). This can inform the pursuit of wild sister species for urban areas based on desirable characteristics and relatedness. For example, *Terminalia catappa* originated in Madagascar, eastern India, the Andaman Islands, and the Malay Peninsula. Because of its large shade leaves and branches, drought-resistance, tolerance of infertile soil, resistance to typhoons, and beautiful growth form, it was widely planted in Hainan and was a success (Wei, 2001). Based on phylogeny, we speculate that *Terminalia catappa*'s close relative *Terminalia neotaliala* would have similar characteristics, and could be widely planted in Hainan. This prediction resulted in the planting of *Terminalia neotaliala* in Hainan (Luo et al., 2012); now both *Terminalia* species are widely cultivated as beautiful street trees in Haikou City.

Future comparative research using our approach to study other cities, as well as the use of standardized field data protocols, could shed light on how to address problems like urban homogenization and invasive species in urban settings, and can help planners to find new species to plant that have appropriate phylogenetic adaptations. We encourage the examination of phylogenetic relationships between trees planted as part of urban greening initiatives; closely related species might share the same desirable features (e.g. drought-resistance, tolerance of infertile soil, resistance to typhoons).

Author contributions

H.F.W. designed the research and wrote the manuscript; Z.X.Z and X.L.C performed experiments; B.S. and J.X.Q. also contributed to write and revise the manuscript. G.Y.C. and H.F.W. created the Fig. 1.

Declaration of Competing Interest

The authors declare no competing financial interests.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ufug.2019.126395.

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