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Trade-Offs in Plant Functional Traits Driven by Soil Changes under Urban Hardened Surfaces

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Abstract: The large-scale surface hardening has changed the urban environment and affected the normal growth of urban plants. However, it is still unclear how the urban hardened surface affects the functional urban plant traits. To explore whether the urban hardened surface affects the ecological strategies of plants by changing the urban soil properties and reflecting them on the plant traits, we studied the physical and chemical properties and plant functional traits of three different types of hardened surface in Shandong Province, China. Our results showed that the physical and chemical properties (soil bulk density, soil total porosity, capillary porosity, non-capillary porosity, soil moisture content, pH, organic carbon, total nitrogen, total phosphorus, total potassium, available phosphorus, and available potassium) of urban soils showed obvious differences with the increase of hardening strength. In this case, the plant functional traits (branch diameter, branch length, leaf thickness, branch weight, internode length, leaf dry weight, leafing intensity, leaf area, specific leaf area, and leaf dry matter content) were also differentiated to varying degrees. Meanwhile, there was a strong correlation among plant functional traits. Nevertheless, hardened surfaces break the quantitative relationship among functional traits of urban trees. They do not affect their stable correlation: as the hardening intensity gradually increases, its correlation weakens. In addition, plant functional traits have a significant response mechanism to soil physicochemical properties. There was a transformation of plant resource utilization strategy by changing plant functional traits to adapt to the hardened environment. Urban trees exhibit strong and rapid resource-allocation strategies. They are mainly reflected in the reduction of branch diameter, branch weight, leaf dry matter content, leaf area, mass ratio of branches and leaves, and the improvement of leafing intensity and leaf thickness. Overall, there were tight connections among urban soil properties, plant branches, and leaves functional properties. This finding reveals that urban trees can change their functional traits and the plasticity of their trait combinations under the background of hardened urban surface expansion, which is conducive to survival and growth.

Keywords: plant functional traits; resource utilization strategy; soil properties; hardened surface



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1. Introduction

The relationship between plant functional traits and environmental and ecosystem functions is a hot topic in ecology and global change research in recent years [1]. The balance and combination of functional traits determine the life history strategy of plants [2]. Among the plant organs, the annual twig is the most dynamic branch of the plant system, and the leaf is the main organ for photosynthesis [3]. The configuration relationship between the size directly affects the mechanical and hydraulic structure traits of the plant, thus determining the life history strategy of the plant [4]. To meet the requirements of the mechanical and hydraulic structure among plant organs, the leaf area supported on the unit-size branches of plants must be in a certain proportion to the cross-sectional area of the supporting branches [3,5]. Therefore, it is helpful to understand the adaptation mechanism of plants to the environment by studying the functional traits of leaves and branches, as well as the changing regularity of their relationship under different environmental gradients.

These interrelated plant traits will show different trade-off strategies in the process of adapting to the environment, such as the trade-off of “investment–income” of resources [6].

In 2023, the urbanization rate of China reached 66.16% (Data from National Bureau of Statistics (CN): <https://www.stats.gov.cn/>, URL (accessed on 4 May 2023), which is in a period of rapid urbanization. The influx of population makes the city expand outward. One of the outstanding manifestations of urban expansion is that the ecological land originally characterized by planting has gradually changed into constructed land mainly with hardened surfaces [7,8]. At present, urban surface hardening has become a serious problem in urban construction. Large-scale surface hardening in cities has changed urban environmental factors, blocked the exchange and circulation of water and gas between soil and atmosphere, and changed the water cycle, heat balance, and nutrient cycle of urban soil [9–11]. At the same time, due to human interference in the process of urban construction, the physical and chemical properties of urban soil have changed greatly compared with natural soil, and the coverage of hardened materials has accelerated the destruction of urban soil structure [12]. This further affects the growth of plants in cities and leads to the exertion of their ecological service functions. The drastic change of surface cover type makes the original ecological service function of soil deteriorate continuously or even lose completely [13]. In addition, urban surface hardening hinders the leaching of soil salt, which accumulates with the metabolic process of trees, plus artificial fertilization, municipal engineering, and sewage irrigation [14]. These will aggravate the salinization of urban soil and soil hardening. At present, the research on surface hardening mostly focuses on the thermal effect and hydrological effect of surface hardening, but less on the influence of surface hardening on plant physiology and ecology [15,16]. To improve the habitat adaptability and risk avoidance ability of plant configuration constructions, plants improve their survival suitability through the plasticity adjustment of functional traits and other phenotypes, which reflects the resource-allocation strategy of plants under the background of global climate change. Therefore, it is of great significance to study the influence of urban hardened surfaces on the relationship between branches and leaves of plants and its causes for understanding the environmental adaptation mechanism of plants.

We measured the soil properties at different degrees of surface hardening, and the functional indexes of plant branches and leaves. Considering many previous studies on the influence of urban environment on plant growth, we concluded that: (i) urban hardened surface can change the physical and chemical properties of soil in its subsurface, and such changes can lead to the differentiation of functional characters of trees; (ii) urban trees can adapt to the changing environment of soil caused by surface hardening by changing the plasticity of the leaf and branch functional traits.

2. Materials and Methods

2.1. Study Area

The experimental plot is located in Jinan (36°40′ N, 117°00′ E), Shandong Province, China, which is located at the edge of North China Plain and belongs to temperate monsoon climate. The annual average temperature is about 13.8 °C, and the annual average precipitation is about 685 mm. The research site was located at the open-air parking lot in Huaiyin District, Jinan City.

2.2. Experimental Design

There were three different types of ground cover: totally impervious cover (TIC), partially impervious cover (PIC), and Turf surface cover (TC) (Figure 1). The three types of ground cover were *P. acerifolia* planted in the same year (2019), and the age of the trees was 12 years. All three types of surface plots were located at the same parking lot, with the same climatic and environmental conditions, original soil types, and artificial management methods (such as watering, fertilizing, etc.). The planning of the parking lot was laid according to three kinds of hardened surfaces. Each small module contains three hardening treatments. TIC was covered with completely impermeable concrete, and 15 trees are

planted with a pit radius of about 0.75 m and an area of 5×10 m in each module. The surface around PIC was covered with water-permeable bricks with certain porosity and permeability, and 15 trees were planted with a pit radius of about 0.75 m and an area of 5×10 m in each module. TC covers the artificially planted lawn, and the grass species was *Festuca arundinacea*. Each module covered an area of 10×10 m, and 30 trees were planted. Therefore, in the sample selection, we selected 12 modules for sampling, and 15 trees were selected in each module (each treatment). Each treatment contains 180 trees. All the target trees are relatively consistent in provenance, age, planting time, and daily management.

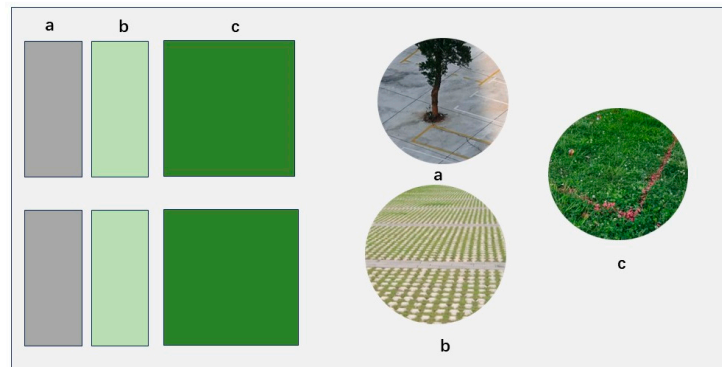


Figure 1. Urban hardened-surface type. (a) totally impervious cover (TIC); (b) partially impervious cover (PIC); (c) Turf surface cover (TC).

2.3. Determination Method

2.3.1. Soil Sampling

On a sunny day in June 2023, 12 representative $4 \text{ m} \times 4 \text{ m}$ quadrats were randomly selected from three types of land cover, and the soil was collected by multi-point mixed sampling method. The depth of the soil layer was 0–15 cm, and each quadrat collected three replicates, and a total of 360 soil samples were obtained. The samples were put into aseptic bags and brought back to the laboratory. Some soil samples were immediately stored in the refrigerator at 4°C for organic carbon mineralization culture and determination of ammonium nitrogen and nitrate nitrogen. The rest of the soil was naturally air-dried, and stones, plant roots, and other impurities were removed and grounded. Part of the soil passed through a 0.15 mm soil sieve for the determination of soil total organic carbon, and another part passed through a 2 mm soil sieve for the determination of other basic physical and chemical properties.

2.3.2. Determination of Soil Properties

Physical and chemical properties such as soil bulk density, soil total porosity, capillary porosity, non-capillary porosity, soil moisture content, pH value, organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), total potassium (TK), and available phosphorus (AP) and available potassium (AK) were determined in this experiment. Bulk density and moisture content are determined by cutting ring method. (The cutting ring method uses a ring cutter with known mass and volume to cut the soil sample, and after weighing, the mass of the ring cutter is subtracted to obtain the mass of the soil. The volume of the ring cutter is the volume of the soil, and then the density of the soil can be obtained. The ring cutter used in this study has an inner diameter of 6 cm, a height of 2 cm, and a thickness of 1.52 mm). The total porosity was calculated by $pt = 93.947 - 32.995 \times b$, where b is the bulk density and pt is the total porosity [15]. Capillary porosity was measured by ring-knife method. Non-capillary porosity was calculated by $po = pt - pc$, where po is non-capillary porosity and pc is capillary porosity. The pH value was determined by potentiometer method with the ratio of water to soil of 2.5:1. Determination method of SOC content: Weigh 5 g of air-dried soil sample passing through 0.15 mm sieve into 100 mL beaker, add 30 mL of 1 mol/L hydrochloric acid solution, soak for 24 h, shake every 2 h; after 24 h,

adjust the soil sample to neutral by washing with distilled water and filtering with suction bottle, dry and crush at 40–60 °C, and measure the organic carbon content in the sample with Elementarvario EL III element analyzer. Total N was digested with potassium sulfate as copper sulfate as selenium powder and determined by automatic analysis with nitrogen determinator. Total p was determined by colorimetry with sulfuric acid as perchloric acid and digestion as molybdenum and antimony [15]. The available P was determined by molybdenum–antimony colorimetric method extracted by sodium bicarbonate. Total K was determined by digestion of flame photometer with hydrofluoric acid as perchloric acid. Available K was extracted by neutral ammonium acetate and determined by flame photometer. For the above analysis methods, see Soil Agrochemical Analysis Methods.

2.4. Determination of Plant Functional Traits

In each module, 15 trees were randomly selected for each surface type, and a total of 12 modules (duplicates) were selected. Therefore, 180 tree samples were selected for each surface type, with a total of 360 trees. In the middle canopy position of each tree, three annual branchlets and 10 leaves were randomly collected in the east, west, south, and north positions, respectively. Each tree has 12 branches and 40 leaves. The length and internode length of annual branchlets were measured with a ruler. The quality of fresh leaves was determined by electronic balance. The leaf area index was obtained by scanning the leaves with WinFOLIA multipurpose leaf area instrument (Regent Instruments, Toronto, ON, Canada). We put the leaves in an oven; we first deactivate them at 105 °C for 20 min, then dry them at 85 °C for 48 h (2 days) and weigh the dry weight. The fresh weight of branches was weighed by electronic balance, and then the dry weight was weighed after drying. The substance content of twig was the ratio of twig mass to fresh twig mass. We cut 2–3 cm twigs, remove bark, and measure their volume by drainage method. We avoid the middle vein and measure the thickness of the three stacked blades with a vernier caliper. Blade thickness (LT) = 3 total thickness of 3 blades/3. LDMC = leaf dry mass/fresh mass. Leaf strength refers to the number of leaves supported per unit twig mass (including leaves and stems), and the total leaf area is the sum of all the leaf areas supported on the twig.

2.5. Statistical Analyses

SPSS 20.0 software and EXCEL 2016 software were used to sort out and calculate the basic data. One-way ANOVA was used to determine the variability of plant functional traits among different environmental factors, and Pearson correlation coefficient was used to test the correlation between plant functional traits. Origin 2019b software was used for variance analysis, correlation analysis, significance analysis, image production, and combination layout.

3. Results

3.1. Impact of Urban Surface Cover on Soil Physical and Chemical Properties

On the whole, the physical and chemical properties of soil under vegetation cover were better than those under hardening cover. Under different cover types, the soil bulk density increased significantly with the increase of hardening degree, and the value of bulk density was $TC < PIC < TIC$ (Figure 2a). The total porosity, capillary porosity, and non-capillary porosity all decrease significantly with the increase of hardening degree. They all showed $TC > PIC > TIC$ (Figure 2b–d). The pH value of soil under three types of surface cover was alkaline, and the pH value of soil under hardened surface was significantly higher than that of other types (Figure 2c–e). There were significant differences in soil organic carbon under three types of land cover, with the highest in PIC ($8.96 \pm 1.08 \text{ g} \cdot \text{kg}^{-1}$), followed by TC ($5.59 \pm 0.63 \text{ g} \cdot \text{kg}^{-1}$), and the lowest in TIC ($2.33 \pm 0.42 \text{ g} \cdot \text{kg}^{-1}$) (Figure 2f). The total nitrogen content was the lowest under the TIC, followed by the PIC, and the TC was relatively high (Figure 2g). The content of total phosphorus in the soil under the TIC was significantly lower than that under the TC, while the TIC was the highest (Figure 2h). There were significant differences in available phosphorus content under three types of

surface cover, among which the available phosphorus content under TC was the highest, and the available phosphorus content under PIC was the lowest (Figure 2i). There were significant differences in soil total potassium and available potassium contents under three types of land cover. Among them, the contents of total potassium and available potassium were the highest under PIC, the total potassium content under the TC was the lowest, and the available potassium content under the TIC was the lowest (Figure 2j,k). There were significant differences in soil moisture content under three types of surface cover, and it tends to decrease significantly with the increase of the hardening degree (Figure 2l).

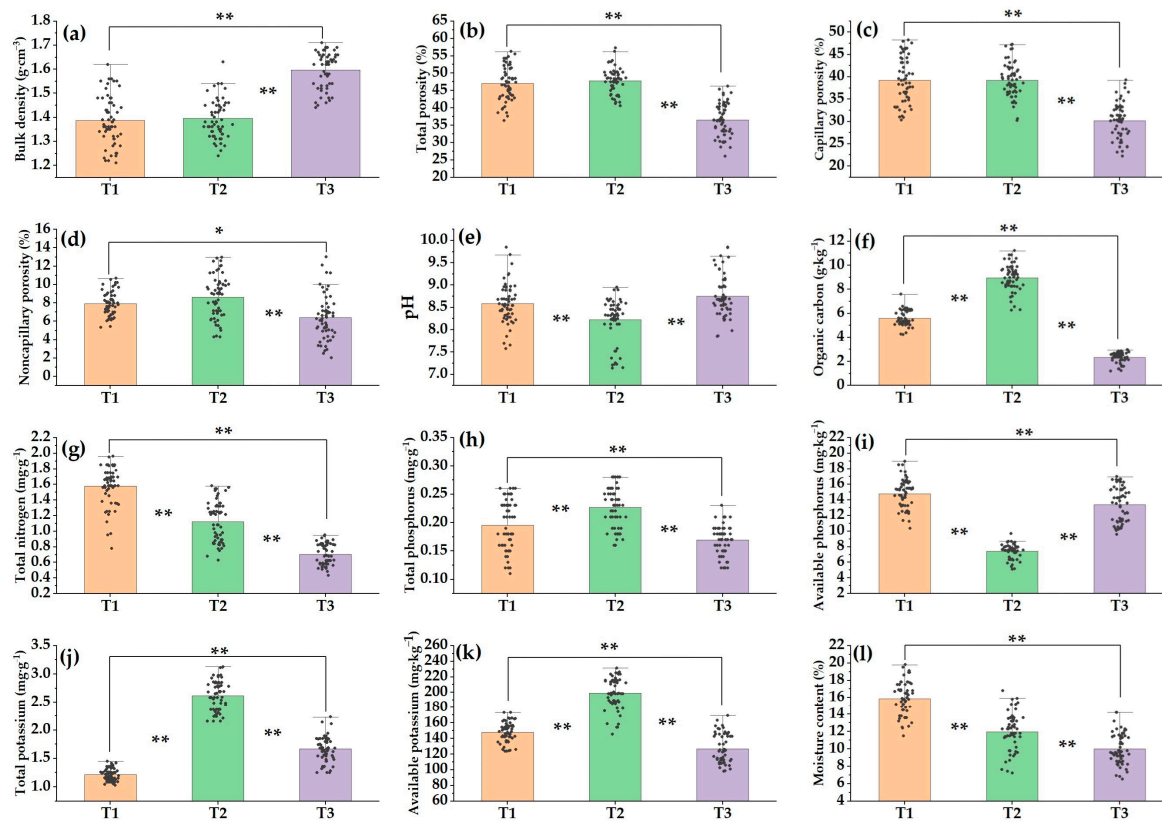


Figure 2. Basic physical and chemical properties of soils with different surface cover types. T1—Turf surface cover (TC), T2—partially impervious cover (PIC), T3—totally impervious cover (TIC). (a) bulk density, (b) total porosity, (c) capillary porosity, (d) non-capillary porosity, (e) pH, (f) soil organic carbon, (g) total nitrogen content, (h) the content of total phosphorus, (i) available phosphorus content, (j) total potassium content, (k) available potassium, (l) soil moisture content. “*” means that the two gradients have reached a significant level, and “**” means that the two gradients have reached a very significant level.

3.2. Effect of Hardened Surface on Plant Functional Traits

Urban hardened surface has a significant impact on plant functional traits (Figure 3). There were significant differences in the basal diameters of annual branchlets under three types of ground cover, and they decreased with the increase of hardening strength (Figure 3a). The base diameter under TC was the largest (6.51 ± 1.09 mm), followed by PIC (5.67 ± 1.26 mm), and the base diameter under TIC was the smallest (4.63 ± 0.77 mm). The length of annual branches under three types of ground cover decreased with the increase in hardening strength (Figure 3b). The branch length under TC was the largest (27.45 ± 11.01 cm), followed by PIC (26.01 ± 11.77 cm), and the basal diameter under TIC was the smallest (9.95 ± 11.50 cm). There were significant differences in leaf thickness under three types of land cover. It increases significantly with the increase of surface hardness (Figure 3c). The leaf thickness under the TIC was the largest (0.24 ± 0.05 mm), followed by the PIC (0.23 ± 0.07 mm), and the leaf thickness under the TC was the smallest

(0.17 ± 0.05 mm). With the increase of hardening degree, the weight of twigs decreased significantly, with the maximum under TC (3.45 ± 2.11 g) and the minimum under TIC (0.55 ± 0.42 g) (Figure 3d). The internode length of branchlets decreased significantly with the increase of hardening degree (Figure 3e), with the maximum under TC (3.42 ± 1.19 g) and the minimum under PIC (1.66 ± 1.26 g). The dry weight of leaves decreased significantly with the increase in hardening degree (Figure 3f). There were significant differences in leafing intensity under different types of hardened surfaces, and it increases significantly with the increase of hardening degree (Figure 3g). Leaf area, specific leaf area, and leaf dry matter content decreased significantly with the increase of hardening degree (Figure 3h–j). The substance content of branches increased with the increase of hardening degree, and it was the highest under the TIC (Figure 3k). The total leaf area and mass ratio of branches and leaves decreased significantly with the increase of hardening degree (Figure 3l,m). The total leaf area was the largest under TC (1732.66 ± 838.61 cm²), the second under PIC (1453.40 ± 864.56 cm²), and the largest under TIC (663.46 ± 409.10 cm²). Similarly, the mass ratio of branches and leaves was the highest under TC (0.31 ± 0.20 g·g⁻¹), the second under PIC (0.24 ± 0.14 g·g⁻¹), and the highest under TIC (0.13 ± 0.10 g·g⁻¹).

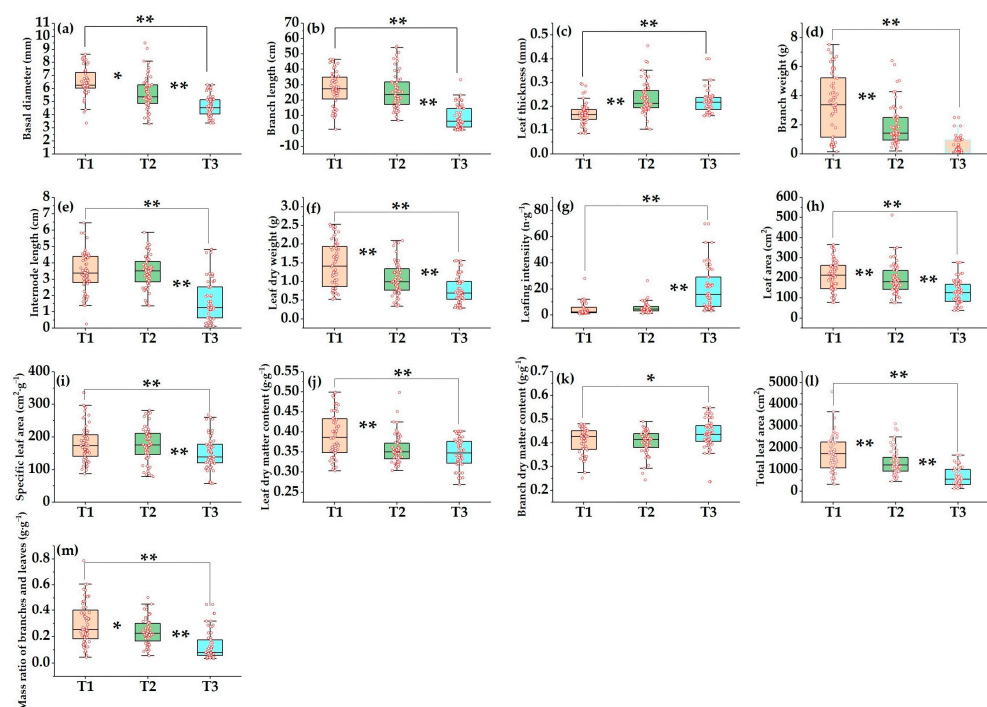


Figure 3. Plant functional traits under different types of hardened surface. (a) Branch diameter, (b) branch length, (c) leaf thickness, (d) branch weight, (e) internode length, (f) leaf dry weight, (g) leafing intensity, (h) leaf area, (i) specific leaf area, (j) leaf dry matter content, (k) branch dry matter content, (l) total leaf area, (m) mass ratio of branches and leaves. T1—Turf surface cover (TC), T2—partially impervious cover (PIC), T3—totally impervious cover (TIC). “*” means that the two gradients have reached a significant level, and “**” means that the two gradients have reached a very significant level.

3.3. Correlation among Plant Functional Traits

On the one hand, there was an obvious correlation among plant functional traits, and on the other hand, we also confirmed that the degree of correlation between plant functional traits was different under different hardened surface types (Table 1). There was a significant positive correlation between branch diameter and branch length, branch dry weight, internode length, leaf dry weight, leaf area, total leaf area, and the mass ratio of branches and leaves, but there was a significant negative correlation between branch diameter and leafing intensity. There was a significant positive correlation between branch

length and leaf thickness, branch dry weight, internode length, leaf dry weight, total leaf area, and branch–leaf mass ratio, but a significant negative correlation between branch length and leaf strength. There was a significant positive correlation between branch dry weight and internode length, leaf dry weight, leaf area, total leaf area, and branch–leaf mass ratio, but a significant negative correlation between twig trunk weight and leafing intensity. There was a significant positive correlation between internode length and leaf dry weight, leaf area, total leaf area, and mass ratio of branches and leaves, but there was a significant negative correlation between internode length and leafing intensity and branch dry matter content. There was a significant positive correlation between leaf dry weight and leaf area and total leaf area, but a significant negative correlation between leafing intensity and specific leaf area. There was a significant positive correlation between leafing intensity and branch dry matter content, but a significant negative correlation between leaf area, total leaf area, and the mass ratio of branches and leaves. There was a significant positive correlation between the specific leaf area and the mass ratio of branches and leaves. There was a significant negative correlation between the leaf dry matter content and the branch dry matter content. There was a significant negative correlation between the branch dry matter content and the total leaf area. The total leaf area was positively correlated with the mass ratio of branches and leaves.

Table 1. Pearson correlation coefficient of plant functional traits.

		BD	BL	LT	BW	IL	LDW	LI	LA	SLA	LDMC	BDMC	TLA
BL	T1	0.750											
	T2	0.611											
	T3	0.519											
LT	T1	−0.152	0.031										
	T2	0.220	0.278										
	T3	0.274	0.388										
BW	T1	0.318	0.547	0.207									
	T2	0.806	0.718	0.226									
	T3	0.716	0.856	0.490									
IL	T1	0.693	0.815	−0.008	0.378								
	T2	0.393	0.807	0.142	0.566								
	T3	0.521	0.919	0.454	0.848								
LDW	T1	0.266	0.497	0.041	0.465	0.369							
	T2	0.468	0.224	0.203	0.579	0.302							
	T3	0.247	0.269	0.271	0.274	0.521							
LI	T1	−0.620	−0.795	−0.078	−0.405	−0.779	−0.497						
	T2	−0.567	−0.482	−0.073	−0.630	−0.595	−0.482						
	T3	−0.365	−0.587	−0.280	−0.668	−0.757	−0.506						
LA	T1	0.441	0.617	−0.088	0.352	0.570	0.512	−0.643					
	T2	0.640	0.458	0.381	0.636	0.488	0.570	−0.464					
	T3	0.302	0.363	0.197	0.411	0.578	0.493	−0.664					
SLA	T1	0.219	0.101	−0.095	−0.188	0.134	−0.549	−0.081	0.284				
	T2	0.106	0.237	0.039	0.022	0.153	−0.544	0.003	0.243				
	T3	0.015	0.010	−0.171	0.075	0.042	−0.539	−0.189	0.345				
LDMC	T1	−0.031	0.142	−0.002	0.191	0.169	0.376	−0.286	0.308	−0.254			
	T2	0.094	−0.110	−0.189	0.073	−0.143	−0.058	0.034	−0.247	−0.078			
	T3	−0.055	0.230	0.187	0.204	0.337	0.402	−0.318	0.242	−0.237			
BDMC	T1	0.081	−0.079	−0.137	−0.288	−0.019	−0.195	−0.028	−0.181	0.072	−0.083		
	T2	−0.388	−0.654	−0.394	−0.490	−0.601	−0.245	0.314	−0.341	−0.008	0.056		
	T3	−0.051	−0.530	0.014	−0.201	−0.463	−0.106	0.300	−0.183	−0.051	−0.273		
TLA	T1	0.417	0.696	−0.055	0.411	0.377	0.557	−0.592	0.871	0.183	0.265	−0.209	
	T2	0.769	0.707	0.447	0.759	0.447	0.462	−0.413	0.846	0.257	−0.195	−0.454	
	T3	0.515	0.754	0.300	0.736	0.799	0.384	−0.713	0.813	0.288	0.121	−0.382	
MRBL	T1	0.585	0.618	0.085	0.085	0.657	−0.162	−0.522	0.377	0.655	−0.042	0.000	0.291
	T2	0.417	0.522	−0.055	0.523	0.474	−0.184	−0.455	0.188	0.620	0.202	−0.198	0.259
	T3	0.560	0.529	0.295	0.777	0.591	−0.154	−0.591	0.345	0.522	0.132	−0.070	0.525

BD: Branch diameter, BL: Branch length, LT: Leaf thickness, BW: Branch weight, IL: Internode length, LDW: Leaf dry weight, LI: Leafing intensity, LA: Leaf area, SLA: Specific leaf area, LDMC: Leaf dry matter content, BDMC: Branch dry matter content, TLA: Total leaf area, MRBL: Mass ratio of branches and leaves. The numerical value in red font indicates that the correlation between indicators is significant.

3.4. Effect of Hardened Surface on Correlation Degree of Plant Traits

Combined with Table 1, we make linear fitting for plant traits with significant correlation. We found that the hardened surface has a significant influence on the correlation degree among plant traits (Figure 4). With the increase of the surface-hardening degree, the correlation coefficients of BD&BL, BD&LI, BL&LDW, BL&LA, BL & MRBL, BW&LDW, BW & BDMC, IL&BW/LW, LDW&SLA, LDW&TLA, LA&TLA, and SLA&BW/LW show a decreasing trend, and the correlation coefficient values were $T1 > T2 > T3$, respectively. The correlation coefficient (degree) of BD&LDW, BD&LA, BW&LA, and LI&LA first increased and then decreased, and the correlation coefficient values were $T2 > T3 > T1$, respectively. The correlation coefficients (degree) of BD&BW, BD&TLA, BL&BW, BL&IL, BL&TLA, BW&IL, BW&LI, BW&TLA, IL&LDW, IL&BDMC, LDW&LI, and LI&TLA were increasing. The correlation coefficient (degree) of BD&IL, BD & MRBL, BL&LI, IL&LI, IL&LA, Li&BW/LW, and LTA & MRBL first decreased and then increased, and the correlation coefficient values were $T1 > T3 > T2$, respectively. To sum up, the hardened surface weakens the correlation between some traits but enhances the correlation between some traits. We suspect that this was an adaptive strategy adopted by plants to deal with the hardened surface.

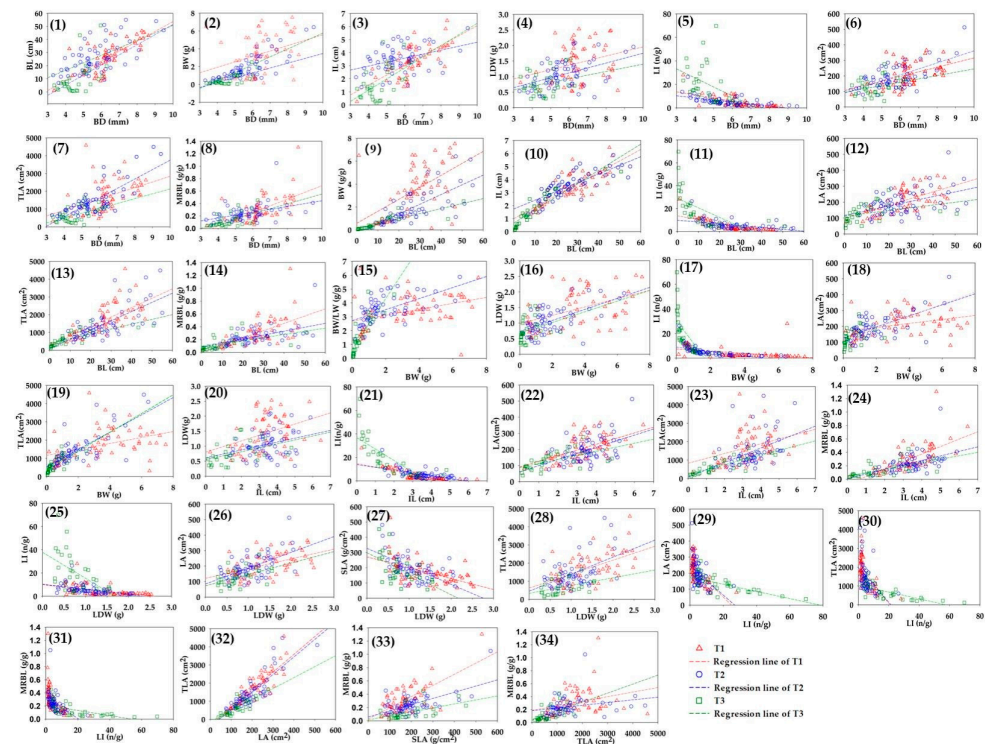


Figure 4. Linear correlation between plant traits under different hardened surface types. BD: Branch diameter, BL: Branch length, BW: Branch weight, IL: Internode length, LDW: Leaf dry weight, LI: Leafing intensity, LA: Leaf area, SLA: specific leaf area, LDMC: Leaf dry matter content, BDMC: Branch dry matter content, TLA: Total leaf area, MRBL: Mass ratio of branches and leaves. (1) BD and BL, (2) BD and BW, (3) BD and IL, (4) BD and LDW, (5) BD and LI, (6) BD and LA, (7) BD and TLA, (8) BL and MRBL, (9) BL and BW, (10) BL and IL, (11) BL and LI, (12) BL and LA, (13) BL and TLA, (14) BL and MRBL, (15) BW and BW/LW, (16) BW and LDW, (17) BW and LI, (18) BW and LA, (19) BW and TLA, (20) IL and LDW, (21) IL and LI, (22) IL and LA, (23) IL and TLA, (24) IL and MRBL, (25) LDW and LI, (26) LDW and LA, (27) LDW and SLA, (28) LAW and TLA, (29) LI and LA, (30) LI and TLA, (31) LI and MRBL, (32) LA and TLA, (33) SLA and MRBL, (34) TLA and MRBL.

3.5. The Correlation between the Differences in Soil Properties Caused by Hardened Surface and Plant Functional Traits

The correlation between plant traits and soil physical and chemical properties was significant (Table 2). Soil bulk density was positively correlated with leaf strength and dry matter content of branches. Soil bulk density showed negative correlation with sand branch diameter, branch length, branch weight, interconnection length, leaf dry weight, leaf area, leaf dry matter content, total leaf area, and mass ratio of branches and leaves. Total porosity, capillary porosity, total nitrogen, and soil water content were positively correlated with branch diameter, branch length, branch weight, interconnection length, leaf dry weight, leaf area, leaf dry matter content, total leaf area, and mass ratio of branches and leaves. Total porosity, capillary porosity, organic carbon, and available potassium were negatively correlated with leafing intensity and branch dry matter content. A positive correlation was found between non-capillary porosity and leafing intensity. Organic carbon showed a significant positive correlation among branch diameter, branch length, branch weight, interconnection length, leaf area, leaf dry matter content, total leaf area, and mass ratio of branches and leaves. Total phosphorus content has a significant positive correlation with branch diameter, branch length, internode length, leaf dry weight, leaf area, total leaf area, and mass ratio of branches and leaves. A significant negative correlation was found between total phosphorus content and leafing intensity. Available phosphorus and leaf dry matter content showed a significant positive correlation. A significant negative correlation was observed between available phosphorus and leaf thickness. Total potassium content showed a significant positive correlation with leaf thickness and a significant negative correlation between total potassium content and branch weight. Available potassium showed a significant positive correlation with branch diameter, branch length, internode length, leaf area, total leaf area, and mass ratio of branches and leaves. Soil moisture content showed a significant negative correlation with leaf thickness, leafing intensity, and branch dry matter content.

Table 2. Correlation between plant functional traits and soil traits.

	BD	BL	LT	BW	IL	LDW	LI	LA	SLA	LDMC	BDMC	TLA	MRBL
SBD	−0.507 *	−0.464 *	0.138	−0.479 *	−0.510 *	−0.335 *	0.486 *	−0.411 *	−0.012	−0.275 *	0.244 *	−0.423 *	−0.443 *
TP	0.414 *	0.495 *	−0.017	0.426 *	0.517 *	0.372 *	−0.527 *	0.438 *	0.006	0.308 *	−0.194 *	0.474 *	0.353 *
CP	0.452 *	0.508 *	−0.018	0.438 *	0.512 *	0.369 *	−0.506 *	0.428 *	0.006	0.306 *	−0.190 *	0.485 *	0.376 *
NP	0.040	0.135	−0.003	0.112	0.189	0.133	−0.235 *	0.176	0.003	0.111	−0.074	0.130	0.059
pH	−0.043	−0.097	−0.031	−0.023	−0.101	0.002	0.136	−0.005	−0.021	−0.013	0.043	−0.048	−0.042
SOC	0.258 *	0.417 *	0.084	0.249 *	0.471 *	0.189	−0.436 *	0.280 *	0.027	0.056	−0.219 *	0.316 *	0.231 *
TN	0.586 *	0.489 *	−0.284 *	0.654 *	0.473 *	0.528 *	−0.505 *	0.381 *	−0.184	0.410 *	−0.234 *	0.458 *	0.425 *
TP	0.244 *	0.296 *	0.110	0.158	0.297 *	0.207 *	−0.274 *	0.258 *	0.051	−0.008	−0.134	0.295 *	0.201 *
AP	0.087	−0.121	−0.362 *	0.101	−0.182	0.130	0.140	−0.048	−0.127	0.199 *	0.132	−0.025	−0.005
TK	−0.189	0.052	0.386 *	−0.229 *	0.147	−0.185	−0.082	−0.014	0.126	−0.236	−0.048	−0.071	−0.070
AK	0.198 *	0.370 *	0.175	0.151	0.450 *	0.086	−0.402 *	0.234 *	0.071	0.083	−0.226 *	0.235 *	0.227 *
MC	0.414 *	0.404 *	−0.258 *	0.506 *	0.440 *	0.471 *	−0.473 *	0.390 *	−0.170	0.290 *	−0.240 *	0.391 *	0.344 *

SBD: Soil bulk density, TP: Total porosity, CP: Capillary porosity, NP: Noncapillary porosity, pH: Potential of hydrogen, SOC: Soil organic carbon, TN: Total N, TP: Total P, AP: Available P, TK: Total K, AK: Available K, MC: Moisture content. BD: Branch diameter, BL: Branch length, LT: Leaf thickness, BW: Branch weight, IL: Internode length, LDW: Leaf dry weight, LI: Leafing intensity, LA: Leaf area, SLA: specific leaf area, LDMC: Leaf dry matter content, BDMC: Branch dry matter content, TLA: Total leaf area, MRBL: Mass ratio of branches and leaves. “*” indicates that there is a significant correlation between the two traits.

4. Discussion

Our experiments showed that the degree of urban hardened surface significantly affects the soil properties under the hardened surface. On the whole, the physical and chemical properties of soil under vegetation cover were better than those under hardening cover. This confirms our first hypothesis. In the urban environment dominated by human activities, the main ecological factors related to the normal growth and development of plants include biological factors (animals, plants, microorganisms), abiotic factors such as climate factors (light, temperature, water, gas), and soil factors (physical and chemical characteristics of soil). They are all strongly disturbed by human activities and have changed to

varying degrees compared with natural ecosystems [17]. Among them, surface hardening is one of the most important factors. Under different cover types, the soil bulk density increased significantly with the increase of hardening degree [18]. The total porosity, capillary porosity, and non-capillary porosity all decrease significantly with the increase of hardening degree [19]. Compared with the natural ecosystem coverage type, the urban ecosystem is broken by the pavement of urban hardened surfaces and buildings. While human activities disturb the urban soil frequently, the material circulation and transformation process of the soil under urban hardened surface coverage are monotonous and slow, which has a significant impact on the population and structure of soil microorganisms [20,21]. At the same time, due to the isolation of hardened pavement, the nutrient elements in litter are prevented from circulating into the soil. Some studies showed that surface hardening has changed the living environment of soil microorganisms and further threatened the normal life activities of microorganisms in soil [22,23]. Soil microbial respiration is an important part of soil respiration, and the variety and quantity of microorganisms and the changes in their life activities will have a certain impact on physical and chemical properties [24,25]. Therefore, the soil properties under different hardened surface types (including soil bulk density, soil total porosity, capillarity porosity, non-capillarity porosity, soil moisture content, and pH value) may be the reasons for the differences in organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), total potassium (TK), available phosphorus (AP), and available potassium (AK) in different degrees.

The research shows that the hardening and compaction make the soil porosity lower, while the air content in the soil decreases and the aerobic respiration of the root system is affected, which limits its growth and development [25]. Branch diameter, branch length, branch weight, interconnection length, leaf dry weight, leaf area, specific leaf area, leaf dry matter content, total leaf area, and the mass ratio of branches and leaves all decrease with the increase of surface hardening degree. However, leaf thickness, leafing intensity, and branch dry matter content increase with the increase of surface hardness. It was pointed out that the specific leaf area can characterize the ability of plants to intercept light resources [26]. In an environment of poor resources and drought stress, plants often have low specific leaf area. In this study, the specific leaf area decreased significantly with the increase of surface hardening intensity, which indicated that urban trees reduced the effective leaf area for transpiration, thus preventing a large amount of water loss. This will be more beneficial for trees to adapt to the stress environment of high temperature and drought, and similar results were found by other scholars [27]. The dry matter content of leaves well reflects the ability of trees to retain, fix, and use their own substances. The higher the dry matter content of leaves, the higher the efficiency of trees in using resources, further preventing the loss and waste of limited resources [26,27]. Leaf tissue density reflects the defensive ability of leaves, which is closely related to leaf growth rate and leaf life. In this study, the density of leaf tissue increases significantly with the degree of surface hardening, which indicates that under the stressful environment of hardened surfaces, more resources are invested in the construction of leaf defense structure. At the same time, its resistance to high-temperature stress is enhanced. In order to reduce the cost of transpiration in high-temperature environments, plants adopt the strategy of reducing the leaf area to reduce the transpiration area, which is basically consistent with the research results of many researchers [28,29].

Leaf traits can reflect the efficiency of trees' acquisition and utilization of their own resources. In the overview of the leaf economics spectrum in the economic pedigree diagram, plants mainly have two different strategies of resource investment income: fast-slow investment-income type [30]. In a specific environment, the resources generally available to plants are not inexhaustible. When the environment changes, when plants invest too much in some structures and functions, the resources available for other structures and functions will be cut accordingly [31]. In this study, in the urban hardened surface environment, there was an obvious correlation between plant functional traits, which shows that plants can meet their own growth needs by adjusting and allocating their existing resources to

cope with the stress of external high temperature [32]. Especially under the long-term stress of the urban surface-hardening environment, urban trees often avoid environmental damage to themselves by surrendering resources invested in certain structures and functions [33]. This confirms our second hypothesis. For example, there is a significant negative correlation between the dry matter content of leaves and dry matter content of branches. There is a significant negative correlation between the substance content of twigs and the total leaf area of branchlets. The correlation between these traits is closely related to the ecological strategy of plants. Under the hardening environment, plants often use more synthetic substances to increase the construction of leaf protection tissues to adapt to the stressful environment due to the change in soil properties. The decrease in the specific leaf area reflects the investment–benefit strategy of plants: the investment in light resource acquisition and photosynthesis is sacrificed, while the investment in resource maintenance and utilization is increased [26,34]. It is worth mentioning that we also found that the urban hardened surface can affect the correlation between urban tree traits, but it does not affect its stable correlation: with the gradual increase of hardening intensity, it will weaken its correlation. When plants face the stress of urban soil environment, they show strong and rapid resource allocation countermeasures. In addition, the correlation between traits remains basically the same, but the change of hardened surface changes their correlation degree (Figure 4).

5. Conclusions

We concluded that with the increase of surface-hardening strength, the physical and chemical properties of urban soils showed obvious differences. In this case, the functional traits of trees were also differentiated to varying degrees. However, there was a strong correlation among plant functional traits. At the same time, we observed that plant functional traits have significant response mechanisms to soil physical and chemical properties. Plants can form a synergistic response model by changing the functional traits of branches and leaves to adapt to the urban surface-hardening environment. Urban hardened surfaces can affect the correlation degree of urban tree traits, but it does not affect its stable correlation: with the gradual increase of hardening intensity, it will weaken its correlation degree. When plants face the stress of the urban soil environment, they showed strong and rapid resource-allocation countermeasures. At this time, the quantitative relationship between traits was broken, which further affects the degree of correlation between them. These findings provided insights on how urban green space trees respond to environmental problems caused by urbanization and put forward new strategies for tree growth. This study reveals the physiological and ecological response of plants to different surface hardening and its changing characteristics, which is of great significance to improve the growth environment of urban plants and improve the ecological service function of green space. At the same time, the study clarified the relationship between plants and urban soil properties, which provided an important reference for further exploring the impact of global climate change on urban plant functional traits. Nevertheless, due to the limitations of the study area, we selected typical tree species in the city. In order to improve the universality of the research results, the types of tree species can be increased in the follow-up research.

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