Leaf Functional Traits Differentiation and Its Trade-off Strategies of Urban Plant are Related to Atmospheric Particulate Pollution

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Abstract

Background: Functional trait-based ecological research has been instrumental in advancing our understanding of understanding of environmental changes. It is still, however, unclear how the functional traits of urban plants respond to atmospheric particulate pollution, and what trade-off strategies are shown. In order to explore the variation of plant functional traits with urban atmospheric particulate pollution gradient, we divided atmospheric particulate pollution into three levels according to road distance, and measured the variation of six key leaf functional traits and their trade-off strategies.

Results: Here, we show that the functional traits of plants can be used as predictors or indicators of the response of plant to urban atmospheric particulate pollution. Within studies, there was a positive correlation between leaf thickness, leaf dry matter content, leaf tissue density, stomata density and leaf dust deposition. While chlorophyll content index and specific leaf area were negatively correlated with the leaf dust deposition. Plants improve the efficiency of gas exchange by optimizing the spatial distribution of stomata of leaves. Dust deposition promotes the regular distribution of stomata. Due to the pressure of atmospheric particles, urban plant shows a trade-off relationship of economics spectrum traits at the leaf level. Taken together, these results indicate that urban atmospheric particulate pollution is the main factor causing the variation of plant functional traits.

Conclusion: Under the influence of urban atmospheric particulate matter, plant show a "slow investment-return" type in the global leaf economics spectrum, with lower specific leaf area, lower chlorophyll content, larger leaf thickness, higher leaf dry matter content, higher leaf tissue density and higher stomatal density. This finding provides a new perspective for understanding the resource trades-off strategy of plants adapting to air pollution environment.

Background

In a world of increasing urbanization, atmospheric particulate matter pollution mitigation is currently one of the most important issues of city planning. Urban trees are of central importance for this issue because they facilitate the deposition of various gases and particles and affect microclimate and air turbulence (Seinfeld, 1989; Kulshreshtha et al., 2009; Lelieveld, J., 2002; Wang et al., 2020). The urban atmospheric particulate contains heavy metal and other harmful components, which seriously affects the health of urban residents (Lelieveld et al., 2015; Wang et al., 2020). In China, the government attaches great importance to the prevention and control of air pollution. In recent years, despite the continuous improvement of the ambient air quality in China, the treatment effect is not stable, especially in the autumn and winter seasons in Beijing-Tianjin-Hebei region and its surrounding areas. Data show that in the autumn and winter of 2018–2019, the average concentration of PM2.5 in Beijing-Tianjin-Hebei and its surrounding areas increased by 6.5% year-on-year, and the number heavy polluted days increased by 36.8% year-on-year (Chang et al., 2019; Gao et al., 2020). Due to the special terrain and meteorological conditions, Beijing has become the gathering center of atmospheric pollutants in North China (Yang et al.,
In addition, the acceleration of urbanization and the rapid development of transportation also bring about the prevention and control of air pollution. serious challenge.

At present, it is impossible to completely rely on pollution sources control to solve environmental problems. Natural removal mechanism is an effective way to relieve the pressure of urban air pollution, and urban trees are the key factor (Nowak et al., 2006; Marc et al., 2010; Dai et al., 2013). As an important part of the urban ecosystem, plants can not only beautify the environment, but also effectively retain and adsorb particulate matter in the atmosphere (Caravanos et al., 2006; Chadwick 2009; Zambrano et al., 2009; Wang et al., 2011; Qiu et al., 2016). It is precisely because of the huge dust reduction benefits produced by urban forests that scholars have carried out extensive research. Previous studies have pointed out that the total amount of dust trapped in the green space of residential areas in Beijing suburbs was 2,170 t in 1995, the amount of PM2.5 trapped in the green spaces of Shanghai was about 3,533 t in 2017. Urban vegetation in London area can reduce the PM10 content in the air by 0.7–2.6% (Zhang 1997; Tallis et al., 2011; Qiu et al., 2018; She et al., 2020). At present, the research of plant dust deposition mainly focuses on the comparison of dust deposition capacity, dust deposition mechanism, dust deposition composition, dust deposition characteristics and so on, and has obtained many research results (Mctainsh et al., 1997; Nowak et al., 2006; Hope et al., 2010; Kou et al., 2015). It is worth noting that the retention of atmospheric particles in plant leaves will affect its growth and development? Do different dust deposits have different effects on plants? There is still a big gap in the study of this problem.

In the long process of evolution and development, plants interact with the environment, and gradually forming many adaptation strategies in internal physiology and external morphology, so as to minimize the adverse effects of the environment (Kearney & Porter 2006; Wilson et al., 2010; Mccormack et al., 2012; Kawai & Okada 2020; Larson et al., 2020). In recent 20 years, new concepts and measurement methods related to plant traits have emerged and their application fields have been expanding. The scientific research involves many aspects of ecological research (Wright et al., 2004). One of the key hot issues is the relationship between plant functional traits and environment, and how the environment affects plant functional traits, thus establishing the close relationship between environment and ecosystem functions. At present, the research on plant traits and environment mainly focuses on climate (such as temperature, precipitation, light, etc.), topography (such as geographic spatial gradient variation, altitude, slope direction, etc.), nutritional status, biological invasion and land use (Hoffmann et al., 2005; Kearney & Porter 2006; Wilson et al., 2010; Leishman et al., 2010; Mccormack et al., 2012; Wills et al., 2018; Huang et al., 2020; Isabelle et al., 2020; Kawai & Okada 2020; Larson et al., 2020). However, there are still few studies on the effects of urban atmospheric particulates on plant functional traits.

*Euonymus japonicus* is one of the most planted landscape trees in Beijing, which plays an important role in urban ecological and social benefits. A study on the interception ability of 29 urban greening plants in Beijing to fine particles in the atmosphere shows that the interception ability of *Euonymus japonicus* to PM2.5 in shrubs is the second only to *Buxus microphylla* (Nowak et al., 2006). Based on this, this study takes *Euonymus japonicus* as the research object, taking the leaf functional traits as the breakthrough
point. The overall goal is to study the relationship between leaf functional traits and the environment. The specific objectives are as follows, (1) Evaluate the response and trade-off rule of plant leaf traits to different dust deposition under the influence of atmospheric particulate matter. (2) Whether the relationship of leaf traits accords to the global leaf economics spectrum in the environment polluted by atmospheric particulate matter.

Results

Leaf dust deposition under different levels of atmospheric particulate matter pollution

As shown in Fig. 1, in three different locations of urban highway, the dust collection capacity of *Euonymus japonicus* leaves gradually decreases from the main road. We found that the dust deposition of *Euonymus japonicus* leaves in the middle of the main road (T3) was $(0.0052 \pm 0.0022 \, g) >$ that between the relief road and the sidewalk (T2) $(0.0025 \pm 0.001g) >$ that of the outer sidewalk (T1) $(0.0019 \pm 0.001g)$. On the main road, due to the large traffic volume, not only a large amount of traffic waste gas is emitted, but also the dust on the ground was driven by the airflow of the vehicle, which was an open pollution source into the atmosphere and an important part of the total suspended particulate matter in the ambient air. Such atmospheric particulate matter mainly diffuses to both sides. The auxiliary road vehicles were mainly non-motor vehicles, and the traffic volume was small, and the suspended particulate matter in the atmosphere was relatively low. However, the main body of the sidewalk was pedestrians, and the particulate matter emitted by vehicle exhaust is greatly reduced compared with the main road. Therefore, the dust accumulation of *Euonymus japonicus* planted in different locations of urban streets was significantly different. In general, the atmospheric particulates matter gradually decreases along the center of the road to both sides.

Effect of urban atmospheric particulate matter on leaf functional traits

Leaf is an important organ for plants to obtain energy, resources and nutrition, and it is also the most sensitive organ to environmental change and has strong plasticity (Franco et al., 2005; Jin et al., 2011). Leaf functional traits can objectively reflect the influence of environmental changes on plants and the adaptability of plants to the environment, and predict the characteristics of plants and urban ecosystems (Eamus 2008; Niinemets 2015; Miner & Bauerle 2019). In this study, it was found that the functional traits of plants change regularly with the change of dust deposition. Figure 4 shows the comparison of leaf function traits (leaf thickness, chlorophyll content index, specific leaf area, leaf dry matter content, leaf tissue density and stomatal density) of *Euonymus japonicus* at different dust deposition rates. In general, with the increase of dust fall, leaf thickness, leaf dry matter content, leaf tissue density and stomatal density increased, while the relative content of chlorophyll and specific leaf area decreased. Compared with T1, the leaf thickness of T2 and T3 were significantly increased, and the difference reached significant level $(P<0.05)$ and extremely significant level $(P<0.01)$. The leaf dry matter content of T3 was
significantly higher than that of T1 and T2 \((P<0.01)\), but the difference between T1 and T2 was not significant. Compared with T1, the stomatal density of T2 and T3 increased significantly \((P<0.01)\). The chlorophyll content index in T2 and T3 decreased significantly, and reached an extremely significant level between T1, T2 and T3 \((P<0.01)\). The specific leaf area of T3 was significantly larger than that of T1 and T2 \((P<0.01)\), but there was no significant difference between T1 and T2.

Studies have shown that specific leaf area is closely related to the growth and survival strategies of plant, which can represent the adaptability of plants to the environment and the ability to obtain resources (Ackerly et al., 2002; Poorter & Jong 2010; Wellstein et al., 2017). Plants with low specific leaf area have stronger adaptability to resource poor and arid environment, while plants with high specific leaf area have stronger ability to maintain nutrients (Wellstein et al., 2017). In this study, the specific leaf area of *Euonymus japonicus* in an environment polluted by atmospheric particulates showed a decreasing trend. This indicates that under the pollution of atmospheric particulate matter, the *Euonymus japonicus* enhances its nutrient deposition capacity by reducing the specific leaf area. Most of the energy of plant photosynthesis comes from the light energy captured by photosynthetic pigments, so the chlorophyll content is closely related to the plant photosynthetic capacity (Kleinschmidt et al., 2020). In this study, the chlorophyll content decreased significantly due to the increase in the amount of dust trapped on the leaf surface, which may be due to the cover of the leaf surface particles, which led to a decrease in the area of light resources captured (Fig. 2). The leaves with a large amount of dust on the leaf surface have higher tissue density and dry matter content, and have stronger drought tolerance and defense capability. This shows that under the influence of atmospheric particulate matter, *Euonymus japonicus* mostly uses nutrients for the construction of defense structure, and reduces the damage of atmospheric particulate matter to leaves by increasing leaf tissue density and leaf dry matter content. Stomata is an important organ for gas exchange between plants and the atmosphere, and plays an extremely important role in regulating the carbon and water cycle of the ecosystem (Woodward 1987; Masterson 1994; Allen et al., 2001). Under drought stress, stomatal density decreases to prevent water loss via transpiration (Woodward et al., 2002). In this study, we found that the dust deposition on the leaf surface increased the density of leaf stomata. This may be because atmospheric particles may block some of the pores and weaken the gas exchange function of stomata. In this case, plants can ensure normal gas exchange and balance of water circulation by increasing stomatal density.

**Influence of atmospheric particulates on the spatial distribution of stomata**

As shown in Fig. 3, the distribution characteristics of stomatal spatial pattern of *Euonymus japonicus* were obviously different in different atmospheric particulate matter environments. The stomata of *Euonymus japonicus* were aggregated at the scales of 0 ~ 42µm(T1), 0 ~ 46µm(T2) and 0 ~ 54µm(T3), randomly distributed at the scales of 42 ~ 69µm(T1), 46 ~ 64µm(T2) and 54 ~ 60µm(T3), and randomly distributed at the scales of 69 ~ 10 µm. This indicates that atmospheric particulates have changed the spatial distribution pattern of stomata of *Euonymus japonicus*, showing that the spatial scale of stomata under different atmospheric particulates has changed from random distribution to uniform distribution.
With the increase of the amount of atmospheric particulate matter trapped in leaves, the spatial distribution pattern of stomata of *Euonymus japonicus* becomes more regular. We suspect that this may be a regulatory strategy adopted by plants to deal with atmospheric particulate matter. *Euonymus japonicus* can prevent the influence of atmospheric particulate matter on water diversion of leaves by adjusting the distribution pattern of stomata.

**Regression analysis of leaf functional traits and leaf dust deposition**

Figure 4 was a linear fit between dust deposition and leaf functional traits. There was a positive correlation between leaf thickness, leaf dry matter content, leaf tissue density, stomatal density and leaf dust deposition. However, chlorophyll content index, specific leaf area and dust deposition of leaves were negatively correlated. The $R^2$ values from large to small were specific leaf area (0.2387), leaf thickness (0.1999), leaf dry matter content (0.1707), leaf tissue density (0.1391), chlorophyll content index (0.1128) and stomatal density (0.0021), and the corresponding root mean square errors were 0.0380 and 0.080, respectively. Therefore, the response of specific leaf area to dust deposition was the most severe.

**Correlation between leaf functional traits of *Euonymus japonicus***

By establishing the relationship between leaf functional characters of *Euonymus japonicus* affected by atmospheric particulate matter pollution, the relationship between leaf functional traits and their functions is further discussed, and the trade-off effect of plant traits on limited resources is clarified. It can be seen from Fig. 5 that there is a certain quantitative relationship between different functional traits due to environmental pressure and plant trade-off strategy. Stomatal density was positively related to leaf thickness and dry matter content. The leaf tissue density was negatively correlated with specific leaf area and positively correlated with dry matter content. The dry matter content was negatively correlated with leaf thickness, chlorophyll content index and specific leaf area. The specific leaf area was negatively correlated with leaf thickness, and positively correlated with chlorophyll content index. The leaf thickness was negatively correlated with chlorophyll content index.

As shown in Table 1, according to the principle that the eigenvalue was greater than 1, two principal components were extracted (the eigenvalues were 2.429 and 1.226 respectively). The contribution rates of these two principal components were 40.5% and 20.4%, respectively, and the cumulative contribution rate was 60.9%, which indicates that these two principal components were the main factors in the change of leaf functional traits. The initial factor loading matrix of the principal components (Table 1) and the loading diagram of principal component analysis (PCA) were used (Fig. 6, it can be seen that leaf thickness, leaf dry matter content, leaf tissue density and stoma density were significantly positively correlated with the first principal component, and chlorophyll content index and specific leaf area were significantly negatively correlated with the first principal component. The correlation (absolute value) size was SLA > LDMC > LT > CCI > LTD > SD. Principal component analysis showed that the indicators that were significantly related to the first principal component can be used as the main indicators of leaf functional
traits, and the principal component contrasts leaf area, leaf dry matter content and leaf thickness have a large amount of interpretation.

### Table 1
Factor matrix and principal component contribution rate of leaf functional traits.

| Leaf traits | Eigenvalues | Scores | Percentage of Variance (%) | Cumulative (%) |
|-------------|-------------|--------|----------------------------|----------------|
|             |             | PC1    | PC2                        |                |
| LT          | 2.429       | 0.404  | -0.524                     | 40.483         |
| CCI         | 1.226       | -0.385 | 0.331                      | 20.436         |
| SLA         | 0.908       | -0.544 | -0.220                     | 15.127         |
| LDMC        | 0.682       | 0.493  | 0.012                      | 11.363         |
| LTD         | 0.525       | 0.293  | 0.753                      | 8.757          |
| SD          | 0.230       | 0.253  | -0.028                     | 3.833          |

### Discussion

**Responses of plant functional traits to atmospheric particulate pollution**

Leaf thickness is often considered to be a very valuable characteristic, which may be related to resource acquisition, water conservation and assimilation (Witkowski & Lamont, 1991; Hanba & Terashima, 1999; Cooper et al., 2004). In the past, the research on leaf thickness and mesophyll thickness was usually limited to the differences between different plants (Sabrina et al., 2005). Leaf tissue thickness was positively correlated with leaf water use efficiency and also closely related to leaf water storage capacity (Vergutz et al., 2012). Previous studies have found that small and thick leaves were the characteristics of plants adapting to a relatively water-deficient environment. The leaves tend to be thicker when the surrounding environment lacks water (Reich et al., 2003; Vergutz et al., 2012). Studies show that the increase in leaf thickness or density was beneficial to increase the distance or resistance of water diffusion from the inside of the leaf to the leaf surface, and reduce the internal water loss of the plant (Durkovic et al., 2012). In this study, we found that the leaf thickness showed a significant increase trend with the increase of atmospheric particulate matter pollution. This indicates that in an environment polluted by atmospheric particles, plants can achieve water conservation by increasing leaf thickness.

Specific leaf area is closely related to the growth and survival strategies of plant, which can characterize plant adaptability to the environment and resource acquisition capabilities (Reich et al., 2003; Wilson et al., 2010). Studies have shown that plants with a lower leaf area are more adaptable to resource-poor and arid environments, while plants with a higher leaf area have a stronger ability to retain nutrients in the
body (Reich et al., 2003; Denis et al., 2005; Wilson et al., 2010). In this study, we found that the specific leaf area of plants generally decreases with the increase of atmospheric particulate matter in cities. Under the influence of atmospheric particulate pollution, urban plants have already adjusted their specific leaf area. Reducing the specific leaf area of plants is very beneficial to the capture of light energy by leaves, at the same time, it reduces the harm caused by atmospheric particulate matter pollution and enhances the adaptability to polluted environment. Therefore, the relatively low specific leaf area of urban plants is the result of their long-term adaptation to urban atmospheric particulate pollution, and is also their long-term survival strategy in polluted environment.

The dry matter content of leaves is a predictive index for plants to obtain resources. It can reflect the adaptability of leaves to arid climates, and it is the most stable variable on the axis of resource acquisition (Willby et al., 2003; Denis et al., 2005). Leaf dry matter content is the preferred index in plant ecology research, it can be a good indicator of the plant's ability to preserve nutrients (Tao et al., 2019). In this study, we found that there were significant differences in dry matter content of leaves under urban atmospheric particulate pollution, and increases with the increase of pollution. With the increase of leaf dry matter content, the distance or resistance of water diffusion from leaves to leaf surfaces was increased, and the water loss in plant was reduced. Therefore, under the influence of atmospheric particles, the dry matter content in leaves of plants was higher, which may increase their environmental adaptability.

Leaf tissue density reflects the mechanical protection capability of the leaf (Yin et al., 2018). Studies have shown that the increase in leaf tissue density is beneficial to reducing transpiration, thus reducing water loss of plants (Houter & Pons 2012; Yin et al., 2018). Meanwhile, the increase in leaf tissue density can slow down the growth of plants and store more carbon for the construction of defense organizations (Reich et al., 2003). In this study, the density of leaf tissue showed an increasing trend with the aggravation of atmospheric particulate matter pollution. This shows that plants strengthen their defense structure to reduce the damage of atmospheric particles to leaves. This was similar to the response strategy of plants to high temperature and drought.

Chlorophyll content index reflects the photosynthesis ability of plants to a certain extent (Gitelson et al., 1996; Steele et al., 2008). In this study, the relative content of chlorophyll was significantly reduced by atmospheric particles. We suspect that, on the one hand, this may be related to the dust falling on the leaf. A large amount of dust was attached to the surface of the blade, which covers the contact area of the blade and the outside, especially the leaf area used for photosynthesis. On the other hand, the decrease of chlorophyll content may be the result of plant resource allocation. Under the condition of limited resources, plants use more resources to build defensive structures, thus weakening the resources for photosynthesis.

Stomatal is an important window for gas and water exchange between plants and the outside world (Allen et al., 2001; Field et al., 2010). This study shows that atmospheric particulate matter has a direct impact on stomatal density of plants, and the aggravation of pollution promotes the increase of stomatal
density. As atmospheric particles were deposited on the blade surface, some air holes may be blocked, which may lead to an imbalance of the blade's ability to exchange gas with the outside world. Therefore, increasing the stomatal density of plants may be a regulation strategy for dealing with atmospheric particulate matter. At the same time, we also found that atmospheric particles have a significant impact on stomatal distribution pattern. Under the influence of atmospheric particles, urban plants can improve their gas exchange function by adjusting stomatal structure and optimizing the spatial distribution pattern of stomata, which is beneficial to their normal physiological metabolism and growth.

The trade-off strategy of plant functional traits on atmospheric particulate pollution and analysis of leaf economics spectrum

Generally, the total resources available to plants are limited. If plants invest more resources in a certain functional trait, they will inevitably reduce their investment in other traits, that is, at the expense of the construction and functional maintenance of other traits (Poorter & Bongers 2006; Tomáš et al., 2012; Wright et al., 2004b). In other words, in a limited resource environment, plants will optimize resource allocation among functional traits (Tomáš et al., 2012). In this study, due to the pressure of atmospheric particulate environment, *Euonymus japonicus* showed a trade-off strategy at the leaf level, which constituted a complex and orderly trade-off relationship of economics spectrum characteristics. *Euonymus japonicus* will adjust, transform or compensate its own functions according to its own resource conditions in the urban environment, so as to achieve and balance the three purposes of "survival, growth and reproduction", which is finally manifested in the functional characteristics of plant leaves. For example, due to the influence of dust deposition, the specific leaf area is significantly reduced, which indicates that plants may use a large part of materials to build protective structures, so as to reduce the damage of atmospheric particles to leaves. The decrease of specific leaf area indicates that the greater the leaf area per unit mass of the plant, the thicker the leaf are. At this time, the more carbon the leaves were used to build the protective structure. It is manifested by the increase of leaf dry matter content and leaf tissue density at the trait level.

It was pointed out that the leaf economics spectrum was a series of interrelated and coordinated combination of functional characteristics, and it also quantitatively represents a series of regular and changing strategies of plant resource balance (Wright et al., 2004a; Wright et al., 2004b; Freschet et al., 2012; Reich et al., 2012; Wright et al., 2012; Read et al., 2014). At one end of this economic pedigree, it shows the ability of "quick investment-return", while at the other end it shows the ability of "slow investment-return" (Wright et al., 2004; Reich et al., 2012). On the whole, under the influence of urban atmospheric particulate matter, *Euonymus japonicus* shows a "slow investment-profit" type in the global leaf economics spectrum, which has low specific leaf area, low chlorophyll content, large leaf thickness, high leaf dry matter content, leaf tissue density and stomatal density (See Fig. 7).
Conclusions

This study discussed the response of leaf functional traits to atmospheric particulate pollution, and provided theoretical basis for monitoring and predicting the impact of future environmental pollution changes on plants and ecosystems. The analysis leads to the following conclusions.

(1) With the increase of dust deposition, leaf thickness, leaf dry matter content, leaf tissue density and stomatal density increased, while chlorophyll relative content and specific leaf area decreased.

(2) Under the influence of atmospheric particulates, *Euonymus japonicus* can improve its gas exchange efficiency by optimizing the spatial distribution characteristics of stomata. The larger the dust deposition on leaves, the more regular the spatial distribution pattern of stomata.

(3) There is a positive correlation between leaf thickness, leaf dry matter content, leaf tissue density, stomatal density and leaf dust deposition. However, the relative content of chlorophyll, specific leaf area and dust deposition of leaves were negatively correlated. The response of specific blade area to dust deposition of blade was the most violent.

(4) Due to the pressure of atmospheric particulate environment, *Euonymus japonicus* showed a trade-off strategy at the leaf level, which constituted a complex and orderly trade-off relationship of economics spectrum characteristics. On the whole, under the influence of urban atmospheric particulate matter, *Euonymus japonicus* shows a "slow investment-return" type in the global leaf economics spectrum, which is characterized by low specific leaf area, low chlorophyll content, large leaf thickness, large stomatal density, high leaf dry matter content and high leaf tissue density.

At the leaf level, leaf functional traits may change among populations, the resource use strategy shifting to best suit the current environmental conditions. At the leaf level, leaf functional traits change in the environment of atmospheric particulate matter. The resource use strategy shifting to best suit the current urban environment. Our study found that leaf functional traits in *Euonymus japonicus* covaried in patterns consistent with the leaf economics spectrum. This discovery provides a profound understanding for the adaptation of leaf functional traits under the background of urban environmental change.

Materials And Methods

Sample plot setting and sampling

As shown in Fig. 8, according to the characteristics of road dust, we divided the pollution degrees of atmospheric particles matter according to the distance from the main road. In September, 2019, the leaves of *Euonymus japonicus* were collected from the outside of sidewalk (T1), between sidewalk and relief road (T2) and the center of main road (T3). There was no rainstorm within 15 days on the sampling day, so as to avoid the influence of rain erosion on dust deposition. We selected 60 plants for each treatment, and collected 3 mature and healthy leaves randomly from the top of each tree. And then the
leaves were placed in a tray and sealed with plastic wrap. The leaf surface was not touched during the whole collection process.

**Dust deposition measurement**

After numbering the slow quantitative filter paper, weigh it \((W_1)\) with a GH-252 electronic balance (accuracy 0.1 mg, Shanghai Youyi Instrument Co., Ltd., Shanghai, China) for later use. Filter the washed liquid with slow quantitative filter paper, and then dry the filter paper to a constant weight by DHG-9143 electric heating blast drying cabinet (Shanghai Yitian Scientific Instrument Co., Ltd., Shanghai, China) at a temperature of 60°C (the difference between the two measured values does not exceed 0.0002 g). After that, the dry filter paper \((W_2)\) was weighed. At the same time, we calculate the quality difference \((\Delta W)\) of the blank control filter paper before and after drying \((\Delta W = W_{CK2} - W_{CK1})\). Total dust deposition of blades \(W = W_2 - W_1 - \Delta W\). Medical sharp-nosed tweezers were used in the sampling and measuring process to avoid direct contact with the blade surface. The blades before and after cleaning are shown in Fig. 9.

**Leaf functional traits measurement**

The weight of fresh leaf (LFW) was weighed with JA1003N one-thousandth electronic balance (± 0.001g, Shanghai Jinghai Instrument Co., Ltd., Shanghai, China), and the measurement was completed within 30 minutes after removal. The leaf area (LA) was measured and automatically calculated with the V39 portable leaf area meter (± 0.01 mm², Seiko Epson Corporation, Shanghai, China). Leaf thickness (LT) is measured with 500-196-30 vernier calipers (± 0.01mm, Suzhou Quantum Instrument Co., Ltd., Suzhou, China), and the thickness is measured at three equidistant points along the main vein of the leaf about 0.25 cm. The thickness of each position is averaged as the leaf thickness of the blade. The leaf volume \((V_L)\) is measured by the drainage method. Put an appropriate amount of distilled water \((V_1)\) in a 500mL graduated cylinder, and then immerse the leaf in water \((V_2)\). The volume difference between the front and back is the volume of the leaf \(V_L = V_2 - V_1\). Soak the leaves in deionized water and place them in a dark refrigerator at 5°C for 12 hours. Take out the leaves. Use absorbent paper to absorb the water on the surface of the leaves and wipe the impurities on the leaves. Weigh the saturated fresh weight (LSFW) of the leaves. Then dry at 60°C to constant weight (48 h), and weigh the dry mass (LDM).

\[
\text{LTD} = \frac{\text{LDM}}{V_L} \quad (1) \\
\text{SLA} = \frac{\text{LA}}{\text{LDM}} \quad (2) \\
\text{LDMC} = \frac{\text{LDM}}{\text{LSFW}} \quad (3)
\]

Temporary slide of stomata is made by imprinting method. A layer of transparent imprinting liquid is evenly coated on the back side of the leaf from the base to the tip of the leaf, avoiding the main vein, and
the imprinting film is torn off with tweezers to make a temporary Slides. Three slides are made for each leaf, and each slide is magnified by XSP-20 optical microscope (Jiangnan Yongxin Optics Co., Ltd., Nanjing, China) and then randomly selected 5 fields of view (713.191µm×958.115µm) for image acquisition. The stomatal density is calculated using image J software.

**Point pattern analysis of stomata**

This analysis considers that each stomatal was a single point distributed on the blade surface, and the middle position of the stomatal opening was the position of this single point. Firstly, the selected micrographs were digitized under the same coordinate system by using the spatial distribution software ArcGIS 10.4, and the coordinate values of each pore of the selected photographs can be obtained. Then, the stomatal pattern was analyzed by using Programita Febrero 2014. Here, we used Ripley's K-Function, a spatial statistical analysis method, to carry out spatial analysis on the digitized stomatal distribution feature point. Ripley's K-Function is a kind of distribution accumulation function, which uses the second-order matrix of all single points distances to explore the two-dimensional distribution patterns of these points on different scales. This paper adopted the paired correlation function g(r) and Ripley's K(r) function. The g(r) function is derived from the K(r) function. The K(r) function is defined as taking any point as centering of the circle. “r” is the ratio of the expected number of points in the circle with the radius to the point density in the sample square. In the g(r) function, a circle is used to replace the circle in the traditional pattern analysis. Among them, the g(r) function can explain the neighbor density and eliminate the cumulative effect of the K(r) function, so the g(r) function is more intuitive than the cumulative calculation of the K(r) function. The expression of g(r) function is as follows (Wiegand & Moloney 2004),

\[ g(r) = \frac{K(r)}{2\pi r} \quad (r \geq 0) \quad (4) \]

Under the assumption of complete spatial randomness, the g(r) value is above the envelope trace, indicating that the pores are clustered and distributed on the r scale. The g(r) value is located between the envelope traces, indicating that the pores are randomly distributed on the r scale. The g(r) value is below the envelope trace, indicating that the pores are uniformly distributed on the r scale.

**Data analysis**

All data were sorted in Excel 2020, and the data were analyzed and plotted with Origin 2019b. One-way analysis of variance (ANOVA) and LSD multiple comparisons were used to test the significance of the differences in leaf functional traits among different pollution gradients. The relationship between leaf characters was analyzed by linear regression, and the relationship between leaf characters and their comprehensive effects were comprehensively analyzed by principal component analysis.

**Declarations**
Ethics approval and consent to participate

This experiment does not involve human experiments and animal experiments. The field trial experiments in the current study were permitted by the local government in China, including the collection of leaf samples.

Consent for publish

Not Applicable.

Competing interests

The authors declare that they have no competing interests. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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Author contributions

J. Z. conceived and designed the study. J. Z. and X. Z. contributed materials and tools. J. Z. and Q. X. performed the experiments. J. Z., Q. X. and C. X. contributed to literature collection and summary of research frontier. J. Z. contributed to data analysis. J. Z. contributed to paper preparation, writing and revision. All the authors read and approved it for publication.

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The English in this document has been checked by at least two professional editors; both were native speakers of English.

Availability of data and materials
The data involved in the article were all shown in the figures and tables. However, there are still available from the first author on reasonable request.

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**Figures**
Figure 1

Dust deposition of plant leaves at different locations on urban streets. * indicates that the indicators have reached a significant difference at the P<0.05 level, and ** indicates that the indicators have reached a significant difference at the P<0.01 level. Same below.
Figure 2

Plant functional traits under the influence of different amounts of dust deposition. Figure (a)-(f) are leaf thickness, chlorophyll content index, specific leaf area, leaf dry matter content, leaf tissue density, and stomatal density.
Figure 3

Effect of atmospheric particulate matter on spatial distribution pattern of stomata in Euonymus japonicus leaves. (a)-(c) respectively represent T1, T2 and T3.
Figure 4

Linear fitting between leaf functional traits and dust deposition. Figure (a)-(f) are leaf thickness, chlorophyll content index, specific leaf area, leaf dry matter content, leaf tissue density, and stomatal density.
**Figure 5**

Correlation between leaf functional characters of *Euonymus japonicus* in the environment polluted by atmospheric particulate matter.
Figure 6

Principal component analysis biplot of leaf functional traits.
Figure 7

Leaf economics spectrum under atmospheric particulate matter environment (developed based on Wright et al., 2004a; Ordonez 2013; Zhu et al., 2020).
Figure 8

Sampling position diagram of leaf samples.
Figure 9

Samples of Euonymus japonicus leaves before and after cleaning. (a) leaves before cleaning, and (b) leaves after cleaning.