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Effects of building shade on photosynthesis and chlorophyll fluorescence of *Euonymus fortunei*

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Urban shading is caused by artificial urban construction and has different effects on the photosynthesis of plant, and this shading will affect the plants in photosynthesis. The purpose of the study was to reveal the plant photosynthetic characteristics in urban shading, provide theoretical basis for improving the ecological benefits of urban vegetation and provide scientific basis for urban plant landscape configuration. We selected leaf samples of *Euonymus fortunei* from three typical urban light environments: full natural light, part-time shade and full urban building shade. We quantified various measures of photosynthesis and chlorophyll fluorescence using the CIRAS-2 photosynthesis and FMS-2 fluorescence systems, respectively. The results indicated that urban shading by artificial structures caused differences in both the spatial and temporal distribution of photosynthetic active radiation (*PAR*). Surprisingly, this was not due to differences to the air temperature (*Ta*), relative humidity and CO_2 concentrations, which were consistent among the light conditions. Urban building shade also caused changes in leaf morphology and chloroplast pigment content of *E. fortunei*. Leaf area (*LA*) increased with part-time shade and decreased with full shade, while lamina mass per unit area (*LMA*) decreased significantly as the shade increased. *Chlorophyll b* content increased and the *chlorophyll a/b* ratio decreased with the decrease of *PAR*. *Pn* of *E. fortunei* displayed an irregular single-peak curve under full light and part-time shade, and the peak for each appeared at 10:00 and 12:00, respectively. *Pn* displayed a double-peak curve under full shade, with peaks appearing at 10:00 and 16:00. *Tr* of *E. fortunei* was significantly correlated with *Pn*. The *Pn-PAR* curve showed that *Pmax*, *LSP*, *LCP*, and *Rd* all decreased along with *PAR*, with the exception of *AQY*, which significantly increased. Chlorophyll fluorescence parameters also changed under the different light environments. *Fo* and *ΦPS*II both increased with the decreases in *PAR*, but *Fv/Fm and NPQ* decreased. Different levels of urban shading caused the changes in adaptive strategies of *E. fortunei*. When there was no direct sunlight appearing, a highest level of shading, *E. fortunei* presented obvious adaptive changes in its physiological photosynthetic processes, morphology, photosynthetic pigments and so on, and this type of the greatest shading caused by urban buildings or other infrastructures can obviously affect the growth of plants.

1. Introduction

With the acceleration of the urbanization process, landscape greening has become an essential part of urban construction, not only for cosmetic reasons, but also for the promotion of physical and mental health for urban populations. Plants in the urban environment have many functions, such as modulating the microclimate [1,2], reducing air and noise pollution [3,4], providing a habitat for urban wildlife in addition to their aesthetic values [5]. It is therefore not surprising that various forms of urban greens paces have been included into the sustainable and strategic development plans of major cities [6]. From an ecological perspective, urban green spaces, which support the biodiversity and interact with the biophysical factors, such as soils, air, temperature, solar radiation, water, etc., constitute an important component of a city as an urban ecosystem [7]. The functions urban green spaces provide are part of a suite of ecosystem services provided by greenery to the urban environment, the levels of which determine the overall well-being of urban dwellers. The ecosystem service functions of urban green spaces will be dependent on the extent to which urban conditions are favorable for such biological processes to be maintained, key of which are photosynthesis, transpiration and overall plant metabolism for growth and maintenance.

But the urban environment, especially in the highly built-up compact cities, present considerable challenges for plant normal growth. These factors may be exerted in the underground space, through inadequate rooting volume, or soils that are excessively compacted, polluted,

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biologically deficient, or with poor drainage. The aerial environment may also be unfavorable through excessive heat [8], air pollution, lack of aerial space for tree canopies [9] and excessive shading from urban buildings and structures [10]. When such limitations are considered against the essential conditions required for photosynthesis, namely adequate levels of water, nutrients, light, and suitable growth temperatures and atmospheric CO_2 concentrations, the factors that most limit urban greening can be then identified and targeted for intervention to circumvent or mitigate these limitations. The first two factors, water and nutrients, can all be adequately fulfilled by thoughtful design and proper urban horticultural and arboricultural maintenance regimes. The latter two factors, temperature and CO_2 concentration, are also unlikely to exceed physiological limits for plant growth under normal urban environments. In fact, higher CO_2 levels and temperatures, which are persistent characteristics of built-up areas arising from urbanization and anthropogenic activities [11], may even be favorable for plant growth. In contrast, far less is understood about plant responses to levels of light in urban areas arising from shade present in different urban morphologies, such as in urban green spaces shaded by buildings.

Light requirement for plants are usually measured as photon between 400 and 700 nm of the solar radiation spectrum, known as photosynthetically active radiation (*PAR*) [12]. Plants in urban regions experience a wide range of light gradients, just as in natural forest under canopies of taller species. The shade conditions in natural forests and urban areas differ in two areas. Firstly, the spectral irradiance under vegetation shade versus shade cast by built structures is expected to be different because of the differential absorption of irradiance at various wavelengths by vegetation canopies. In particular, it is well-documented that red (R) to far-red (FR) ratio of photon irradiance is reduced under vegetation canopies. The sensing of this change by plants in turn triggers morphological and physiological responses to enhance growth and survival [13]. But light is more difficult to control [14], and light change not only affects plant morphology, physiology and microstructure but also has a large impact on production and quality [15, 16]. Plant growth requires an appropriate level of light intensity; excessively high or low intensity will prevent photosynthesis in the plant. Based on their relative growth in shaded environments, plants are currently broadly classified as either shade tolerant or shade intolerant. Shade-tolerant plants have high light-induced morphological plasticity, slow relative growth rate, extensive foliar display, low net photosynthesis rate (*Pn*), dark respiration rate (*Rd*), light compensation point (*LCP*), and high apparent quantum yield (*AQY*). Shade-intolerant plants, as expected, exhibit the opposite characteristics [17–19].

Several studies point to the role of shading in limiting plant growth in urban regions, but none have been conducted for compact cities in tropical zones. Studies in North America showed that shaded street canyons received about 10 ~ 21% of solar radiation under unobstructed conditions [20]. Takagi and Gyokusen [21] also suggested that lower solar radiation in urban areas could be more favorable for street tree photosynthesis through avoidance of photo inhibition. Tan et al. reported that the level and distribution of *PAR* and the growth of plants within urban green spaces in Singapore [6,10], and found that the reduced *PAR* levels were correlated with lower vegetative and reproductive growth of several species of shrubs, and increased slenderness of two tree species, the shade environment created by buildings was longer periods of high instantaneous *PAR* during a diurnal cycle.

Shade trees also affect the energy use for heating and cooling of buildings [22]. Berry et al. [23] reported that tree canopy shade could reduce solar irradiance received by building walls, reduce their surface temperature and provide cooling benefits. Meanwhile, the majority of urban green spaces are located between buildings, resulting in overly shaded environments with limited sunshine and light intensity. Importantly, shade can change several aspects of the light environment, including the spectrum, intensity and spatial distribution [24,25], all of which affect plant growth and development. Therefore, the appropriate selection of understory plants for use in green spaces is necessary to establish a stratified planting structure and improve the ecological benefits of green space [21,26].

Euonymus fortunei, an evergreen shrub or vine, has been widely planted across the Shandong Province, China. This is a prominent species in urban parks, residential areas and road green space due to its high durability, good flexibility, and resistance to trimming and colorful display of red leaves in autumn. Studies of shade tolerance of *E. fortunei* have been conducted, but have focused primarily on growth in artificial environments rather than natural shade [27]. The artificial environments could not reflect the actual changes of the urban environment and the plants adaptation to the changes, the field experiment had become the important method to explore the relations between the urban environmental changes and the plant physiological ecology [21]. In this study, we examined the photosynthesis and chlorophyll fluorescence of *E. fortunei* under building shade in order to examine the photosynthetic behavior characteristics of this greening plant in a natural urban environment. This work revealed several adaptive mechanisms of this plant to different light environments, provided a theoretical basis for the ecological benefit of urban vegetation, and provided a scientific basis for plant planning and urban configuration.

2. Material and methods

2.1. Plant materials and growth conditions

E. fortunei strip planting (0.8 m wide and 0.5 m high) was 0.5 m from the building wall and planted in 2009 at a test site that was located on the south campus of Shandong Agricultural University (Taian, Shandong province). Multilevel residential buildings (18 m high), which had 40% greening rate, covering an area of 50 hm^2, were constructed of reinforced concrete. These residential buildings were rectangle, measuring 25 m south-north and 6–10 m east-west. Three typical building shade environments were selected: full sunshine (T1), partial sunshine (T2), and full shade (T3) (Fig. 1). T1 was located in front of the building and received approximately 11 h of sunshine (7:00 to 18:00). T2 was located between the buildings, and exposed to sunlight from 11:30 to 13:30 (2 h sunlight). T3 was located behind the building, and received about one hour sunlight at 16:00.

2.2. Microclimate measurements

A TES-1330A luxmeter was used to measure photosynthetically active radiation (*PAR*) on the upper 20 cm of *E. fortunei*. A GXH-305 portable infrared CO_2 instrument was used to measure the CO_2 concentration and relative humidity. These parameters were measured every 2 h from

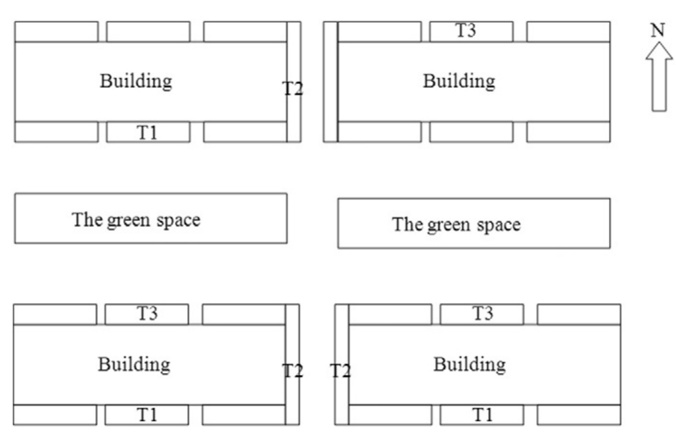

Fig. 1. Distribution of observing sites.