Growth and nutrient status in climbing plant (*Parthenocissus tricuspidata* (Siebold & Zucc.) Planch.) seedling in response to soil water availability

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ABSTRACT. A pot experiment was conducted to investigate the effects of different soil water supply on growth features and nutrient status in *Parthenocissus tricuspidata* (Siebold & Zucc.) Planch. seedlings. Decreased soil moisture had significantly reduced the length of stem, internode and petiole, but resulted in an increase of root length. Soil water supply appeared to affect stem biomass to a lesser extent than root and leaf. The seedlings grown under high water supply invested more biomass in leaf (in terms of leaf number and leaf area). The N concentration in various plant organs followed in the order leaf>stem>root>petiole while K and P concentrations remained relatively constant at different soil moisture levels. Soil water supply had significantly affected N use efficiency, but did not affect P and K use efficiency. Moreover, there was a higher P use efficiency than N or K. In addition, *P. tricuspidata* had a low K concentration (below 10 $mg \cdot g^{-1}$) in all its plant tissues, which may allow the plants to limit its stomatal opening and reduce its water loss. The growth and nutrient responses of *P. tricuspidata* to different soil water supply indicated that this species could resilient to water availabilities and adapt to water stress conditions very well.

Keywords: Biomass allocation; Growth; Nutrient distribution; Nutrient use efficiency.

INTRODUCTION

Parthenocissus tricuspidata (Siebold & Zucc.) Planch. is a subtropical deciduous woody liana of the Vitaceae family, which have rapid growth to cover almost anything in their path, and may climb 20 m or more by adhesive tendrils attaching supports. The species have attractive bluish black fruits and handsome foliage that turns scarlet, crimson, or orange in the fall. Its ability to adapt to disadvantageous growing conditions such as low nutrient soils, drought stress, a wide range of temperature and irradiation as well as its habit with great leaf area, rapidly climbing growth rate constitute the possible use of vegetation establishment for vertical surfaces such as rock slope, wall and building. *Parthenocissus tricuspidata* can not only make a fine green cover for vertical surface but also control soil erosion, detain dust, clean air, and has become a popular ornamental plant for city green and environment management (Zhang et al., 2000; Zhang et al., 2004). In addition, the species is also valued for its pharmaceutical properties. The fruit, stem, root bark and leaves are a good source of secondary products such as tannins, dyes and alkaloids (He, 1996).

The alterations in nutrients and water availability are in correlations to shape, and size of plant growth (Seyed and Majid, 2007). Water stress reduces the transpiration of the plant, which affects biomass formation and nutrient uptake with the transpiration stream. *Parthenocissus tricuspidata* have particularly narrow stems in relation to the leaf surface area they supply, however, the relationships between soil water supply, nutrient requirement and morphological changes have not been well studied.

The aim of this study is to determine how the growth features of *P. tricuspidata* respond to different soil water content by exploring the growth, dry weight, N, P, and K nutrient use efficiency and their distribution in various plant organs, and to what extent these traits may be considered as explicit selection criteria for adaptation to water stress conditions.

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MATERIALS AND METHODS

Plant material and treatments

Seeds of *P. tricuspidata* were germinated in pots containing sand and peat (v/v 3:1). After 20 days, each seedling was transplanted into each plastic pot (30 cm high, 25 cm diameter) containing 5 kg clayed loam soil (pH 6.5, organic matter 22.08 $g \cdot kg^{-1}$, total N 1450 $mg \cdot kg^{-1}$, total P 1110 $mg \cdot kg^{-1}$, total K 780 $mg \cdot kg^{-1}$). At the same time, all the pots received an application of 0.6 $g \cdot kg^{-1}$ soil of fertilizer (N-P_2O_5-K_2O, 15-15-15). Five levels of water supply treatments were imposed at the six-leaf seedling stage with field capacity at 5% (W1), 15% (W2), 30% (W3), 60% (W4), and 100% (W5). Each treatment was replicated 10 times. Water was applied by pouring it into three plastic pipes (diameter: 1 cm) placed in the soil in order to limit the heterogeneity of the soil water content (Flenet et al., 1996). To minimize soil evaporation, the soil surface was covered with plastic film. Throughout the experiment, pots were weighed daily at 16:00 to replenish lost water. The experiment was conducted in a greenhouse where the temperature was maintained at 30-35°C during the day and 20-25°C at night. Air humidity was 65%-70%.

Data collection and analysis

The leaf relative water content (RWC) was estimated by determining fresh mass, dry mass, and the mass at full turgor after hydrated for 24 h with distilled water (Kumar and Singh, 1998) and calculated as follows:

$$\text{RWC \%} = \frac{\text{fresh mass - dry mass}}{\text{full turgor mass - dry mass}} \times 100$$

Seedlings were harvested 60 days after the fist induction of water supply treatments (from August to October). The measured morphological features measured were root length, stem length, stem diameter, internode length, petiole length, total shoot length, branch number and leaf number. The total leaf area per plant was measured using a Li-3000 leaf area meter (Li-COR, Lincoln, Nebraska). Each plant organs (leaves, stems, and roots) was dried at 70°C for 48 h. After dried completely, plant organs were ground and passed through a 20 mesh screen for the tissue nutrient (N, P and K) concentrations estimation (Ru, 2000). Total nutrient content of each tissue type was calculated by multiplying their respective dry mass by their tissue nutrient concentrations. Total plant dry mass or nutrient content was calculated as a sum of the dry mass or nutrient contents of an individual's stem, roots, and leaves.

Nutrient use efficiency (NUE) of N, P and K were calculated using the following equation (Baligar et al., 2001):

$$\text{NUE} = \frac{\text{TDW}}{\text{Root X content + Stem X content + Leaf X content}}$$

Where TDW is total dry weight of plant in $g \cdot plant^{-1}$; X stands for N, P or K content in $g \cdot plant^{-1}$.

Data were analyzed with STATISTICA package 5.0 software. The Duncan test was used to perform multiple comparisons at a significance level of $P<0.05$.

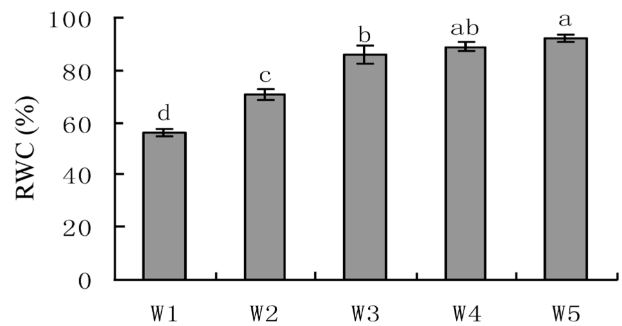

Figure 1. Leaf relative water content (RWC) of *P. tricuspidata* seedling under different water supplies condition. Different letters in the column represent significant difference at $P_{0.05}$ level by Duncan's new multiple range test.

RESULTS

Leaf relative water content (RWC)

Leaf RWC reflects the water content in plant tissue and is often used as a parameter to assess the severity of water stress. Figure 1 showed that Leaf RWC significantly decreased along with the decreasing water supply which was 92% in W5, 89% in W4, 86% in W3, 71% in W2 and only 56% in W1, that reflected the sensitive response of *P. tricuspidata* for changing of soil water content.

Growth morphology

The morphology of *P. tricuspidata* seedlings was significantly affected by water supply (Table 1). Increasing water supply led to increase in stem diameter, internode length and petiole length of seedlings, but decrease root length. The branch number, total branch length, leaf number and total leaf area of seedlings grown under lower water supply was lower as compared to those seedlings grown under higher water supply. W4 had the highest stem length (79.7 cm) than other treatments. This result represented 68% decrease in W1 and 36% in W5 as compared with seedlings under W4 treatment.

Dry biomass and biomass partition

Figure 2 showed that total biomass accumulation was significantly decreased with soil water supply decreasing from W4 to W1. Under lower soil water supplies, root growth constituted the largest proportion of the biomass (Figure 3). The ratio of root / above ground dry biomass partition had decreased along with increasing water supply. The highest value (0.44) was observed in W1 and the lowest value (0.15) in W5. The ratio of leaf / stem biomass under different water supply exceeded 1, except for W1 (0.49) (Figure 3). Under soil water supply between W2 and W5, leaf has accounted for more than 40% of total plant biomass, while stem, root and petiole accounted for less than 36%, 20% and 6%, respectively (Figure 3).

Table 1. Effects of water supply on morphological characteristics of *Parthenocissus tricuspidata* Planch. seedling.

Parameter	W1	W2	W3	W4	W5[a]
Root length cm	31. 7±2.6a	26.2±2.3b	20.3±1.5c	20.0±3.8c	13.3±2.7d
Stem length cm	25.4±1.6d	45.2±7.6c	65.5±6.6b	79.7±9.4a	51.3±4.3c
Stem diameter mm	3.2±0.4c	4.2±0.8bc	4.8±0.8ab	4.7±0.5ab	5.3±0.5a
Internode length cm	1.7±0.2b	2.1±0.3ab	2.4±0.4a	2.4±0.2a	2.5±0.3a
Petiole length cm	1.4±0.3d	2.2±0.2c	2.3±0.2c	2.8±0.3b	3.1±0.2a
Branch number	0	2. 7±0.5c	3. 7±0.8a	3. 7±0.5a	3.2±0.2b
Total branch length cm	0	4.0±1.4c	10.7±2.2ab	12.7±2.1a	9.0±1.8b
Leaf number	13.8±2.8d	22.5±2.1c	26.3±1.5b	30.8±1.7a	21.5±1.3c
Total leaf area (cm^2)	102±32c	405±138b	523±30b	692±89a	414±51b

[a]Figure in the table represent means ± standard error; Different letters in the column means significant difference at $P = 0.05$ by Duncan's new multiple range test. Same for all tables in this paper.

Tissue N concentration, N content, and N distribution

The tissue N concentration followed a linear order of leaf>stem>root>petiole under five different water supply treatments (Table 2). The N concentration of leaf and stem were not significantly different among W2, W3 and W4 treatments. Root and petiole N concentration under W2 treatment had a much higher value than that of plants grown under other treatments. N content in root, stem, leaf and petiole of seedlings grown under W4 condition was the highest among all other water supply treatments. The plant total N content had increased with an increase of water supply (from W1 to W4) except in W5 which was only decreased. Leaf was the main tissue for nitrogen accumulation, accounting for 45-60% of total accumulated nitrogen in plant between W2 and W5.

Tissue P concentration, P content, and P distribution

Table 3 shows that tissue P concentration of stem was not significantly affected regardless of water supplies. P concentration of root, leaf and petiole was significantly decreased under W1 and W5 treatments. The P content was mainly distributed in leaf and shoot, accounting for 37-44% of the total accumulated phosphorus in plant between W2 and W5. The plant total P content had increased (from W1 to W4) with the increasing of water supply except in W5 which was decreased.

Tissue K concentration, K content, and K distribution

The K concentration, K content and K distribution in different parts of the seedling (leaves, stem, root and petiole) were presented in Table 4. It was evident that K concentration in different parts of the seedling had only slight differences and therefore was not significantly affected by the different water treatments. Leaf and stem tissues contained higher K content than root and petiole, except for treatment W1. Leaf K partition in whole plant K was ever increased along with increasing water supply while a contrary trend in root K partition which was decreased. Stem K partition in whole plant K had no clear difference under the different water supply treatments as it ranged from 33-42%. With an increase of water supply (from W1 to W4), the plant total K content had increased except in W5.

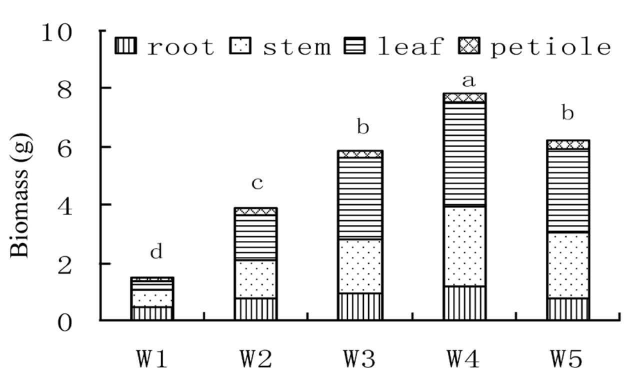

Figure 2. Effect of biomass of *P. tricuspidata* under different soil water supply.

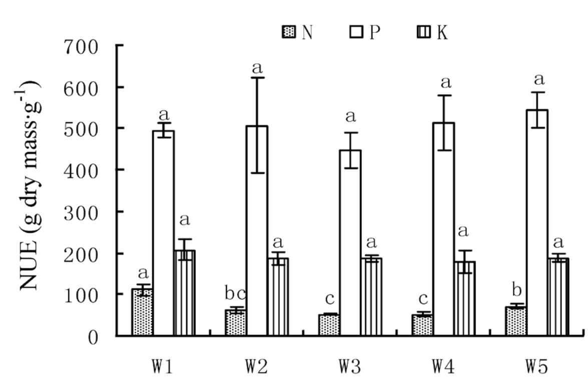

Figure 3. Nutrient (N, P and K) use efficiency of *P. tricuspidata* seedling under different water supplies.

Table 2. Nitrogen concentration and content in leaf, shoot, root, petiole and total plant tissues and nitrogen distribution in leaf, shoot, root and petiole tissues as percent of total plant N content of seedlings of *P. tricuspidata* seedling under different water supplies.

Parameter	W1	W2	W3	W4	W5
Nitrogen concentration ($mg \cdot g^{-1}$)					
Root	7.7±2.5d	17.0±1.6a	14.2±1.2ab	12.3±0.2bc	11.0±1.5c
Stem	8.0±1.7b	14.7±0.8a	15.6±0.5a	17.2±0.8a	10.8±3.3b
Leaf	12.1±1.3c	19.2±3.7ab	23.2±0.6a	22.2±2.8a	17.4±3.0b
Petiole	5.6±1.8c	8.5±0.3a	7.8±0.4ab	7.1±1.1abc	6.2±0.7c
Nitrogen content ($mg \cdot plant^{-1}$)					
Root	3.5±1.1c	13.4±1.4a	13.3±1.7a	14.9±1.0a	8.9±1.4b
Stem	5.1±1.9d	18.9±4.8c	29.4±1.7b	47.8±5.0a	24.4±8.1bc
Leaf	3.7±0.5d	29.8±7.3c	64.3±1.6ab	79.6±7.9a	50.0±9.7b
Petiole	0.6±0.3b	2.0±0.2a	1.9±0.2a	2.3±0.5a	1.9±0.2a
Total plant	13.0±3.3d	64.1±5.8c	109.0±0.8b	144.5±3.4a	85.3±3.5c
Nitrogen distribution %					
Root	27	21	12	10	10
Stem	39	30	27	33	29
Leaf	29	46	59	55	59

Table 3. Phosphorus concentration and content in leaf, shoot, root, petiole and total plant tissues and phosphorus distribution in leaf, shoot, root and petiole tissues as percent of total plant P content of seedlings of *P. tricuspidata* seedling under different water supplies.

Parameter	W1	W2	W3	W4	W5
Phosphorus concentration ($mg \cdot g^{-1}$)					
Root	1.5±0.4c	2.3±0.2a	2.3±0.1a	1.7±0.1a	1.7±0.3b
Stem	2.6±0.2a	2.2±0.9a	2.8±0.4a	2.3±0.1a	2.2±0.2a
Leaf	1.2±0.2b	1.9±0.2ab	1.9±0.2a	1.8±0.6a	1.7±0.1b
Petiole	1.2±0.1b	1.3±0.1b	1.6±0.3a	1.3±0.1ab	1.2±0.1b
Phosphorus content ($mg \cdot plant^{-1}$)					
Root	0.7±0.2c	1.8±0.2a	2.2±0.3a	2.1±0.1a	1.4±0.2b
Stem	1.6±0.4b	2.9±1.4b	5.4±0.9a	6.4±0.9a	5.0±0.4a
Leaf	0.4±0.1c	3.0±0.5b	5.3±0.7a	6.1±1.4a	4.8±0.3a
Petiole	0.1±0.04c	0.3±0.02b	0.4±0.09ab	0.4±0.07a	0.4±0.05ab
Total plant	2.8±0.7e	8.0±1.2d	13.2±1.2b	15.0±0.6a	11.5±0.4c
Phosphorus distribution %					
Root	25	22	16	14	12
Stem	57	37	40	43	44
Leaf	13	37	41	40	41
Petiole	5	4	3	3	3

Table 4. Potassium concentration and content in leaf, shoot, root, petiole and total plant tissues and potassium distribution in leaf, shoot, root and petiole tissues as percent of total plant K content of seedlings of *Parthenocissus tricuspidata* Planch. seedling under different water supplies.

Parameter	W1	W2	W3	W4	W5
Potassium concentration ($mg \cdot g^{-1}$)					
Root	6.7±1.0a	7.1±0.6a	6.1±0.5ab	5.4±0.4b	6.3±0.4ab
Stem	5.5±0.6a	5.8±0.6a	5.6±0.02a	5.9±0.5a	5.5±3.0a
Leaf	4.0±0.1b	5.0±0.3ab	5.1±0.4a	5.3±1.0a	5.2±0.4a
Petiole	3.3±0.2b	5.7±0.9a	6.1±0.4a	6.8±1.1a	5.6±0.8a
Potassium content ($mg \cdot plant^{-1}$)					
Root	3.1±0.5d	5.5±0.3bc	5.7±0.3b	6.5±0.1a	5.1±0.3c
Stem	3.4±0.5e	7.4±1.0d	10.6±0.3c	16.4±0.7a	12.5±1.8b
Leaf	1.2±0.1d	7.9±1.6c	14.1±0.6b	18.7±3.6a	15.0±1.4b
Petiole	0.3±0.1c	1.4±0.3b	1.5±0.1b	2.1±0.4a	1.7±0.2ab
Total plant	8.0±0.7d	22.2±0.7c	31.9±0.2b	43.8±4.6a	34.4±1.0b
Potassium distribution %					
Root	38	25	18	15	15
Stem	42	33	33	37	36
Leaf	16	36	44	43	44
Petiole	4	6	5	5	5

Table 5. Whole plant N-P-K tissue contents (expressed relative to P content) of *P. tricuspidata* seedling under different water supplies.

	W1	W2	W3	W4	W5
N	4.6	8.2	8.3	9.7	7.4
P	1	1	1	1	1
K	2.9	2.8	2.4	2.9	3.0

N-P-K ratios

Plant tissues contained more N than K and more K than P for all treatments in this study (Table 5). Relative to P content, the N content ranged from 4.6 (W1) to 9.7 (W4) and the K content ranged from 2.4 (W2) to 3.0 (W5). The N-P-K ratio was the highest in W4 treatment among all soil water supply treatments.

Nutrient use efficiency

Figure 4 shows that there were no significant effects for P and K use efficiency under different water stressed conditions, however N use efficiency of W3 and W4 treatments was clearly lower than W1 and W5 ($p<0.01$). In general, P use efficiency was higher than either N or K under the five soil water supply treatments.

DISCUSSION

Seedling growth

Many studies have shown that soil water supply can affect the growth of plant organs (Rascio et al., 1990; Spollen et al., 1993), which result in an alteration of its morphology and nutrient uptake (French and Turner, 1991). Consequently, the pattern of dry mass accumulation and nutrient distribution within the plant may be affected (Chartzoulakis et al., 1993; Cox and Conran, 1996; Zhou and Chen, 1997). Under low soil water availability, *P. tricuspidata* seedlings had invested more biomass distribution in root growth (Figure 3) as root elongation was stimulated (Table 1) in order to absorb more water for higher survival competitive capacity under water stress (Rodrigues et al., 1995). The increased root dry mass ratio under lower water supply was in accordance with early studies in other plants (Sharp et al., 1990). In this study, soil water availability appeared to affect stem biomass less than root and leaf. As the soil moisture content increased from W2 to W5 treatments, the biomass of stem relative to the total biomass varied from 32% to 36%, while the variation of the root biomass is from 13 to 20% and the range of the leaf biomass is from 40 to 47% (Figure 3). The seedlings grown under high water supply invested more biomass in leaf as observed in an increase of leaf number and leaf area (Table 1). Changes in leaf biomass may adjust transpiration to control plant water status of the species to adapt different soil water supply.

Unlike trees species, climber species typically have a very high leaf : stem ratio and relatively little structural support, so the slender stem only transport nutrient and water (Putz and Harold, 1991). *Parthenocissus tricuspidata* showed a high phenotypic plasticity which may enhance its capacity to survive and reproduce under different soil water conditions. Under low soil water condition, *P. tricuspidata* showed a decrease in its stem, internode and branch length to shorten the distance of water transportion, while its stem diameter increased with the increasing of soil water content to enlarge water flux. These morphological changes in the stem structures in response to soil water supply indicated that it is an important way to change the length and diameter of stem to suit for soil water condition.

Nutrient status

The nutrient status of a plant played a significant role in altering the rate of development, extent of growth, and even morphological features (Epstein and Arnold, 2005). Given rapid growth rates and voluminous leaf production, climbing plants certainly must have special characteristics in their nutrient cycling mechanism (Putz and Harold, 1991). Water supply was the main variable controlling nutrient uptake in the plant. As suggested by Erlandsson, 1975, water stress tends to reduce nutrient uptake by roots and transport from roots to shoots due to restricted transpiration rates and membrane permeability. This study examined the performance of the different essential nutrients of *P. tricuspidata* related to leaf, root growth, and biomass allocation under different soil water supply. Decreasing of water supply decreased foliar N, P and K concentration but increased root N and P concentration, and had no significant effect on stem N, P and K and root K. The W1 (severe drought) and W5 (overfull water) treatments had a negative effect on nutrient uptake. According to N-P-K ratio under five water supply treatments (Table 5), the average N content in plant is 4.5 to 9.7 times than that of P, 2 to 3 times than that of K. These results may support a conclusion that water supply has constrained N uptake to a much greater extent than to P and K in *P. tricuspidata*. It is therefore suggest that N management is essential for enhancing biomass production of *P. tricuspidata*.

Many studies have indicated that increased nutritional supply (particularly P) confers increased drought tolerance under dry conditions (Premchandra et al., 1990; Singh et al., 2006). Table 3 showed that root P concentration was higher than other parts, it will contribute to root growth and root hydraulic conductivity to uptake soil water and nutrients (Schnitzer and Bongers, 2000). P concentrations of plant under optimal growth conditions vary between 1.5 $mg \cdot g^{-1}$ and 5 $mg \cdot g^{-1}$ (Raghothama, 1999). The tissue P concentration of *P. tricuspidata* was 1.2-3 $mg \cdot g^{-1}$ under all water supply treatments, which had relative lower P concentration. P use efficiency was not significantly affected by soil water supply (Table 6), and higher P use efficiency and lower P concentration also indicated that *P. tricuspidata* is a species adapted to low P environments.

Plant tissue K concentrations can vary within a wide range, from 10 $mg \cdot g^{-1}$ to 40 $mg \cdot g^{-1}$, and K concentration below 10 $mg \cdot g^{-1}$ will lead to deficiency symptoms in most species (Markus and Pascal, 2007). However, the tissue K concentration of *P. tricuspidata* was determined to range from 3 $mg \cdot g^{-1}$ to 7 $mg \cdot g^{-1}$ under all water supply treatments. This concentration was much lower than the critical value of K deficiency. Potassium is the main osmotic solute in plants (Wyn Jones et al., 1979). High K concentration in plants has been shown to favor water uptake and stomatal opening while potassium-deficiency may result in an earlier stomatal closure and inhibit transpiration (Tomemori et al., 2002; Kudoyarova et al., 2007). *Parthenocissus tricuspidata* has slender stem and large leaf area. The thin stem limit water and nutrient flux while the large leaf biomass may accelerate transpiration. Under this especial growth structure condition, the low K concentration in the tissues of *P. tricuspidata* may be advantageous as this may cause the reduction of cell turgor which could result in stomatal closure that lead to the reduction of transpiration rate and therefore restricts further water loss. Plants with efficient stomatal control ability are able to survive well in drought environments (Saliendra et al., 1995). Further research is certainly needed to evaluate this phenomenon of low K concentration in *P. tricuspidata*, as this may be a unique drought tolerance mechanism for this species.

Nutrient storage mainly depends on the rate of biomass accumulation and nutrient concentration in different plant organs (Swamy et al., 2003). In *P. tricuspidata,* leaf was the main tissue for nutrient accumulation, accounting for more than 45% (N), 35% (P), and 35% (K) of the total accumulated nutrients in the plant tissues across different water supply conditions in this study W2-W5. Some reports showed that there was a strong positive correlation between foliar nutirent content and photosynthesis (Brown et al., 1995; Paquin et al., 2000). Moreover, *P. tricuspidata* has allocated a large proportion of its biomass to leaves. Therefore, this may be a plausible physiological adaptation to ensure an optimal photosynthetic capacity of the species.

Parthenocissus tricuspidata could adjust biomass, nutrient allocation and nutrient use efficiency in response to soil water availability. Higher P use efficiency, lower P and K acquisition compared with N, indicated that *P. tricuspidata* had different nutrient adaptation strategies to optimize its uptake of N, P and K under different soil water supply. Based on these results, we suggested N nutrient should be preferentially selected to fertilize. Further research would be undertaken to investigate photosynthesis and water use efficiency of *P. tricuspidata* under different soil water availability as this will help in understanding the complex growth mechanisms of this species.

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土壤水分對攀緣植物爬山虎幼苗生長和養分吸收的影響

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本文研究了在土壤盆栽條件下，不同土壤含水量對攀緣植物爬山虎幼苗生長和營養特性。結果表明：土壤水分減少，顯著減少主莖、節間和葉柄長度，但增加根的長度。土壤水分供應對爬山虎根和葉生物量影響高於對主莖生物量的影響，較高的土壤水分使葉生物量增加顯著。在不同的土壤含水量條件下，爬山虎的各器官氮養分濃度的順序是葉 > 莖 > 根 > 葉柄，而各器官的磷和鉀的養分濃度值保持相對穩定，但爬山虎有低的鉀濃度（小於 10 $mg \cdot g^{-1}$），可能控制爬山虎的葉片的氣孔開放，降低葉片的水分散失。土壤含水量顯著影響爬山虎的氮的利用率，但對磷鉀利用率影響不顯著，磷的利用率顯著高於氮和鉀利用率。

關鍵詞 : 生物量；生長；營養特性；利用率。