Effects of Ontogenetic Development on Seedling Regeneration Dynamics of *Quercus Acutissima* Plantation in Mount Tai

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Abstract

Background: Natural regeneration is critically important for the sustainable management of artificial forests. Studies have been investigated for the effects of seedlings height distribution and ontogenetic adaptability in a 60-year-old *Quercus acutissima* artificial pure forest in Mount Tai.

Results: The results showed that the height distribution of seedlings under the forest was pyramidal-shape from the year 2010 to 2017. In 2017, the density of seedlings under the forest was only 61.63% of that in 2010, and the number of individuals at each height class was lower than that in 2010, especially the individuals at 20-40cm height class only 32% of that in 2010. With the increase of seedling height under the forest, seedling biomass (SB), ground diameter (GD), root mass ratio (RMR), total root length (TRL), root volume (RV), root average diameter (RAD) and nonstructural carbohydrates (NSC) increased significantly, but leaf mass ratio (LMR), leaf area ratio (LAR), photosynthetic/non-photosynthetic tissue ratio (P/NP), specific root length (SRL) and specific root surface area (SRA) decreased significantly. Correlation analysis showed that SB was negatively correlated with LMR, LAR, P/NP, SRL and SRA, and positively correlated with RMR, TRL, RV, RAD and NSC. NSC was negatively correlated with LMR, LAR, P/NP, SRL and SRA.

Conclusions: Therefore, with the increase of seedlings height, the increased carbon storage was helpful for the seedlings of *Q. acutissima* to survive under the forest for a long time, but the reduced ability of light interception, photosynthetic tissue ratio, water and nutrient absorption capacity contributed to their low survival ratio under the forest.

Background

Man-made forest has grown rapidly global wise from 1990 to 2015. The percentage increase was from 4.06 to 6.95% of the total forest area between 1990 and 2015 [1]. Man-made forest is playing an increasingly crucial role in timber production, environmental improvement, landscape rehabilitation and climate change mitigation [2]. Natural regeneration is a vital for sustainable forest management. Naturally regenerated forests have the advantages of better plant establishment [3], self-regenerated material and high seedling densities [4, 5]. However, unreasonable managements make the planted forests unable to complete the natural regeneration [2, 6, 7]. Stand structure [8], litter density and grass cover [9], seedling adaptation [10, 11, 12], stand management [13, 14] and year-to-year stand conditions [15] are considered to be vital factors affecting natural forest regeneration. Natural regeneration of plantation is a long-term and complex process, which is affected by many factors. At present, the regeneration mechanisms of plantation are still poorly understood.

Sufficient seedling bank is the foundation to the success of natural forest regeneration [16, 17, 18, 19]. The structure and composition of natural tree regeneration is closely related to stand density [17], canopy opening [15, 20], seedling adaptability of tree species [16, 18, 19, 21] and forest management [14]. Long term monitoring on tree seedlings revealed that the fraction of seedlings eventually reach to the sapling class is very small due to high seedling mortality [15, 22, 23]. The transformation from seedlings to saplings requires higher light intensity, which is hard to achieve under the forest. Usually the demand for light is closely related to the shade tolerance for specific trees [24]. With the increase of seedling size, the proportion of non-photosynthetic tissues to total sapling biomass increased and so as respiration costs [25, 26, 27, 28]. Minimum light-demanding tree species rose with increasing seedling size, which led to the decrease of shade tolerance [29, 30]. Kunstler et al. [31] considered that strong morphological adaptation was an important reason for long-term survival of *Fagus sylvatica* seedlings under forest. However, Sinz et al. [18] suggested the establishment and persistence of *Fraxinus pennsylvanica* seedlings beneath closed canopies showed no significant relationships with their morphological adaptation. Soto et al. [32] thought light and nitrogen interact to influence regeneration in old-growth *Nothofagus*-dominated forests in south-central Chile. Therefore, the current understanding of the dynamics of seedling banks under forest is still very limited.

Nonstructural carbohydrates (NSC) storage is a fundamental process that allows organisms to meet variable demand for resources during their development and buffer environmental fluctuations in resource supply. Phenology is a key factor influencing seasonal variability of NSC concentrations in trees [25, 33]. Reduced NSC reserve in the root system of *Populus tremuloides* and *P. balsamifera* seedlings during severe drought contributed to the root death of seedlings during the dormant season by compromising the frost tolerance of the root system [34]. In shaded forest understories, NSC in tree seedlings would act like a buffer during the periods of negative net carbon balance against herbivores and diseases [35], defoliated [36] and suddenly shade increase [37], etc. Under severe shading, NSC in seedlings will be greatly consumed [38, 39], or even with very little remaining [38], which determines the survival time under the forest. However, Piper et al. [40] suggested that carbohydrate storage was not related to low-light survival in *Nothofagus* species, but supported the view that understory survival is primarily a function of net carbon gain. Imaji and Seiwa [41] found *Quercus* preferentially invested more carbon in defense than in storage. In addition, some studies have shown that the effects of NSC on seedling survival are related to water stress [39], seedling size [42], defoliation [35], and forest type [43]. Therefore, the relationship between NSC and survival of seedlings has not yet formed a unified understanding.

China has the largest plantation area in the world. For a long time, plantation management pays too much attention to short-term productivity and economic benefits, but ignores its natural regeneration [2]. *Quercus acutissima*, a deciduous tree belonging to *Quercus* in *Fagaceae* Family, is the main component tree of forest vegetation in warm temperate and subtropical regions of China, a pioneer tree in barren mountains and barren land and an excellent tree species for soil and water conservation, with high ecological, economic and landscape values. At present, there are few studies on natural regeneration of *Q. acutissima* plantation. *Q. acutissima* has certain shade tolerance, and its seedlings rarely die under more than 12% full light [44]. Xue et al. [45] found there are a large number of seedlings in the secondary forest of *Q. acutissima*, but there are few saplings. In order to further explain the restriction mechanism of natural regeneration of *Q. acutissima* plantation, this paper takes the artificial pure forest of *Q. acutissima*, the main forest type of Mount Tai as the research object, and two questions were addressed: (1) the structural change of *Q. acutissima* seedlings under the forest in a long-term period; (2) how seedlings adapt with the individual growth.

Results

The diameter structure of *Q. acutissima* plantation

The density of *Q. acutissima* adult trees in 2010 stands was 634 N ha^{-1} , trees in the DBH class 2-5cm accounting for 19.70%, 5-10cm only for 3.44%, and 15-35cm for 70.94%. In 2017, the density of adult trees was 675 N ha^{-1} , trees in the DBH 2-5cm accounting for 14.81%, 5-10cm for 0, and 15-35cm for 77.78%. In 2017, compared with 2010, the density of trees in the DBH 2-5cm decreased by 4.89%, 5-10cm trees disappeared, and the density of 15-35cm trees increased by 6.84% (Fig. 1A).

The distribution of seedlings in 2010 and 2017 was pyramid-shaped (Fig. 1B). The tree number in the height class 0-20cm and 20-40cm showed the maximum, and then gradually decreased with the height increasing. Compared with 2010, the density of seedlings in 2017 was only 61.63% of that in 2010, showing a significant decrease. Moreover, seedlings of all height levels were reduced, especially at the height of 20-40cm, which was only 32% of that in 2010. All seedlings at 140-150cm died in 2017.

Seedling size traits with the increase of height

The results of variance analysis showed that seedling height had a significant effect on biomass ($F = 17.53$, $P < 0.01$) and ground diameter ($F = 12.56$, $P < 0.01$). Biomass and ground diameter increased significantly with height (Fig. 2A and B).

Adaptation traits of seedlings with increasing height

Biomass allocation

The results of variance analysis showed that seedling height had significant effects on LMR ($F = 9.98$, $P < 0.01$), RMR ($F = 8.41$, $P < 0.01$), LAR ($F = 7.16$, $P < 0.01$), P/NP ($F = 8.72$, $P < 0.01$), but not on SMR ($F = 1.79$, $P = 0.20$) and SLA ($F = 0.07$, $P = 0.98$). With the increase of height, LMR, LAR and P/NP all increased first and then decreased (Fig. 3A, E, F), but RMR decreased first and then increased (Fig. 3B).

Root traits

The results of variance analysis showed that seedling height had significant effects on total root length ($F = 4.10$, $P < 0.05$), root volume ($F = 31.47$, $P < 0.01$), average root diameter ($F = 76.12$, $P < 0.01$), specific root length ($F = 14.40$, $P < 0.01$), but not on specific root surface area ($F = 1.47$, $P = 0.27$). With the increase of tree height, the total root length, root volume and average root diameter increased significantly, while the specific root length and root surface area decreased significantly (Fig. 5).

Non-structural carbohydrate (NSC)

The results of variance analysis showed that height had significant effects on the NSC content of root ($F = 17.96$, $P < 0.01$), stem ($F = 21.73$, $P < 0.01$) and leaf ($F = 26.52$, $P < 0.01$). With the increase of tree height, NSC content of root, stem and leaf all increased significantly (Fig. 5). NSC of root was about that of leaf, and both of which were greater than that of stem.

Correlation analysis among seedling traits

SB was negatively correlated with LMR, LAR, P / NP, SRL and SRA, and positively correlated with RMR, TRL, RV, RAD and NSC (Table 2). LMR, LAR and P/NP were negatively correlated with RMR, TRL, RV and RAD. NSC was negatively correlated with LMR, LAR, P / NP, SRL and SRA, and positively correlated with RMR, TRL, RV and RAD.

Table 1
Seedling indexes, abbreviations and units

Indexes	Abbreviations	Units
Seedling biomass (leaf + stem + root mass)	SB	g
Leaf mass ratio (leaf dry mass/total seedling dry mass)	LMR	$\text{g}\cdot\text{g}^{-1}$
Stem mass ratio (stem + petiole mass)/total plant mass	SMR	$\text{g}\cdot\text{g}^{-1}$
Root mass ratio (root dry mass/total seedling dry mass)	RMR	$\text{g}\cdot\text{g}^{-1}$
Specific leaf area (total leaf area/total leaf dry mass)	SLA	$\text{cm}^2\cdot\text{g}^{-1}$
Leaf area ratio (total leaf area/total seedling dry mass)	LAR	$\text{cm}^2\cdot\text{g}^{-1}$
Photosynthetic tissues/non-photosynthetic tissues [leaf mass/(stem + root mass)]	P/NP	$\text{g}\cdot\text{g}^{-1}$
Total Root length	TRL	cm
Root volume	RV	cm^3
Root average diameter	RAD	mm
Root total surface area	RSA	cm^2
Specific root length (root length/dry root mass)	SRL	$\text{cm}\cdot\text{g}^{-1}$
Specific root area (root surface area/ dry root mass)	SRA	$\text{cm}^2\cdot\text{g}^{-1}$
Root NSC	RNSC	$\text{mg}\cdot\text{g}^{-1}$
Stem NSC	SNSC	$\text{mg}\cdot\text{g}^{-1}$
Leaf NSC	LNSC	$\text{mg}\cdot\text{g}^{-1}$

Table 2

Correlations among seedling characteristics of *Quercus acutissima*. SB: seedling biomass; LMR: leaf mass ratio; RMR: root mass ratio; SMR: stem mass ratio; LAR: leaf area ratio; TRL: total root length; TRA: total root surface area; RV: root volume; RAD: root average diameter; SRL: specific root length; SRA: specific root surface area; P/NP: non-photosynthetic tissues; RNSC: root nonstructural carbohydrate concentration; SNSC: stem nonstructural carbohydrate concentration

Indexes	SB	LMR	RMR	SMR	SLA	LAR	TRL	TRA	RV	RAD	SRL	SRA	P/NP	RNSC
SB	1													
LMR	-0.706**	1												
RMR	0.666**	-0.895**	1											
SMR	-0.335	0.374	-0.748**	1										
SLA	-0.053	-0.162	0.146	-0.062	1									
LAR	-0.701**	0.923**	-0.810**	0.312	0.223	1								
TRL	0.655**	-0.556*	0.570*	-0.357	-0.011	-0.557*	1							
TRA	0.368	-0.184	0.294	-0.338	0.237	-0.088	0.661**	1						
RV	0.990**	-0.753**	0.701**	-0.338	-0.019	-0.737**	0.654**	0.328	1					
RAD	0.846**	-0.718**	0.639**	-0.261	0.024	-0.704**	0.649**	0.255	0.897**	1				
SRL	-0.666**	0.420	-0.367	0.138	-0.044	0.390	-0.367	-0.250	-0.657**	-0.734**	1			
SRA	-0.678**	0.475	-0.450	0.230	0.015	0.472	-0.630**	-0.346	-0.671**	-0.769**	0.927**	1		
P/NP	-0.669**	0.998**	-0.888**	0.361	-0.178	0.917**	-0.540*	-0.168	-0.719**	-0.693**	0.389	0.447	1	
RNSC	0.774**	-0.575*	0.542*	-0.271	-0.053	-0.601*	0.739**	0.423	0.780**	0.841**	-0.751**	-0.847**	-0.554*	1
SNSC	0.791**	-0.569*	0.486*	-0.164	-0.133	-0.623**	0.661**	0.384	0.806**	0.847**	-0.705**	-0.757**	-0.547*	0.932
LNSC	0.815**	-0.670**	0.541*	-0.128	-0.065	-0.701**	0.687**	0.364	0.838**	0.884**	-0.708**	-0.761**	-0.651**	0.951

Discussion

The seedling density of *Q. acutissima* plantation in this paper was 14063 N ha⁻¹ in 2010 and 8667 N ha⁻¹ in 2017. According to the Austrian forest inventory, regeneration densities on sites with less than 2,500 trees ha⁻¹ are classified as insufficient [46]. Therefore, there are sufficient seedlings under the *Q. acutissima* plantation, which is related to the ability of shade tolerance in seedling stage [44]. The distribution of seedlings in 2010 and 2017 was pyramid-shaped, indicating that the seedling bank was relatively stable. The seedling density in the height class 0–20 cm in 2010 was similar to that in 2017, which was related to the continuous germination of seeds under the forest [22, 47]. Compared with 2010, the stand density changed little in 2017, but the seedling density decreased significantly, only 61.63% of that in 2010. Szwagrzyk et al. [22] also found seedlings of *Fagus sylvatica* which could eventually enter the sapling stage in submontane beech-dominated forests is very small due to high mortality at very low light levels under closed canopies. Many studies have shown that the conversion rate from seedlings to saplings is very low due to the insufficient relative light intensity under the forest for long-term survival [15, 22, 23, 47]. Studies on natural regeneration of *Quercus* suggested that higher light intensity was needed for successful regeneration [17, 21]. Therefore, relatively low light intensity may be an important reason for the gradual death of *Q. acutissima* seedlings under the forest.

With increasing size, LMR and LAR decreased significantly in *Q. acutissima* seedlings in this paper, which indicated that the light utilizing efficiency decreased. This result was consistent with that of Balandier et al. [27] and Lusk [48]. However, Sinz et al. [18] found that *Fraxinus pennsylvanica* regeneration maintains a fixed morphology relative to size through seedling and sapling development. In this paper, P/NP of *Q. acutissima* seedlings decreased as tree size increased, which was in good agreement with the results reported by Balandier et al. [27] and Gaucher et al. [25]. The proportion of non-photosynthetic tissues increases with increasing seedling size causes an increase in respiratory and construction costs in large individuals, which leads to the increase of minimum light requirement [25, 29, 30]. The increase of minimum light requirement in taller seedlings is a vital reason for the low understory survival for light demanding trees species [29, 30]. Grubb [49] proposed that tree species by maximizing net carbon gain in low light could persist in the understory for a long time. With the increase of seedling height, the increasing RAD indicated that the fraction of fine roots decreased. The significant decrease of SRL and SRA with increasing height indicated the ability of root system to absorb water and nutrients decreased [50]. Correlation analysis showed that SB was negatively correlated with LMR, LAR, P/NP, SRL and SRA. Therefore, with the increase of seedling size, the decrease of the light utilizing efficiency, the proportion of non-photosynthetic tissue and the absorption capacity of root system are an important reasons to limit the long-term survival of *Q. acutissima* seedlings under the forest.

With the increase of height, the concentration of NSC in *Q. acutissima* seedlings increased, which agreed with the results reported by Lusk and Piper [42]. SB of *Q. acutissima* was significantly positively correlated with NSC concentration, suggesting a progressive accumulation of carbohydrate reserves during seedling development. Some studies have shown that the higher the content of NSC in the seedlings, the longer the survival time under shade [35, 38, 39]. Furthermore, carbohydrate storage in stems and roots enhances long-term survival in shade by enabling seedlings to cope with periods of biotic and abiotic stress [35, 42]. *Q. acutissima* seedlings also showed high content of NSC in roots, which was positively related to TRL, RV and RAD. Therefore, the long-term survival of *Q. acutissima* seedlings under the forest is closely related to the high level of NSC in roots. However, NSC was negatively correlated with LMR, LAR, P/NP, SRL and SRA, which indicated that there was competition between NSC storage and light utilization capacity, the proportion of photosynthetic tissue and root absorption capacity, that is, there was a trade-off between carbon storage and growth. Therefore, with the increase of individual size, sacrificing growth and increasing carbon storage can improve the persistence time of *Q. acutissima* seedlings under the forest.

Conclusion

The natural regeneration of plantation is a complex and long process, and the adaptability of seedlings under the forest is one of the key foundations for its successful regeneration. In the sample plot of *Q. acutissima* plantation, the seedling bank was sufficient and stable, which was closely related to its shade tolerance. With the increase of height, the RMR and NSC content of seedlings increased, which was helpful for their long-term persistence under the forest. However, compared with the seedling bank in 2010, the number of seedlings decreased significantly in 2017. With the increase of height, the capacity of light utilization, the fraction of photosynthetic tissue and the capacity of water and nutrient absorption decreased significantly. Eventually the significant decrease of LMR, LAR, P/NP, SRL and SRA led to the survival failure of *Q. acutissima* seedlings in the forest. The study on natural regeneration of other *Quercus* trees shows that higher light intensity is needed for successful regeneration. Therefore, it is necessary to further study the relationship between natural regeneration and light environment of *Q. acutissima* plantation, and clarify the light intensity range of successful natural regeneration, so as to provide theoretical basis for the sustainable management of *Q. acutissima* plantation.

Methods

Study area

Mount Tai lies in the middle of Shandong province, China, between Jinan and Tai 'an. The study area belongs to the warm temperate continental monsoon climate zone, the average annual temperature is 12.6°C, the frost-free period is 196 days, and the accumulated temperature greater than or equal to 10°C is 3821°C. The average annual precipitation is 758 mm, and the precipitation is centered from June to September. The soil type is mainly brown loam with pH value of about 6.0 and soil thickness of 15 ~ 60 cm. Most of the vegetation in Mount Tai was planted in the 1950s and 1960s, with a total forest area of about 9,490 hm² and a forest coverage rate of 81.5%. The main tree species include *Platycladus orientalis*, *Q. acutissima*, *Robinia pseudoacacia*, *Pinus thunbergii*, *Pinus densiflora*, *Pinus tabulaeformis*, etc [51, 52].

Investigation of *Q. acutissima* plantation

The investigation of *Q. acutissima* plantation was conducted in the Mountain Tai Forest Ecosystem Research Station of State Forestry and Grassland Administration (117°06'48.2" N, 36°20'05.3" E), whose technical support unit is Shandong Agricultural University. The forest was artificially planted in 1960 using one-year-old seedlings from seeds collected from *Q. acutissima* forest in Mount Tai. The plantation is a pure forest with an age of 60a and locates at 730 m. The permanent fixed plot was established in 2010 with an area of 0.48 hm². Twelve 20 m × 20 m quadrates were set up in the fixed plot. In each quadrat, we measured the diameter at breast height (DBH) for all trees with height ≥ 150 cm, which were defined as adult trees. Saplings below 1.5 m in height were divided into 8 levels according to the height: <20 cm, 20-40cm, 40-60cm, 60-80cm, 80-100cm, 100-120cm, 120-140cm and 140-150cm. Adult trees were classified into DBH sizes, with one diameter class for every 5 cm. The permanent fixed plot was reviewed in May 2017. The sampling and investigation methods in this paper referred to the forestry industry standard of the People's Republic of China issued by the State Forestry Administration [53]. The formal identification of the samples was undertaken by the corresponding author Peili Mao, and the specimen information of the species involved in this study are available at "China Plant Species Information System".

Determination of seedling traits of *Q. acutissima*

On May 10, 2016, 19 seedlings with a height between 9 and 46 cm were selected and dug out in *Q. acutissima* plantation of Yaoxiang forest farm. These seedlings were divided into 4 groups according to height: 5 cm < height < 15 cm (I), 16 cm < height < 25 cm (II), 26 cm < height < 35 cm (III), 36 cm < height < 45 cm (IV). And there were 3–5 seedlings within each height group. The height, diameter and number of leaves of the seedlings were measured. Then, each seedling was carefully excavated from soil with hand tools and the whole *Q. acutissima* seedling was sealed and stored in a self-sealing bag and brought back to the laboratory.

In the laboratory, the seedlings were divided into leaves, stems and roots. The age of seedlings was determined by counting the number of annual rings. The area of each leaf of each seedling was measured one by one with CI-202 portable laser leaf area meter (CID Inc., Washington, USA). After being rinsed with clean water, these roots were scanned by HP Scanjet 8200 scanner, and the scanned images were analyzed by root parameter analysis software (Delta-T Area Meter Type AMB2) to obtain length and surface area of roots. The roots, stems and leaves of seedlings were dried at 80°C until constant weight, then the dry weight was weighed and recorded. After dried samples of roots, stems and leaves were pulverized, their concentrations of soluble sugar and starch were determined by anthranone - H₂SO₄ colorimetry, respectively [54]. Starch and soluble sugars in each plant organ were added together to determine nonstructural carbohydrate concentration (NSC).

Statistical analysis

The seedling indexes were shown in Table 1. Relevant data were analyzed by SPSS20.0 (SPSS Inc., Chicago, USA) statistical analysis software for one-way ANOVA. The responses of functional traits to height were compared and multiple comparisons were made. At the same time, the correlation analysis of each index is carried out. The test level was $P = 0.05$.

Abbreviations

- SB**
Seedling biomass (leaf + stem + root mass)
- LMR**
Leaf mass ratio (leaf dry mass/total seedling dry mass)
- SMR**
Stem mass ratio (stem + petiole mass)/total plant mass
- RMR**
Root mass ratio (root dry mass/total seedling dry mass)
- SLA**
Specific leaf area (total leaf area/total leaf dry mass)
- LAR**
Leaf area ratio (total leaf area/total seedling dry mass)
- P/NP**
Photosynthetic tissues/non-photosynthetic tissues [leaf mass/(stem + root mass)]
- TRL**
Total Root length
- RV**
Root volume
- RAD**
Root average diameter
- RSA**
Root total surface area
- SRL**
Specific root length (root length/dry root mass)
- SRA**
Specific root area (root surface area/ dry root mass)
- RNSC**
Root NSC
- SNSC**
Stem NSC
- LNSC**
Leaf NSC

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

All of the data and materials supporting our research findings are contained in the methods section of the manuscript.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

PLM and BHC conceived and guided the project. PLM, LMG, ZXL and QZL conducted the experiments. LMG, ZXL, QZL, CYY, PG, JWD and BPZ collected and analyzed the data; PLM, LMG, ZXL, QZL carried out the experiments and performed software; PLM and LMG wrote the manuscript; PLM and BHC reviewed the manuscript. All authors have read and approved the final manuscript.

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Figures

Figure 1

Diameter at breast height classes of adult trees (A) and height classes of seedlings (B) distribution patterns of *Quercus acutissima* in 2010 and 2017, respectively

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Diameter at breast height classes of adult trees (A) and height classes of seedlings (B) distribution patterns of *Quercus acutissima* in 2010 and 2017, respectively

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Diameter at breast height classes of adult trees (A) and height classes of seedlings (B) distribution patterns of *Quercus acutissima* in 2010 and 2017, respectively

Figure 2

Changes of seedling biomass (SB, A) and ground diameter (GD, B) with the increase of seedling height of *Quercus acutissima*

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Changes of seedling biomass (SB, A) and ground diameter (GD, B) with the increase of seedling height of *Quercus acutissima*

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Changes of seedling biomass (SB, A) and ground diameter (GD, B) with the increase of seedling height of *Quercus acutissima*

Figure 3

Changes of biomass allocation with the increase of seedling height of *Quercus acutissima*. A: LMR; B: RMR; C: SMR; D: SLA; E: LAR; F: P/NP

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Changes of biomass allocation with the increase of seedling height of *Quercus acutissima*. A: LMR; B: RMR; C: SMR; D: SLA; E: LAR; F: P/NP

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Changes of biomass allocation with the increase of seedling height of *Quercus acutissima*. A: LMR; B: RMR; C: SMR; D: SLA; E: LAR; F: P/NP

Figure 4

Changes of root traits with the increase of seedling height of *Quercus acutissima*. A: TRL; B: RSA; C: RV; D: RAD; E: SRL; F: SRA

Figure 4

Changes of root traits with the increase of seedling height of *Quercus acutissima*. A: TRL; B: RSA; C: RV; D: RAD; E: SRL; F: SRA

Figure 4

Changes of root traits with the increase of seedling height of *Quercus acutissima*. A: TRL; B: RSA; C: RV; D: RAD; E: SRL; F: SRA

Figure 5

Changes of the content of non-structural carbohydrates of root, stem and leaf with the increase of seedling height of *Quercus acutissima*

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