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Seasonal allometric coordination of growth, pigments and roots in *Pinus yunnanensis* seedlings of different quality grades

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Abstract

Pinus yunnanensis is an important afforestation species in the southwest region, with high ecological and economic value. In this study, seedlings were divided into three grades (grade III > grade II > grade I) using the mean $\pm$ standard deviation method, and the growth relationships and correlations of ground line diameter-seedling height, photosynthetic pigments, and root system indicators were analyzed. Consistent with the growth patterns, photosynthetic pigment traits also showed grade-specific correlations. The results revealed that seedling height and ground line diameter of seedlings in all grades presented an extremely significant allometric growth relationship ($p < 0.01$). Specifically, root growth was dominated by elongation in the early growth stage, whereas radial thickening became predominant at the later stage. The higher the grade, the better the growth coordination between seedling height and ground line diameter. The allometric growth of photosynthetic pigments showed significant grade differences and varied with the seasons. Overall, total chlorophyll accumulated faster than chlorophyll a (grade III > grade II > grade I, while chlorophyll b accumulated faster (grade III > grade II > grade I). The rate of total chlorophyll accumulation in grade I seedlings was higher than the accumulation rate of carotenoids, whereas in grade II and grade III, the two were relatively consistent. Most pigments showed highly significant positive correlations with total chlorophyll, while ratio indices were mostly negatively correlated. There are also hierarchical differences in root growth strategies: grade I seedlings exhibit a

flexible root growth strategy, characterized by taproot elongation in the early stage, expansion of root surface area in the middle stage, and coordinated growth in the late stage, and they possess strong recovery capacity; grade II seedlings show no distinct strategy and have poor stress tolerance; grade III seedlings have a simple root structure, poor coordination, and no discernible root growth strategy. Correlations of root indicators in grade I seedlings were stable, while those in grades II and III were mostly negative, easily fluctuating with seasonal effects, indicating weaker stress resistance. As a result, grade I seedlings exhibit the most stable growth coordination, grade II seedlings show relatively poor coordination, and grade III seedlings demonstrate the weakest coordination.

Keywords: *Pinus yunnanensis*, allometric growth, ground line diameter, seedling height, photosynthetic pigment, root growth characters

Background

Allometric growth is the pattern in which different parts of an organism grow at different relative rates, leading to systematic changes in proportionality with increasing body size ^[1, 2]. It is of great significance to the research of forest genetics, forest cultivation and forest conservation. Study demonstrates that tree biomass allocation is governed by universal allometric constraints and simultaneously modulated by environmental optimization^[3]. Moreover, the allometry of trees, the relationship between size and shape, has a substantial effect on forest structure and function ^[4], and allometric growth is determined by species-specific growth characteristics, but it is also influenced by external factors^[5]. For example, by exploring the different effects of nitrogen-phosphorus combinations on biomass accumulation, allocation, and allometric growth relationships of *P. yunnanensis* seedlings after top-pruning, it found that the roots, stems, and buds of *P. yunnanensis* are mainly affected by phosphate fertilizer ^[6]. Plants adapt to the environment by regulating resource allocation between organs, forming different biomass allocation patterns, thereby establishing certain allometric growth relationships, such as those between tree diameter and seedling height, plant biomass and leaf area, root biomass and individual biomass, as well as allometric growth relationships among various structures within leaf anatomy ^[7-10]. Tang et al. (2025) research effects of top-pruning intensity gradient on root system architecture and allometric patterns in *P. yunnanensis* seedlings, and find there are significant differences in the allometric growth indices of *P. yunnanensis* seedlings ^[10].

Photosynthesis is the foundational process for plant growth and biomass accumulation ^[11]. As a crucial pigment in plants, chlorophyll plays an important role in the procession of photosynthesis, growth and development, which is responsible absorbing light and converting it into chemical energy ^[12, 13]. Photosynthetic pigments refer to chlorophyll a, chlorophyll c, carotenoids, and total chlorophyll. Chlorophyll and Carotenoids, which are important pigments for exploring many processes of photosynthesis, understanding the physiological growth of plants responses to the environmental fluctuations or the consequences of particular mutations ^[14]. Carotenoids serve as a protective agents against oxidative stresses, which can transfer the absorbed light energy to chlorophyll a to assist in photosynthesis ^[15]. The content of total chlorophyll is positively correlated with photosynthetic capacity and can also serve as an indicator of stress response intensity, which makes chlorophyll crucial for plant growth and development. Changes in plant chlorophyll content, which affect photosynthesis, are often influenced by external factors such as shading treatment, fertilization ratio or elements, stress, temperature, and radiation ^[16-20]. Tang et al. (2025) found that spraying different ratios of nitrogen and phosphorus elements on the leaf surface significantly affected the relative growth relationship between chlorophyll a content and chlorophyll b content ^[10], and this changed with the growth of the seedlings.

Root system architecture (RSA) is the spatial distribution of plant roots in the growing medium ^[21], and biomass allocation to roots increases with tree size, with results supporting the allometric biomass partitioning theory ^[21, 22]. Studying the allometric relationships of different root indicators can establish the allocation characteristics and growth patterns of plant roots during the growth process. For instance, Arredondo et al. (2011) study the allometric growth relationship between taproots and lateral roots ^[23], which exhibit that there is a significant negative allometric relationship between the taproot axis and first-order lateral roots, and the taproot axis is positively correlated with the number and length of roots, the estimated utilization efficiency of secondary roots, and the specific root length. In addition, studies by Jia et al. (2017) have confirmed that the biomass of the taproots and lateral roots of *P. yunnanensis* increases with the increase in diameter grade ^[24]. There is a significant positive correlation between root collar-taproot, root collar-total roots, lateral roots-taproot and DBH-tree height, while there is a significant negative correlation between taproot-total roots and DBH-tree height ^[24]. Notably, Various indicators of root growth characteristics like, average volume, total root length, average length-all lateral roots and taproot length/total root length ratio, significantly impacted by drought stress, Variety category ^[21].

P. yunnanensis, as an evergreen and deciduous coniferous species of the Pinaceae family, is widely distributed in the southwest region, and has both high economic value and important ecological significance. Besides, *P. yunnanensis* serves as a pioneer tree species and an important timber tree species for afforestation in barren hills in southwest China [25]. Current research on the allometric growth relationship of *P. yunnanensis* under different treatments, Zhu et al. (2025) exhibit that there are differences in the allometric growth relationships among various organs with the combined application of nitrogen and phosphorus [26]. In addition to that, Wang et al. (2025) studied that under different gradients of shading, the sensitivity to light varies among different organs of annual *P. yunnanensis*, and the biomass allocation of different organs is affected by shading [27]. This changes the biomass of individual plants, resulting in isometric growth and allometric growth patterns in the plants [27]. However, Seedlings of *P. yunnanensis* at different grades also show significant differences in chlorophyll content and gene expression. Li et al. (2025) study that the expression of genes related to chlorophyll synthesis was significantly upregulated in grade I seedlings, while the expression of genes associated with chlorophyll degradation was more active in grade III seedlings [11].

Materials and Methods

Research site

The experimental site was established at the nursery of Southwest Forestry University in Kunming City, Yunnan Province, located at 102°45'41" east longitude and 25°04'00" north latitude, with an altitude of approximately 1945 m. The average annual temperature is 14.7 °C, belonging to the northern subtropical semi-humid plateau monsoon climate.

Material sources and seedling grading

The nursery used in this study is maintained by Southwest Forestry University located in Kunming (N 25°04'00", E 102°45'41'). In May, after the seeds were mixed, they were disinfected. Then, management measures such as regular watering and weeding were carried out according to weather conditions and seedling growth. After the seeds finished germinating, they were given normal water and fertilizer management. After 100 days of cultivation, more than 1,200 seedlings were graded. The grading was done during the first index determination, using the method of mean value $\pm$ standard deviation. Based on the grading results, the differences in seedling height growth were divided into three grades [28]. After grading, seedlings of different grades were cultivated under the same conditions to facilitate subsequent data measurement.

Measurement of seedling height and ground diameter

The data survey started in January of the first year, with monthly measurements of basic indicators such as seedling height and ground line diameter of *P. yunnanensis*. In January of the second year, the seedling height was directly measured using a ruler (accurate to 0.1 cm), and the ground line diameter was measured using an electronic vernier caliper (accurate to 0.01 mm). Phenotypic data for one growth cycle of the seedlings were measured in total. After statistics, IBM SPSS Statistics 21.0 software was used to analyze the growth of indicators such as seedling height and ground line diameter of *P. yunnanensis* seedlings of different grades, and to calculate and compare the differences in growth indicators between seedlings of different grades.

Measurement of seedling root system indicators

Five seedlings per grade were sampled on each of five sampling dates (January, March, May, August, and December), resulting in a total of 75 seedlings (3 grades $\times$ 5 seedlings $\times$ 5 dates). The sampling time for other subsequent indicators is the same as that for biomass sampling). The entire seedlings were dug out without damaging their tissues, washed, dried with water, and taken back to the laboratory for determination. The root system was scanned using a root scanner to calculate 6 root growth indicators: taproot length, total root length, average diameter, surface area, projected area, and total volume. Then, the seedling roots were placed in an oven at 110°C for 30 minutes to inactivate enzymes, and then placed in an oven at 80°C to dry completely until the mass was constant. The dry weight data measured after the seedling roots were completely dried is the root biomass. By studying the relative growth relationships of various indicators of roots, the differences in root growth among seedlings of different grades of *P. yunnanensis* were observed.

Subsection

After grading *P. yunnanensis* by growth grade, their chlorophyll contents were determined and compared via the acetone extraction method [29]. Tender needles that were healthy and disease-free were randomly collected from seedlings of different grades, mixed for sampling, and 9 seedlings per grade were randomly selected for needle mixing. After sampling, the samples were brought back to the laboratory for measurement, with each sample tested once. The collected needles were cut into pieces with scissors and mixed. A 0.5g sample of the chopped needles was placed into a clean mortar that had been rinsed with the testing solution and naturally air-dried. A small amount of quartz sand and calcium carbonate powder was added for grinding, after which 2–3 mL of 80% acetone was added and ground

into a slurry. Then, 10 mL of 80% acetone was added, left standing until the tissue turned white, and the entire slurry was transferred into a 25 mL brown volumetric flask, and the volume was then adjusted with 80% acetone and mixed well. The extract was poured into a cuvette with a diameter of 10 mm, with 80% acetone as the blank control. A spectrophotometer was used to measure the optical density at wavelengths of 663 nm, 645 nm, and 470 nm, and the values were recorded. Chlorophyll a, chlorophyll b, carotenoids, and total chlorophyll contents were then calculated.

For the measurement, samples were randomly selected from the upper new stem segments of healthy *P. yunnanensis* seedlings. Samples of each grade were randomly collected, and the leaves were basically consistent across the plants. Mixed sampling was performed for repeated seedlings of different grades, and sampled seedlings were not used for subsequent related experiments.

Statistics and data of analysis

Taking three grades of *P. yunnanensis* seedlings as the research objects, six root indices, seedling height, and ground line diameter indices were measured, and allometric growth research was conducted. After the data were subjected to basic statistical collation using Excel, IBM SPSS 21.0 software was used to perform one-way analysis of variance on each index, and Duncan's multiple comparison method was employed to test the significance of differences in each index among seedlings of different grades. The allometric growth model reflects a pattern of biomass allocation in plant growth. The model of allometric growth relationship of *P. yunnanensis* biomass is described with reference to the model by Enquist et al. [30]:

$$y = ax^b$$

Linear transformation: $\lg y = \lg a + b \lg x$

Where y and x are the component biomasses that change depending on individual size; a is the intercept of the trait relationship; b is the allometric growth exponent, i.e., the slope of the linear relationship [31]. The slope b is compared with 1 for significance of difference: when $p > 0.05$, it is isometric growth; when $p < 0.05$, it is allometric growth. OriginPro 2024b software was used to perform linear fitting on the allometric growth relationships between various indices of the seedlings and draw fitting curves. Meanwhile, the SMART software in R language was used to further analyze the linear correlation characteristics of allometric growth between various growth indices of *P. yunnanensis* seedlings of different grades, so as to reveal the allometric growth laws and internal connections between root indices, chlorophyll content, and seedling growth of *P. yunnanensis* seedlings of different grades.

Results

Growth trends of ground line diameter and seedling height

The height and ground line diameter of *P. yunnanensis* seedlings of different grades are extremely significantly positively correlated ($p < 0.01$), with good fitting throughout the year, showing a stable coordinated growth relationship. The scatter values are distributed in a step pattern of grade I > grade II > grade III, meaning the higher the seedling grade, the more obvious the cumulative advantage of coordinated growth between height and ground diameter. From January to April (Fig. 1a, b, c), seedlings of all grades grow in height faster than in diameter; from May to December (Fig. d, e, f, g, h, i, j, k), in the middle and later stages, the growth curve slope of grade II and III seedlings rises, with the growth focus gradually shifting from height to diameter; for grade I seedlings, the allometric growth slope is negative throughout.

Exploring the allometric growth relationship between chlorophyll a and total chlorophyll

The relative growth relationship between chlorophyll a and total chlorophyll in seedlings of different grades changes over time. In January, grade I seedlings exhibit an allometric growth relationship, while grade II and grade III seedlings show an isometric growth relationship; grades I, II, and III seedlings exhibit an isometric growth relationship in March and May, and an allometric growth relationship in August; in December, grade I and II seedlings show an isometric growth relationship, whereas grade III seedlings show an allometric growth relationship. The slope of grade I seedlings ranges from 0.793 to 1.395 (Fig. 2), being less than 1 (Fig. 2b, c) in March and May, and greater than 1 in January, August, and December (Fig. 2a, d, e); except for January where the slope is less than 1 (Fig. 2a), the slopes of grade II seedlings range from 0.926 to 1.486 (Fig. 2), being greater than 1 in the other months; the slopes of grade III seedlings are greater than 1 in all months. Overall, grades I, II, and III seedlings show that the total chlorophyll accumulation rate is higher than that of chlorophyll a, with the magnitude of the rate difference in the order: grade III > grade II > grade I.

Exploring the allometric growth relationship between chlorophyll b and total chlorophyll

The relative growth relationship between chlorophyll b and total chlorophyll in different grades of *P. yunnanensis* seedlings changes over time. grade I seedlings show an allometric growth relationship

from January to December (Fig. 3). grade II seedlings show an isometric growth relationship only in January (Fig. 3a), and an allometric growth relationship from March to December (Fig. 3b, d, c, d). grade III seedlings show an isometric growth relationship only in March (Fig. 3b), and an allometric growth relationship from January, May to December (Fig. 3a, c, e). The slopes of grade I, grade II, and grade III seedlings are all less than 1 (Fig. 3). The comparison of the slope magnitudes among the three is as follows: for grade I seedlings, the rate is the highest in January, medium in August, and the lowest in March, May, August and December; for grade II seedlings, the slope is the smallest in January and August, and the rate is medium in March, May, and December; for grade III seedlings, except in January, the rate from March to December is the highest among the three (Fig. 3). This indicates that the accumulation rate of chlorophyll b in grade I, grade II, and grade III seedlings is faster than that of total chlorophyll, and the trend of the accumulation rate of chlorophyll b being faster than that of total chlorophyll is: grade I > grade II > grade III (Fig. 3).

Exploring the allometric relationship between carotenoids and total chlorophyll

The relative growth relationship between carotenoids and total chlorophyll in *P. yunnanensis* seedlings of different grades changes over time. grade I seedlings show an isometric growth relationship in January and May, and an allometric growth relationship in March, August, and December. grade II seedlings show an isometric growth relationship in all months. grade III seedlings show an allometric growth relationship in March and May, and an isometric growth relationship in January, August, and December. Except that the slope of grade I seedlings is always greater than 1 (Fig. 4), indicating that the relative accumulation rate of total chlorophyll is greater than that of carotenoids, the slopes of grade II and grade III seedlings change over time. For grade II seedlings, the slope is significantly less than 1 (Fig. 4), in August (Fig. 4d), while in the other months it is close to 1 (Fig. 4a, b, c, d), indicating that the overall accumulation rates of total chlorophyll and carotenoids in grade II seedlings are relatively consistent. For grade III seedlings, the slope is less than 1 (Fig. 4a, c, d) in all months except March and December, and it is greater than 1 in January, May, and August.

Correlation analysis of photosynthetic pigments and their ratios

Monthly correlation analysis of pigments for graded seedlings (Fig. 5) revealed chlorophyll a, b and carotenoids were mostly extremely positively correlated with total chlorophyll ($p < 0.01$), whereas chlorophyll a/b and carotenoid/total chlorophyll ratios were negatively correlated with pigment concentrations. For grade I, all pigments correlated extremely significantly in January, August and

December ($p<0.01$), with pigment ratios showing significant negative correlations ($p<0.05$). Only chlorophyll a and carotenoids strongly linked to total chlorophyll in March and May. Grade II had full significant pigment correlations in March, May and December ($p<0.01$) and negative ratio-pigment correlations ($p<0.05$); weaker positive pigment correlations and negative ratio trends appeared in January and August. Throughout all months of grade III, pigment components were extremely positively correlated with total chlorophyll ($p<0.01$), with only non-significant negative relationships between pigment ratios and pigment contents.

Exploring the relative growth relationship between the total root length and taproot length

From Fig. 6, it illustrates the relative growth relationship between taproot length and total root length for seedlings of different grades. Except for grade I seedlings in January, which have a slope greater than 1 (Fig. 6), the slopes of grade I, II, and III seedlings in other months are all less than 1 (Fig. 6), indicating that *P. yunnanensis* seedlings in general show a pattern where the taproot length grows faster than the total root length. The slope values differ among seedlings of different grades; except in August, where the growth rate order is grade III > grade II > grade I, in other months the order is grade I > grade II > grade III, indicating that higher-grade *P. yunnanensis* seedlings tend to prioritize the development of taproot length.

Exploring the relative growth relationship between total root length and average diameter

The relative growth of the average diameter and total volume of seedlings of different grades changes over time. The degree of fit for seedlings of different grades fluctuates greatly, indicating that the relative growth relationship between the average root diameter and root volume of seedlings of different grades is not stable, but there are still certain differences among the three. The slopes of grade I seedlings are negative throughout the year, reaching a minimum in December while the goodness of fit reaches a maximum ($R^2 = 0.831$) (Fig. 7e). This indicates that the average root diameter and total root length exhibit a stable negative relative growth relationship, meaning that grade I seedlings tend to prioritize increasing root diameter over total root length. For grade II seedlings, the relative growth relationship between total root length and average root diameter is unstable (with a low goodness of fit), suggesting disordered resource allocation and a transitional growth pattern. For grade III seedlings, in

the early growth period (January and March), the relative growth relationship shows that the average diameter grows slower than total root length. During the middle and late periods (May, August, and December), the slopes are negative and close to 0 (Fig. 7c, d, e), but the overall goodness of fit for grade III seedlings is low throughout the year, indicating no significant relative growth relationship between average diameter and total root length for grade III seedlings.

Exploring the relative growth relationship between total root length and surface area

The relative growth relationship between total root length and total surface area varies for seedlings of different grades in different months, reflecting the characteristic that the coordinated growth of total root length and surface area is not affected by seasonal changes. For grade I seedlings, from January to May, the relative growth rate of total surface area is faster than that of total root length, and it increases step by step, reaching the maximum slope in May ($b = 6.356$) (Fig. 8b). This indicates that grade I seedlings prioritize the growth of total root length during the early and middle growth stages (January, March, and May). In August, the slope of grade I seedlings decreases significantly, and by December, the slope is already less than 1 (Fig. 8e), indicating that the seedlings gradually reduce the growth of total root length during the mid-late and late growth stages (August and December), ultimately reaching a nearly isometric growth balance in December. Grade II seedlings maintain slight overall growth, with a slender form, a consistently stable coordination, and good morphological consistency. Grade III seedlings show stable coordination during the growing season, but there are significant individual differences during the dormant season, resulting in unstable growth strategies and noticeable fluctuations in fitting. Grade III seedlings exhibit large growth differences during the dormant season, with low fitting accuracy.

Explore the relative growth relationship between total root length and total volume

The relative growth relationship between total root length and total volume of seedlings of different grades varies over time (Fig. 9). For grade I seedlings, the fit between total root length and total volume in January ($R^2 = 0.000$) and August ($R^2 = 0.041$) is very poor, showing no significant correlation; in March ($R^2 = 0.730$) and May ($R^2 = 0.972$), the correlation improves, with similar slopes showing a strong positive correlation; in December ($R^2 = 0.995$), the fit is the highest, with the slope reaching its maximum,

indicating that grade I seedlings are most sensitive to root length growth response to root volume in winter, and the rate of root length increase is much higher than that of root volume. For grade II seedlings, the fit of the relative growth relationship between total root length and total volume remains relatively stable throughout the year ($R^2 = 0.200\text{--}0.606$), showing a positive correlation, but the overall slope is less than 1, indicating that as total root volume increases, the growth of root length is much slower than the increase in volume. For grade III seedlings, the total root length and total volume show very high fit in January ($R^2 = 0.975$), March ($R^2 = 0.931$), and August ($R^2 = 0.879$); in August ($R^2 = 0.461$), the fit drops sharply, and in December ($R^2 = 0.003$), the linear relationship is almost lost. Overall, they show a positive correlation, but the growth rate of total root length compared to total volume becomes increasingly slower over time.

Exploring the relative growth relationship between total root length and projected area

The analysis results of the relative growth of root length and root projection area for seedlings of different grades show that: grade I seedlings had moderate fitting in January ($R^2 = 0.583$) and March ($R^2 = 0.304$), and very high fitting in May ($R^2 = 0.993$) and December ($R^2 = 0.954$), with both showing a positive correlation. In the early stage, in January, the total root length growth rate was significantly higher than the projection area growth rate. In March and May, the growth rates of the two tended to synchronize, while in August and December, the total root length growth rate was obviously lower than the projection area. grade II seedlings exhibited very high fitting in January ($R^2 = 0.932$), March ($R^2 = 0.916$), and May ($R^2 = 0.992$), which sharply decreased in August ($R^2 = 0.492$) and December ($R^2 = 0.492$), maintaining a medium fitting intensity. The two remained positively correlated: from January to May, the growth rate of total root length was always higher than that of the projection area, but the growth advantage of root length relative to projection area gradually weakened month by month; from August to December, the growth rate of root length was significantly lower than that of the projection area, showing faster projection area growth. grade III seedlings had high fitting in January ($R^2 = 0.916$) and May ($R^2 = 0.816$), medium intensity in August ($R^2 = 0.443$), low in March ($R^2 = 0.169$), and nearly zero in December ($R^2 = 0.011$). The relationship between the two was clearly affected by time: in January and May, the growth rate of total root length was significantly higher than that of the projection area; in March, the growth rates were comparable; in August, the projection area expanded rapidly, with a growth

rate significantly exceeding that of total root length; in December, the slope was negative and close to 0, indicating no coordinated growth pattern between root length and projection area.

Study on correlation of root system indicators

The correlations among root indicators of grade I seedlings are more stable in most seasons, with positive correlations dominating. This is directly associated with the enhanced regularity of seedling growth rhythm under intense resource competition. In contrast, grade II and grade III seedlings exhibit more negative correlations during stressful seasons (summer and winter). This indicates that the decline in seedling grade intensifies growth trade-offs under environmental stress. Seedlings compensate for the limitations of resource space by regulating lateral root biomass allocation and optimizing root architecture, which reflects the adaptive strategy of phenotypic plasticity.

Discussion

Effects of allometric growth relationships on phenotypic indicators of seedlings at different grades

The allometric relationship between seedling height and ground line diameter fundamentally regulates light capture capacity and structural stability of young trees. A universal pattern across woody plants is that seedlings prioritize height growth over stem thickening, and thus exhibit larger allometric scaling exponents than mature trees^[32]. Seedlings Prioritizing height growth facilitates light competition and soil nutrient uptake, explaining the consistently faster height increment relative to ground line diameter.^[33] Our observation of pronounced allometric scaling between height and ground line diameter in graded *P. yunnanensis* seedlings is consistent with this general rule. the allometric growth relationship between seedling height and ground line diameter in *P. yunnanensis* is characterized by primarily height growth in the early stages of seedlings and primarily ground line diameter growth in the later stages^[34]. This is due to the temporal asynchrony of optimal temperatures for stem diameter and seedling height, resulting in the temperature that promotes seedling height growth appearing 1–2 months earlier than the temperature that promotes stem diameter growth. Therefore, seedlings exhibit an allometric growth phenomenon where the peak of height growth occurs before the peak of stem diameter growth^[35]. However, grade II and grade III seedlings conform to the growth pattern of "height growth prior to ground diameter growth". In contrast, high-quality grade I seedlings maintain continuous height growth in the later growth stage, while their ground diameter growth nearly stagnates. According to studies showing that trees always allocate biomass to above-ground parts first^[36, 37], grade I dominant seedlings complete

carbon storage in roots and stems during the early and middle growth stages. Their biomass allocation strategy shifts in the later stage: soluble sugars and starches in roots are preferentially transported to terminal buds and new leaves to boost height growth, which enables the seedlings to sustain a competitive edge in capturing canopy light. However, this process allocate less carbon to stem radial growth, resulting in stagnant ground diameter growth. The growth of seedling height and stem diameter in seedlings of different grades is significantly different, which is consistent with the results of the scatter plot in Figure 1 showing a clear gradient ^[10].

Overall, grade III seedlings may be limited in their height and ground line diameter, so during the growth process, the slope of ground line diameter to seedling height from May to December is approximately 1 (Fig. 1c, d, e) for grade III seedlings, thereby simultaneously ensuring the plant's photosynthetic and mechanical support capacity along with resources for biomass accumulation; grade II seedlings, having better ground line diameter thickness, focus more on vertical extension during growth; grade I seedlings, having the best ground line diameter thickness and seedling height, may first rapidly increase in height to quickly capture light resources, and after reaching the height limit, they develop ground line diameter growth, causing a negative growth trend in seedling height. Once their height increment reaches a plateau, they shift resources to ground line diameter expansion, accompanied by a reduced height growth rate. These research phenomena reveal divergent allometric scaling patterns between seedling height and ground line diameter in *P. yunnanensis* seedlings of different grades.

Effects of different seedling grades on the allometric growth relationship of photosynthetic pigments

Under resource stress conditions, most plants tend to mitigate stress by enhancing their potential resource absorption capacity ^[38]. Chlorophyll is a core pigment with high photoreactive activity, and during leaf senescence, the safe and efficient degradation of the photosynthetic apparatus is related to the breakdown of chlorophyll ^[39]. Carotenoids are pigments that play a key role in the photoprotective function of photosynthesis under environmental stress ^[40]. The allometric growth relationships of chlorophyll a, chlorophyll b, and carotenoids with total chlorophyll indicate that different grades of allometric growth relationships change over time, reflecting the phenotypic plasticity and biomass allocation patterns of seedlings at different grades ^[38].

The results show that differences among seedlings of different grades are significant or not significant in most seasons; in January and December, the differences in chlorophyll a content among

the three grades are not significant; in May, significant differences were detected between grade I and grade II seedlings, as well as between grade III and grade II seedlings; in August, the differences between grade I and grade II seedlings compared to grade III seedlings are significant. In addition, the allometric index b of chlorophyll a for seedlings at different grades is mostly greater than 1 (Fig. 2), indicating that the accumulation rate of total chlorophyll is faster than that of chlorophyll a , and its proportion in total chlorophyll decreases as its own content increases. Research indicates that under low-temperature stress, plant pigments spontaneously degrade, and because chlorophyll a is more sensitive, it experiences the greatest reduction in content^[41]. In this study, the allometric growth indices of chlorophyll a in seedlings of different grades were high in December, possibly due to the drop in temperature, resulting in the accumulation rate of chlorophyll a in seedlings of different grades being lower than that of total chlorophyll. From Fig. 2, grade III seedlings generally showed this trend from January to December, and this trend was particularly evident in seedlings of different grades from August to December. In March and May, the allometric growth indices were mostly close to 1 (Fig. 2b), reflecting the gradual stabilization of the photosynthetic system and the tendency of the proportion of each photosynthetic pigment content to reach equilibrium.

Apart from chlorophyll a , chlorophyll b acts as the main light-harvesting pigment and displays distinct allometric patterns across seedling grades. Chlorophyll b is a light-harvesting antenna pigment, and its content is lower than that of chlorophyll a . Plants can adaptively improve light energy utilization efficiency by upregulating the expression of the chlorophyll b synthesis gene chlorophyllide a oxygenase (CAO) and increasing the accumulation of light-harvesting complex II (LHCII) proteins^[42, 43]. Studies have shown that in stage III seedlings of *P. yunnanensis*, presumably higher transcription levels of chlorophyll-degrading genes such as chlorophyllase (CLH), pheophytinase (PPH), red chlorophyll catabolite reductase (RCCR), and stay-green (SGR) accelerates chlorophyll degradation, reduces the photosynthetic capacity of the seedlings, and consequently limits growth^[11, 44]. This study shows that seedlings of different grades all exhibit a chlorophyll b accumulation rate greater than the total chlorophyll accumulation rate, and the relative growth relationship between chlorophyll b and total chlorophyll changes over time. grade I seedlings, due to their relatively high seedling height and stem diameter, may have chlorophyll b accumulation driven by the expression of the CAO gene, with the allometric growth chlorophyll b index ranging from 0.074 to 0.321 (Fig. 3), representing the fastest accumulation rate. From January to December, they all exhibit an allometric growth relationship,

enhancing the photosynthetic efficiency of the seedlings. Compared with grade I seedlings, the allometric growth index of chlorophyll b in grade III seedlings ranges from 0.864 to 0.235 (Fig. 3). Although grade III seedlings had a higher chlorophyll b allometric exponent than grade I seedlings, this value cannot be interpreted as faster chlorophyll b accumulation. The elevated expression of chlorophyll catabolic genes in grade III seedlings accelerates chlorophyll b degradation and reduces its net accumulation, leading to distorted pigment proportional scaling. Such divergent allometric trajectories of chlorophyll b further demonstrate that seedling grade shapes pigment allocation strategies, which is a critical manifestation of intraspecific phenotypic plasticity under seasonal abiotic stress.

Beyond chlorophyll fractions, carotenoids function as vital photoprotective pigments and present grade-dependent allometric variation with total chlorophyll. Carotenoids can transfer energy to chlorophyll in the photosystem and can enhance plant tolerance to heat and light stress by preventing damage to proteins and chlorophyll [44–46]. The allometric relationship between carotenoids and total chlorophyll also changes over time, and interspecific differences also vary. Except for January and December, when interspecific differences in carotenoids are not significant, in March, May, and December, significant differences exist between grade I seedlings and grade II seedlings compared to grade III seedlings. The allometric growth coefficient b of carotenoids in grade I seedlings is 1.182–1.777 (Fig. 4), for grade II seedlings it is 0.234–1.170 (Fig. 4), and for grade III seedlings it is 0.016–1.182 (Fig. 4), indicating that the carotenoid accumulation rate is fastest in grade I seedlings relative to total chlorophyll accumulation and slowest in grade III seedlings. Studies have shown that when plants are exposed to strong light, they rapidly synthesize carotenoids to protect the plants and thus reduce damage from strong light [45, 47]. One-year-old seedlings of *P. yunnanensis* are shade-tolerant species [27], and the average height of grade I seedlings in this experiment was the highest, so they had relatively strong light conditions; the average height of grade III seedlings was the lowest, with relatively weak light conditions. Therefore, this may potentially explain why the relative accumulation rate of carotenoids was fastest in grade I seedlings, while the relative accumulation rate of carotenoids was weaker in grade III seedlings.

Correlation analysis of photosynthetic pigments

Research shows that chlorophyll a, chlorophyll b, and total chlorophyll are lowest in winter and highest in autumn; carotenoids varies dynamically, mediating seasonal shifts of photosynthetic pigments of photosynthetic pigments in seedlings of different grades for light protection, serving as a direct marker

of the functional integrity and regulatory capacity of their photosynthetic systems ^[48, 49]. In previous studies on the annual growth cycle of grape (*Vitis vinifera* L.), chlorophyll a, chlorophyll b, and total chlorophyll exhibited a strong positive correlation, indicating that the synthesis and degradation of photosynthetic pigments in plant leaves are coordinated ^[50]. This is basically consistent with the phenomenon of related pigments in seedlings of different grades throughout the year observed in this study ^[50]. This study observed seasonal variations in chlorophyll content, which is consistent with research on *Taxus* species showing that chlorophyll a, chlorophyll b, and total chlorophyll content reach their lowest values in winter and peak in autumn, indicating that seasonal environmental changes can significantly regulate both the synthesis and degradation of photosynthetic pigments ^[51]. The early differentiation, mid-term adjustment, and late recovery pattern of grade I seedlings is a typical characteristic of high-quality seedlings: in the early stage, the photosynthetic pigment system is well-developed, with chlorophyll a, chlorophyll b, and carotenoids functioning both cooperatively and with functional differentiation; in May and August, by adjusting the chlorophyll a/b and carotenoids/total chlorophyll ratios, they reduce photoinhibition and remove reactive oxygen, actively responding to stress. After stress is relieved in December, correlations among various indicators become highly significant, indicating that the photosynthetic system has stabilized, demonstrating the strong recovery ability of grade I seedlings. The changes in grade II seedlings are relatively passive, with generally developed photosynthetic systems and limited regulatory capacity; they fail to initiate effective photoprotective adjustments in May and August, and the correlations among indicators are not obvious. Even by December, full recovery is difficult, suggesting that both the stability and plasticity of their photosynthetic function are at a medium grade. Grade III seedlings may seem to show obvious early correlations, but this could actually indicate poor development of the photosynthetic system, as pigment component changes are too synchronous without functional differentiation. Grade III seedlings cannot cope with high-temperature stress in May and August on their own, ultimately leading to metabolic dysregulation and complete imbalance in correlations, fully aligning with the characteristics of photosynthetic function decline in low-quality seedlings.

During summer when plants reach their growth peak with accelerated chlorophyll synthesis, chlorophyll a serves as the core pigment of photosynthetic reaction centers, whereas chlorophyll b primarily undertakes light-harvesting functions ^[52, 53]. In summer, the correlation between chlorophyll a and chlorophyll b weakened in grade I seedlings, a strategy to reduce the proportion of light-harvesting

and avoid photodamage under intense irradiance. In contrast, grade III seedlings maintained persistently strong chlorophyll a-chlorophyll b correlations, signifying that their photosynthetic apparatus lacks this protective regulatory capacity.

Carotenoids have both photoprotective and antioxidant functions, and an increase in the carotenoids/total chlorophyll ratio is an important mechanism for seedlings to cope with stress^[54, 55]. In grade I seedlings, carotenoids show a negative correlation with chlorophyll-related indicators in summer, indicating that the increase in carotenoids contents and decrease in chlorophyll contents are a typical stress response; whereas grade III seedlings show no such change, and by winter, chlorophyll a/b becomes significantly negatively correlated with various indicators, which may result from a disruption in their own chlorophyll metabolism.

Discussion on the relative growth relationship between total root length and other indicators

By exploring the relative growth relationships between the total root length of *P. yunnanensis* seedlings and their total volume, average root diameter, taproot length, and root surface area, the study reveals the growth patterns reflected in the temporal changes of phenotypic plasticity indicators in seedlings of different grades. The slope of grade I seedlings from January to August during the growth period was consistently negative, indicating that grade I seedlings thicken in the early and mid growth stages. After the high-temperature drought stress in August, the growth rate of total root length in grade I seedlings exceeded that of the average diameter in December (winter), indicating a tendency toward elongation in December. This reflects the complete growth rhythm and flexible strategy of grade I seedlings, which are typical characteristics of high-quality seedlings.

Previous studies have shown that in the early growth season, the taproot rapidly elongates vertically to access deep soil water; in the later stage, lateral roots branch extensively and spread horizontally to expand the range of superficial nutrient capture, while in winter, root lignification accelerates, and biomass is preferentially allocated to the taproot to enhance water storage capacity^[56, 57]. As shown in Fig. 6, the relative growth relationships between root length and taproot length of grade I, II, and III seedlings converge, with the exception of the slope in January for grade I being greater than 1. The growth slope indices for grades I, II, and III are all less than 1, indicating a trend of prioritizing taproot development, with high R^2 values in January, March, and May. For example, grade III in January ($R^2 = 0.934$) (Fig. 6a), grade III in March ($R^2 = 0.987$) (Fig. 6b), and grade I in May ($R^2 = 0.843$) (Fig. 6c),

indicating that taproot elongation in the early growth season directly drives increases in total root length. In August and December, the overall fit for grades I, II, and III seedlings decreases significantly. The allometric relationship between taproot and total root length in grade I and II seedlings weakens, while in grade III seedlings, the relationship nearly stagnates, indicating that in the later stage, the growth of lateral and fine roots becomes the main contributor to total root length, and taproot growth enters a certain stagnation period. This partially validates previous research findings. Overall, the growth slopes of total root length versus taproot length are less than 1, and in May and December, the growth slope for grade III seedlings is negative, indicating that seedlings prioritize taproot extension to access deep soil water, while lateral root growth may be inhibited by low temperatures ^[57].

Following the allometric patterns of taproot length, root surface area also exhibited pronounced grade-specific seasonal scaling with total root length. Research shows that high temperature and drought in summer can lead to stagnation in fine root growth or even hinder the increase in root surface area, while the taproots remain relatively stable ^[58]. In May, grade I seedlings exhibited the maximum allometric exponent ($b = 6.356$) for the scaling relationship between total root length and root surface area (Fig. 8c), indicating that root surface area expanded far more rapidly than total root length via massive fine root proliferation. This indicates that grade I seedlings experience extensive proliferation and growth of fine roots in May, thereby increasing the growth of surface area. However, in August, the slope of grade I seedlings decreases significantly, which exactly confirms previous findings that high temperature and drought in summer can cause stagnation in fine roots or even hinder surface area growth ^[59]. Moreover, comparatively, during the peak growing season in May, the order of slope magnitudes is: grade I > grade II > grade III, showing that the higher the seedling grade, the more likely it is to increase the number of fine roots during the peak growing season. Grade III seedlings displayed a negative allometric exponent in December, reflecting nearly arrested fine root development. This outcome can be attributed to irreversible damage to fine roots induced by summer heat-drought stress in August, coupled with the weak intrinsic stress tolerance of inferior-grade seedlings. This aligns with previous research findings that higher-grade seedlings usually have larger stem diameters, more developed root systems, and more reasonable root-to-shoot ratios. These structural characteristics directly enhance water absorption and stress resistance, while lower-grade seedlings exhibit significant morphological and structural deficiencies ^[59].

The average root diameter is considered to determine the efficiency of root strength, while the total

root length represents the overall soil stabilization and absorption potential ^[60]. Studies have shown that drought leads to a decrease in the average diameter of seedlings ^[61]. When modeling the allometric relationship between total root length and average root diameter, the sign of exponent b directly mirrors the root growth trade-off: a negative b value indicates faster radial thickening relative to root elongation, whereas a positive b denotes more rapid linear extension than diameter expansion. From January through August, grade I seedlings sustained negative b values, implying they invested resources in radial root growth to boost mechanical stability throughout the early and mid growing stages. After exposure to intense summer heat and drought in August, this exponent turned positive in December, signifying a strategic shift toward root longitudinal growth where total root length outpaced increases in average diameter. These dynamic, season-dependent adjustments in root allometry highlight the full developmental rhythm and remarkable phenotypic plasticity characteristic of high-quality seedlings.

There are still differences in the relative growth relationship between total root length and total volume of seedlings of different grades. In January, the fitting coefficient of grade I seedlings was the lowest. Considering that the taproot elongation rate of grade I seedlings was relatively weaker than the total root length growth rate, it is speculated that some grade I seedlings may have experienced taproot swelling, lateral root necrosis, or callus proliferation, leading to a decoupling between total volume changes and total root length changes. The fitting coefficient for grade III seedlings ($R^2 = 0.975$) (Fig. 9a) was high, and the slope among the three grades was relatively close to 1 ($b = 0.602$) (Fig. 9a). This indicates that grade III seedlings exhibit relatively uniform root elongation, and total root length and total volume show a relatively coordinated growth pattern, resulting in a simple and stable structure. In May and August, the slopes of seedlings of different grades were close to 0 or negative. The fitting coefficients among the three root morphological indicators in August decreased significantly compared to May, indicating that seedlings prioritize taproot growth while inhibiting lateral root development and the expansion of absorptive surface area. This indirectly supports the physiological phenomenon previously observed, where lateral roots senesce and fall off in summer ^[62], reflecting the strategy of seedlings to preferentially develop the taproot and suppress lateral root growth under stress. In December, grade I seedlings exhibited high fitting coefficients for total volume and total root length ($R^2 = 0.995$) (Fig. 9e), with slopes close to 1 ($b = 0.958$) (Fig. 9e). Total volume and total root length of grade I seedlings grew synergistically in December, while taproot length and total root length simultaneously weakened, indicating that lateral root branching increased total volume, resulting in a synergistic relationship

between total volume and total root length. This aligns with previous findings that in the later stages of conifer seedling growth, lateral root branches replace the taproot as the main contributor to root length growth^[63]. The slopes of grade II ($b = 0.048$) (Fig. 9e) and grade III seedlings ($b = 0.003$) (Fig. 9e) were both near 0; the fitting coefficient for grade II seedlings ($R^2 = 0.345$) (Fig. 9e) was low, and that for grade III seedlings ($R^2 = 0.003$) (Fig. 9e) was almost 0. This indicates poor coordination between total root length and total volume in grade II seedlings, and no correlation between the two in grade III seedlings, with overall root system growth completely halted and vitality low.

From the perspective of temporal changes, in January and December, most root system indicators of seedlings at various grades (taproot length, total root length, average diameter, root surface area, projected area, total volume) are significantly positively correlated. The elongation of the taproot root, thickening of the root system, and increase in volume are strongly coordinated, which corresponds to the growth strategy of seedlings under low-temperature and drought conditions to prioritize strengthening the root structure and enhancing water and nutrient absorption capacity. In March, possibly due to the relatively suitable temperature and moisture conditions for growth, the number of lateral roots increased. The root indicators of seedlings of all grades maintained a stable positive correlation, with good overall growth coordination. In May and August, likely affected by high temperature and drought stress, the correlation between root indicators of some seedling grades shifted from positive to negative, and the correlation intensity decreased significantly. This is consistent with the finding that warming under plateau climate disrupts the original coordinated growth relationship of root systems^[64]. To maintain basic survival, seedlings prioritize the growth of taproots, which restricts the development of lateral roots and the thickening of the root system to a certain extent.

In summary, *P. yunnanensis* seedlings of different grades adapt to environmental growth conditions at different times by adjusting the allocation of root system indices, which indirectly confirms that the dynamic adjustment of allometric root growth is a key adaptive strategy for plants in response to environmental changes. However, this study has certain limitations, as it only focuses on allometric root growth during the seedling stage and does not explore the regulatory roles of environmental factors such as soil moisture and nutrients. At different time points, *P. yunnanensis* seedlings of different grades adapt to Kunming's climate by regulating the coordination and trade-off relationships among root system indices. This is an important adaptive mechanism for different grades of *P. yunnanensis* seedlings to achieve regeneration and survival in the natural environment. The results can provide useful references

for cultivating high-quality robust *P. yunnanensis* seedlings and managing artificial forests. Future research could further elucidate the molecular and physiological regulatory pathways underlying root allometric scaling, providing more theoretical support for the sustainable cultivation and management of mountain economic tree species in Yunnan Province.

Correlation analysis of various root indicators

We further analyzed seasonal shifts in correlation coefficients of multiple root morphological traits across three seedling grades to clarify grade-specific underground adaptive strategies. From January to March, all root morphological traits of grade I seedlings displayed significant positive correlations., with all root morphology indicators changing in coordination, though a few weak negative correlations already appeared. This is because grade I seedlings have more fully developed root systems, with a high degree of differentiation between lateral and fine roots, making the root structure more complex. Length, diameter and volume develop asynchronously owing to complex root differentiation, which prevents all traits from showing uniformly strong positive correlations. In May and August, the correlations between indicators decreased significantly, with length-related indicators showing negative correlations with diameter and volume indicators, influenced by high temperatures and environmental stress. In December, Weak negative correlations detected in grade I seedlings during summer vanished by December, and all root traits regained stable positive correlations, and in the later stage, the indicators once again restored a stable positive correlation. This is consistent with the findings of Pan et al. (2025), who concluded that grade I seedlings have strong tolerance to stress, and after stress, the physiological state of the roots can self-repair, growth coordination recovers well, and overall growth is stable ^[65]. In January and March, the indicators of grade II seedlings show strong correlations, with a clear trend of coordinated growth overall and few significant negative correlations were detected. According to Fig. 11, grade II seedlings mainly grow in the taproot, the lateral root development is average, and the root structure is simple, with the growth rhythm of various indicators being relatively uniform. In May and August, the correlation among the indicators of grade II seedlings slightly decreases, but the fluctuation is much smaller than that of grade I seedlings, with fewer negative correlations and relatively smooth changes. The environmental stress caused by rising temperatures in May and August may cause some irreversible damage to the roots of grade II seedlings, resulting in insufficient root repair ability, and overall growth and stability are weaker than those of grade I seedlings. Grade II seedlings exhibit moderate root differentiation. Under stress, their adjustment range is narrower than that of grade I seedlings with less

fluctuating correlation; however, their root repair capacity is limited, and damage cannot be fully restored. Therefore, in December, grade II seedlings still exhibited some negative correlations among indicators, and the root traits could not return to a state of synchronized growth. For grade III seedlings in January and March, all root indicators were strongly correlated and showed highly positive relationships. Since the taproots of grade III were in the weakest condition, this resulted in weak seedling growth, poor root development, insufficient lateral root differentiation, reliance solely on the elongation of the primary root, a simple root structure, and highly consistent changes across all indicators. In May and August, the correlations related to grade III seedlings showed almost no significant changes and remained generally stable. This may be attributed to the inherently low vitality and suppressed root growth of grade III seedlings; their root morphological traits barely undergo dynamic adjustments in response to external environments, thus maintaining stable inter-trait correlations. In December, however, the negative correlations among root indicators of grade III seedlings increased, and most root indicators did not show significant correlations with each other. This indicates that the original synergistic growth relationships among the various root indicators were completely disrupted. Under long-term environmental stress, the weak root systems of grade III seedlings accumulate damage continuously, cannot metabolize or repair normally, resulting in disordered root structures and greatly reduced growth capacity. This seasonal root adjustment strategy coordinates with the photoprotective pigment allocation patterns observed in leaf tissues, jointly constituting the integrated phenotypic plasticity of *P. yunnanensis* seedlings under fluctuating climate. almost no significant negative correlation.

Consistent with the seasonal correlation patterns of root morphological traits above, seedling grade determines the overall resource allocation strategy of underground systems. Previous studies have shown that the grade of seedlings determines the photosynthetic capacity and nutrient storage ability of plants, thereby affecting resource allocation and growth potential ^[54]. As a result, the absolute growth of high-grade *P. yunnanensis* seedlings is often higher than that of low-grade seedlings, which also leads to significant differences in the correlations of root system indices for different *P. yunnanensis* seedlings across different months: Seedlings of higher grades exhibit stronger dynamic regulatory capacity for root trait correlations, accompanied by more obvious seasonal fluctuation of correlation coefficients, the greater the seasonal fluctuations in root correlations, and the better the recovery after stress ^[65, 66]. The results of this study indicate that: grade I seedlings show significant fluctuations in correlation under

environmental changes, can autonomously adjust root growth patterns under stress, and are able to recover effectively in the later stage; grade II seedlings have ordinary regulatory abilities and find it difficult to fully recover after damage; grade III seedlings have overly simple and stable correlations in the early stage, with obvious severe physiological dysfunction in the later stage, resulting in the poorest seedling quality. Overall, seedling quality is closely related to root physiological coordination, environmental adaptability, and damage repair capability. Grade I seedlings have the best overall growth stability and are more suitable as high-quality afforestation seedlings. These findings provide a morphological reference for rapid screening of high-quality *P. yunnanensis* seedlings by root structural characteristics under local plateau climate. physiological collapse.

Conclusion

The results indicate that: Seedlings of different grades exhibited a highly significant allometric relationship between seedling ground line diameter and seedling height throughout the growing season ($p < 0.01$). The higher the grade of the seedling, the more pronounced the synergistic effect between vertical and radial growth: grade I seedlings primarily developed in height during the early and middle stages of growth, with a marked shift towards thickening in the later stages; grade II seedlings grew predominantly in height; whereas grade III seedlings developed in height during the early stages, with height and diameter growing at similar rates in the middle and later stages. The allometric relationship between photosynthetic pigments (chlorophyll a, chlorophyll b and carotenoids) and total chlorophyll is not fixed but varies with the seasons, and there are also marked differences between the various classes. Overall, the accumulation rate of total chlorophyll is faster than that of chlorophyll a, with the order of accumulation rates being grade III > grade II > grade I; conversely, chlorophyll a accumulates faster than total chlorophyll, with the order of accumulation rates being grade I > grade II > grade III. Interestingly, grade I seedlings actively reduce the accumulation rate of chlorophyll b and increase that of carotenoids during summer; this is a typical manifestation of adaptation to strong light and stress resistance, and also indicates that grade I seedlings exhibit more active photoprotection and antioxidant responses. Grade II seedlings, constrained by their own conditions, exhibit a relatively delayed response; for grade III seedlings, the relationships between various pigments may be unstable, possibly due to higher expression of genes related to degradation. Judging by various root system indicators, the relative growth relationships between the taproot length, total root length, average diameter, surface area, projected area and total volume of seedlings of different grades are influenced not only by the season but also by the

seedling grade. In most months, the taproot grows faster than the total root mass. grade I seedlings exhibit a relatively flexible root growth strategy, with distinct priorities at different stages: early elongation focusing on taproot development, mid-stage expansion of surface area, and late-stage coordinated growth. They are able to respond promptly and proactively to environmental stressors and demonstrate strong recovery capacity. The root system strategy of grade II seedlings is less pronounced; although it is broadly consistent with that of grade I seedlings, the differences are not marked. Furthermore, due to inherent conditions, their stress tolerance is generally poor and they are susceptible to seasonal stresses. Grade III seedlings exhibit the least distinct strategy; the relative growth relationships between various indicators show poor fit, they are most significantly affected by seasonal variations, and their resilience is poor. Furthermore, due to an overly simple root structure and low vitality, coordination is very poor in the later stages of growth, and no clear growth strategy is evident. In terms of correlations: regarding photosynthetic pigments, in most months there was a highly significant positive correlation between each pigment and total chlorophyll, whilst ratios such as chlorophyll a/b and carotenoids/total chlorophyll were generally negatively correlated. Grade I seedlings exhibited a very strong positive correlation between all pigments—chlorophyll a, chlorophyll b, carotenoids and total chlorophyll indicating a high degree of synergy in the synthesis and accumulation of photosynthetic pigments. Grade II seedlings, whilst in the transitional phase from normal growth to stress, began to show a marked impairment in the synergy of pigment metabolism, yet still demonstrated a certain degree of physiological regulatory capacity; grade III seedlings have weak regulatory capacity; in the later stages of growth, the synergistic regulatory mechanisms among pigments are severely impaired, and pigment metabolism is largely out of balance. Correlations among root system indicators also follow a similar pattern: for grade I seedlings, positive correlations predominate in most months; although seasonal fluctuations are significant, they are able to respond and recover promptly; grade II seedlings exhibit relatively stable correlations, but their recovery capacity is generally poor; grade III seedlings show an excessive concentration of positive correlations in the early stages, indicating a monotonous structure, whilst negative correlations increase in the later stages, and there is essentially no significant correlation between the various indicators, suggesting that the relative growth relationships among the root systems have become disordered and that there is no clear growth strategy. Overall, seedling grade has a significant impact on the height and ground line diameter of *P. yunnanensis* seedlings, their photosynthetic pigments, and the root system's ability to cope with and recover from environmental stress. Grade I seedlings grow most steadily and

exhibit the highest resistance, making them the ideal high-quality material for practical afforestation; grade II seedlings display moderate capabilities across all aspects and are more susceptible to seasonal stress; grade III seedlings show the poorest overall balance and the weakest resistance. These findings suggest that seedling grading based on morphological traits can be a practical tool for selecting high-quality planting stock, and that grade I seedlings are more resilient to seasonal environmental fluctuations.

Declarations

Ethics approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication

Not applicable

Availability of data and material

All data generated or analyzed during this study are included in this article. All data generated or analyzed during this study are available from the corresponding author on reasonable request.

Author Contributions

Q.Z. wrote the manuscript. Q.Z., Y.J. and L.C. Y.X analyzed data. L.C., Y.X. and N.C. conceptualized and designed the experiments. Q.W., L.C., and Y.X. conducted the investigation. Q.Z., L.C., K.X., Y.J., T.X. and Y.X. reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Figure Legends

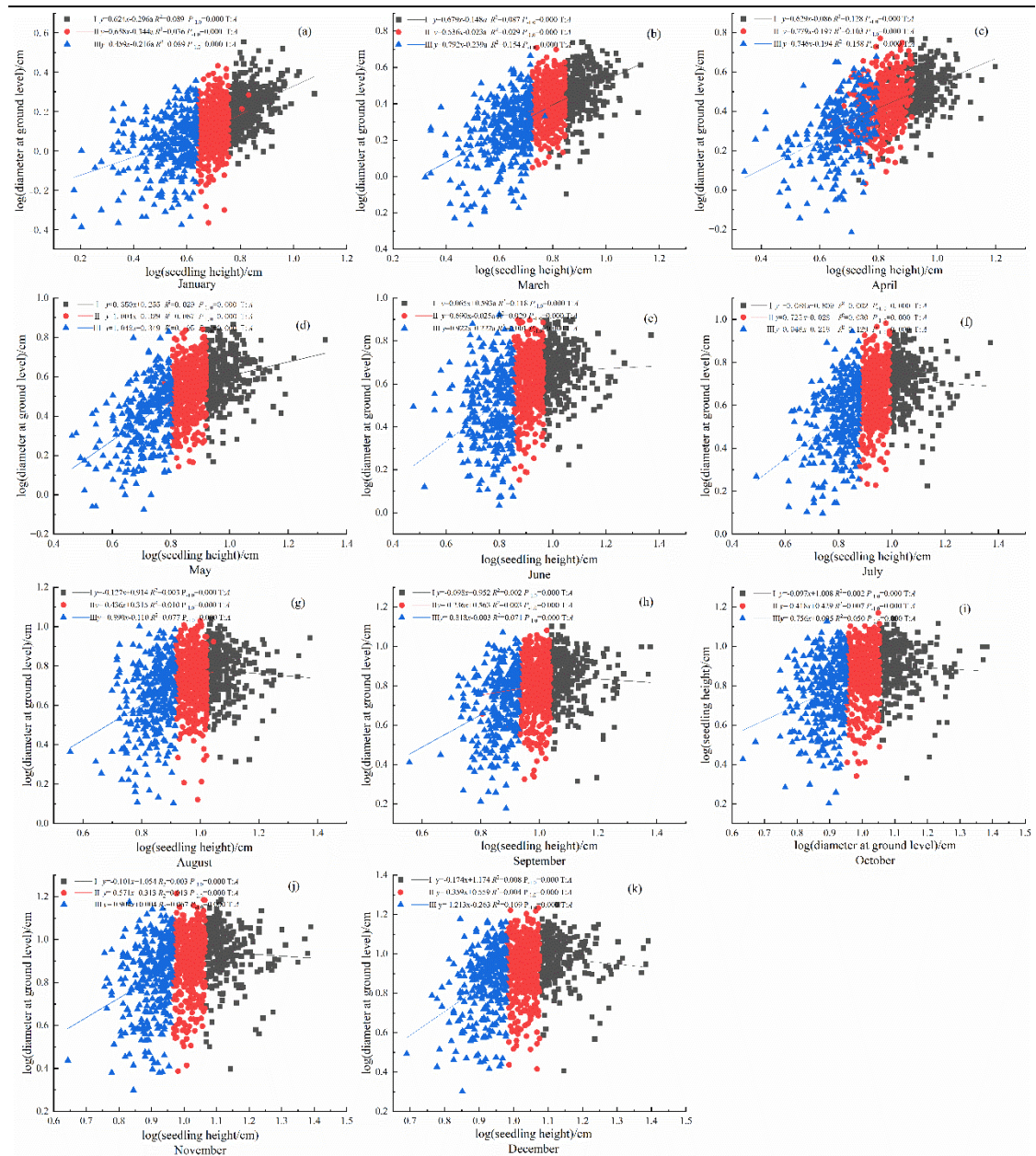


Fig. 1 Different lowercase letters indicate significant differences among different grades ($p < 0.05$). R^2 represents the degree of fit of the fitted line. $P_{1.0}$ indicates the significance of the difference between the slope and the theoretical value $b = 1.0$, and relationships were categorized (T) as allometric (A) or isometric (I).

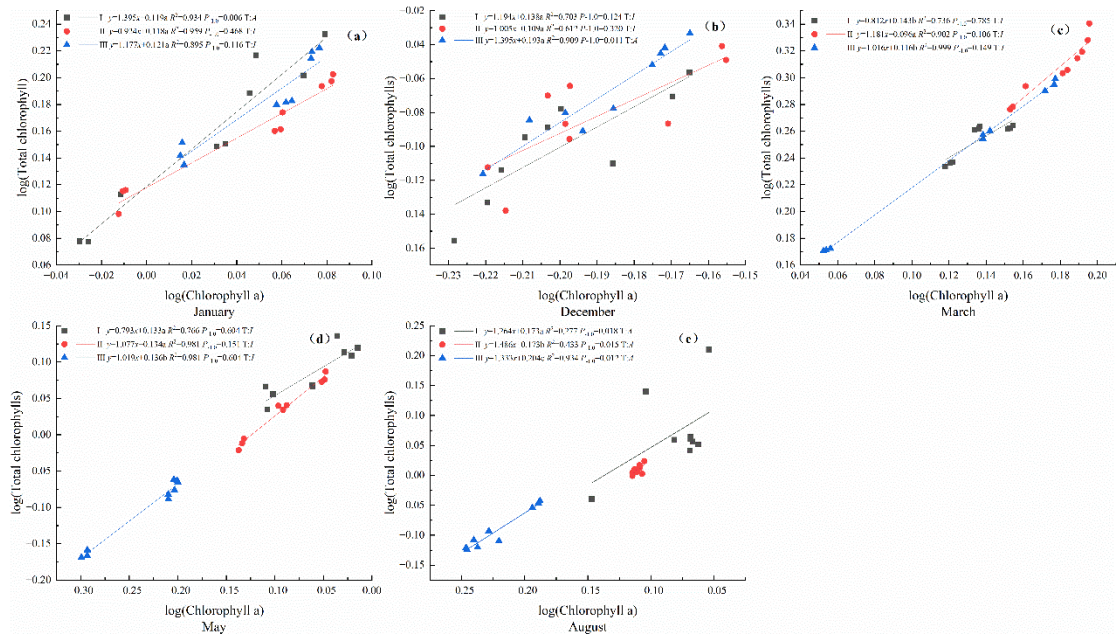


Fig. 2 Different lowercase letters indicate significant differences among different grades ($p < 0.05$). R^2 represents the degree of fit of the fitted line. $P_{-1.0}$ indicates the significance of the difference between the slope and the theoretical value $b = 1.0$, and relationships were categorized (T) as allometric (A) or isometric (I).

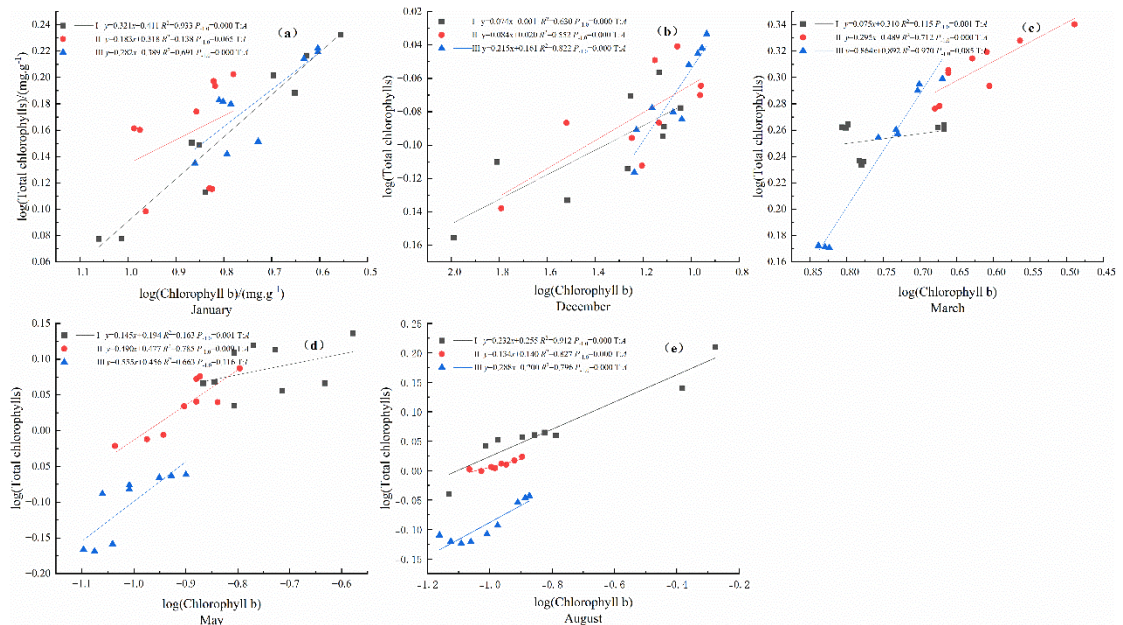


Fig. 3 Different lowercase letters indicate significant differences among different grades ($p < 0.05$). R^2 represents the degree of fit of the fitted line. $P_{-1.0}$ indicates the significance of the difference between the slope and the theoretical value $b = 1.0$, and relationships were categorized (T) as allometric (A) or isometric (I).

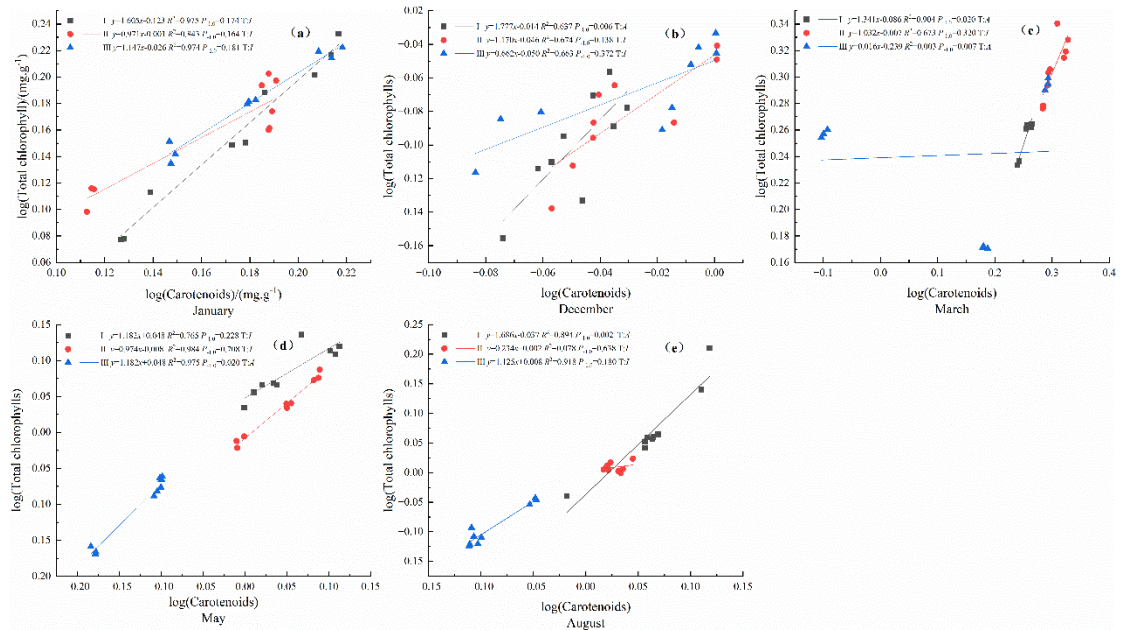


Fig. 4 Different lowercase letters indicate significant differences among different grades ($p < 0.05$). R^2 represents the degree of fit of the fitted line. $P_{-1.0}$ indicates the significance of the difference between the slope and the theoretical value $b = 1.0$, and relationships were categorized (T) as allometric (A) or isometric (I).

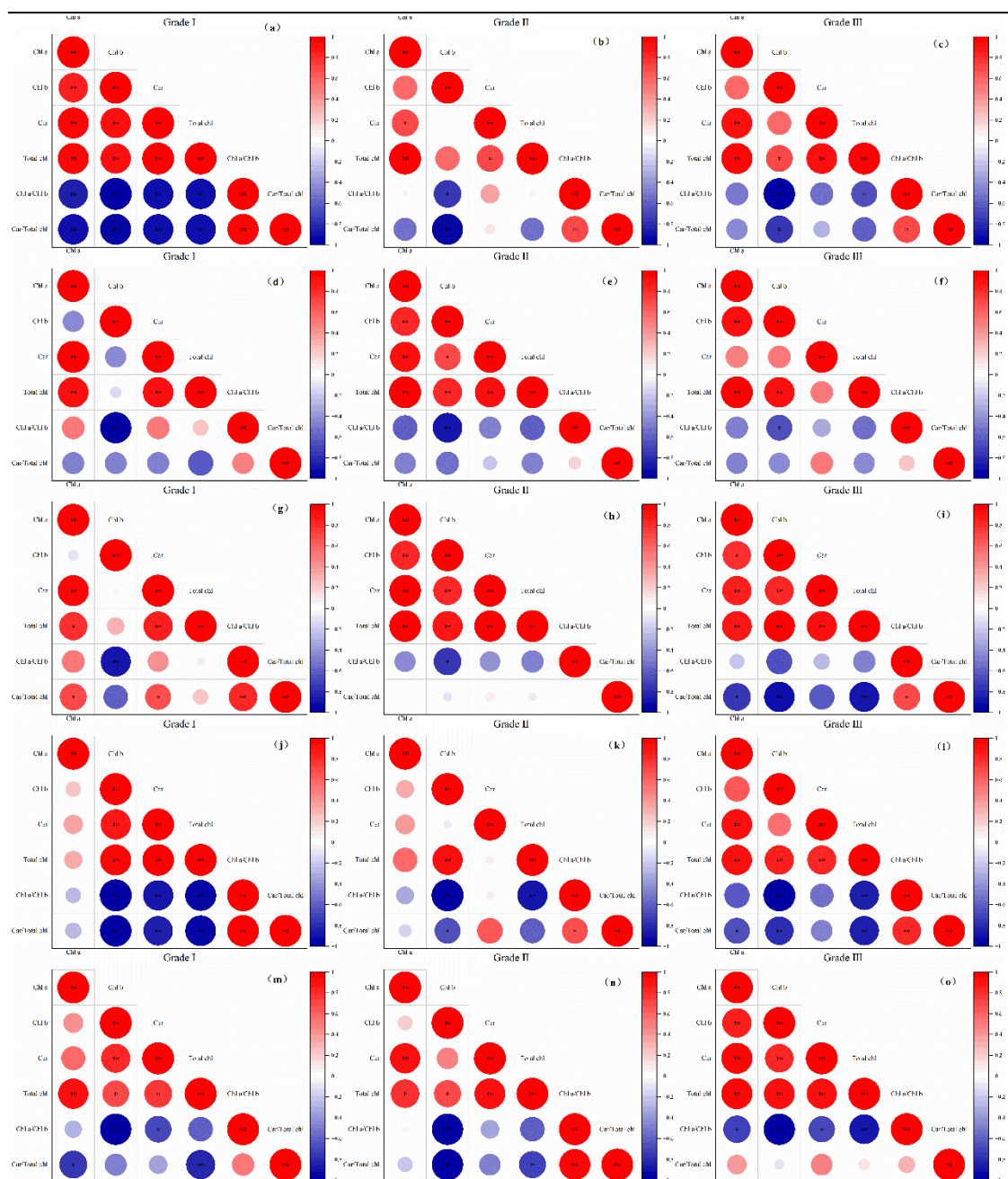


Fig. 5 Analysis of the seasonal correlations of photosynthetic pigment indices in Yunnan pine seedlings of different grades. The color gradient represents the direction and strength of the Pearson correlation coefficient, with red indicating positive correlation and blue indicating negative correlation (* $p < 0.05$, ** $p < 0.01$). Chlorophyll a (Chl a); Chlorophyll b (Chl b); carotenoids (Car); Total chlorophyll (Total chl); Chlorophyll a/b (Chl a/Chl b); Carotenoids/Total chlorophyll (Car/Total chlorophyll).

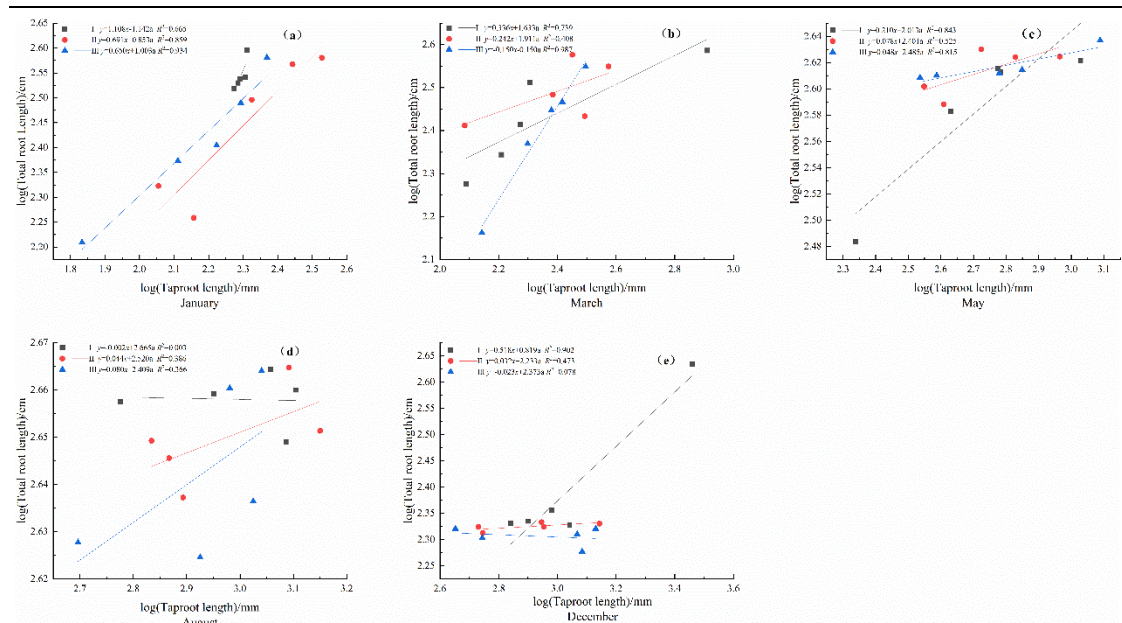


Fig. 6 The slope represents the relative growth rate of the taproot to the total root, and R^2 indicates the fitting goodness of the fitted curves for seedlings of different grades.

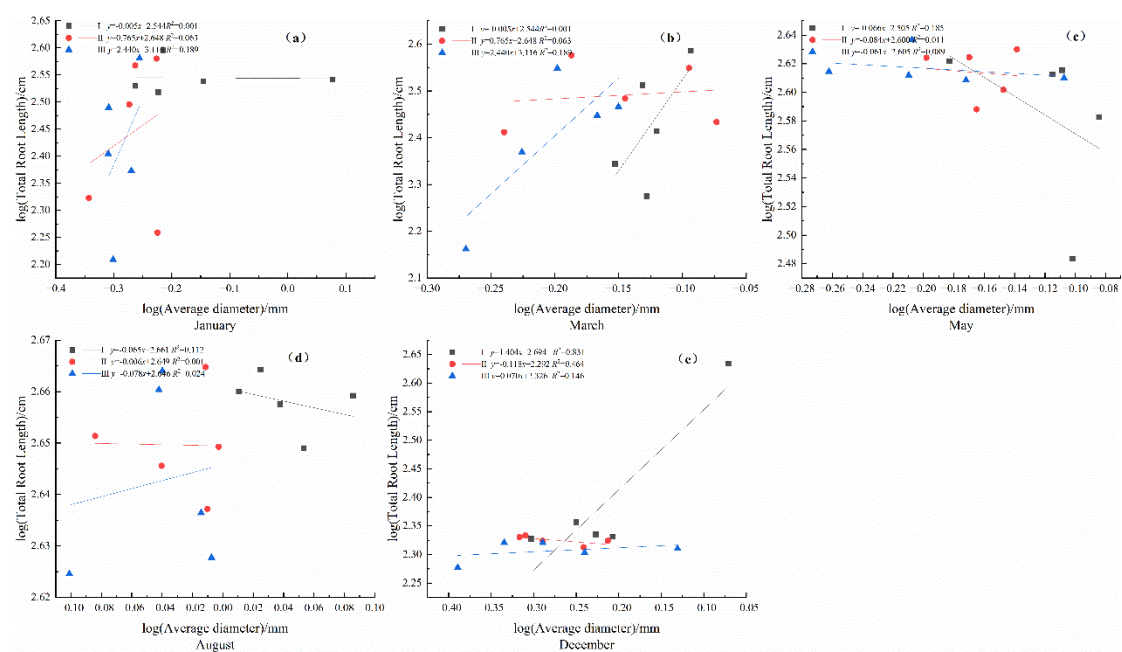


Fig. 7 The slope represents the growth index of total root length and average diameter, R^2 denotes the goodness of fit of linear regression, and letters indicate inter-group differences.

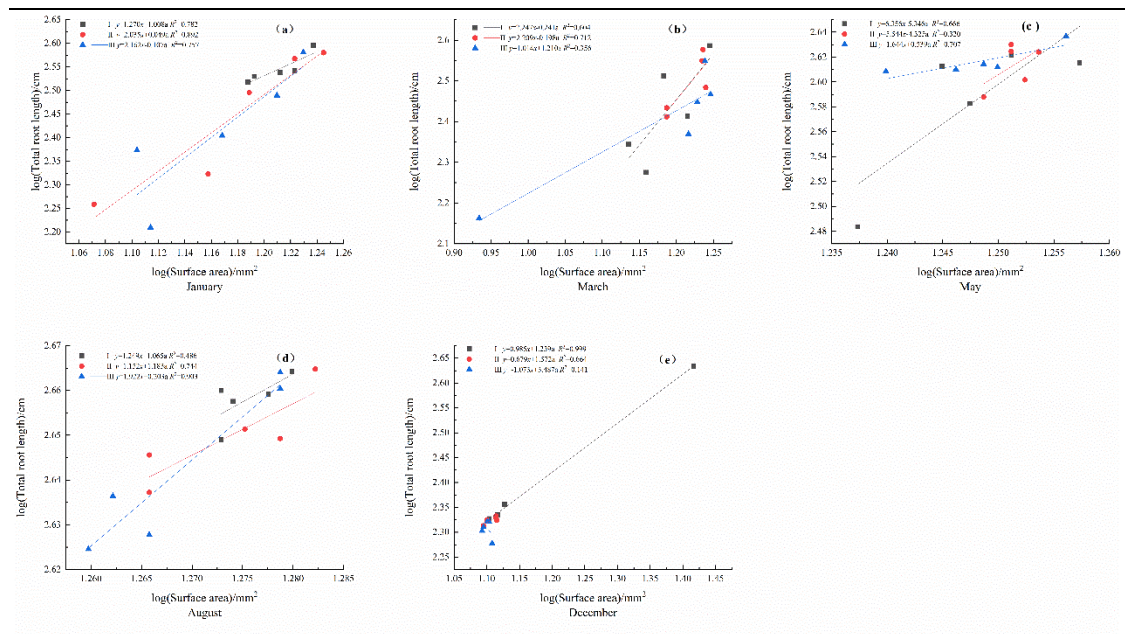


Fig. 8 The slope represents the relative regression rate of total root length to total surface area, and R^2 indicates the goodness of fit of the fitted straight line, and letters indicate inter-group differences.

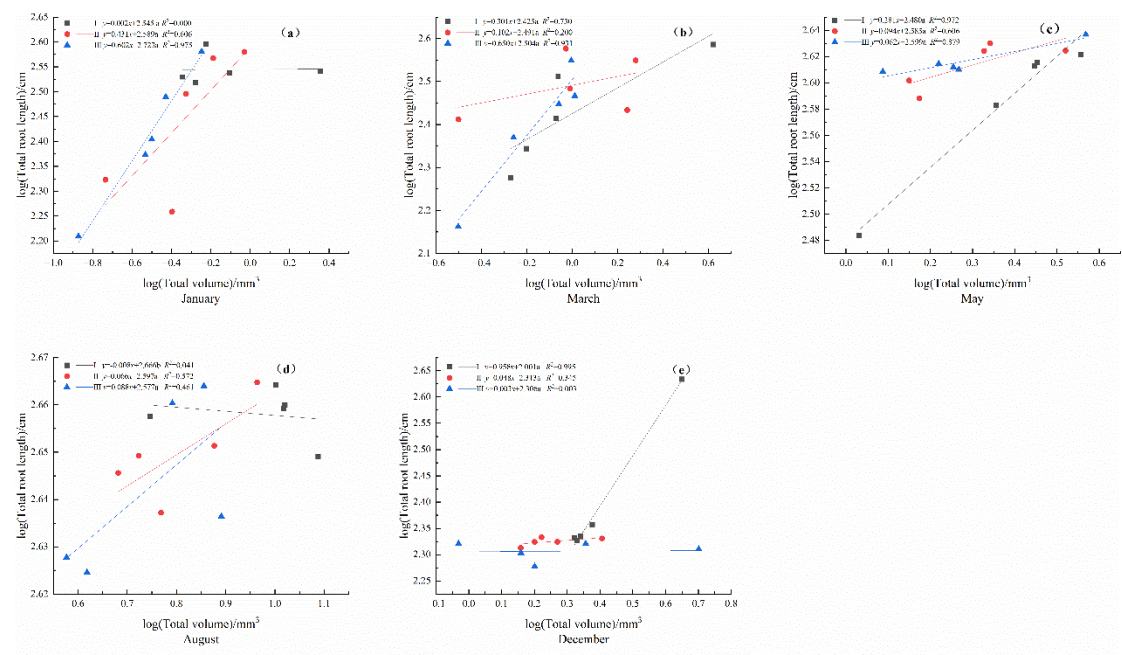


Fig. 9 The slope represents the relative regression rate of total root length to total volume, and R^2 indicates the goodness of fit of the fitted straight line, and letters indicate inter-group differences.

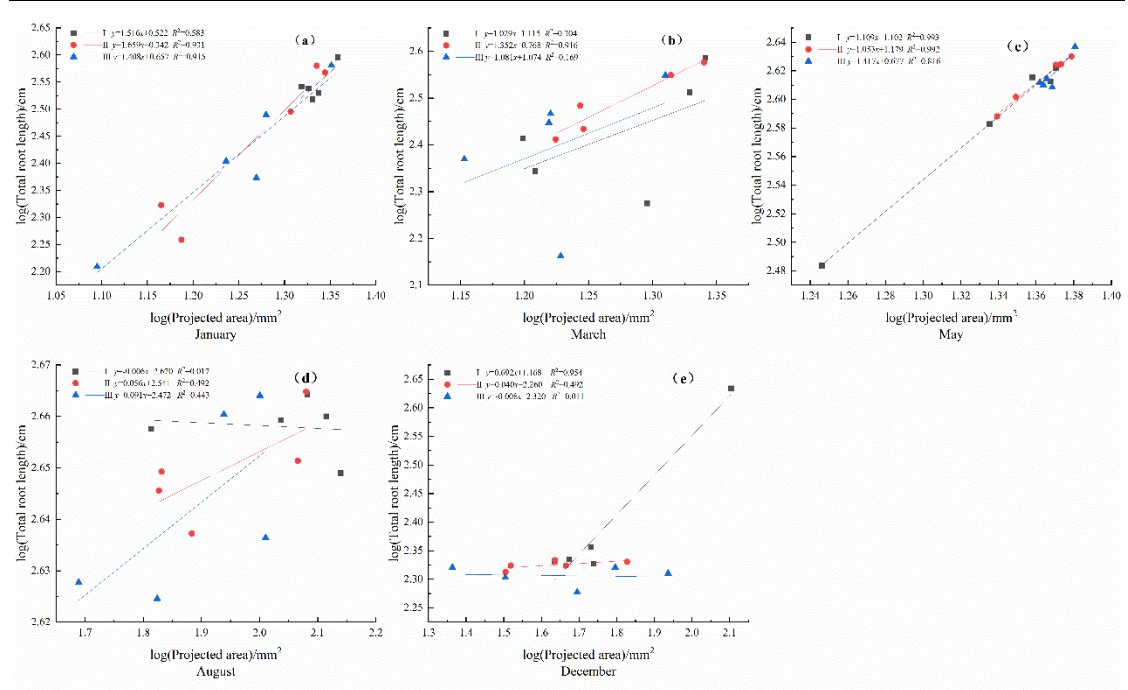


Fig. 10 The slope represents the relative regression rate of total root length to total projected area, and R^2 indicates the goodness of fit of the fitted straight line.

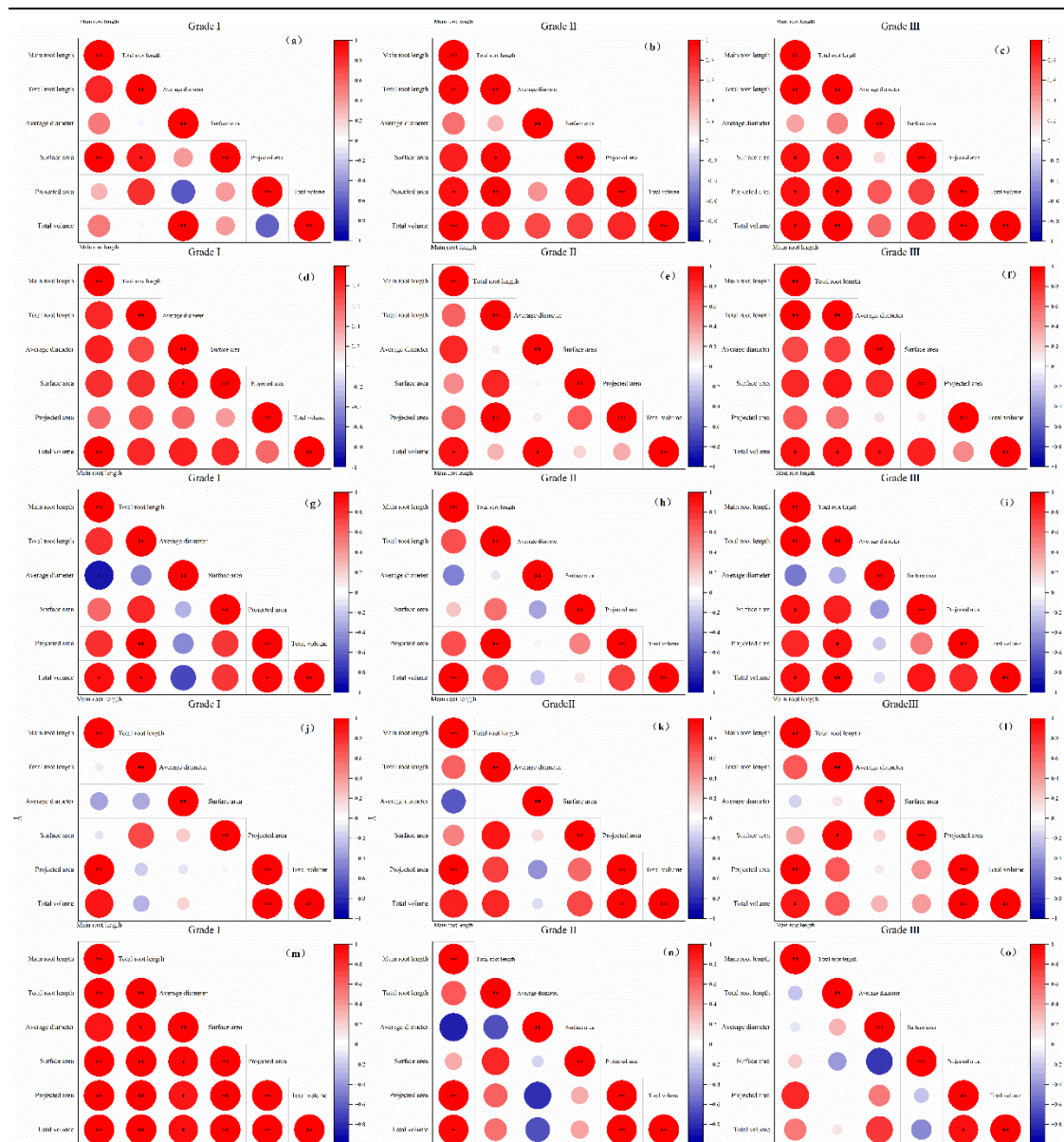


Fig. 11 Correlation bubble plot of morphological indicators of *P. yunnanensis* seedlings across different months and grades. The color gradient represents the direction and strength of the Pearson correlation coefficient, with red indicating positive correlation and blue indicating negative correlation (* $p < 0.05$, ** $p < 0.01$).