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Impact of Pruning Period and Intensity on the Growth and Yield of *Rosa roxburghii*: A Sustainable Approach for Enhanced Agricultural Productivity

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ABSTRACT

This study aimed to investigate the effects of pruning period and intensity on the growth and yield of *Rosa roxburghii* Tratt, a shrub fruit species with significant economic value, to inform optimized pruning practices for its cultivation and management. The experiment was conducted in a 7 year old *R. roxburghii* orchard in southwest China. A randomized block design with two factors, pruning period (maturity period, dormancy period, and germination period) and pruning intensity (no pruning, light pruning, moderate pruning, and severe pruning), was employed. Growth indicators such as the number, diameter, and length of new shoots, as well as single fruit weight and yield per tree, were measured to assess the effects of pruning. Data were statistically processed using two-factor analysis of variance and principal component analysis. Both pruning period and intensity significantly affected the number of new shoots, new shoot diameter, new shoot length, single fruit weight, and yield of *R. roxburghii* trees. Moderate pruning during the dormancy period was most effective in increasing the number and diameter of new shoots, while light pruning during the germination period also showed positive effects. An increase in pruning intensity led to higher single fruit weight across all pruning periods, with no significant effect of the pruning period. There was a significant interaction between pruning intensity and period on yield per tree, with moderate pruning during the dormancy period being the most effective in enhancing yield. Moderate pruning, particularly during the dormancy period, is an effective strategy for improving the growth and yield of *R. roxburghii*. This approach not only controls tree height and crown width effectively but also significantly promotes yield. The study recommends "moderate pruning during the dormancy period" as the optimal practice for the production and management of *R. roxburghii*, especially in biogeographically suitable areas.

1 | Introduction

Rosa roxburghii Tratt, a deciduous shrub native to the *Rosa* genus, is prominently cultivated in the ecologically diverse regions of Guizhou, Yunnan, and Sichuan in southwest China (Hou et al. 2020; Yang et al. 2020). This species has been the subject of considerable research and commercial interest due to its multifaceted utility, encompassing both nutritional and medicinal values (Li et al. 2023; Tang et al. 2023; Xu et al. 2019; Yan et al. 2022). The economic significance of *R. roxburghii* is underscored by its status as a key agricultural product in Guizhou province, where it has been extensively cultivated for its high market demand and potential health benefits. The leadership of Guizhou province in the cultivation of *R. roxburghii* is exemplified by the vast expanse of its orchards, which cover 140,000 ha within the province (Li et al. 2022).

Significant advancements have been made in various research fields regarding *R. roxburghii* in recent years. It has been shown that the fruit of the rose hip is not only rich in vitamin C but also contains a variety of bioactive substances, such as polysaccharides, organic acids, flavonoid compounds, triterpenoid compounds, and possesses high superoxide dismutase activity (Li, Wang, et al. 2024). These components endow the rose hip with multiple pharmacological effects, including antioxidant, anti-inflammatory, antidiabetic, and anticancer effects (Liu et al. 2024; Zhang et al. 2024; Zhou et al. 2024). Furthermore, genomic research on the rose hip has revealed key genes that regulate the quality of its fruit, such as the role of the HD-Zip gene family in the formation of trichomes on the rose hip's epidermis (Qin et al. 2024), and key genes regulating the synthesis of quercetin derivatives identified through transcriptomic and metabolomic approaches (Su et al. 2024). In the field of food science, the quality assessment and sorting technology of rose hip fruits have also been developed. Through image processing technology, researchers have been able to estimate the mass and volume of the fruit based on its size and projected area, thus achieving automated grading (Xie et al. 2024). In addition, research on packaging materials for rose hip fruits has also made progress, with the development of composite films based on polyethylene, coated with carboxymethyl chitosan, sodium alginate, and lactic acid streptococcal to extend the shelf life of the fruit (Cheng et al. 2024). In terms of environmental adaptability, the growth status and nutrient cycling mechanisms of rose hips in karst desertification areas have also attracted attention. It has been found that the stoichiometric coupling relationships of C, N, P, and K in the litter and soil of rose hip forests are influenced by the degree of desertification and seasonal changes (Li, Du, et al. 2024). These research results provide important information for understanding the ecological adaptability and nutrient management of rose hips under different environmental stresses. In summary, the research achievements of rose hips not only cover the identification and functional research of its bioactive components but also include the assessment of fruit quality, improvement of packaging technology, and research on ecological adaptability in specific habitats.

The expansion of *R. roxburghii* cultivation has been accompanied by a critical need for sophisticated agronomic practices to maintain and enhance the productivity of these orchards. Among these practices, pruning has emerged as a pivotal technique for manipulating tree growth and development, with the dual objectives of improving yield and ensuring the longevity of the fruiting cycle (Fan et al. 2001a, 2001b). Despite the well-documented benefits of pruning in horticulture, its adoption among *R. roxburghii* growers has been less than universal, resulting in suboptimal tree health and reduced economic returns. Neglected pruning can lead to a myriad of issues, including stunted growth, sparse branching, excessive flowering without corresponding fruit set, and a decline in both yield and the quality of the fruit produced. These phenomena not only shorten the productive life of the orchards but also diminish the financial viability of the cultivation enterprise.

The scientific literature is replete with evidence supporting the role of pruning in enhancing the yield and vigor of fruit trees (Kumar et al. 2010; Lazare et al. 2021; Sharma et al. 2018; Tosto et al. 2022; Zahid et al. 2021). The impact of pruning on growth and production is multifaceted, with effects that are contingent upon the method and timing of the intervention (Cronje et al. 2021; Nowakowski et al. 2018; Zhang et al. 2022). The selection of an appropriate pruning strategy must consider the unique characteristics of the tree species, including branch architecture, growth patterns, and physiological responses to pruning stimuli. The overarching aim of such strategies is to enhance fruit yield, improve fruit quality, and bolster economic efficiency (He et al. 2022; Ou et al. 2023; Westling et al. 2021).

A multitude of global research efforts has been dedicated to examining the impact of pruning on the growth, development, photosynthetic capabilities, physiological traits, productivity, and quality of commercially significant forests (Betz 2019; du Toit et al. 2020; Shashi et al. 2022; Zare 2021; Zhang et al. 2022). For example, various studies have demonstrated that well-timed and fitting pruning practices can optimize the distribution of branches and foliage, as well as the structure and ratio of branch components, thereby maximizing the photosynthetic surface area of the tree canopy and enhancing the accumulation, dispersion, and application of nutrients (Cronje et al. 2021; Gokavi et al. 2021; Sakhidin et al. 2021; Tosto et al. 2022). This equilibrium in growth and fruiting processes subsequently translates into enhanced yields and superior quality (Albarracín et al. 2019; Gokavi et al. 2021; Lazare et al. 2021; Vosnjak et al. 2022). In the case of *R. roxburghii*, it has similarly been observed that pruning can boost its yield (Fan et al. 2001a, 2001b; Zhang et al. 2022). However, prior research, while suggesting appropriate pruning techniques for *R. roxburghii*, has not pinpointed the most advantageous timing for pruning within this species. In the daily management of *R. roxburghii*, fruit growers spend a lot of inefficient pruning time, resulting in a large amount of workload and the challenge of labor resource allocation, which hinders the development of the *R. roxburghii* industry to varying degrees.

The results of this research are expected to provide empirical evidence for the optimization of pruning practices in *R. roxburghii* cultivation. By identifying the most effective pruning period and intensity, this study aims to contribute to the body of knowledge on horticultural management techniques for this economically important species. The findings will be instrumental in guiding growers in the implementation of targeted pruning strategies that can enhance the growth, yield, and economic prospects of *R. roxburghii* orchards. Furthermore, this study will explore the potential for these findings to be extrapolated to other regions and climatic conditions, thereby broadening the applicability of the recommendations. The ultimate goal is to empower the agricultural community with evidence-based practices that can lead to sustainable and profitable *R. roxburghii* cultivation.

2 | Materials and Methods

2.1 | Experimental Location

The research was conducted in Gujiao Town, Longli County, Guizhou Province, China, which is situated between 26°10′ and 26°49′ N and 106°45′ and 107°15′ E. This area is a typical karst landscape, and experiences a humid subtropical monsoon climate characterized by a mean annual temperature of 14.8°C. The lowest recorded temperature is −6°C, and the highest is 32°C. The chillest month has an average temperature of 4.6°C, whereas the warmest month averages at 23.6°C. Annual precipitation in the region amounts to approximately 1100 mm, predominantly falling during the summer season. The village enjoys 1160 h of sunshine per year, has a frost-free period spanning 283 days, and is underlain by yellow soil with a depth ranging from 50 to 80 cm.

2.2 | Field Trial Arrangement

A 7-year-old *R. roxburghii* orchard of the "Guinong No. 5" variety, exhibiting feeble canopy expansion, served as the subject for the study. The orchard featured trees with an average stature of 1.5 m, a canopy spread of 110 cm by 120 cm, and a spacing between rows of 2 m by 3 m. Individuals for the pruning intervention were chosen at random from the plants present. These trees displayed uniform development and were free from infestations or ailments.

The method of crown contraction pruning, which entails pulling back the upper section of the canopy and trimming a specific length from the exterior towards the core, was implemented (Fan et al. 2001b). The selection of pruning periods and intensities was based on the physiological growth cycle of *R. roxburghii*, preliminary surveys of local orchard management practices, and established horticultural principles for perennial deciduous trees. The three pruning periods correspond to key phenological stages: post-harvest nutrient recovery (Maturity), winter dormancy with minimal sap flow (Dormancy), and the onset of spring growth (Germination). The pruning intensities were defined to represent a gradient from mild shaping to severe renewal, reflecting the range of practices observed in the region and aligning with quantitative intensity classes used in pruning studies for other fruit species (Kumar et al. 2010). A randomized block design with two variables, pruning timing and severity, was laid out. The first factor had three pruning periods: (1) mature period (September of the current experimental year), (2) dormant period (December of the current experimental year), and (3) germination period (March of the following year). Four pruning intensities were set for the second factor: (1) no pruning (retaining the original state of the tree as a control), (2) mild pruning (cutting the part of the crown height above 25% and shrinking the crown diameter from the outside to the inside), (3) moderate pruning (cutting the part of the crown height above 33% and shrinking the crown diameter from the outside to the inside), and (4) severe pruning (cutting the part of the crown height above 50% and shrinking the crown from the outside to the inside). A total of 12 distinct treatments, each replicated three times, resulted in 36 experimental units. Each plot, spanning an area of 54 square meters, was positioned in a random pattern, with buffer rows established among them. Fertilization was administered on two occasions throughout the study, utilizing a balanced fertilizer (with a ratio of Nitrogen: Phosphorus: Potassium = 15:15:15), in early April and mid-July. Weed control measures were taken in March, July, and October. The plots were dependent on natural precipitation for moisture, and no herbicides were employed.

2.3 | Collection of Growth and Yield Information

In July 2020, a sample of nine *R. roxburghii* trees from each plot was chosen to assess growth indicators, such as the quantity, length, and girth of new growth, focusing on spring shoots exceeding 3 cm in length. During the fruit ripening phase, a subset of three *R. roxburghii* plants per plot was selected to ascertain individual fruit mass and overall yield per tree. The dimensions of the spring shoots were taken with a measuring tape and a digital vernier caliper. The mass of the fruit was measured using an electronic scale, and the yield per tree was quantified with a digital weighing scale.

2.4 | Data Analysis

The experimental data were systematically arranged with Microsoft Excel 2016. For evaluating the normalcy of the dataset, Data Processing System (DPS) software, version 20.05, was utilized (Tang and Zhang 2013). Data adhering to a normal distribution underwent analysis of variance (ANOVA), followed by multiple comparisons, with the Least Significant Difference (LSD) method applied for significance testing. Principal component analysis (PCA) was executed on the normalized raw data, also facilitated by DPS 20.05. The overall score for each principal component was calculated by aggregating the product of its score and the corresponding contribution rate, ranked by score magnitude, to pinpoint the optimal pruning period and intensity. For data visualization, Origin 2024b software was deployed.

3 | Results

3.1 | Effect of Pruning on Shoot Growth

3.1.1 | Effect of Pruning on the Number of New Shoots

The quantity of new growth in *R. roxburghii* fluctuated across various levels of pruning severity within the same pruning timeframe (Figure 1a). Typically, there was an initial surge in the count of new shoots, which then declined as the pruning severity escalated. Pruning that was moderate during the stages of fruit maturity and dormancy, and light during the sprouting phase, yielded the most significant boost in new shoot proliferation. In contrast to the untreated control group, these pruning strategies corresponded to increases of 39.50%, 70.43%, and 6.56% in new shoot counts, respectively. Across various pruning timeframes, pruning during the dormancy phase maximized the proliferation of new shoots in *R. roxburghii*, with the maturity phase and the sprouting phase following suit under the remaining three pruning intensities (Figure 1b). It is noteworthy that intense pruning during the sprouting phase actually reduced the quantity of new shoots. A two-way ANOVA (Table 1) substantiated the significant impact of both the pruning period and intensity, as well as their interactive effect (pruning period × pruning intensity), on new shoot production. These results underscore the necessity of fine-tuning the timing and degree of pruning, either independently or in tandem, to optimally regulate the number of new shoots in *R. roxburghii*.

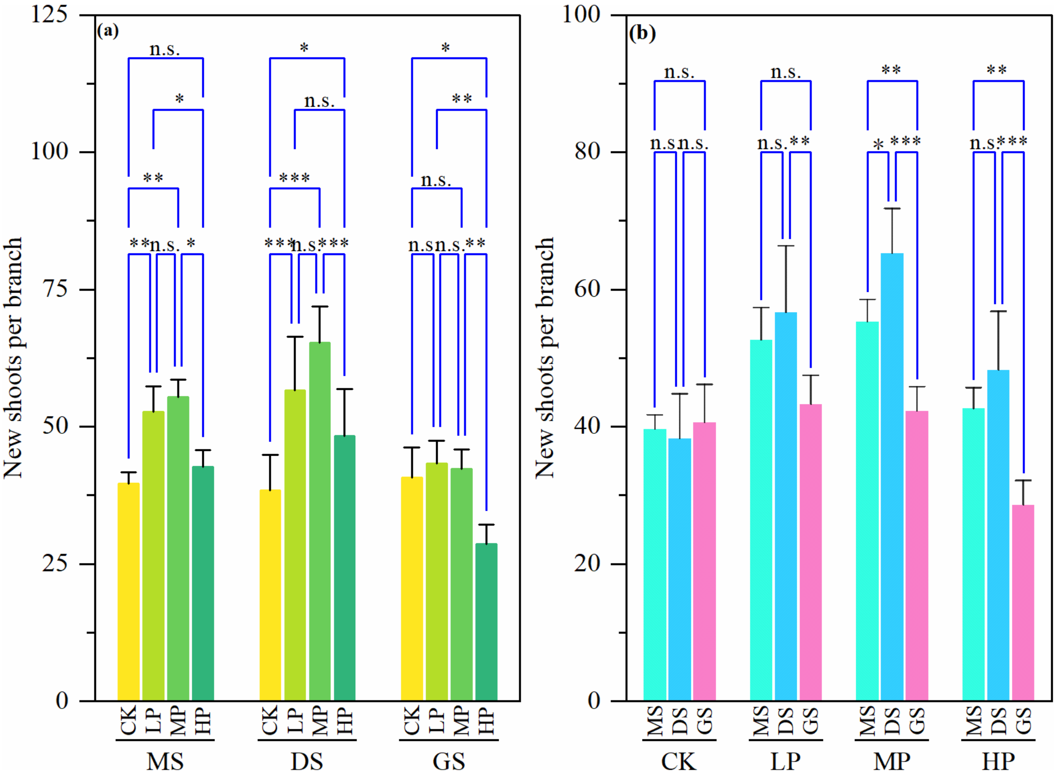

FIGURE 1 | Effect of pruning practices on new shoot development in *R. roxburghii*. CK, no pruning; DS, dormancy stage; GS, germination stage; HP, heavy pruning; LP, light pruning; MP, moderate pruning; MS, maturity stage. n.s., *, **, and *** denote no significant difference, $p<0.05$, $p<0.01$, and $p<0.001$, respectively.

TABLE 1 | Two-way ANOVA for the effects of pruning periods and intensity on the number of new *R. roxburghii* shoots.

Source of variation	df	Mean square	*F*	*p*
Pruning period	2	558.083	18.100	**
Pruning intensity	3	516.333	16.746	**
Pruning period × Pruning intensity	6	97.639	3.167	*

Note: * and ** denote significant differences at $p<0.05$ and $p<0.01$, respectively.

3.1.2 | Influence of Pruning on New Shoot Diameter

Regarding shoot girth, the girth of new shoots expanded with escalating pruning intensity within the same pruning period (Figure 2a). Pruning executed during the maturity and dormancy phases notably augmented the girth of new shoots. Furthermore, while not reaching statistical significance, moderate to severe pruning during the germination phase also contributed to an increase in shoot diameter. Across various pruning periods, pruning during the dormancy phase was most effective in enhancing the diameter of new shoots, with the maturity phase and germination phase following under the other three pruning intensities (Figure 2b). It should be noted that the control group was not subjected to any pruning. A two-way ANOVA (Table 2) established that both the timing of pruning and the degree of intensity exerted a highly significant influence on the shoot diameter of *R. roxburghii*. However, the interaction between the pruning period and intensity was not statistically significant. These findings suggest that adjusting the timing and intensity of pruning can significantly affect the diameter of *R. roxburghii* shoots.

3.1.3 | Impact of Pruning on New Shoot Length

The extension of new shoots grew in response to higher levels of pruning intensity across all three considered pruning periods (Figure 3a). However, no statistically significant variations in shoot length were observed between the severely and moderately pruned groups in contrast to the control group. Despite this, shoots from plants that underwent severe pruning showed a tendency to be longer compared to those that were moderately pruned. When examining the impact of various pruning periods, new shoot lengths, under the three pruning intensities (light, moderate, and heavy), followed this sequence: dormant period > mature period > germination period (Figure 3b). Notably, there were significant differences in shoot lengths between plants pruned during the pre-dormant and mature periods compared to those pruned during the germination period. A two-way ANOVA (Table 3) confirmed that both the timing of pruning and the intensity of pruning had a highly significant impact on the length of *R. roxburghii* shoots. However, the interaction between the pruning period and intensity was not statistically significant. These results indicate that modifying the pruning period and fine-tuning the pruning intensity can significantly affect the length of *R. roxburghii* shoots.

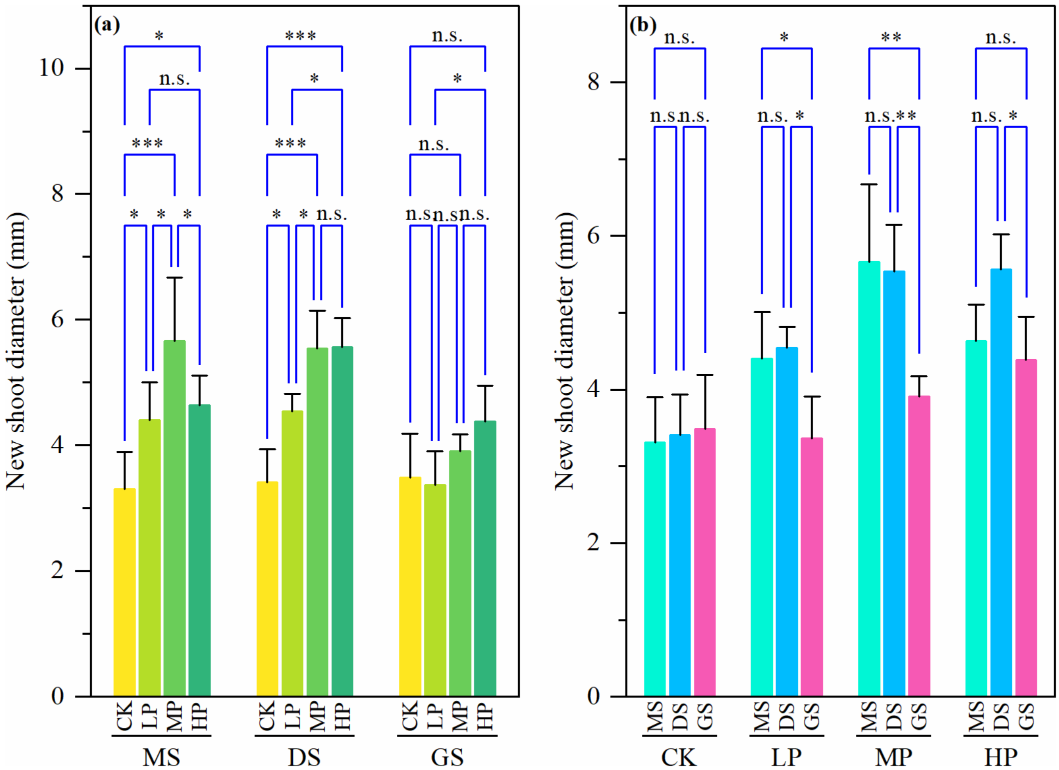

FIGURE 2 | Effect of pruning on the expansion of new shoot diameter in *R. roxburghii*. CK, no pruning; DS, dormancy stage; GS, germination stage; HP, heavy pruning; LP, light pruning; MP, moderate pruning; MS, maturity stage. n.s., *, **, and *** denote no significant difference, $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

TABLE 2 | Two-way ANOVA for the effects of pruning periods and intensity on the diameter of new *R. roxburghii* shoots.

Source of variation	df	Mean square	*F*	*p*
Pruning period	2	3.070	9.018	**
Pruning intensity	3	5.080	14.922	**
Pruning period × Pruning intensity	6	0.741	2.175	*

Note: * and ** denote significant differences at $p < 0.05$ and $p < 0.01$, respectively.

3.2 | Impact of Pruning on Fruit Production

3.2.1 | Influence of Pruning on Individual Fruit Mass

The individual fruit mass of *R. roxburghii* escalated with heightened pruning intensity across the three pruning periods (Figure 4a). Significantly, the mass of individual fruits of *R. roxburghii* was notably affected by varying pruning intensities throughout all periods, with the exception of light pruning during the maturity phase. The individual fruit mass peaked during the dormancy period under moderate to severe pruning intensities (Figure 4b). However, the variation in individual fruit mass across the three pruning periods was not statistically significant, irrespective of the pruning intensity applied. The two-way ANOVA (Table 4) revealed that it was solely the pruning intensity that exerted a significant impact on the individual fruit mass of *R. roxburghii*, whereas the effect of the pruning period and the interaction between pruning period and intensity were not significant. This indicates that adjusting the pruning intensity has a substantial influence on the individual fruit mass of *R. roxburghii*.

3.2.2 | Influence of Pruning on Per-Tree Fruit Yield of *R. roxburghii*

The production of fruit per *R. roxburghii* tree rose to a peak with moderate pruning and then diminished as the intensity of pruning increased during the three distinct pruning periods (Figure 5a). It is particularly noteworthy that the highest per-tree yield was realized with moderate pruning efforts. Pruning executed during the tree's dormancy phase was most impactful for yield, with the maturity and germination phases following in effectiveness across all pruning intensities, excluding the non-pruned control group (Figure 5b). The most beneficial yield enhancement for *R. roxburghii* was observed with moderate dormancy pruning. A two-way ANOVA analysis (Table 5) confirmed that both the timing of the pruning and the degree of its intensity, as well as their combined interaction, significantly influenced the per-tree yield. This finding underscores the substantial influence that the strategic alteration of the pruning period and intensity, either independently or in tandem, can exert on the per-tree yield of *R. roxburghii*.

3.3 | Identification of Optimal Pruning Timing and Severity

In this study, parameters such as the quantity, girth, and length of new shoots, the mass of individual fruits, and the fruit yield

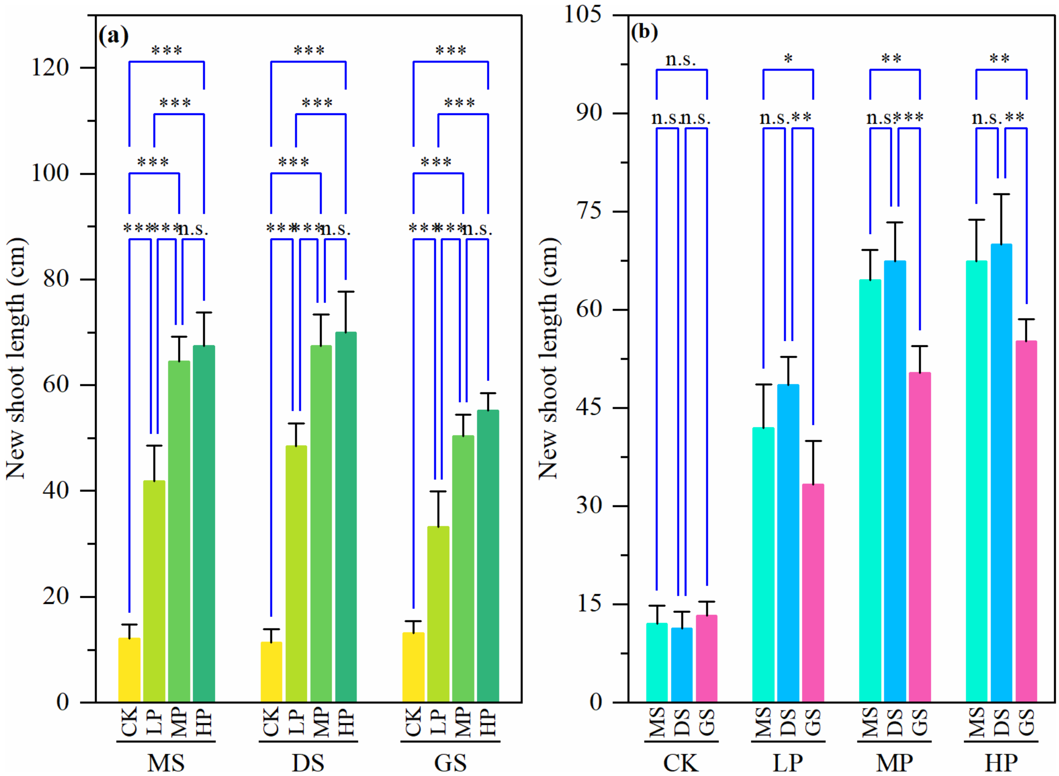

FIGURE 3 | Impact of pruning on new shoot length of *R. roxburghii*. CK, no pruning; DS, dormancy stage; GS, germination stage; HP, heavy pruning; LP, light pruning; MP, moderate pruning; MS: maturity stage. n.s., *, **, and *** denote no significant difference, $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

TABLE 3 | Two-way analysis of variance assessing the impact of pruning timing and severity on new shoot length in *R. roxburghii*.

Source of variation	df	Mean square	*F*	*p*
Pruning period	2	413.631	15.865	**
Pruning intensity	3	5113.165	196.118	**
Pruning period × Pruning intensity	6	66.458	2.549	*

Note: * and ** denote significant differences at $p < 0.05$ and $p < 0.01$, respectively.

per tree were employed as key performance indicators. Data manipulation was conducted using the PCA feature within DPS software, version 20.05. The PCA's computation of the characteristic roots, along with the individual and cumulative contribution rates from the correlation matrix of these five indicators, disclosed that the initial two characteristic roots amassed a substantial 94.22% of the cumulative contribution. Table 6 presents a comprehensive view of the characteristic vectors and their respective contribution rates for each index. The foremost principal component boasted a contribution rate of 76.85%, with the eigenvector for tree yield being the most pronounced positive, signifying its substantial influence on this component. Meanwhile, the second principal component held a contribution rate of 17.36%, with the eigenvector for the number of new shoots being the most significant positive, denoting its considerable impact on the second principal component. This analysis underscores the pivotal role of tree yield and new shoot count in shaping the principal components.

Employing the principal component analysis formula, a composite score encompassing five key indicators was formulated. This analysis allowed for the derivation of a comprehensive score for 12 different combinations of pruning periods and intensities (Table 7). The "moderate pruning during the dormancy period" achieved the highest score, indicating its superiority. It was followed by "heavy pruning during the dormancy period", "light pruning during the dormancy period", and so forth, with the "heavy pruning during the germination period" receiving a lower score. The least effective, in terms of score, were the "no pruning" options for each stage. The principle guiding these results is that a higher composite score for *R. roxburghii* pruning treatments correlates with greater benefits for the tree's growth and yield. Consequently, "moderate pruning during the dormancy period" was identified as the most effective, providing the optimal conditions for growth and yield enhancement. In contrast, "heavy pruning during the germination period", excluding the "no pruning" scenarios, was found to be the least effective. This comprehensive scoring system offers valuable insights for developing pruning strategies that can significantly enhance the productivity and overall health of *R. roxburghii* trees.

4 | Discussion

The aim of this study was to explore the impact of pruning period and intensity on the growth and yield of *R. roxburghii*, in order to verify the previous hypothesis that pruning is a key technique for improving the productivity of fruit trees. Through

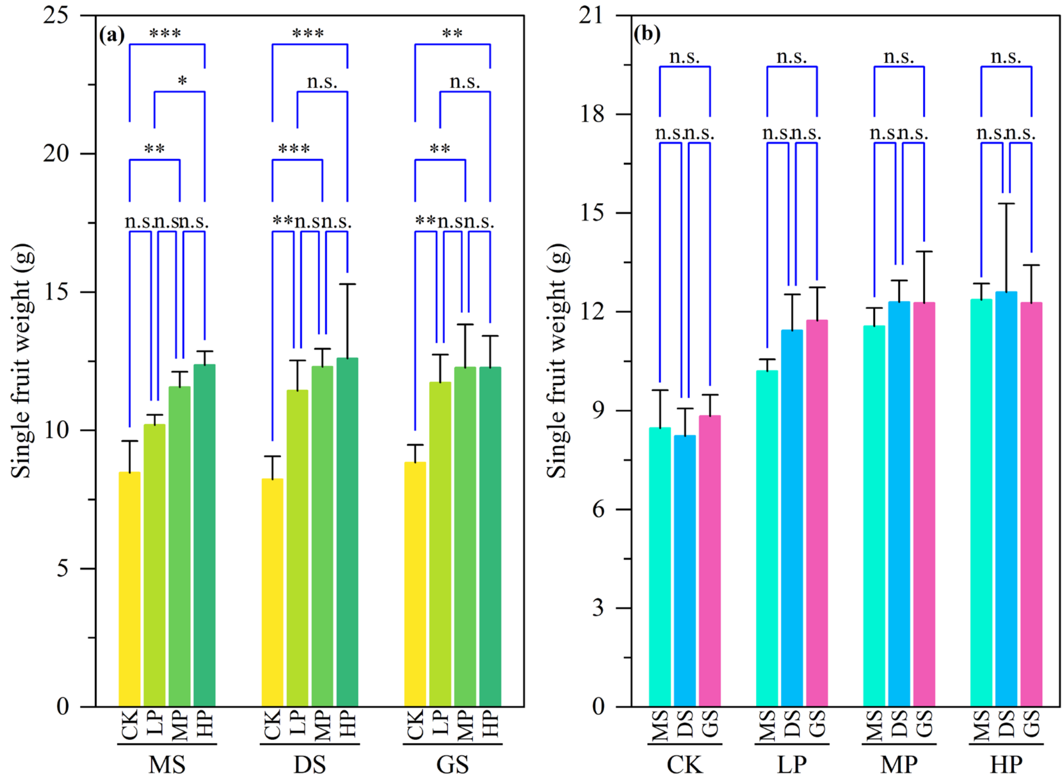

FIGURE 4 | Impact of pruning on the individual fruit weight *of R. roxburghii*. CK, no pruning; DS, dormancy stage; GS, germination stage; HP, heavy pruning; LP, light pruning; MP, moderate pruning; MS, maturity stage. n.s., *, **, and *** denote no significant difference, $p<0.05$, $p<0.01$, and $p<0.001$, respectively.

TABLE 4 | Two-way ANOVA assessing the impact of pruning period and intensity on individual fruit weight *of R. roxburghii*.

Source of variation	df	Mean square	*F*	*p*
Pruning period	2	1.300	0.930	**
Pruning intensity	3	27.869	19.942	**
Pruning period × Pruning intensity	6	0.519	0.371	*

Note: * and ** denote significant differences at $p<0.05$ and $p<0.01$, respectively.

the implementation of different pruning strategies on 7 year old *R. roxburghii* in the southwestern region of China, it was found that pruning has a significant positive effect on the growth of new shoots and fruit yield. Particularly, moderate pruning carried out during the dormancy period significantly increased the number and diameter of new shoots, while also enhancing the weight of individual fruits and the yield per tree. These results are similar to the research on olive tree pruning conducted by Lodolini et al. (2023), who found that winter pruning helps to promote the growth of new shoots. However, this study further reveals the importance of pruning intensity in regulating the growth and production of fruit trees, providing more specific guidance for the orchard management of *R. roxburghii*. In addition, the findings of this study contrast with the research on peach tree pruning from Conesa et al. (2019), who found that summer pruning has a positive impact on yield. This difference may be related to the biological characteristics of the tree species and their response to environmental conditions, emphasizing the variability of pruning strategies between different regions and tree species (Poni et al. 2023; Santos, Dalzot, et al. 2023; Santos, Pereira, et al. 2023).

By comparing and analyzing the results from different pruning periods, it was revealed that pruning during the dormancy period has superiority in enhancing the growth and yield of *R. roxburghii*. This finding holds significant practical implications for orchard management as it provides a clear time window during which pruning can maximize production benefits (Doke et al. 2024). Additionally, the results of the study emphasized the role of pruning intensity in regulating the growth and production of fruit trees, indicating that moderate pruning can promote the growth of new shoots and the development of fruits. The optimization of this pruning strategy can not only improve the yield and fruit quality of *R. roxburghii* but also enhance the economic benefits and sustainability of orchards. However, the findings of this study differ from the research on walnut pruning by Chen et al. (2018), who found that spring pruning is more conducive to the growth of "Lvling" walnuts (*Juglans regia*). This discrepancy in optimal pruning periods can be attributed to variations in tree species and climatic conditions. Furthermore, for some fruit trees, spring pruning may be suitable, although it is important to consider the risk of bleeding during the dormancy period, which can lead to nutritional deficiencies or imbalances, especially when excessive (Bai et al. 2019; Cinosi et al. 2024). This difference may be related to the biological characteristics of the tree species and their response to environmental conditions. Therefore, the results of this study underscore the importance of considering the characteristics of the tree species and regional climatic conditions when implementing pruning strategies in orchard management (Morgani et al. 2023).

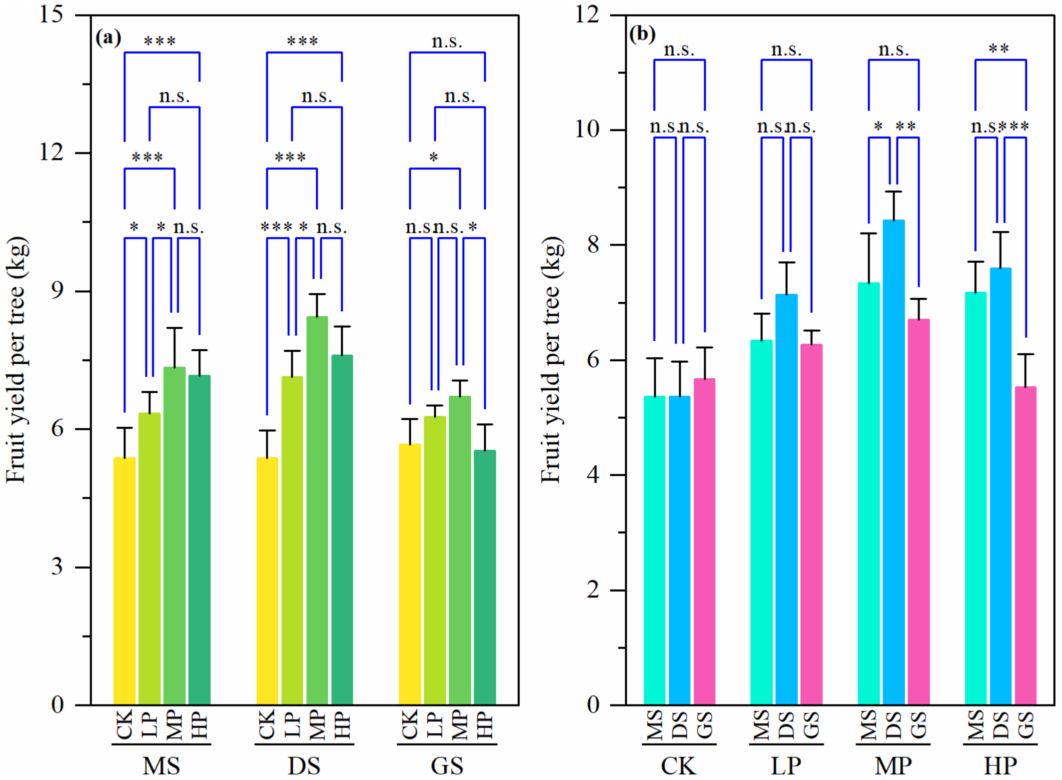

FIGURE 5 | Impact of pruning on fruit yield per tree of *R. roxburghii*. CK, no pruning; DS, dormancy stage; GS, germination stage; HP, heavy pruning; LP, light pruning; MP, moderate pruning; MS, maturity stage. n.s., *, **, and *** denote no significant difference, $p<0.05$, $p<0.01$, and $p<0.001$, respectively.

TABLE 5 | Two-way ANOVA for the effects of pruning period and intensity on fruit yield per tree of *R. roxburghii*.

Source of variation	df	Mean square	*F*	*p*
Pruning period	2	3.581	11.037	**
Pruning intensity	3	6.301	19.421	**
Pruning period × Pruning intensity	6	1.026	3.162	*

Note: * and ** denote significant differences at $p<0.05$ and $p<0.01$, respectively.

The results of this study not only provide practical guidance for the orchard management of *R. roxburghii* but also enrich the theoretical framework of fruit tree pruning, particularly building upon the need for species-specific protocols as emphasized by Matias et al. (2023). Our research extends this foundational view by demonstrating that for *R. roxburghii*, the superiority of dormancy pruning is mechanistically linked to carbohydrate reallocation and improved canopy light environment, thereby operationalizing the source-sink balance theory. Our findings elucidate that moderate dormancy pruning promotes new shoot growth and fruit development primarily through these mechanisms, complementing and extending the general principles of pruning effects reported in other species, such as guava (Gomasta et al. 2024), by providing a species-specific physiological explanation. Moreover, we advance the methodology of pruning science by employing PCA, which provides a quantitative, multi-criteria tool for identifying optimal strategies, moving beyond the qualitative frameworks that often dominate the field. This methodological innovation enables orchard managers to holistically assess pruning effects beyond single metrics and supports evidence-based decisions applicable to other fruit tree systems. The study also reinforces the need to tailor pruning strategies to species-specific traits and regional climatic conditions, a view consistent with existing literature but strongly supported by our empirical data (Al-Saif et al. 2023). For instance, the superiority of dormancy pruning in *R. roxburghii* may be attributed to its deciduous habit and local cold tolerance, contrasting with evergreen species or those in Mediterranean climates. Collectively, these insights enhance our understanding of how pruning influences fruit tree growth and productivity, enabling more scientific and precise orchard management (Goke et al. 2020).

In this study, an in-depth exploration was conducted on the impact of pruning period and intensity on the growth and yield of *R. roxburghii*, providing new insights for orchard management. However, the study also has some limitations. Firstly, the experiments were conducted at only one location, which may not fully represent the environmental conditions of other regions. Secondly, the findings are based on data from a single annual cycle. As a perennial crop, the growth and yield of *Rosa roxburghii* are subject to inter-annual climatic fluctuations and potential alternate bearing tendencies; thus, while our design is robust for comparing the relative efficacy of treatments within a season (Kumar et al. 2010; Lazare et al. 2021), the long-term sustainability and stability of the identified optimal practice require further validation. Thirdly, the study primarily focused on mid-aged fruit trees, and the pruning response of young trees or

TABLE 6 | Standardized indicator vectors and their principal component (PC) contributions.

Index	PC1	PC2	PC3	PC4	PC5
Number of new shoots	0.361	0.737	0.258	0.502	−0.085
New shoot diameter	0.472	0.043	−0.769	0.065	0.424
Length of new shoots	0.480	−0.339	−0.151	0.095	−0.789
Single fruit weight	0.421	−0.542	0.493	0.313	0.432
Yield per tree	0.488	0.214	0.276	−0.798	0.056
Eigenvalue	3.843	0.868	0.235	0.041	0.013
Contribution rate (%)	76.854	17.364	4.693	0.824	0.265
Cumulative contribution rate (%)	76.854	94.217	98.911	99.735	100.000

TABLE 7 | Rankings of pruning period and intensity pairings according to principal component scores.

	Principal component analysis score						
Treatment	Y_1	Y_2	Y_3	Y_4	Y_5	Comprehensive score	Rank
NPMP	−2.741	0.539	−0.148	−0.054	−0.040	−2.020	11
LPMP	−0.122	0.745	−0.174	0.360	−0.164	0.030	6
MPMP	1.975	0.428	−0.660	0.136	0.035	1.562	3
HPMP	1.149	−0.906	0.076	−0.281	−0.248	0.726	5
NPDP	−2.811	0.533	−0.335	−0.162	−0.015	−2.085	12
LPDP	0.949	0.715	0.360	0.189	0.004	0.872	4
MPDP	3.066	1.117	0.214	−0.104	0.044	2.560	1
HPDP	2.180	−0.463	−0.408	−0.221	0.141	1.575	2
NPGP	−2.344	0.549	−0.090	−0.158	0.110	−1.711	10
LPGP	−0.843	−0.388	0.986	0.121	0.121	−0.667	8
MPGP	0.128	−0.776	0.654	−0.066	−0.048	−0.006	7
HPGP	−0.587	−2.095	−0.474	0.241	0.060	−0.835	9

Note: Colors are employed for visualization purposes only to make the data stand out. The color hues themselves should not be interpreted as having statistical significance.
Abbreviations: HPDP, heavy pruning in dormancy period; HPGP, heavy pruning in germination period; HPMP, heavy pruning in mature period; LPDP, light pruning in dormancy period; LPGP, light pruning in germination period; LPMP, light pruning in mature period; MPDP, moderate pruning in dormancy period; MPGP, moderate pruning in germination period; MPMP, moderate pruning in mature period; NPDP, no pruning in dormancy period; NPGP, no pruning in germination period; NPMP, no pruning in mature period.

trees at different age stages has not been fully explored. Future studies should therefore be directed towards addressing these limitations. Specifically, research should consider: (1) repeating the experiments in different geographical locations and climatic conditions to verify the universality and adaptability of pruning strategies; (2) implementing multi-year trials to confirm the long-term stability of the optimal pruning strategy under varying climatic conditions and to account for biennial bearing cycles; and (3) investigating the pruning response of trees at different developmental stages to understand its impact over the entire life cycle. Moreover, long-term tracking of the effects of pruning on soil health, nutrient cycles, and the ecosystem services of orchards is also necessary. Through such targeted studies, a more comprehensive understanding of the role of pruning in orchard management can be achieved, providing a scientific basis for the realization of sustainable fruit tree production.

5 | Conclusion

Pruning is essential for boosting the growth and productivity of *R. roxburghii* trees. Our study, through a systematic single-year comparison of various pruning strategies, concluded that moderate pruning during the dormancy period is optimal for enhancing fruit yield. This method not only modulates tree height and crown spread but also stimulates the growth of new shoots, which significantly amplifies the fruit yield. We recommend "moderate (33%) pruning during the dormancy period" as the best practice for cultivating and managing *R. roxburghii*, especially in regions with favorable biogeographical conditions. This approach not only fine-tunes tree vigor but also serves as a yield-boosting strategy. Moreover, by managing tree dimensions, it facilitates orchard operations such as harvesting and maintenance, thereby increasing overall efficiency. Adopting the right pruning techniques allows growers to regulate tree vigor, augment yields, and improve the productivity of *R. roxburghii* orchards.

Author Contributions

Yangzhou Xiang: writing – review and editing, formal analysis, conceptualization, visualization, investigation. **Jun Luo:** writing – review and editing, formal analysis, conceptualization. **Yawen Zhang:** writing – review and editing, conceptualization. **Ying Liu:** software, investigation, data curation. **Jing Fan:** writing – review and editing, conceptualization, investigation, funding acquisition. **Yuan Li:** writing – review and editing, conceptualization, investigation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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