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RECEIVED 19 April 2023

ACCEPTED 15 May 2023

PUBLISHED 22 June 2023

CITATION

Hong R, Li J, Wang J, Zhu X, Li X, Ma C, Cao H, Wang L and Wang Q (2023) Effects of prescribed burning on understory *Quercus* species of *Pinus yunnanensis* forest. *Front. For. Glob. Change* 6:1208682. doi: 10.3389/ffgc.2023.1208682

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Effects of prescribed burning on understory *Quercus* species of *Pinus yunnanensis* forest

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Introduction: Positioning studies on prescribed burning in *Pinus yunnanensis* forests have been conducted for several years, focusing on the effects of fire on the composition and structure, growth, regeneration, relative bark thickness, and bark density of understory oak species in *Pinus yunnanensis* forests.

Methods: The study was conducted on Zhaobi Mountain, Yi-Dai Autonomous County of Xiping, Yuxi City, Yunnan Province. In the prescribed burn after restoration of full 1 year of the area and did not implement the prescribed burn area were set up 10 m × 10 m sample plots 30 pairs of comparisons, and all the oak trees in the sample plots were recorded, each sample plot in the four apexes and the middle were set up five 2 m × 2 m small sample squares, the shrubs in the small sample squares for each plant survey, comparison, statistics and analysis of all data.

Results: The study results showed that (1) prescribed burning significantly affected the species composition of the understory of *Pinus yunnanensis* forests. In both tree and shrub layers, the important values of *Quercus aliena*, *Quercus serrata*, *Quercus fabri*, and *Quercus variabilis* were significantly reduced in the burned areas. In contrast, the important values of *Quercus acutissima* increased somewhat. (2) The under crown height of oak trees in the burned areas was significantly lower than in the burned areas, but the height of oak trees in the burned areas was not significantly different from that in the burned areas. In the shrub layer, the height and cover of oak plants in the prescribed burning areas were significantly lower than in the unprescribed burned areas, effectively reducing the vertical continuity of the forest surface combustible material and reducing the possibility of fire converting from surface to canopy fire along the “ladder fuel.” (3) The regeneration of oak plants in the burned area is mainly by sprout tillers, and very few young sprouts are regenerated by seed germination. Renewed young sprouts are difficult to survive the prescribed burn areas the following year due to their lack of fire tolerance. (4) The relative bark thickness and density of oak plants in prescribed burn areas were significantly higher than those in unprescribed burn areas due to the fire tolerance exhibited by oak plants in long-term prescribed burns.

Discussion: Prescribed burning has profoundly altered the structural composition and growth of oak plants in the understory of *Pinus yunnanensis* forests, and oak plants have shown significant fire-adapted traits to resist fire under long-term fire disturbance. The study can provide a scientific basis for prescribed burning, forest fuels, and forest fire management.

KEYWORDS

Quercus, species composition, growth condition, regeneration methods, bark, *Pinus yunnanensis* forest, prescribed burning

Introduction

Fire has historically shaped China's ecosystems' structure, composition, and function (Hu et al., 2017; Wu et al., 2019; Gao et al., 2021). With economic and social growth, forest fires have become increasingly prominent (Guo et al., 2017). To effectively consume combustible material in forests and reduce forest fire risk, prescribed burns are now widely used in China to achieve specific forest management objectives. Prescribed burning is the purposeful, planned, and systematic application of fire to combustible material under the forest canopy in a defined area under human control to achieve the intended fire purpose (Trent et al., 2011). Prescribed burning can regulate a load of combustible material in forests (Fernandes, 2015; Penman et al., 2020) and effectively reduce the severity of forest fires (Finney et al., 2005), and has also been proposed for the management of grasslands (Orsolya et al., 2014; Policelli et al., 2019). Prescribed burning can improve plant resistance to pests and diseases (Hood et al., 2016), is an important forestry practice to promote tree growth (Mitchell et al., 2006), and provides an important way to manage forest ecosystems under suitable conditions (Van Lear et al., 2005). The impacts of prescribed burning on ecosystems and climate are complex and carry risks (Altangerel and Kull, 2013). Numerous experts and scholars have focused on the ecological impacts of prescribed burning, including effects on air pollutants (Sullivan et al., 2014; Liu et al., 2017), the environment (Burrows and Mccaw, 2013; Fernandes et al., 2013), microorganisms in the soil (Hannu et al., 1993; Oliver et al., 2015), effects on biodiversity (Altangerel and Kull, 2013; Durigan et al., 2020), effects on hydrology (Holden et al., 2015) and studies on the structure of understorey species (Burrows et al., 1989; Peterson and Reich, 2008; Potts and Stephens, 2009).

Some scholars have focused on the effects of long-term prescribed burns on species composition and structure in oak forests (Brose and Van Lear, 1999; Blake and Schuette, 2000; Burton et al., 2011; Hutchinson et al., 2012a). The majority of these studies have focused on oak forests in North America. Studies have shown that long-term repeated burning reduces the density of oak plants to some extent and causes some reduction in the cover of oak stands. The high frequency of prescribed burn removals had a significant impact on smaller diameter at breast height (DBH) oak plants, with all plants less than 11 cm DBH removed in the annual repeated burn study area in Missouri (Knapp et al., 2015). Studies of oak trees within the LBL National Recreation Area, Kentucky and Tennessee showed that for mature stands, prescribed burning had

little effect because the trees were somewhat fire resistant prescribed burning reduces the density of young trees, but when combined with suitable thinning, the density may increase, for example, for oak trees less than 3.8 cm in DBH, the density increases after prescribed burning with suitable thinning (Franklin et al., 2003).

Oak plants are more fire-adapted than other common plants because of their vigorous germination capacity and are adapted to relatively dry conditions (Brose et al., 2013). Burning positively affects oak plant reproduction and regeneration, promoting pollination, increasing fruit set, facilitating germination, and promoting young sprout development (Arthur et al., 2012; Hutchinson et al., 2012b). After repeated fires, oak plants can germinate more quickly than other regenerating woody plants and gain a greater competitive advantage (Brose et al., 2013). However, high fire frequency and intensity can lead to reduced stand recovery due to the relative allocation of germination to seeding in oak species determined by the nature of fire disturbance, with fire-free periods too short to accumulate seed banks (Hutchinson et al., 2005). Shorter fire cycles may affect post-fire response by depleting the energy resources required for oak regeneration (Malkinson et al., 2011).

Fire-adapted traits are developed due to plant performance being characterized in a fire-spatial environment, improving the ability of plants to survive fire disturbance (Keeley et al., 2011; Pausas, 2015a; He et al., 2016). Oak plants interact with fire factors and influence each other, gradually developing intrinsic physiological and external morphological responses and adaptive responses, mainly in the form of increased under crown height, thick bark, high wood density, rapid-fire scar resilience, and altered understorey apoplastic burnability (Romero et al., 2009; Varner et al., 2016). Tree species in fire-prone habitats, particularly those maintained by frequent low-intensity surface fires, have thicker bark than those in fire-prone habitats (Cavender-Bares et al., 2004; Poorter et al., 2014; Rosell et al., 2014; Pausas, 2015b). In most species with frequent fire habitat characteristics, bark thickness is a key factor in the survival of individual plants in the fire; the thicker the bark, the better the fire resistance of the species, and thick bark reduces the likelihood of fire damage to vascular formations and the sapwood (Michaletz and Johnson, 2007; Michaletz et al., 2012). The bark of oak species is usually thicker than that of other broad-leaved species distributed in the same growing area, specialized for a cork, such as the European cork oak (*Quercus suber* L.) (Touhami et al., 2020). Typically oak species with bark thicknesses greater than 3.4 cm provide good protection to the bast and formative

layers of the trunk against thermal damage, and the tree is less likely to be killed by fire (Curt et al., 2009).

Unlike the study area in North America, China has a unique oak population, and there is still a need for more research on the effects of frequent prescribed burns on oak populations within forests where *Pinus yunnanensis* is the dominant species. As an important component of the understorey composition of *Pinus yunnanensis* forests, the *Quercus* species has a particular response pattern to long-term disturbance by low-intensity fire. This paper focuses on the species composition, growth, and regeneration of oak plants after prescribed burning and the adaptive physiological changes of oak plants to fire to investigate the effects of long-term prescribed burning on oak plants and to provide a reference for sustainable forest management.

Materials and methods

Study site and experimental design

The field survey of this study was conducted from February 2022 to March 2023. The study area is located in Yi-Dai Autonomous County of Xinping, Yuxi City, central Yunnan Province, 102°0'7"~102°0'8"E, 24°2'38"~24°2'41"N. The terrain is mainly plateau and mountainous, with a high northwest and low southeast topography. The Zhaobi Mountains are located in the north-south transition zone of the subtropical plateau monsoon region, with an average annual precipitation of 1050 mm, a maximum temperature of 32°C, a minimum temperature of 1°C and an average temperature of 15.1°C, and a main soil type is red soil. The region has a large area of *Pinus yunnanensis* forest, which has good habitat due to the excellent geographical conditions. The main oak species in the region are *Quercus aliena* var. *acutiserrata* Maximowicz ex Wenzig, *Quercus serrata* Murray, *Quercus fabri* Hance, *Quercus variabilis* Blume, and *Quercus acutissima* Carr.

The number of forest fires in Xinping County fluctuates greatly from year to year, with an average of 10 fires per year from 2001 to the present. The number of fires peaked in 2005 and 2012, with 34 fires in 2005 and 24 fires in 2012. Fires in Xinping County are highly seasonal, with fires mostly concentrated in winter and spring, when they are drier and more likely to occur. In addition, fires mainly occur near residential areas and fires are influenced by population activities.

The prescribed burns are low-intensity fires that reduce the combustible material (Figure 1). Because of the air pollution problems caused by the prescribed burn, the prescribed burn was suspended for 2 years in 2020 and 2021 and continued in 2022. The 2023 prescribed burn started with a small-scale burn on February 8 and continued until February 19, with the remaining prescribed burn area being burned on a large scale on February 20. By spreading the prescribed burn over a longer time, large-scale air pollution is effectively avoided.

Comparison of prescribed and unprescribed burn areas (Figure 2), where a dense shrub and herb layer is evident in the unprescribed burn areas. In this study, 30 randomly selected sample plots were established where prescribed burns were carried out, and 30 randomly selected sample plots were selected as control plots in controlled burn areas where prescribed burns had never been

carried out (Figure 3). To avoid the influence of altitude, slope direction, and light on the experimental results, the altitude of both the experimental and control plots was within the range of 2000–2100 m, and the slope direction was consistently southwest, with the slope position being uphill.

The survey plots were each 10 m × 10 m in size, with five 2 m × 2 m plots for the shrub survey (Figure 4). Five plots were located at the four corners of the survey plots and in the middle of the survey plots, and the plots were numbered 1–5 in sequence. Each sample was numbered, and slope, canopy cover, altitude, latitude, and longitude were recorded. Those ≥ 1 m tall and < 10 cm DBH were treated as shrubs during sampling (Knapp et al., 2015). Trees in the sample plots were surveyed per tree, with a diameter at the under crown height, DBH, and height measured and recorded. The shrubs in each small sample were recorded, and their height and cover were measured. The sprouting pattern of oak young sprouts less than 1.5 m in height was additionally recorded. The mortality of oak plant young sprouts was recorded after prescribed burnout.

Data processing

Calculation of important values

To explore the position and role of oak plants in the community, the important value index was calculated to explore changes in species composition and structure before and after the prescribed burn.

Important Value (IV):

$$(IV) = \frac{\text{Relative Abundance} + \text{Relative Frequency} + \text{Relative Dominance}}{3}$$

Relative Abundance (RA):

$$(RA) = \frac{\text{Number of individuals of a single species}}{\text{Number of individuals of all species}}$$

Relative Frequency (RF):

$$(RF) = \frac{\text{Number of samples in which a single species occurs}}{\text{Number of total samples}}$$

Relative Dominance (RD):

$$(RD) = \frac{\text{Average cross-sectional area at breast height of individual species}}{\text{Sum of average cross-sectional areas at breast height of all species}}$$

(trees)

$$(RD) = \frac{\text{Sum of individual species cover}}{\text{Sum of all species cover}}$$

(shrubs)

Bark thickness and density

To investigate whether the bark thickness and density of oak plants are altered by successive years of prescribed burning, the

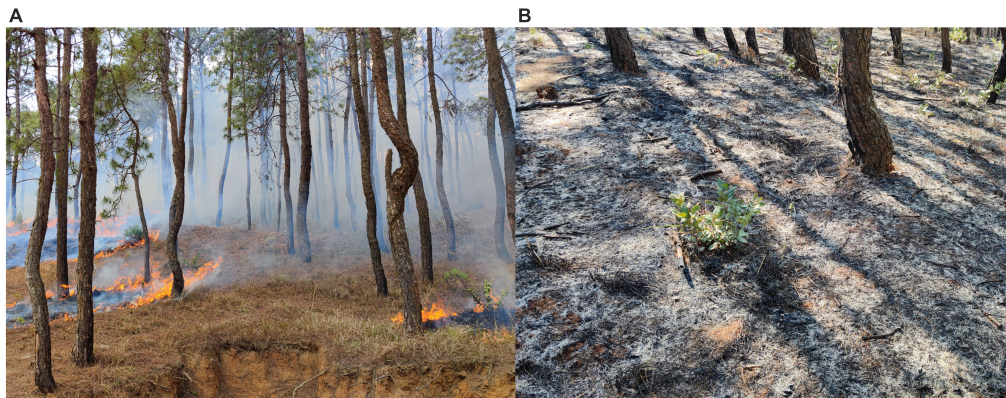


FIGURE 1
Photos of prescribed burning in *Pinus yunnanensis* forest. (A) Prescribed burning, and (B) forest after the fire.

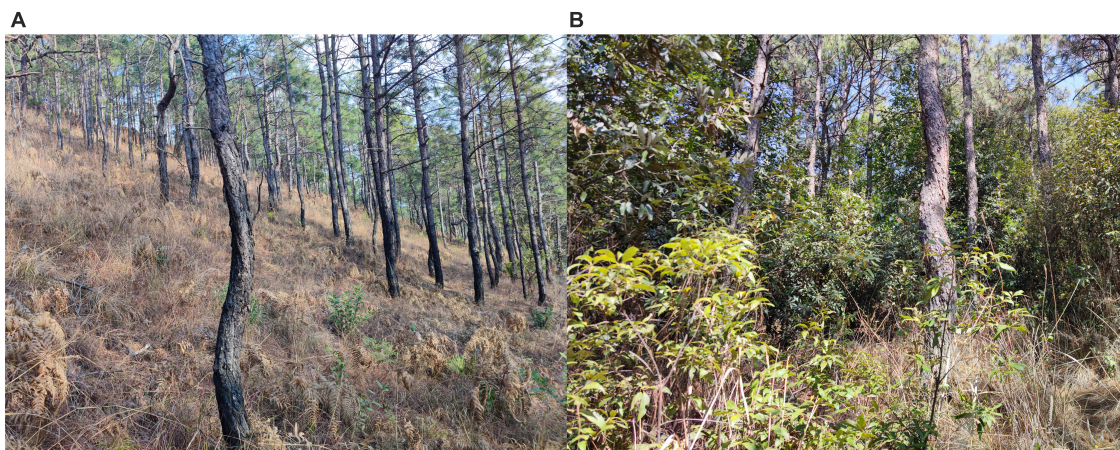


FIGURE 2
Photos to contrast the stand structure of panel (A) the prescribed burning area, and (B) the unprescribed burning area.

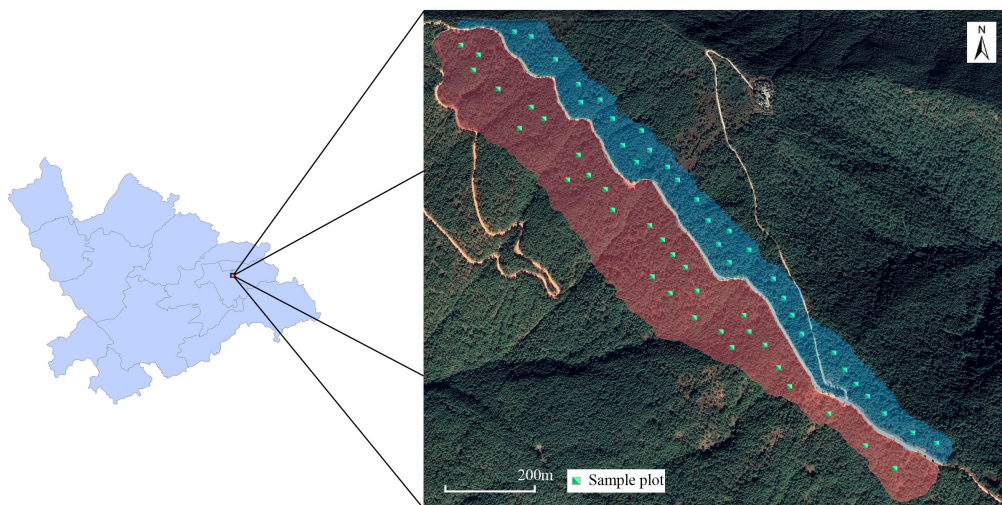
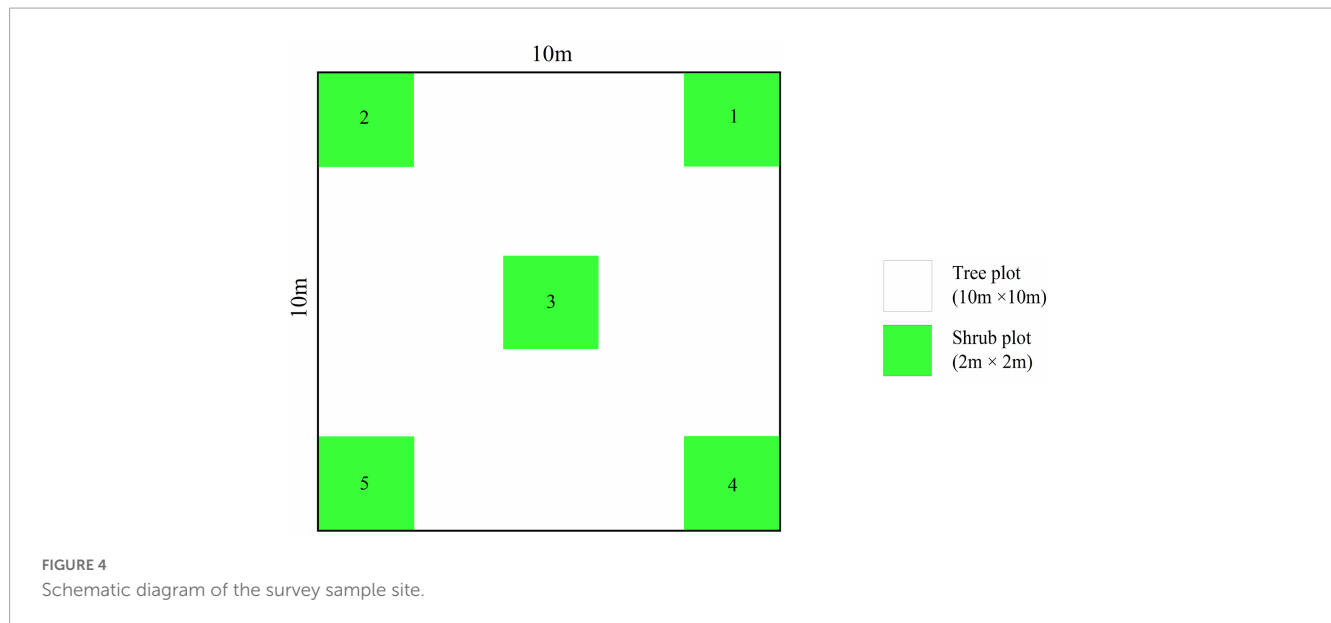


FIGURE 3
Pictures of the location of the study site, Zhaobi Mountain, in Xiping County. The situation of the study area and the distribution of the sample plots on Zhaobi Mountain were marked. Red is the study area for prescribed burning, blue is the study area for unprescribed burning.



relative bark thickness and density of oak trees were measured to investigate the response of oak bark to successive low-intensity fires.

Bark thickness measurement

The total bark thickness was measured at three heights (50, 100, and 150 cm) for oak trees over 5 m tall in the survey sample. To avoid serious tree damage during bark extraction, the bark was extracted to a controlled area of $5 \times 2 \text{ cm}^2$ without damaging the xylem. Measurements were taken on a randomly selected trunk side, and each piece of bark was extracted with a hammer and chisel. Using vernier calipers, total bark thickness was measured at equally spaced intervals on each sample. Relative bark thicknesses were calculated for the study to compare differences in bark thickness between trees of different diameters (Graves et al., 2014).

$$\text{Relative bark thickness} = \frac{\text{Absolute bark thickness}}{\text{DBH}} \times 100$$

Bark density measurement

Bark density was measured using a high-precision densitometer. To avoid errors in the measurements due to water loss or decomposition of the bark, the high-precision densitometer was transported by car to the vicinity of the study area, and the bark density measurements were carried out within 1 h of the completion of the sampling.

Statistical method

In this paper, we used analysis of variance (ANOVA) to compare the differences in tree height in the tree layer, under crown height, height in the shrub layer, shrub layer cover, relative total bark thickness, and total bark density of oak plants in the prescribed burned area with those in the unburned area. Statistical significance can be established when the probability of a Type-I error is less than 0.05. $p < 0.05$ indicates significant differences, and $p < 0.01$ indicates significantly greater differences.

Results

The impact of species composition of oak plants

A total of five oak species were found to be present in the study area, namely *Quercus aliena*, *Quercus serrata*, *Quercus fabri*, *Quercus variabilis*, and *Quercus acutissima*. Each species is found in prescribed and unburned areas, but the distribution patterns differ. As species distribution in the tree and shrub layers is distinct, the distribution of plants within the tree and shrub layers is analyzed separately.

In the tree layer (Table 1), *Pinus yunnanensis* was the dominant species, with significantly higher important values than other species in both prescribed and unburned areas. The important values and relative abundance of *Q. variabilis*, *Q. serrata*, *Q. fabri*, and *Q. aliena* in the tree layer decreased significantly after prescribed burning, with important values decreasing by 0.114, 0.105, 0.067, and 0.76. The distribution of *Q. variabilis*, *Q. serrata*, *Q. fabri*, and *Q. aliena* in the tree layer was significantly reduced in the prescribed burned area.

Unlike other oak species, the relative multiplicity of *Q. acutissima* increased by 0.08, and the important value increased by 0.017 in the prescribed burn area, which is more adapted to survive in the prescribed burn area.

In the shrub layer (Table 2), oak plants showed a clear dominance, especially in the unburned area, where *Q. serrata* had the highest important value of all plants at 0.300. In contrast, *Q. fabri*, *Q. variabilis*, and *Q. aliena* also had important values of 0.263, 0.244, and 0.164, respectively. The important values for *Q. serrata*, *Q. fabri*, *Q. variabilis*, and *Q. aliena* were lower than those for unburned areas by 0.212, 0.187, 0.131, and 0.098.

In the area of prescribed burning, the *Q. acutissima* showed a trend toward increased dominance in the shrub layer, with an increase in important value of 0.009. This is the same trend

the *Q. acutissima* showed toward greater survival dominance in the tree layer.

Growth of oak plants

Tree height and under crown height

Five *Q. acutissima* were found in the unprescribed burn area and eight in the prescribed burn area, too small a sample to

be statistically significant. Therefore, the growth of *Q. acutissima* was not explored.

To study the effect of prescribed burning on the height of oak trees in the tree layer, the distribution of oak tree height in the prescribed burning sample plots and the control sample plots were counted (ANOVA: *Q. aliena*: $F = 0.936, p = 0.34$; *Q. serrata*: $F = 0.002, p = 0.966$; *Q. fabri*: $F = 5.26, p = 0.427$; *Q. variabilis*: $F = 0.02, p = 0.899$) (Figure 5). There were no significant differences in the height distribution of the various oak species, and prescribed

TABLE 1 Species composition of the tree layer.

Species	Unprescribed burning				Prescribed burning			
	RA	RF	RD	IV	RA	RF	RD	IV
<i>Pinus yunnanensis</i>	0.642	1.000	0.693	0.778	0.762	1.000	0.781	0.848
<i>Quercus variabilis</i>	0.068	0.567	0.047	0.227	0.028	0.267	0.045	0.113
<i>Quercus serrata</i>	0.078	0.533	0.061	0.224	0.039	0.300	0.019	0.119
<i>Keteleeria fortunei</i>	0.050	0.533	0.048	0.210	0.050	0.600	0.042	0.231
<i>Quercus fabri</i>	0.056	0.500	0.042	0.199	0.034	0.333	0.028	0.132
<i>Quercus aliena</i>	0.065	0.433	0.079	0.192	0.043	0.200	0.042	0.095
<i>Lithocarpus glaber</i>	0.025	0.267	0.033	0.108	0.002	0.033	0.004	0.013
<i>Myrica rubra</i>	0.016	0.233	0.017	0.089	0.014	0.167	0.011	0.064
<i>Vaccinium bracteatum</i>	0.012	0.133	0.015	0.054	0.007	0.067	0.013	0.029
<i>Quercus acutissima</i>	0.010	0.100	0.007	0.039	0.018	0.133	0.015	0.056

TABLE 2 Species composition of the shrub layer (no data available means this species was not found in the prescribed burning area).

Species	Unprescribed burning				Prescribed burning			
	RA	RF	RD	IV	RA	RF	RD	IV
<i>Quercus serrata</i>	0.062	0.800	0.039	0.300	0.007	0.233	0.025	0.089
<i>Duhaldea cappa</i>	0.194	0.667	0.015	0.292	0.261	0.733	0.079	0.357
<i>Lithocarpus glaber</i>	0.106	0.633	0.102	0.281	0.066	0.500	0.251	0.272
<i>Quercus fabri</i>	0.037	0.733	0.018	0.263	0.013	0.200	0.012	0.075
<i>Pinus yunnanensis</i>	0.238	0.533	0.018	0.263	0.566	0.833	0.014	0.471
<i>Quercus variabilis</i>	0.040	0.667	0.026	0.244	0.011	0.300	0.028	0.113
<i>Rhododendron simsii</i>	0.034	0.467	0.163	0.221				
<i>Vaccinium bracteatum</i>	0.041	0.467	0.077	0.195	0.014	0.267	0.100	0.127
<i>Myrica rubra</i>	0.018	0.300	0.268	0.195	0.006	0.167	0.364	0.179
<i>Michelia yunnanensis</i>	0.051	0.433	0.061	0.182	0.004	0.100	0.019	0.041
<i>Quercus aliena</i>	0.041	0.433	0.016	0.164	0.010	0.167	0.021	0.066
<i>Myrsine africana</i>	0.041	0.400	0.011	0.151	0.018	0.200	0.020	0.079
<i>Elaeocarpus decipines</i>	0.024	0.267	0.081	0.124				
<i>Spiraea thunbergii</i>	0.017	0.267	0.009	0.098	0.014	0.267	0.027	0.102
<i>Quercus acutissima</i>	0.011	0.233	0.031	0.092	0.009	0.267	0.028	0.101
<i>Laggera crispata</i>	0.019	0.233	0.024	0.092	0.002	0.033	0.011	0.016
<i>Photinia serratifolia</i>	0.009	0.133	0.010	0.051				
<i>Machilus nanmu</i>	0.005	0.100	0.014	0.040				
<i>Rubus corchorifolius</i>	0.004	0.100	0.001	0.035	0.002	0.033	0.002	0.012
<i>Grona triflora</i>	0.004	0.067	0.012	0.028				
<i>Vaccinium vitis-idaea</i>	0.003	0.033	0.003	0.013				

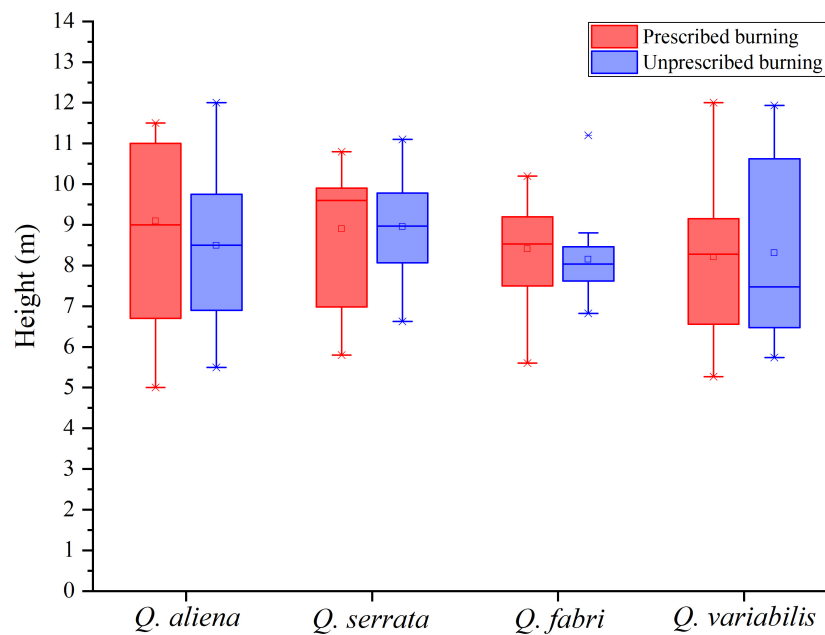


FIGURE 5
Tree height comparisons of oak plants in the arborous layer.

burning did not significantly affect the height of oak trees at the tree level.

Statistics on under crown height distribution of oak in the tree layer in the prescribed burn and control sample plots (ANOVA: *Q. aliena*: $F = 38.803$, $p < 0.001$; *Q. serrata*: $F = 12.379$, $p = 0.001$; *Q. fabri*: $F = 53.377$, $p < 0.001$; *Q. variabilis*: $F = 52.505$, $p < 0.001$) (Figure 6). Prescribed burning had a highly significant effect on the under crown height of each oak species, with a substantial increase in mean under crown height. The mean under crown height of *Q. aliena*, *Q. serrata*, *Q. fabri*, and *Q. variabilis* was 0.928, 0.538, 0.519, and 0.814 m higher in the control area, respectively.

Shrub layer height and cover

The effect of prescribed burning on the height of oak plants in the shrub layer was studied. Statistics on the height distribution of oak plants in the prescribed burn and control sample plots (ANOVA: *Q. aliena*: $F = 22.063$, $p < 0.001$; *Q. serrata*: $F = 20.63$, $p < 0.001$; *Q. fabri*: $F = 16.783$, $p < 0.001$; *Q. variabilis*: $F = 13.995$, $p < 0.001$; *Q. acutissima*: $F = 17.474$, $p = 0.001$) (Figure 7). Prescribed burn removal had a highly significant effect on the height distribution of each oak species, with the mean heights of *Q. aliena*, *Q. serrata*, *Q. fabri*, *Q. variabilis*, and *Q. acutissima* decreasing by 0.815, 1.149, 0.586, 0.62, and 0.725 m, respectively.

Statistics on the distribution of oak cover in the prescribed burn and control sample plots (ANOVA: *Q. aliena*: $F = 12.593$, $p = 0.001$; *Q. serrata*: $F = 28.647$, $p < 0.001$; *Q. fabri*: $F = 17.964$, $p = 0.001$; *Q. variabilis*: $F = 22.167$, $p = 0.001$; *Q. acutissima*: $F = 19.941$, $p = 0.001$) (Figure 8). Prescribed burning had a highly significant effect on the cover distribution of each oak species, with the mean height of *Q. aliena*, *Q. serrata*, *Q. fabri*, *Q. variabilis*, and *Q. acutissima* decreasing by 0.512, 1.259, 0.588, 0.797, and 0.916 m² respectively. Prescribed burning reduced the mean height and cover of oak in the shrub layer, effectively

disrupting the vertical continuity of forest combustibles and reducing the spread of forest fire from ground fire to canopy fire. The prescribed burning reduces the average height and cover of the shrub layer of oak, which effectively destroys the vertical continuity of combustible forest material and reduces the potential for forest fires to spread from ground fire to canopy fire.

The effect of prescribed burning on the regeneration patterns of oak plants

The renewal methods of oak young sprouts up to 150 cm in height in the study area were investigated. The renewal methods of oak plants were divided into sprout tillers and seed germination.

Different characteristics of oak young sprout regeneration in prescribed and unprescribed burned areas (Table 3). Oak in the burned area was mainly replaced by asexual regeneration through sprout tillers. The residual oak residues left after the prescribed burn provided the original nutrient accumulation for sprout tillers, and new plants were formed using shoots from the stumps and root systems left on the burned sites. *Q. aliena* and *Q. fabri* were not found to be renewed by seed germination in prescribed burning areas. Only one young sprout each of *Q. serrata* and *Q. variabilis* was found to be seed sprouting, and only two young sprouts of *Q. acutissima* were found to be seed sprouting in the study area. Young sprouts of oak plants were very rare in the prescribed burning areas.

The number of young shoots that germinated by seed was higher than the number of young shoots renewed by sprouting in all oak species in the unprescribed burn area. The cause of oak plant mortality in the unprescribed burn areas was usually disease or insect infestation, and these plants could usually re-sprout from the

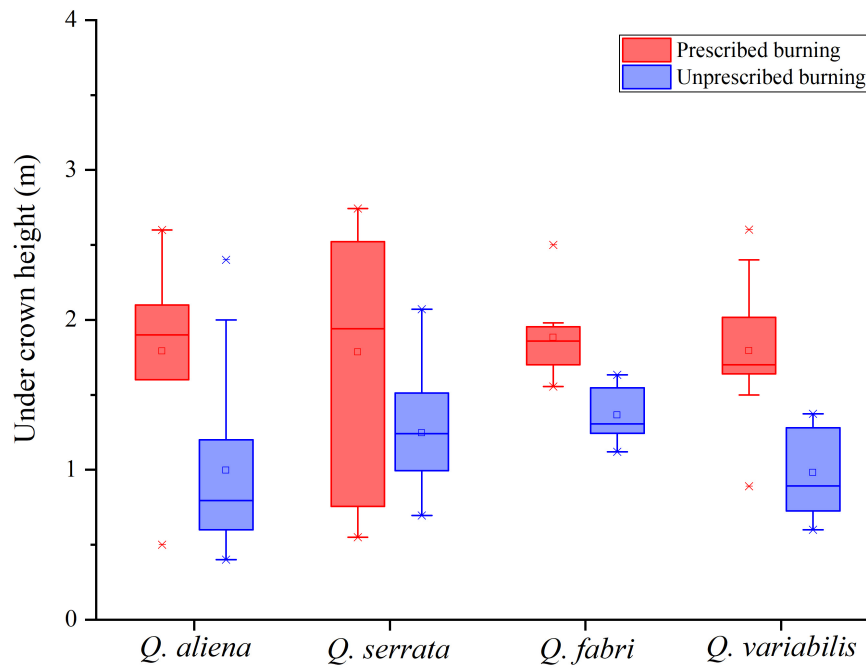


FIGURE 6 Under crown height comparisons of oak plants in the arborous layer.

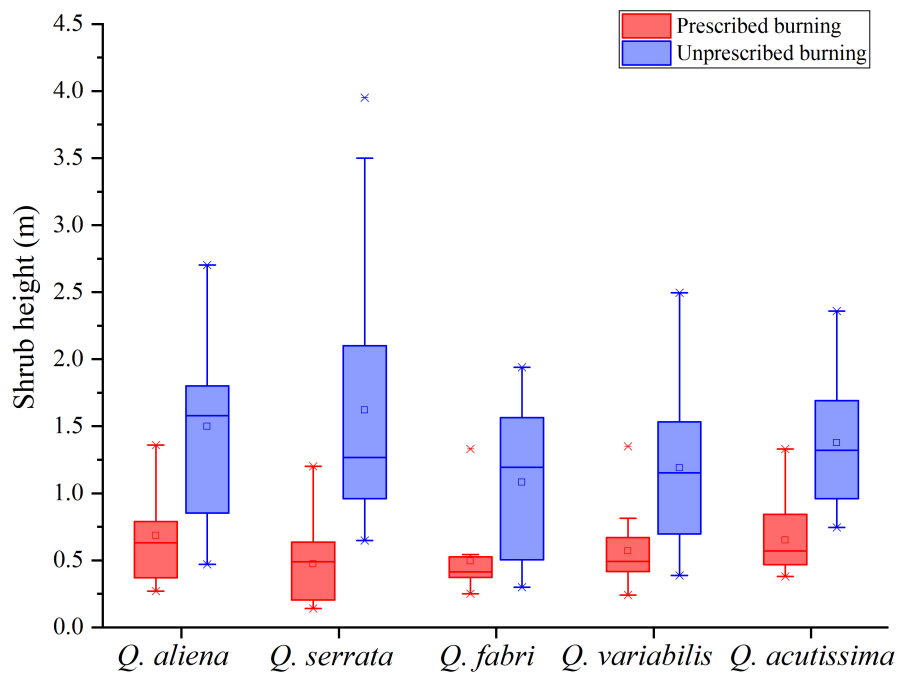


FIGURE 7 Height comparisons of oak plants in the shrub layer.

roots. However, the number of oak plants that died due to disease or insect infestation was only a minority of the total sample. The main method of oak plant regeneration in the unprescribed burn areas was still seed germination.

The survival of oak young sprouts after prescribed burning was investigated 1 month after the prescribed burn by revisiting

the burned sites. All oak young sprouts under 50 cm in height died after the prescribed burn, only one *Q. serrata* and two *Q. variabilis* young sprouts survived in the 50–100 cm height range, only two *Q. fabri* young sprouts survived in the 100–150 cm height range, and one *Q. aliena* and one *Q. acutissima* each survived (Figure 9). Oak young sprouts

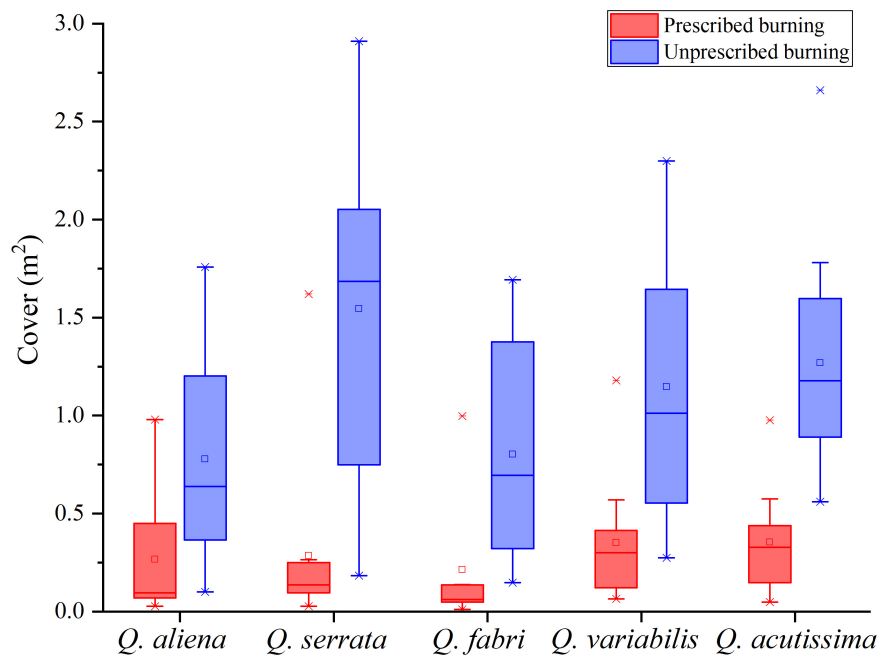


FIGURE 8 Cover comparisons of oak plants in the shrub layer.

TABLE 3 Comparison of the number of sprout tillers and seed germination in oak young sprouts.

Species	Prescribed burning		Unprescribed burning	
	Sprout tillers	Seed germination	Sprout tillers	Seed germination
<i>Q. aliena</i>	7	1	8	12
<i>Q. serrata</i>	6		6	13
<i>Q. fabri</i>	12	1	5	9
<i>Q. variabilis</i>	8		4	16
<i>Q. acutissima</i>	8	2	1	6

lack resistance to prescribed burns, and young sprouts that resprout after the prescribed burn have difficulty surviving the burn the following year. The prescribed burn is scheduled for February and March each year when the seeds of oak plants have already fallen to the ground, and the burn will kill many fallen seeds. This will further reduce the ability of oak plants to regenerate.

Effect of prescribed burning on the bark of oak plants

Bark samples were taken from oak trees in the study plots at 50, 100, and 150 cm above ground level, and total bark thickness and total bark density were measured. *Q. acutissima* sample was too small to be statistically significant, so it was not explored.

Relative total bark thickness

The significance of the effect of prescribed burning on the relative total bark thickness of oak plants was investigated. The relative total bark thickness of oak plants in prescribed burn

and control sample plots was ANOVA calculated (Table 4), and their distribution was counted (Figure 10). Relative bark thickness was significantly higher in prescribed burn areas than unprescribed burn areas, a trend evident at different heights for all four oak species. The mean relative bark thicknesses of *Q. aliena*, *Q. serrata*, *Q. fabri*, and *Q. variabilis* were 5.506, 2.975, 4.774, and 6.175, respectively, higher in the prescribed burned areas than in the unprescribed burned areas, and significantly higher at different heights in the prescribed burned areas than in the unprescribed burned areas.

Total bark density

Bark density was measured by a high-precision densitometer and found that there was a tendency for the bark density of oak plants to increase in the planned burned areas compared to the unplanned burned areas. Statistics on the distribution of oak bark density in the prescribed burn and control sample plots (ANOVA: *Q. aliena*: $F = 14.967, p < 0.001$; *Q. serrata*: $F = 16.946, p < 0.001$; *Q. fabri*: $F = 27.894, p < 0.001$; *Q. variabilis*: $F = 38.784, p < 0.001$) (Figure 11). Prescribed



FIGURE 9 *Quercus serrata* that tillering and then burn to death.

TABLE 4 ANOVA of relative total bark thickness.

Species	50 cm		100 cm		150 cm		Average relative total bark thickness	
	F	p-values	F	p-values	F	p-values	F	p-values
<i>Q. aliena</i>	51.566	<0.001	44.405	<0.001	31.983	<0.001	45.323	<0.001
<i>Q. serrata</i>	47.243	<0.001	71.44	<0.001	83.825	<0.001	74.27	<0.001
<i>Q. fabri</i>	73.904	<0.001	92.752	<0.001	65.7	<0.001	108.655	<0.001
<i>Q. variabilis</i>	136.987	<0.001	92.747	<0.001	46.573	<0.001	96.84	<0.001

burning had a highly significant effect on bark density. The mean bark densities of *Q. aliena*, *Q. serrata*, *Q. fabri*, and *Q. variabilis* increased by 0.075, 0.114, 0.111, and 0.828 g/cm³ after prescribed burning. The bark densities of oak plants were higher in prescribed burning areas than in unprescribed burning areas.

Discussion

Effect of prescribed burning on the distribution and growth status of oak plants

As a widely distributed species of oak in the understory of *Pinus yunnanensis* forests, the prescribed burn significantly reduced the importance and relative abundance of *Q. aliena*, *Q. serrata*, *Q. fabri*, and *Q. variabilis* in both tree and shrub layers. It significantly suppressed the oak distribution in the prescribed burn area.

The average tree height of oak plants in the tree layer in the prescribed burn areas did not change significantly, but the under crown height was significantly higher than in the

unprescribed burn areas. The increase in under crown height indicates the adaptation of oak plants to successive years of prescribed burning. The increase in under crown height effectively reduced the impact of prescribed burning on oak plants. Within the shrub layer, the height and cover of oak plants were significantly lower in prescribed burn areas than in unprescribed burn areas, and the average height and cover of oak plants showed a significant decrease.

The distribution of oak plants, the dominant species in the understory of *Pinus yunnanensis* forests, was suppressed after prescribed burning, and the average height and average cover of the shrub layer were reduced. From a forest fire prevention perspective, this reduces the vertical continuity of forest combustibles, reduces the likelihood of fire converting from surface fire to canopy fire along the “ladder fuel,” and achieves the objective of prescribed burning to prevent major forest fires.

Compared to other oak species, *Q. acutissima* is more suitable for survival in prescribed burn areas. The important values of *Q. acutissima* were higher in the prescribed burn areas than in the unprescribed burn areas in the tree and shrub layers. This may be because, in this study area, the competitive ability of *Q. acutissima* is low. After the prescribed burn, the abundance of

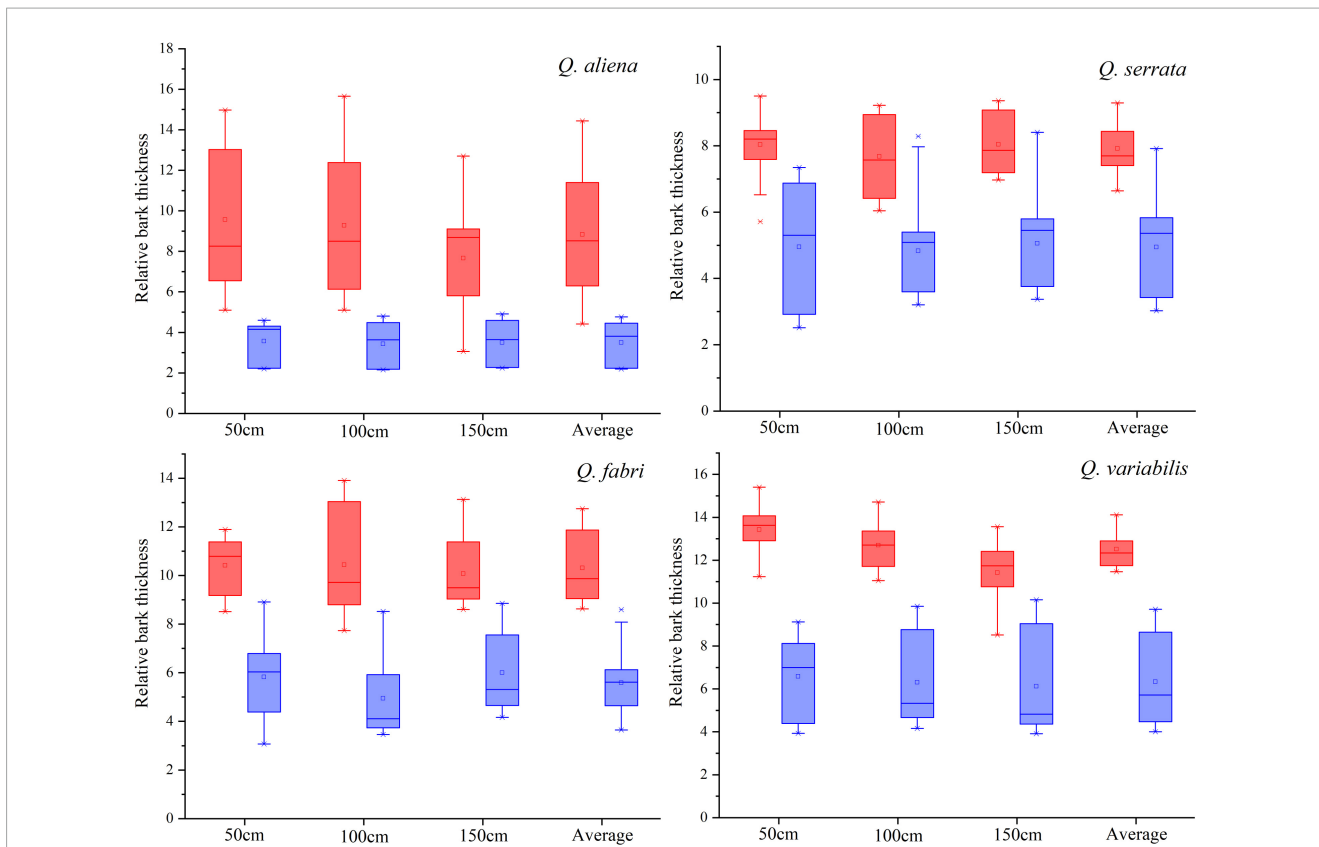


FIGURE 10
Relative total bark thickness at different heights. Red represents plants affected by prescribed burning; blue is plants unaffected by prescribed burning.

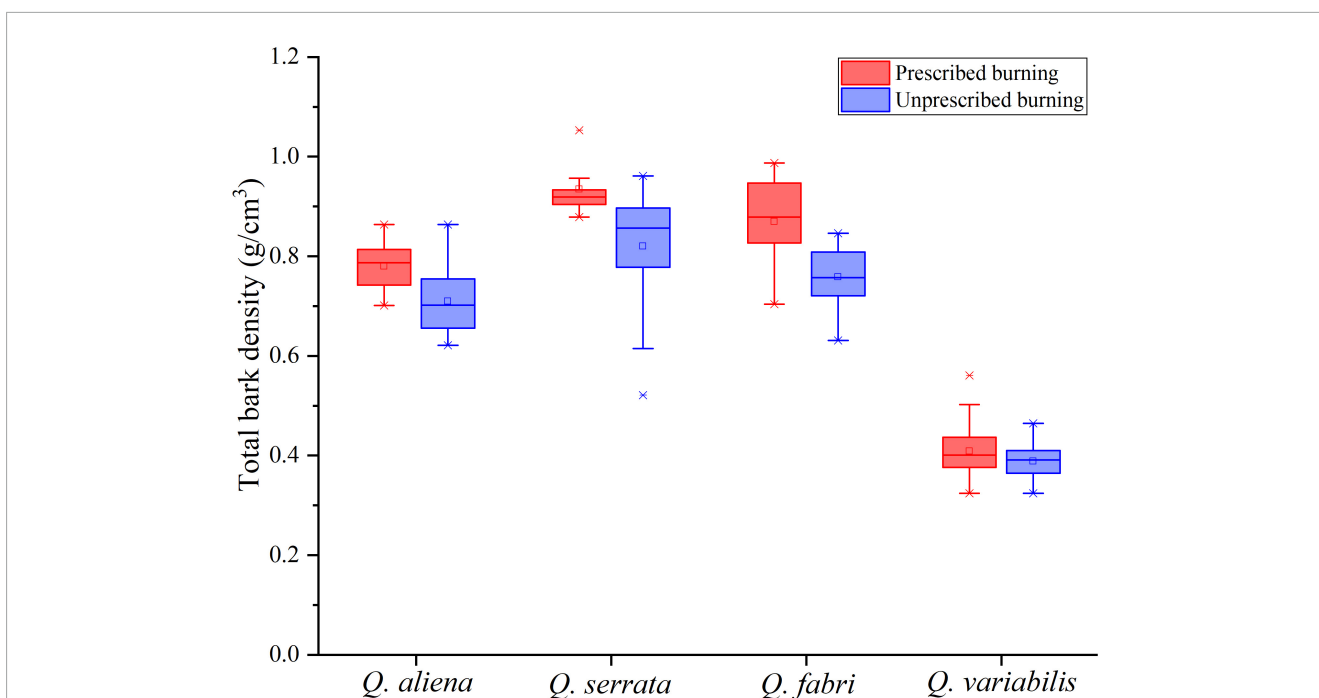


FIGURE 11
Comparison of total bark density.

other species decreases sharply, reducing the competitive pressure on *Q. acutissima*; therefore, *Q. acutissima* grows better in the prescribed burn. However, the effect of successive prescribed burns on *Q. acutissima* in areas where *Q. acutissima* is the dominant species needs further study.

Impact of prescribed burning on oak renewal methods

In the burned areas, oak plant regeneration was mainly by sprout tillers, with new plants sprouting from shoots on the rhizomes of plants that had survived the fire. In the unprescribed burn areas, significantly more oak plants were regenerated by seed germination than sprout tillers. There are few young sprouts of oak plants in the prescribed burn areas because the prescribed burn is scheduled for February and March each year when the seeds of oak plants have fallen to the ground. A large number of seeds die in the prescribed burn. Even if there are young sprouts that germinate successfully, it is very difficult for them to grow to fire resilient in the continuously prescribed burn environment. It is also difficult for sprouting young sprouts to survive repeated prescribed burns, and the ability of plant rhizomes to keep young shoots sprouting to sustain annual re-sprouting needs further study. The result is that oak plants are likely to age after a long period of prescribed burning, and the lack of new young stands to replenish them makes forest regeneration difficult. To ensure the regeneration of the forest, the time or interval between prescribed burns can be adjusted to some extent. Prescribed burns are carried out in February and March because it is relatively dry and the water content of fuel is low, making it easy for the understory to ignite. Whether prescribed burns can be carried out at other times requires further practice. For the prescribed burn interval, can be appropriate interval of a few years to stop the prescribed burn, when a new batch of oak young sprouts to establish a certain fire resistance, the prescribed burn again.

In unprescribed burn areas, oak plants are more often regenerated by seed germination, but some are still regenerated by rootstock germination. This part of the oak plant stem death is mainly due to pests or disease, but no oak plant death due to pests or disease was found in the prescribed burn area. It is assumed that prescribed burning has a suppressive effect on pests and diseases, but the suppressive effect will need to be discussed further in future studies.

Effect of prescribed burning on bark

In the area of prescribed burning, the relative thickness of the bark of all oak plants increased significantly, and the bark density also increased to different degrees depending on the oak species after being subjected to prescribed burning for a long time. The bark is an important tissue to protect the tree from fire disturbance. When subjected to low-intensity fires such as prescribed burns, the relative total bark thickness and bark density increase are self-protection mechanisms for oak plants. They are expressions of the adaptability of oak plants to fire.

Whether fire-adapted features can be retained after cessation of prescribed burnout

In prescribed burn areas, oak plants exhibit fire adaptations: increased under crown height, thicker bark, and increased bark density are among the traits. These traits allow oak plants to survive the low intensity of fire disturbance in prescribed burns each year. There are two speculations as to the reasons for these traits:

- (I) Oak plants have developed these traits to adapt to fire disturbance;
- (II) These traits do not arise from fire disturbance, but individuals that do not possess bark resistant to fire and disturbance are eliminated, and branches that are too short are killed by fire.

Further research is needed to address both of these speculations. This raises another question: whether fire-adapted traits in oak plants will be retained or even passed on to the next generation long after prescribed burning has ceased. If oak plants produce these traits to adapt to fire, then whether these fire-adapted traits will be retained or even inherited will require more long-term research.

Conclusion

This study was conducted in the Zhaobi Mountains, Xiping County, Yunnan Province, where prescribed burns have been carried out for several years. Unlike other areas, prescribed burns in this region are low-intensity fires with controlled fire regimes. This paper examines the response patterns of oak plants in the understory of *Pinus yunnanensis* forests after successive low-intensity fires. Conclusions were drawn by comparing oak plants' structural composition, growth, regeneration, relative total bark thickness, and bark density in prescribed and unprescribed burned areas. The importance value and relative abundance of *Q. aliena*, *Q. serrata*, *Q. fabri*, and *Q. variabilis* in the burned areas were significantly lower than in the non-burned areas. The importance value and relative abundance of *Q. acutissima* were slightly higher than in the non-burned areas. The average height of oak trees in the tree layer was not significantly different between the burned and unburned areas. The mean height and cover of the shrub layer were significantly lower in the prescribed burned areas than in the unprescribed burned areas. These differences reflect the effectiveness of prescribed burning in reducing the load of fuel in the forest and reducing the vertical continuity of combustible material. This can effectively reduce fire risk levels in Yunnan. Prescribed burning areas are regenerated by oak plants mainly through sprout tillers, while very few oak plants are regenerated through seed germination. Renewed oak young sprouts have difficulty surviving prescribed burns the following year due to their lack of fire resistance. Under the influence of successive prescribed burns, oak plants show some fire-adapted characteristics. The average under crown height of oak plants was significantly higher in prescribed burn areas than unprescribed burn areas. The

relative total bark thickness and bark density were significantly higher than in unprescribed burn areas. These traits help reduce damage to oak plants in prescribed burns, effectively reducing the thermal impact and giving them a competitive advantage. Overall, prescribed burning had a significant effect on suppressing the distribution of *Quercus* species, while under prolonged fire disturbance, *Quercus* species developed some adaptive capacity to fire.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RH, JL, and QW contributed to the study conception and design. RH, JL, JW, XZ, XL, CM, HC, and QW performed the experiments. RH, JL, and LW contributed to the data analysis, interpretation of results, and draft manuscript preparation. QW revised and edited the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

Funding

This study was supported by the National Natural Science Foundation of China (Grant Numbers: 32160376 and 31960318),

the Key Development and Promotion Project of Yunnan Province (Grant Number: 202202AD080010), and the Scientific Research Project of Yunnan Education Department (Grant Number: 2023Y0778).

Acknowledgments

We are grateful for the diligence in maintaining this study by Jun Pu, Wanhui Bai, and other Xinping Department of Conservation personnel, as well as the many individuals involved with the initiation and early phases of this study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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