Effects of prescribed burning on species diversity of understory in Pinus yunnanensis forests of southwest China

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Abstract

Background

The *Pinus yunnanensis* forest in southwestern China is a unique and significant vegetation type. However, it is susceptible to frequent fires. To mitigate the risk of hazardous fires, prescribed burning has often been employed in these forests. Nevertheless, it is important to consider the potential impact of prescribed burning on the structure of plant communities and species diversity in *Pinus yunnanensis* forests. To investigate the specific changes in plant community characteristics of caused by prescribed burning, a study was conducted in the *Pinus yunnanensis* forest located in Zhaobi Hill, Xinping county.

Results

Prescribed burning has had minimal effects on canopy trees, but has partially altered the characteristics of the understory community. It has decreased the number of shrub species from 26 to 19, with a shift in dominance from saplings of *Lithocarpus mairei* and *Pinus yunnanensis* in the unburned area to *Duhaldea cappa* and *Craibiodendron stellatum* in the burned area. Additionally, prescribed burning has partially altered the abundance of species and reduced the average height of shrubs. Furthermore, prescribed burning has increased the number of herb species from 27 to 40, but has had minimal impact on their abundance, height, and importance value. It is worth noting that prescribed burning has different impacts on the species diversity of shrubs and herbs. It significantly decreases the α species diversity of shrubs, but only has minimal effects on the α species diversity indices of herbs. The β diversity indices indicate that the species composition in both burned and unburned areas is similar, but the impact of prescribed burning on shrubs is greater than on herbs. Overall, prescribed burning appears to be the primary factor affecting the species diversity index of shrubs, while altitude, forest structure, and soil nutrient content exert greater influences on the species diversity index of the herbaceous layer.

Conclusions

Prescribed burning had little impacts on overstory trees of the *Pinus yunnanensis* forest, it had slightly positive effects on the height of herbs, and increased species richness of herbs from 27 to 40. However, the effects of prescribed burning on the species diversity and the height of shrub layers were significant and negative. Prescribed burning was the dominant factor shaping the community structure and species diversity of the shrub layer, and the missing saplings of trees in shrub layers might influence future forest succession in a long time.

1. Background

Pinus yunnanensis is a unique and indigenous coniferous tree species found in southwestern China. The *Pinus yunnanensis* forest represents the dry subtropical regions of western China and is widely spread across the Yunnan-Guizhou Plateau, with central Yunnan being at its core (Wu et al. 1987). This forest type is abundant in Yunnan Province and has significant carbon storage potential (Jin et al. 2004; Su et al. 2015). The *Pinus yunnanensis* forest belongs to the category of forests that have transitioned from subtropical evergreen broad-leaved forests due to prolonged droughts and frequent wildfires (Wu et al. 1987; Jin et al. 2004; Su et al. 2015). While most of the Yunnan pine forests today are man-made, having been established through air-seeding in the late 1970s, a few original pristine forests still exist in remote areas of northwestern and central Yunnan (Jin et al. 2004). The distribution area of *Pinus yunnanensis* forests is particularly susceptible to forest fires. This susceptibility arises from the natural tendency of *Pinus yunnanensis* to shed its lower branches, combined with its occurrence in regions characterized by dry and warm climates (Tian et al. 2017). The inherent characteristic of natural pruning in Yunnan pine increases the risk of forest fires if dead needles accumulate on lower branches during the dry season (Ma et al. 1991). Prescribed burning, a widely used technique in various regions, refers to controlled fires of low intensity that aim to reduce fire hazards in forest ecosystems and modify the characteristics of fire disturbances by reducing the fuel loads on forest surfaces (Fernandes et al. 2003; Boer et al. 2009; Van Wilgen et al. 2010; Burrows et al. 2013; Fernandes et al. 2013; McCaw et al. 2013; Holland et al. 2017; Bradshaw et al. 2018; Price 2023). This practice is commonly employed in different ecosystems, including the South African fynbos (Boer et al. 2009), woodlands and forests of Australia (McCaw 2013; Burrows and McCaw 2013; Fernandes et al. 2013; Holland et al. 2017; Bradshaw et al. 2018; Price 2023), fire-prone areas in Mediterranean regions (Casals et al. 2016; Duane et al. 2019), fire-suppressed forests in the USA (Brockway and Lewis 1997; Carter et al. 2004; Glasgow et al. 2007; Knapp et al. 2015; Kobziar et al. 2015; Chen et al. 2019; Regmi et al. 2023), and fire-prone ecosystems in China (Franklin et al. 2003; Wang et al. 2018; Su et al. 2015; Fernandes and Botelho 2003; Dou et al. 2023).

Prescribed burning has an impact on the structure of plant communities and the diversity of species in forests, and these effects varied depending on the different plant strata and types of vegetation (Fernandes et al. 2013; Van Wilgen 2013; Céspedes et al. 2014; Knapp et al. 2015; Kobziar et al. 2015; Holland et al. 2017; Eales et al. 2018; Wang et al. 2018; Mahood and Balch 2019; Barefoot et al. 2019; Koivula and Vanha-Majamaa 2020; Durigan et al. 2020; Bassett et al. 2020; Zald et al. 2020; Roberton and Rebar 2022; Kumar 2022; Vaughan et al. 2022; Price 2023). Although low-intensity prescribed burning has minimal effects on the overstory strata of forests and herbaceous plants, it significantly reduces the cover and stem density of shrubs in the midstory (Van Wilgen et al. 2013; Knapp et al. 2015; Kobziar et al. 2015; Eales et al. 2018; Barefoot et al. 2019; Chen et al. 2019; Koivula and Vanha-Majamaa 2020; Durigan et al. 2020; Bassett et al. 2020; Vaughan et al. 2022; Dou et al. 2023; Regmi et al. 2023). Frequent prescribed burning has been found to have detrimental effects on the frequency and relative abundance of important shrubs in fynbos ecosystems (Van Wilgen 2013; Kobziar et al. 2015). However, in dry sclerophyll forests in south-eastern Australia, burning may have a positive impact on species richness of plants less than 1m in height, while negatively affecting taller plants. It can also reduce the density and canopy cover of the overstory, leading to the loss of woody seedlings and saplings, but increasing the abundance and richness of understory species (Kobziar et al. 2015). In broadleaf forests, burning has been shown to significantly enhance the richness of vascular plants, exotic plants, and herbs

(Céspedes et al. 2014; Barefoot et al. 2019). Similarly, in oak savanna ecosystems, burning has been observed to increase canopy openness and the percentage of vegetative cover in the understory (Bassett et al. 2020). On the other hand, the effects of burning on the diversity of vascular plant species and exotic species in Arizona Ponderosa Pine Forests are more subtle (Koivula and Vanha-Majamaa 2020).

Understory vegetation plays a crucial role in various aspects of the forest ecosystem, including nutrient cycling, water conservation, forest climate regulation, and animal habitats (Kobziar et al. 2015; Knapp et al. 2015). Therefore, maintaining the stability of the community structure and species diversity in the understory is essential for the overall stability of the forest ecosystem. Prescribed burning primarily affects understory plants, while its impact on the overstory is generally minimal (Van Wilgen 2013; Céspedes et al. 2014; Wang et al. 2018; Mahood et al. 2019; Koivula and Vanha-Majamaa 2020; Zald et al. 2020; Kumar 2022; Roberton et al. 2022). The changes in understory vegetation structure caused by burning may influence the future development of the forest ecosystem (Kobziar et al. 2015). While *Pinus yunnanensis* forests generally have a lower abundance of understory vegetation, the importance of understory for the stability of forest ecosystems should not be overlooked (Su et al. 2015). However, the effects of prescribed burning on the species composition and diversity of the understory in *Pinus yunnanensis* forests remain uncertain. We hypothesized that prescribed burning could have a significant impact on the species composition and plant heights of the understory. However, we believed that the impact of burning on canopy strata of *Pinus yunnanensis* forests should be minor. It is possible that these effects could be influenced by other factors, such as altitude and soil nutrient levels. In order to investigate this further, we conducted a comprehensive plant study in both the prescribed burning area and an adjacent unburned area in the *Pinus yunnanensis* forests of central Yunnan. Our study aimed to address the following questions: 1) How does prescribed burning affect the species richness and diversity of both the overstory and understory in Yunnan Pine forests? 2) Are the effects of prescribed burning on the shrub and herb layers in the understory similar? 3) To what extent do other factors, such as altitude or soil nutrient levels, interact with the effects of prescribed burning on the plant community structure of the understory in this region?

2. Materials and Methods

2.1 Study area

This study was conducted in a *Pinus yunnanensis* forest, which was aerially seeded in Zhaobi Hill, Xinping county, Yunnan province, southwestern China (Fig. 1). The region has a south subtropical humid monsoon climate with distinct wet and dry seasons, an average annual temperature of 18.1 °C, an annual mean precipitation of 869 mm, and an annual total sunshine duration of 2838 hours. The dominant soil type in this region is red soil, and the major forest vegetation is *Pinus yunnanensis* forest, which was established through afforestation by aerial seeding in the 1970s. The vegetation community of Yunnan pine forests is divided into three layers: the tree layer, the shrub layer, and the herb layer. The tree layer includes *Pinus yunnanensis*, *Keteleeria evelyniana*, *Cyclobalanopsis glaucoides*, *Castanopsis orthacantha*, *Castanopsis delavayi*, and *Quercus acutissima*. The understory includes the shrub layer and herb layer; plants in the shrub layer include *Vaccinium duclouxii*, *V. fragile*, *Lyonia ovalifolia*, *Craibiodendron stellatum*, *Duhaldea cappa*, and the herb layer is mainly composed of *Anaphalis* sp., *Arundinella setosa*, *Capillipedium assimile*, *Elsholtzia rugulosa*, *E. bodinieri*, *Eulalia pallens*, *E. quadrinervis*, *Hedyotis* sp., *Leontopodium* sp., *Pteridium aquilinum*, and *Erigeron* sp., *Pseudognaphalium* sp. and *Laggera alata*. Prescribed burning has been a consistent practice in this region since 2016 as a preventative measure against forest fires. These prescribed burns typically occur in late January or early February, with low-intensity fires being utilized between the years 2016 and 2019 and discontinued in 2020 and 2021. The burned area is then restored for three years since the last prescribed burning period.

2.2 Field Measurements

In January 2022, field surveys were conducted in both unburned areas and planned burned areas. Fourteen sample plots were established in each area, with each plot consisting of three 20 m × 20 m subplots, The distance between each plot is approximately 200–500 m, while the distance between each subplot is less than 100 m. This resulted in a total of 84 subplots. All subplots had a similar aspect, and other basic information, such as altitude, slope, and canopy density, showed minimal variation between prescribed burning and unburned plots (Fig. 1). The survey plots were strategically placed at least 50 m from the road, with elevations ranging from 1950–2200 m. These plots were predominantly located on sunny and moderate slopes (Table 1). Within each 20 m x 20 m plot, the diameters at breast height (DBH) of individual plants, with a DBH greater than 2 cm, were measured and recorded. Additionally, tree height and height under lower branches in the tree layer were recorded. In each 20 m x 20 m plot, five 5 m x 5 m quadrats were set in a clover shape to investigate the height, crown breadth, and number of plant species in the shrub layer. Furthermore, within each of the five shrub quadrats, five 1 m x 1 m sub-quadrats were set to investigate the number and coverage of plants in the herbaceous layer. Lastly, five soil samples were collected from the 0–10 cm soil layer to measure the chemical stoichiometric characteristics of soil C, N, P, and K.

Table 1
Basic information of sample plots

plots	Altitude(m)	Slope (°)	Canopy density	DBH (cm)	Basal area (m^2/ha)	Height(m)	Tree density (stems / ha)
CK	2043 ± 42a	13.0 ± 4.0a	0.43 ± 0.05a	17.50 ± 1.92a	3515.06 ± 918.52a	8.27 ± 0.93a	1235.29 ± 361.75a
PB	2019 ± 33a	10.0 ± 2.0a	0.38 ± 0.04a	18.37 ± 2.56a	3295.66 ± 859.53a	8.93 ± 1.40a	1163.39 ± 461.65a

The values in the table are mean ± standard deviation, and different letters indicate a significance level of α = 0.05

2.3. Laboratory Analysis

All trees and shrubs in all sample plots were classified based on their respective species, following the guidelines provided in the Yunnan Flora and the unpublished Xinping Flora. For herbs, identification was done at the specific species level, and unable to identify the species of the herbaceous plant, identified only the genus (refer to Table 1).

The sampled soils underwent air-drying and were subsequently passed through a US Standard 60 mesh to exclude small rocks and fine roots. The resulting mineral soils were then analyzed for total soil carbon (TC), soil organic carbon (SOC), total nitrogen (TN), hydrolysable nitrogen (A-N), available potassium (A-K), and soil available phosphorus (A-P). Additionally, the C/N ratio was calculated based on the total carbon and total nitrogen content of the soils. The TC analysis was conducted using ZYT-2000 analyzer, while SOC was measured using a Dichromate titration method. TN and A-N was determined using SKD-200 analyzer. A-K was measured using FP6410 analyzer, and A-P was determined using a UV-visible spectrophotometer analyzer.

2.4. Statistical Analysis

To evaluate the structure and composition of the *Pinus yunnanensis* forest community, plant importance value, species abundance, and height were measured. The α diversity indices, such as the Shannon-Winner diversity index *(H')*, Simpson's dominance index (*D*), Pielou's evenness index (E_H), and Margalef's richness index (*F*), were calculated to assess community diversity. Additionally, beta diversity indices including the Jaccard Index (β_j), Cody index (β_c), and Morista-Horn Index (C_{MH}) were used. For the shrub layer, *H'*, *D*, E_H, and *F* were utilized to measure species diversity. Due to the challenges in accurately counting the number of herbs, *H'*, *D*, and E_H were employed to assess the species diversity in the herb layers. The diversity index was calculated using the methodology described in Ma et al. (1995).

$H' = -\sum_{i=1}^{S} P_i ln p_i$ (1) $D = 1 - \sum_{i=1}^{S} (P_i)^2$ (2)

$$E_H = H'/lnS$$

3

$$F = (S-1)/lnN$$

4

$$P_i = n_i/N$$

5

$$\beta_c = (g(H) + l(H))/2$$

6

$$\beta_j = j/(a+b-j)$$

7

$$C_{MH} = 2 \times \sum an_i \times bn_i/((\sum an_i^2/a^2 + \sum bn_i^2/b^2) \times a \times b)$$

8

where P_i indicates the proportion of plant species *i* in a specific sample site, n_i denotes the count of individual plants belonging to species *i*, *S* denotes the number of plant species in a sample site, and *N* denotes the total count of all plant species in the sample site. In the equations of β_c, β_j and C_{MH}, $\mathrm{g}\,(H)$ represents the number of species increasing along the habitat gradient H, $l\,(H)$ represents the number of species decreasing along the same gradient, *a* represents the number of species in sample A, *b* represents the number of species in sample B, and *j* represents the number of species shared by both sample A and B, $\mathrm{an_i}$ and $\mathrm{bn_i}$ represents the coverage of individual plants belonging to species *i* in sample A and sample B, respectively. Different values of the Jaccard similarity index (β_j) represent different meanings. Values of 0 to 0.25 indicate extremely dissimilar community compositions, 0.25 to 0.50 represents moderately dissimilar, 0.50 to 0.75 indicates moderately similar, and 0.75 to 1.00 represents extremely similar communities. The Morisita-Horn index (C_{MH}) represents the coefficient of similarity between communities undergoing planned burning, while the Cody index (β_c) represents the dissimilarity of species composition.

We utilized the Wilcoxon Rank Sum Test (WX) to identify disparities in species abundance, coverage, height, and species diversity index. Additionally, we employed NMDS to explore differences in understory community structure between the burned area and unburned area. We identified the influential factors of α species diversity by using Spearman correlation. Furthermore, we conducted multivariate regression analysis (MLM) to analyze the relative contribution of factors to the α diversity indexes. Finally, we investigated the associations between species composition and various environmental factors, including fires, altitudes, upper vegetation characteristics, and soil nutrients, using the structural equation model (SEM).

NMDS is used to visually evaluate the structure of plant communities and their environmental resources (such as soil organic layer thickness, moisture content, pH, total carbon, nitrogen, and phosphorus). NMDS is a widely used multivariate analysis method, suitable for complex iterative sorting analysis of nonlinear data. It reflects the relationships between entities in a geometric space using the distances between points in a low-dimensional space through dimensional reduction and sorting, and could simultaneously handle multiple dependent and independent variables and visually display the relationships between variables in a sorting plot.

SEM is a multivariate statistical method used to establish, estimate, and test causal relationships. Compared to traditional statistical methods, SEM can study both observable variables and variables that cannot be directly observed (latent variables), and can indicate direct or indirect relationships between variables. SEM could handle multiple dependent variables simultaneously and visually display the relationships between variables in a path diagram. SEM is used to quantitatively evaluate the direct and indirect impacts of factors such as burning and topography on the surface plant communities of *Pinus yunnanensis* forests and conduct path analysis.

All analyses were performed in R version 4.2.1 (R Core Team 2022). The WX test was conducted using the 'Wilcox.test' package, the NMDS analyses were performed using the 'vegan' package, MLM was executed using the 'gvlma' package, and the SEM analysis was conducted using the 'sem' package.

3. Results

3.1. Effects of prescribed burning on species composition of wood layers

There were no significant variations in the species composition or number of tree species in the tree layer between the burned and unburned plots (Table 1). However, the DBH (diameters at breast height) and tree heights were slightly larger in the prescribed burning plots compared to the unburned plots. On the other hand, the prescribed burning plots showed slightly lower values for canopy density, basal area, and tree density (stems per hectare). No significant changes were observed in the arboreal layer related to the canopy density, canopy height, DBH, tree density, and basal area between the prescribed burning and unburned plots.

3.2. Effects of prescribed burning on composition structure of understory layers

3.2.1 Effects of prescribed burning on composition structure of shrub layers

Prescribed burning had a significant impact on the plant community in the shrub layer, resulting in changes in species richness and plant height (Table 2, Fig. 2). The number of plant species in the shrub layer decreased from 26 in the unburned plots to 19 after prescribed burning (Table 2, Fig. 2). In addition, the abundance of plants within the shrub layer was also affected (Table 2, Fig. 3). *Tetrastigma yunnanense*, *Lithocarpus mairei*, and saplings of five tree species including *Pinus yunnanensis*, *Quercus acutissima*, *Quercus variabilis*, *Castanopsis delavayi*, and *Schima wallichii*, disappeared from the burned plots. The abundance of *Morella rubra*, *Vaccinium fragile*, and *Keteleeria evelyniana* significantly declined. On the other hand, *Melastoma polyanthum*, *Raphiolepis indica*, and *Osteomeles schwerinae* were newly discovered in the burned plots. Compared to the unburned plots, only Duhaldea cappa showed a significant increase in abundance, while the other co-existing species both in burned and unburned plots did not show such a substantial change.

Prescribed burning also resulted in a reduction in the height of most plants in the shrub layer. *Vaccinium duclouxii, Vaccinium fragile, Rubus calycinus, Lyonia ovalifolia, Keteleeria evelyniana, Symplocos sumuntia, Vaccinium bracteatum, Engelhardtia spicata*, and *Anneslea fragrans* showed significantly lower heights in the burned plots compared to the unburned plots. However, *Cyclobalanopsis glaucoides* and *Ficus tikoua* experienced a significant increase in height, excluding the newly found shrubs. Overall, prescribed burning led to a considerable decrease in the average height of the shrub layer, decreasing from 84.60 ± 28.83 cm in the unburned plots to 50.42 ± 27.71 cm in the burned plots.

The importance value (IV) of many plants in the shrub layer showed changes in the prescribed burning plots compared to the unburned plots, although most of these changes were not easily noticeable (Table 2). However, the IV of *Duhaldea cappa* and *Craibiodendron stellatum* exhibited a significant increase in the prescribed burning plots, while *Lyonia ovalifolia* and *Vaccinium fragile* clearly decreased. The dominant plants in the shrub layer also shifted from *Lithocarpus mairei* and *Lyonia ovalifolia* in the unburned area to *Duhaldea cappa* in the prescribed burning area. Furthermore, the NMDS analysis results provided further evidence of the notable impact of prescribed burning on the vegetation in the shrub layer. This assertion is supported by the graphical representation of NMDS at a 95% confidence interval. It is worth mentioning that the stress value obtained from ranking the NMDS for the shrub layer was 0.135, indicating that NMDS can yield accurate results (Fig. 4).

Table 2
The importance value, plant abundance, and height of shrub layers in prescribed burning and unburned plots

Species	Abundance		Height (cm)		Importance value (IV)	
	CK	PB	CK	PB	CK	PB
Craibiodendron stellatum	12.57 ± 11.82	11.08 ± 9.05	75.42 ± 44.9	54.92 ± 28.1	0.35 ± 0.05	0.46 ± 0.15*
Lithocarpus mairei	24.00 ± 15.66	-**	127.72 ± 64.20	-**	0.47 ± 0.05	-**
Pinus yunnanensis	6.88 ± 7.69	-	51.04 ± 15.97	-	0.35 ± 0.07	-
Morella rubra	3.50 ± 2.50	0.64 ± 0.98	204.24 ± 95.18	114.89 ± 91.46	0.30 ± 0.08	0.22 ± 0.10
Anneslea fragrans	1.50 ± 0.50	1.46 ± 0.86	43.50 ± 22.50	22.50 ± 2.50*	0.14 ± 0.02	0.13 ± 0.03
Engelhardtia spicata	3.33 ± 3.30	0.35 ± 0.14	106.33 ± 33.99	43.00 ± 0.82**	0.16 ± 0.03	0.10 ± 0.01
Schima wallichii	3.00 ± 2.00	-	30.50 ± 24.50	-	0.10 ± 0.03	-
Vaccinium bracteatum	7.00 ± 5.10	1.00 ± 1.56	71.44 ± 20.86	36.25 ± 16.14*	0.22 ± 0.01	0.19 ± 0.10
Symplocos sumuntia	0.50 ± 0.50	0.17 ± 0.37	200.00 ± 12.50	65.00 ± 5.60**	0.13 ± 0.01	0.04 ± 0.02
Keteleeria evelyniana	1.33 ± 0.94	1.05 ± 0.43	89.50 ± 57.50	22.33 ± 3.80**	0.24 ± 0.11	0.12 ± 0.04
Cyclobalanopsis glaucoides	1.50 ± 0.50	0.43 ± 0.25	200.60 ± 119.40	210.00 ± 190.00	0.14 ± 0.08	0.24 ± 0.15
Quercus acutissima	1.67 ± 0.94	-	75.78 ± 19.51	-	0.11 ± 0.02	-
Castanopsis delavayi	2.00 ± 1.00	-	72.17 ± 48.17	-	0.19 ± 0.13	-
Lithocarpus hancei	10.00 ± 5.00	4.50 ± 3.50	65.90 ± 15.30	40.81 ± 4.19	0.34 ± 0.03	0.23 ± 0.04
Quercus variabilis	1.00 ± 0.30	-	315.00 ± 13.50	-	0.15 ± 0.02	-
Melastoma polyanthum	-	0.14 ± 0.35	-	65.00 ± 6.80		0.07 ± 0.01

Species	Abundance		Height (cm)		Importance value (IV)	
	CK	PB	CK	PB	CK	PB
Raphiolepis indica	-	0.37 ± 0.17	-	30.00 ± 0.50	-	0.16 ± 0.05
Osteomeles schwerinae	-	1.00 ± 0.03	-	105.00 ± 11.40	-	0.13 ± 0.02
Tetrastigma yunnanense	1.00 ± 0.02	-	5.00 ± 0.90	-	0.13 ± 0.01	-
Vernonia cumingiana	0.50 ± 0.34	-	243.00 ± 13.50	-	0.07 ± 0.02	-
Myrica nana	0.67 ± 0.47	-	246.50 ± 9.50	-	0.20 ± 0.01	-
Rhododendron simsii	17.00 ± 0.60	-	53.59 ± 1.60	-	0.19 ± 0.04	-
Duhaldea cappa	4.00 ± 2.00	33.45 ± 25.87**	53.29 ± 17.48	44.23 ± 17.75	0.26 ± 0.07	0.60 ± 0.14**
Lyonia ovalifolia	5.92 ± 4.68	8.18 ± 11.22	99.44 ± 77.75	55.02 ± 27.58*	0.45 ± 0.13	0.37 ± 0.08*
Vaccinium fragile	15.9 ± 12.21	2.80 ± 4.94*	20.76 ± 11.33	14.31 ± 3.5*	0.39 ± 0.12	0.24 ± 0.12**
Campylotropis hirtella	0.50 ± 0.50	0.99 ± 0.86	21.00 ± 1.50	20.25 ± 0.75	0.06 ± 0.02	0.20 ± 0.10
Vaccinium duclouxii	5.25 ± 4.97	3.64 ± 1.38	51.60 ± 16.37	27.18 ± 3.70*	0.21 ± 0.05	0.16 ± 0.01
Rubus calycinus	6.00 ± 0.40	1.12 ± 0.50	34.80 ± 3.70	18.00 ± 0.90**	0.69 ± 0.04	0.10 ± 0.02
Ficus tikoua	1.00 ± 0.20	1.00 ± 0.03	7.00 ± 0.50	9.00 ± 0.50	0.03 ± 0.01	0.05 ± 0.02

** represents $p \leq 0.05$, * represents $0.05 < p \leq 0.10$, and "-" indicates that the species was not found in sample plots.

3.2.2. Effects of prescribed burning on composition structure of herb layers

Prescribed burning resulted in an increase in the number of herb species from 27 to 40 (Table 3, Fig. 5). Three species, including *Crassocephalum crepidioides*, *Cyperus rotundus*, and *Gamochaeta pensylvanica*, disappeared in the burned plots. On the other hand, 15 species, such as*Parochetus communis*, *Themeda* *triandra*, *Erigeron canadensis*, *Gerbera delavayi*, *Centella asiatica*, *Clinopodium repens*, *Lespedeza bicolor*, *Asteraceae japonica*, *Taraxacum mongolicum*, *Scutellaria indica*, *Desmodium concinnum*, *Hedyotis diffusa*, *Bothriochloa ischaemum*, *Imperata cylindrica*, and *Ainsliaea yunnanensis*, were only found in the burned plot. The majority of the newly-found species belonged to the Poaceae and Asteraceae families (Fig. 6).

Prescribed burning had minimal impact on the abundance of herbs. Apart from the newly discovered species, no other species showed a significant increase in abundance. Only *Pteridium aquilinum* exhibited a significant decrease in abundance, apart from undiscovered species (Table 3, Fig. 6). The average height of herb layers in unburned plots increased from 25.83 ± 9.61 cm to 34.36 ± 22.28 cm in the burned plots. The burning treatment partially altered the importance values of the herb layer plants. In the unburned plots, the species with the highest Importance Value (IV) was *Arundinella setosa*, while in the burned plots, it was *Elsholtzia rugulosa*. Except for *Eulalia quadrinervis*, *Hedyotis uncinella*, *Pteridium aquilinum*, and *Desmodium microphyllum*, which were no longer present, and the newly added species, most of the coexisting species in the burned and unburned plots showed no significant difference in their importance values.

The NMDS results strongly indicate that the impact of planned burning on herbaceous layer plants can be disregarded. This is confirmed by the graphical representation of NMDS and the 95% confidence interval. The stress values assigned to the NMDS of the herb layer were remarkably low (0.186), which highlights the effectiveness of NMDS in producing accurate results (Fig. 7).

Table 3
The importance value, coverage, and height of herbs in prescribed burning areas and in unburned areas

Species	Abundance		Height (cm)		Importance value (IV)	
	Unburned	PB	Unburned	PB	Unburned	PB
Elsholtzia rugulosa	9.01 ± 6.96	6.83 ± 3.50	31.14 ± 14.18	30.83 ± 11.74	0.46 ± 0.06	0.49 ± 0.02
Pteridium aquilinum	30.59 ± 24.48	11.71 ± 10.43*	60.66 ± 27.85	57.96 ± 21.96*	0.31 ± 0.12	0.45 ± 0.05**
Arundinella setosa	33.75 ± 26.40	17.37 ± 7.72	35.96 ± 18.53	68.94 ± 32.78*	0.52 ± 0.13	0.35 ± 0.13
Ageratina adenophora	11.56 ± 8.02	4.53 ± 9.07	28.70 ± 14.11	16.16 ± 7.07	0.30 ± 0.03	0.29 ± 0.07
Hedyotis uncinella	1.29 ± 1.04	1.45 ± 0.57	8.38 ± 4.69	7.63 ± 4.07	0.28 ± 0.04	0.25 ± 0.03*
Eulalia pallens	26.57 ± 24.53	17.10 ± 12.55	54.17 ± 26.05	74.66 ± 43.48	0.39 ± 0.15	0.36 ± 0.10
Eulalia quadrinervis	15.68 ± 11.01	16.66 ± 9.49	23.25 ± 11.62	29.42 ± 21.91	0.43 ± 0.11	0.28 ± 0.11*
Parochetus communis	-	1.65 ± 1.42**	-	2.73 ± 0.30**	-	0.34 ± 0.01**
Carex cruciata	20.92 ± 19.34	19.22 ± 11.5	25.92 ± 9.46	36.35 ± 9.34	0.27 ± 0.07	0.33 ± 0.05
Themeda triandra	-	22.40 ± 12.61**	-	65.75 ± 33.8**	-	0.33 ± 0.12**
Capillipedium assimile	29.61 ± 12.25	12.06 ± 7.31	45.67 ± 17.17	47.25 ± 16.18	0.25 ± 0.06	0.26 ± 0.06
Hedyotis auricularia	0.57 ± 0.49	0.77 ± 0.65	5.33 ± 4.03	9.00 ± 8.39	0.18 ± 0.03	0.18 ± 0.03
Pseudognaphalium adnatum	1.15 ± 0.81	1.31 ± 0.43	6.33 ± 4.03	3.88 ± 0.22	0.14 ± 0.06	0.16 ± 0.04
Leontopodium dedekensii	6.16 ± 5.14	0.64 ± 0.47	18.57 ± 5.95	17.81 ± 14.93	0.28 ± 0.16	0.18 ± 0.01
Desmodium microphyllum	1.68 ± 1.55	0.82 ± 0.40	5.75 ± 2.75	22.97 ± 19.92	0.08 ± 0.02	0.16 ± 0.03*
Heteropogon contortus	29.77 ± 27.67	4.60 ± 3.78	27.92 ± 1.56	11.50 ± 4.50	0.26 ± 0.12	0.11 ± 0.02

** represents p ≤ 0.05, * represents 0.05 < p ≤ 0.10, and "-" indicates that the species was not found in sample plots

Species	Abundance		Height (cm)		Importance value (IV)	
	Unburned	PB	Unburned	PB	Unburned	PB
Juucus effusus	13.38 ± 4.49	1.84 ± 1.19	12.17 ± 1.03	15.75 ± 8.61	0.22 ± 0.01	0.15 ± 0.01
Anaphalis margaritacea	3.44 ± 1.68	1.52 ± 1.29	8.88 ± 6.62	11.25 ± 8.32	0.17 ± 0.03	0.16 ± 0.06
Erigeron canadensis	-	1.48 ± 0.99**	-	5.78 ± 2.27**	-	0.19 ± 0.01**
Duchesnea indica	0.09 ± 0.05	3.07 ± 2.66	2.00 ± 0.40	5.78 ± 2.64	0.05 ± 0.02	0.19 ± 0.02
Elsholtzia bodinieri	14.34 ± 13.90	3.67 ± 2.33	5.38 ± 2.22	6.57 ± 2.56	0.15 ± 0.04	0.17 ± 0.06
Rubia podantha	20.81 ± 0.60	2.92 ± 0.56	39.00 ± 0.80	5.88 ± 2.13	0.15 ± 0.02	0.12 ± 0.03
Galium bungei	2.03 ± 1.20	1.84 ± 1.36	4.00 ± 1.00	3.83 ± 1.55	0.10 ± 0.01	0.12 ± 0.01
Laggera alata	3.95 ± 3.34	1.36 ± 1.02	29.50 ± 14.50	22.00 ± 19.91	0.10 ± 0.01	0.13 ± 0.06
Ophiopogon japonicus	0.09 ± 0.03	1.92 ± 1.52	20.00 ± 0.40	18.25 ± 6.25	0.05 ± 0.01	0.08 ± 0.01
Gerbera delavayi	-	6.85 ± 6.19	-	4.50 ± 2.04	-	0.12 ± 0.07
Arthraxon hispidus	17.24 ± 0.70	4.24 ± 0.52	30.00 ± 0.80	20.00 ± 1.70	0.11 ± 0.02	0.09 ± 0.01
Centella asiatica	-	0.03 ± 0.01	-	3.00 ± 0.40	-	0.04 ± 0.01
Crassocephalum crepidioides	0.06 ± 0.05	-	7.00 ± 0.40	-	0.03 ± 0.01	-
Lespedeza bicolor	-	0.90 ± 0.40	-	10.67 ± 5.3	-	0.07 ± 0.03
Asteraceae japonica	-	0.67 ± 0.01	-	3.00 ± 2.00	-	0.05 ± 0.01
Clinopodium repens	-	1.33 ± 0.20	-	4.00 ± 0.30	-	0.06 ± 0.03
Taraxacum mongolicum	-	0.36 ± 0.10	-	3.00 ± 0.06	-	0.03 ± 0.04

** represents $p \leq 0.05$, * represents $0.05 < p \leq 0.10$, and "-" indicates that the species was not found in sample plots

Species	Abundance		Height (cm)		Importance value (IV)	
	Unburned	PB	Unburned	PB	Unburned	PB
Scutellaria indica	-	0.34 ± 0.20	-	2.50 ± 0.03	-	0.03 ± 0.01
Desmodium concinnum	-	0.07 ± 0.04	-	10.00 ± 0.70	-	0.02 ± 0.02
Hedyotis diffusa	-	0.54 ± 0.30	-	4.00 ± 0.05	-	0.03 ± 0.01
Bothriochloa ischaemum	-	0.02 ± 0.01	-	14.00 ± 2.50	-	0.02 ± 0.01
Miscanthus sinensis	-	4.07 ± 0.30	-	40.00 ± 3.20	-	0.06 ± 0.03
Cyperus rotundus	0.46 ± 0.30	-	3.00 ± 0.20	-	0.05 ± 0.01	-
Gamochaeta pensylvanica	1.13 ± 0.4	-	3.50 ± 0.5	-	0.05 ± 0.02	-
Imperata cylindrica	-	20.53 ± 19.00	-	34.17 ± 20.17	-	0.09 ± 0.04
Scutellaria barbata	3.27 ± 2.95	3.23 ± 2.87	19.67 ± 8.96	31.80 ± 3.66	0.34 ± 0.01	0.40 ± 0.07
Ainsliaea yunnanensis	-	0.50 ± 0.03	-	17.00 ± 4.10	-	0.20 ± 0.01

** represents $p \leq 0.05$, * represents $0.05 < p \leq 0.10$, and "-" indicates that the species was not found in sample plots

3.3. Effects of prescribed burning on diversity indices of understory species

The effects of prescribed burning on species diversity indexes differed between shrub layers and herb layers (Fig. 8). Prescribed burning had a significant impact on the Shannon-Winner diversity index (H'), Simpson's dominance index (D), Pielou's evenness index (E_H), and Margalef's richness index (F) of shrub layers (Fig. 8a), resulting in a decrease in these indexes. However, the positive effects of prescribed burning on H' and D of herb layers were limited, and it had slightly negative effects on E_H of herb layers (Fig. 8b).

Different β diversity indexes showed varying responses in herbs and shrubs to prescribed burning. The Jaccard index (β_j) indicated that there was a moderate similarity in the number of plant species between the areas subjected to prescribed burning and those that were not burned, with slightly higher similarity in the herbaceous layer compared to the shrub layer. On the other hand, the Cody index (β_c) suggested a higher species turnover in the herbaceous layer compared to the shrub layer. However, the Morista-Horn index (C_{MH}) indicated a higher similarity in the herbaceous layer in both the burned and unburned areas.

The same letter represents no significant difference, different letters indicate a significance level of α = 0.05.

Table 4
Effects of prescribed burning on beta diversity index of the understory

Layer	Treatments	Number of increased species	Number of decreased species	Cody (β_c)	Jaccard (β_j)	Morista-Horn (C_{MH})
Shrub layer	Unburned-burned	3.000	10.000	6.500	0.552	0.269
Herb layer	Unburned-burned	16.000	3.000	9.500	0.558	0.736

3.4. Analysis of major factors affecting species biodiversity of understory

It had notable differences of influenced factors between the shrub and herb layers (Table 5, Table 6, and Fig. 9). The multiple regression analysis (MLM) showed that the diversity index of the shrub layer calculated by Shannon's index was mainly affected by soil pH, which accounted for 26.08% of its importance. Similarly, Margalef's index was primarily influenced by pH, with an importance value of 29.81%. When considering Pielou's index, the dominant influencing factor was found to be altitude, with an importance of 19.53%. On the other hand, fire regimes emerged as the most influential factor for Simpson's index, with an importance value of 19.92%. Moving on to the herb layer, both Pielou's index and Shannon's index were predominantly affected by tree diameter at breast height, with importance values of 30.57% and 26.25% respectively. Lastly, Simpson's index in the herb layer was primarily influenced by altitude, with an importance value of 17.51%.

The structural equation model (SEM) revealed the relations among α species diversity indexes of the understory vegetation and their possible influenced factors (Fig. 10). For the shrub layer (Fig. 10a), it existed significant negative correlations between Simpson's index and Shannon's index and fire (prescribed burning), with path coefficients of -0.25 and − 0.34 ($p < 0.01$) respectively (Fig. 10). Additionally, Margalef's index, Simpson's index, Shannon's index, and Pielou's index displayed significant correlations with soil pH, with path coefficients of -0.52, -0.50, -0.47, and − 0.34 ($p < 0.05$) respectively. Similarly, Simpson's index, Shannon's index, and Pielou's index exhibited positive correlations with altitude, with path coefficients of 0.44, 0.37, and 0.54 ($p < 0.01$) respectively. For the herb layer (Fig. 10b), Simpson's index had a significant correlation with fire (prescribed burning) and altitude with path coefficients of 0.46 and 0.72 ($p < 0.001$) respectively. Additionally, Shannon's index was found to be significantly influenced by tree diameter at breast height and soil pH, with path coefficients of 0.78 and

0.31 ($p < 0.001$) respectively, and Pielou's index was also significantly correlated with tree diameter at breast height and soil A-N, with path coefficients of 0.72 and 0.44 ($p < 0.01$) respectively.

Density represents tree density, Trees.H represents tree height, C/N represents soil total carbon/total nitrogen, A-K represents soil available potassium, A-P represents soil available phosphorus, A-N represents soil hydrolyzable nitrogen, SOC represents soil organic carbon, DBH represents tree diameter at breast height, Fire represents prescribed burning, Alt represents altitude. The size of the circle represented the importance of each variable. Orange represented a positive correlation, blue represents a negative correlation. The darker the color, the stronger the correlation. The bar graph represents the total explanatory power of canopy structure factors, environmental factors, and soil nutrient factors on plant diversity variation.

Density represents tree density of overstory, DBH represents tree diameter at breast height, Fire represents prescribed burning, A-K represents soil available potassium, SOC represents soil organic carbon, A-N represents soil hydrolyzable nitrogen. Red represents negative correlation, black represents positive correlation, dashed lines represent insignificant correlations. Solid lines represent significant causal relationships between two variables, with significance levels of $P < 0.05$ (*), 0.01 (**), and 0.001 (***)

4. Discussion

Prescribed burning had minimal impacts to overstory trees of the *Pinus yunnanensis* forest (Franklin et al. 2003; Bassett et al. 2020; Cowman and Russell 2021), while its effects on understory were relatively larger (Penman et al. 2008; Fuentes et al. 2018).

Prescribed burning altered species composition in the shrub layer of the understory and impacted species individual amount and the height of shrubs layer species with frequent burning resulting a decline of species richness for species taller than 1 m and a relative increase of smaller species less than this height, this was similar with the effects of frequency fire on shrubby dry sclerophyll forests of south-eastern Australia (Penman et al. 2008), Mediterranean-Climate Shrublands (Van Wilgen et al. 2010) and understory vegetation of Arizona ponderosa pine forests (Fowler et al. 2008), a *Pinus halepensis* forest in Northeastern Spain (Fuentes et al. 2018), and Appalachian oak-dominated forests (Perles et al. 2021). Three years after prescribed burning, species richness of the shrub layer in the prescribed burning plots is still clearly lower than that in unburned plots (McCaw 2013), McCaw (2013) showed the effects of prescribed burning on the Shannon-Winner diversity index (H'), Simpson's dominance index (D), Margalef's richness index (F), and Pielou's evenness index (E_H) of understory of *Pinus halepensis* forests in Northeastern Spain were negative. On the contrary, Perles et al. (2021) indicated understory species richness of Appalachian oak-dominated forests was not affected by burning, and Borden et al. (2021) showed periodic burning increase understory plant density and diversity of an open New England woodland and caused a shift in understory composition. The varied impacts of prescribed burning on understory of forests might because the different of forest types and the post-fire time (Eales et al. 2018; Borden et al. 2021; Perles et al. 2021). Missing the saplings of *Pinus yunnanensis*, *Schima wallichii*, *Quercus acutissima* and *Lithocarpus mairei* in understory this *Pinus yunnanensis* forest after prescribed burning may affect forest regeneration processes and the future of the forest ecosystem (Casals et al. 2016), Perles et al. (2021) also showed prescribed burning promoted oak seedlings over maple seedling of Appalachian oak-dominated forests, though it did not affected understory species richness. Prescribed burning obviously declined the height of shrubs, the decreased height of shrubs in burned area may strongly reduce fuel load and spatial continuity (Fuentes et al. 2018).

Prescribed burning has been shown to enhance species richness of herbaceous plants in *Pinus yunnanensis* forests, with the highest increase observed in pioneer plants belonging to the Compositae and Gramineae families. These findings align with the effects of frequent fires on herbaceous vegetation in upland oak forests in the eastern United States (Burton et al. 2011). The dominant species in the herb layer remained unchanged in the prescribed burning plots, while the changes in herbaceous understory abundance and height were also minimal, resembling patterns observed in Ponderosa Pine forests (Kerns et al. 2006; Cowman and Russell 2021).

Fires could directly impact the structure of forest plant communities and indirectly influence them by altering soil nutrient content (Scharenbroch et al. 2012; Weiser et al. 2021; López-Cruz et al. 2022). Our study also indicated that fire is the most influential factor affecting species diversity in the shrub layer, the α diversity index of the shrub layer exhibited a significant correlation with soil pH, A-K, and A-P content, while the α species diversity of the herbaceous layer was closely related to soil pH, SOC, and A-N.

5. Conclusions

We here investigated the impact of prescribed burning on plant community structure characteristics of the understory in the *Pinus yunnanensis* forests of central Yunnan. We compared the plant community structure in a prescribed burning area with an unburned area. Results showed:

(1) Prescribed burning significantly altered the structure of the understory vegetation community in the shrub layers of the *Pinus yunnanensis* forests. The number of species in the shrub layers decreased from 26 to 19, and all tree saplings disappeared. Additionally, the dominant species in the shrub layer changed from *Lithocarpus mairei* to *Duhaldea cappa*, and there was a considerable decrease in the height of shrub layer species. The Shannon-Winner diversity index (*H'*), Simpson's dominance index (*D*), and Margalef's richness index (*F*) for the shrub layer experienced a significant decrease.

(2) Prescribed burning had a slight effect on the species composition in the herb layers. It increased the number of herbs from 27 to 40, the effects of prescribed burning on species abundance, height and α diversity indexes of herbs was minimal, though there was an overall increase in the height of most herbs. Although the effects of prescribed burning on overstory were little, our study demonstrated that prescribed burning partly altered the community structure of the understory vegetation in *Pinus yunnanensis* forest, particularly the shrub layers.

(3) The impact of prescribed burning on the species composition of shrub layers and herb layers was found to be influenced by other factors. Prescribed burning emerged as the primary factor shaping the

community structure and species diversity of the shrub layer, whereas the diversity of herbaceous plant species was largely influenced by forest canopy structure factors and soil nutrient levels.

Declarations

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Author Contributions:

Conceptualization, Xiaona Li, Qiuhua Wang, Huiping Pan and Lizhen Jiang; data curation, Huiping Pan and Lizhen Jiang; investigation, Xiaona Li, Huiping Pan, Han Yang, Lizhen Jiang and Jin Wang; methodology, Xiaona Li, Qiuhua Wang, Yuanjie Xu, Huiping Pan and Lizhen Jiang; formal analysis, Xiaona Li, Huiping Pan and Yinqianxue Pan; writing—original draft, Xiaona Li, Huiping Pan, Lizhen Jiang and Yuanjie Xu; investigation, Xiaona Li and Qiuhua Wang; project administration, Xiaona Li and Qiuhua Wang; supervision and funding acquisition, Xiaona Li and Qiuhua Wang. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

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Figures

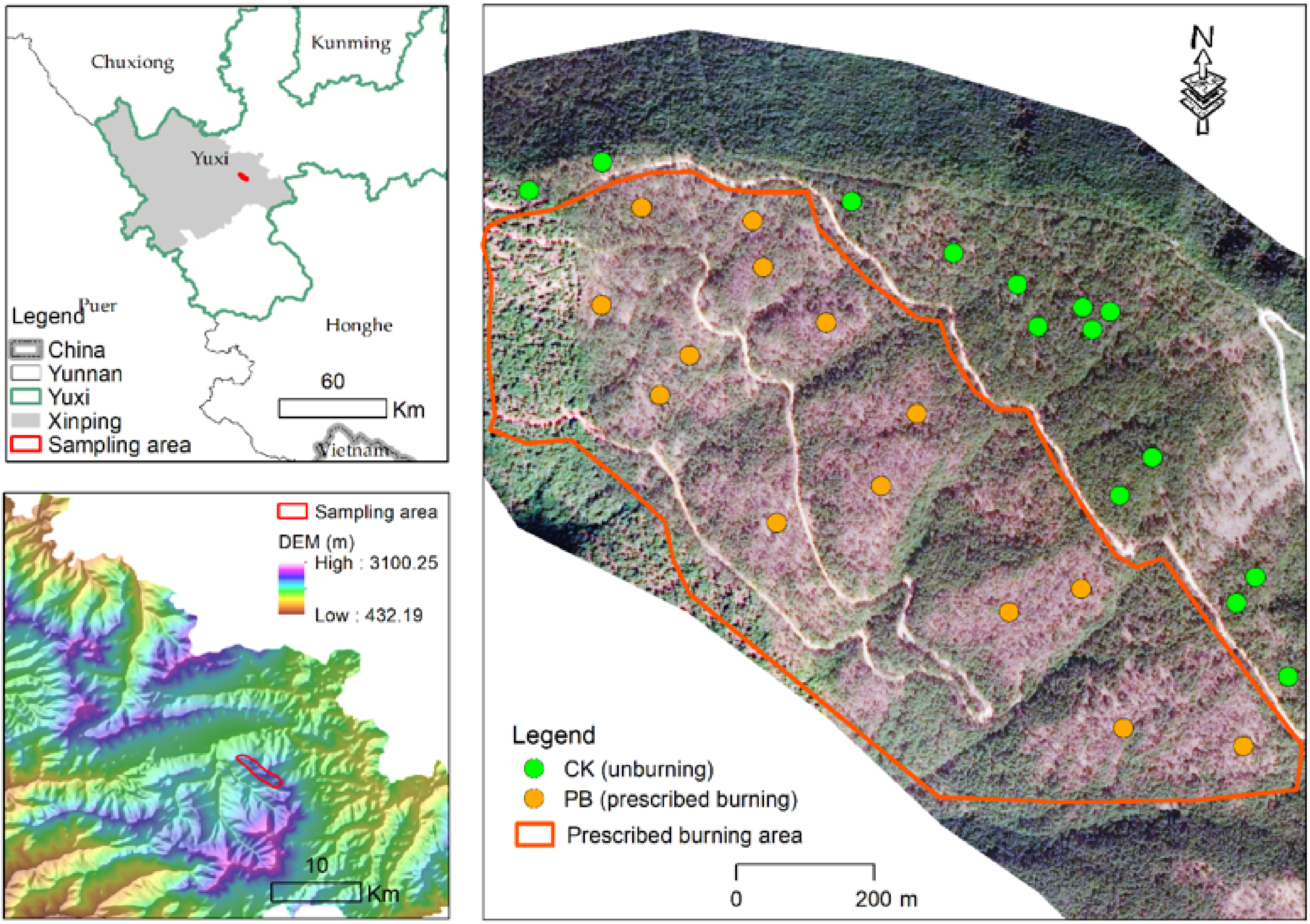

Figure 1

Sampling spots in the study area

Figure 2

The understory plant characteristics between unburned areas and prescribed burning areas

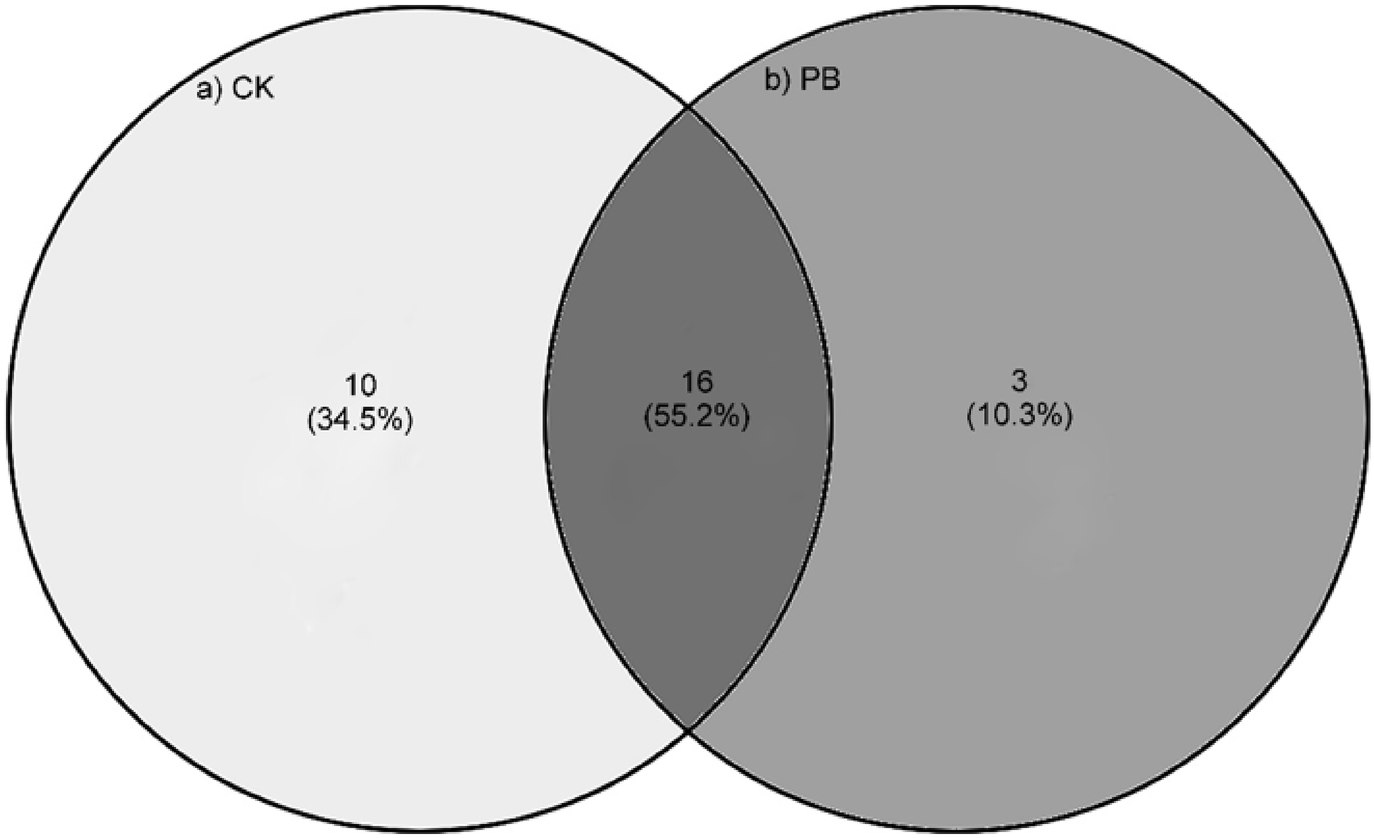

Figure 3

Fig. 2 The number of plant species of shrub layers in unburned (CK) and prescribed burning (PB) sampling sites

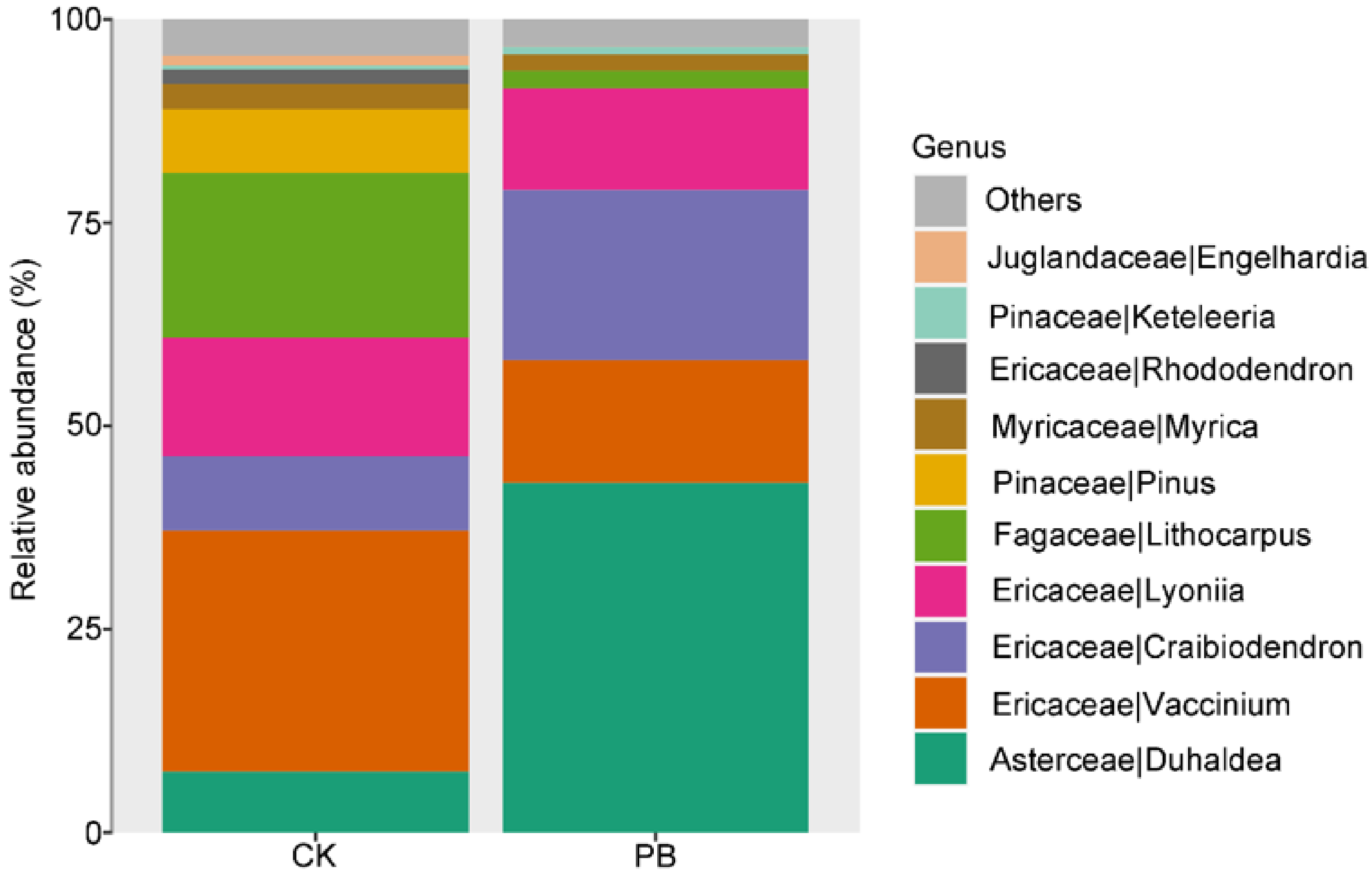

Figure 4

Fig. 3 Top ten genera of plant abundance in shrub layers

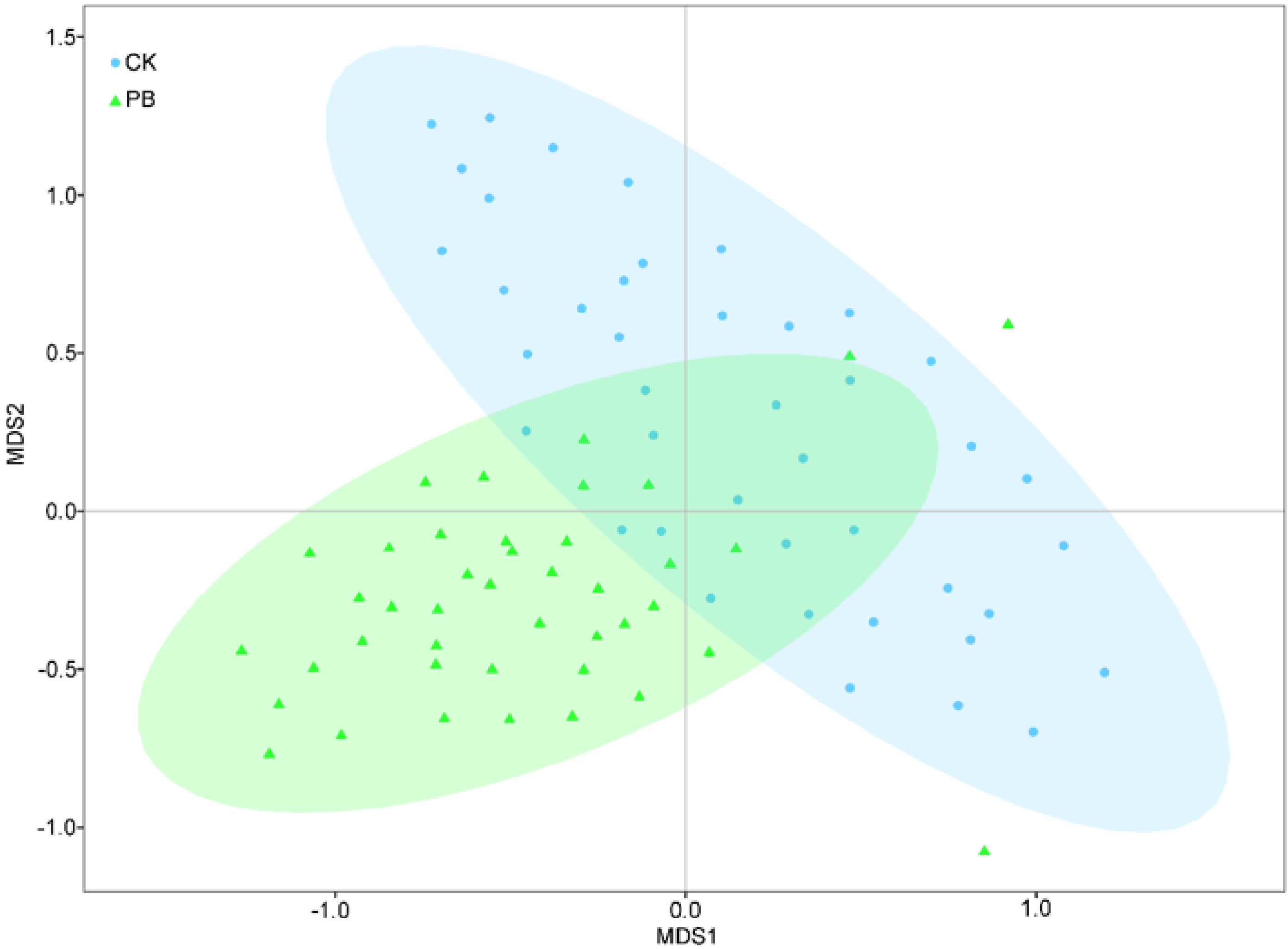

Figure 5

Fig. 4 Two-dimensional NMDS visualization of community composition in the shrub layer (CI=95%, C represented unburned plots, and PB represented prescribed burning plots

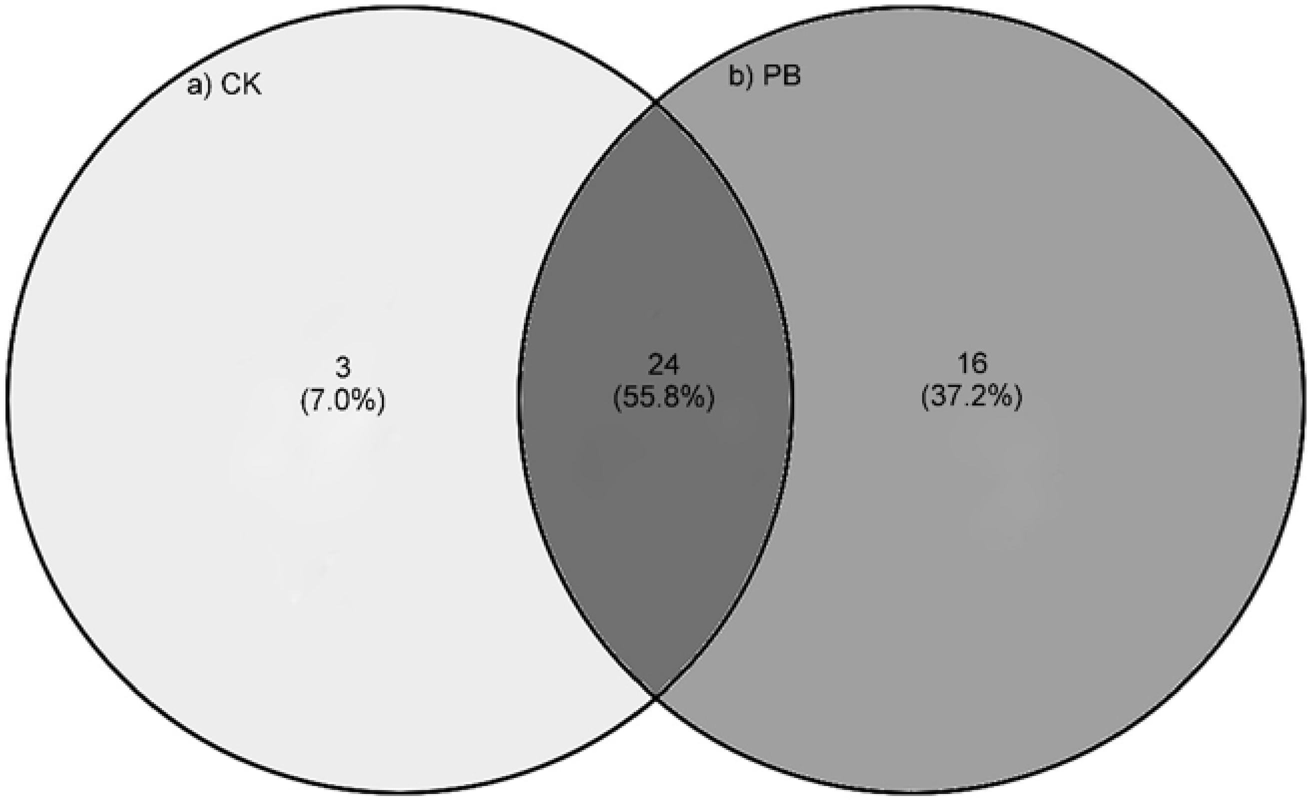

Figure 6

Fig. 5 The number of plant species of herb layers in unburned (CK) and prescribed burning (PB) sites

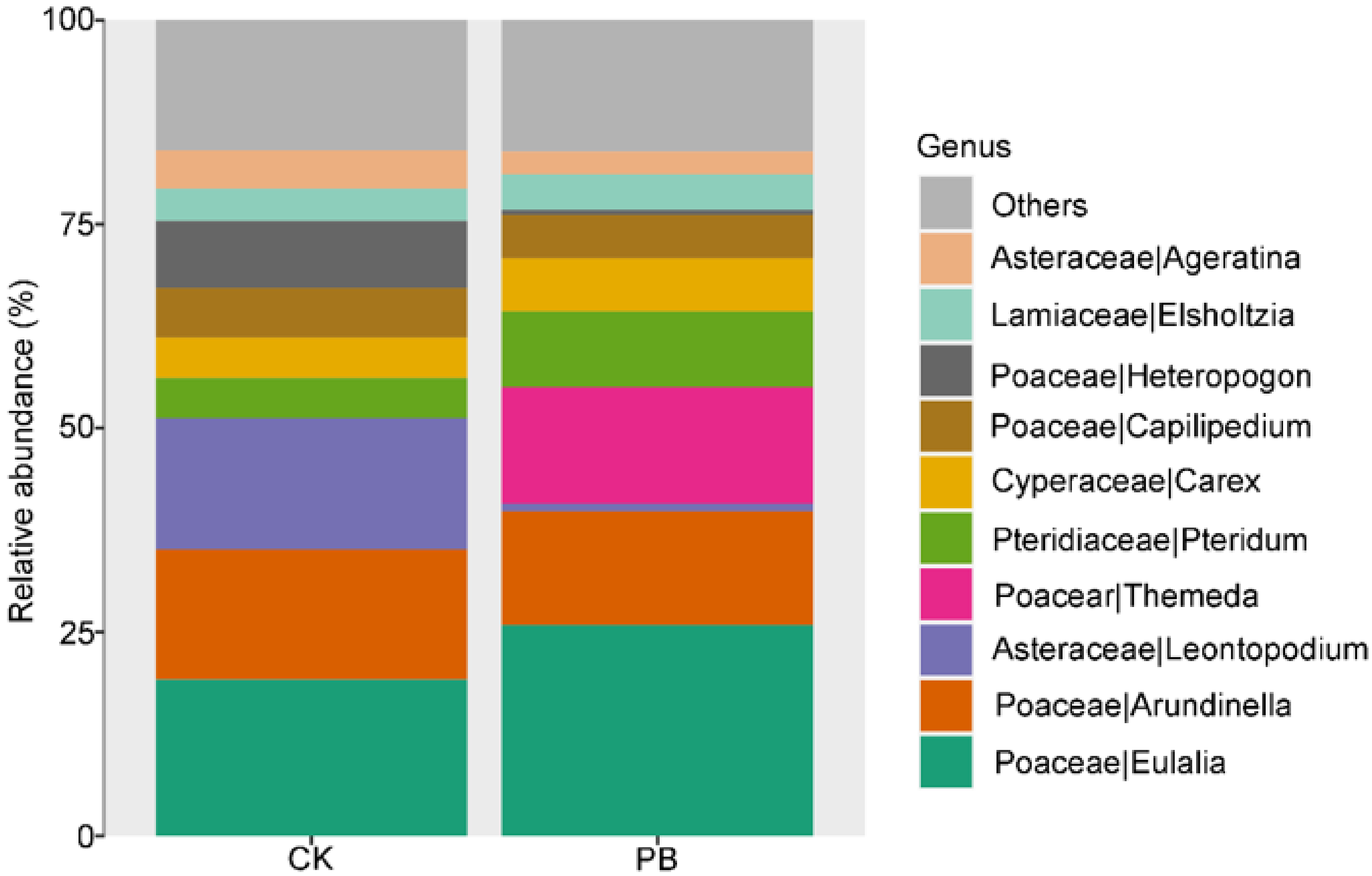

Figure 7

Fig. 6 Top ten genera of plant abundance in herb layers

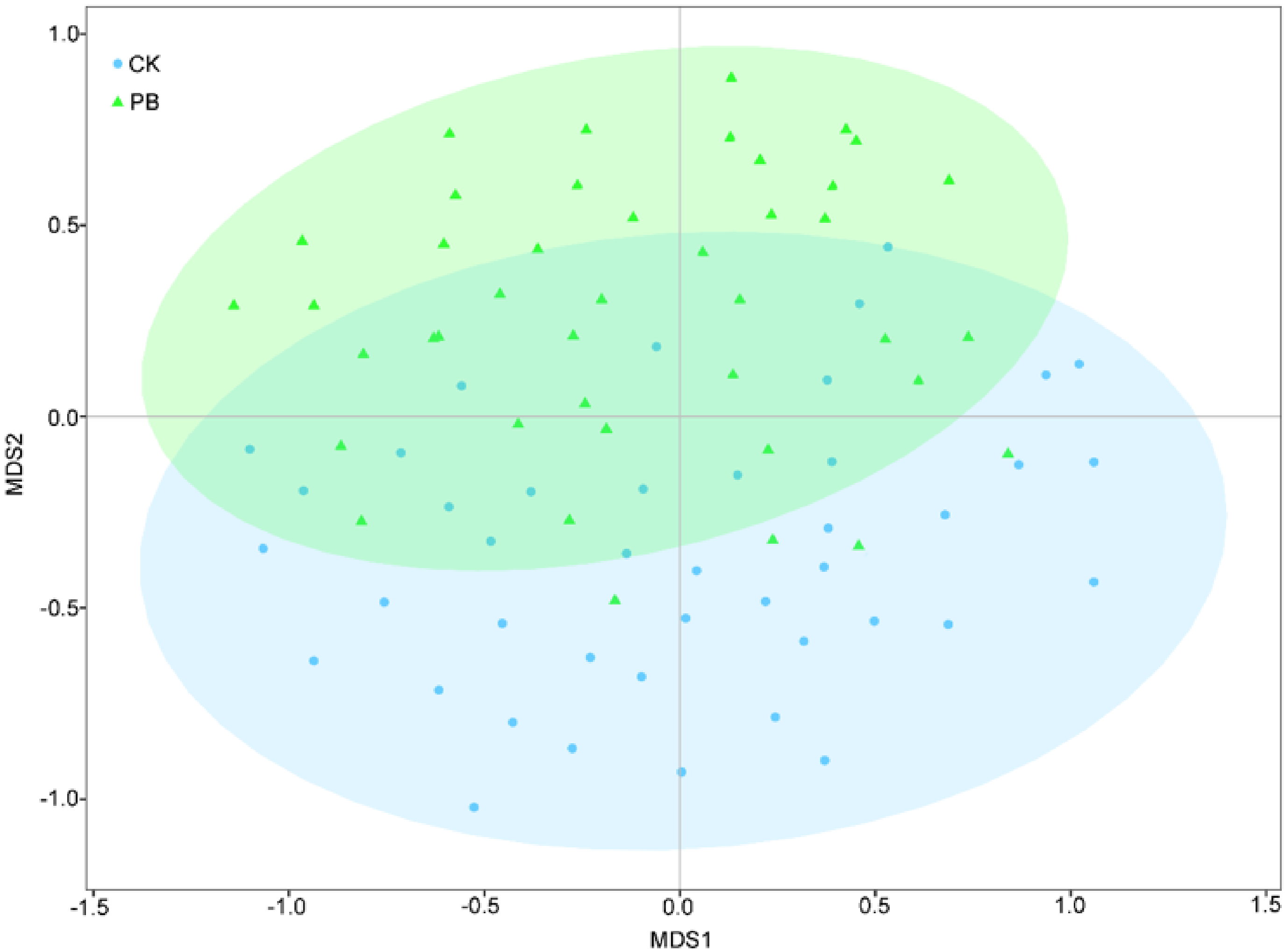

Figure 8

Fig. 7 Two-dimensional NMDS visualization of community composition in herb layers (CI=95%, C represented unburned plots, and PB represented prescribed burning plots

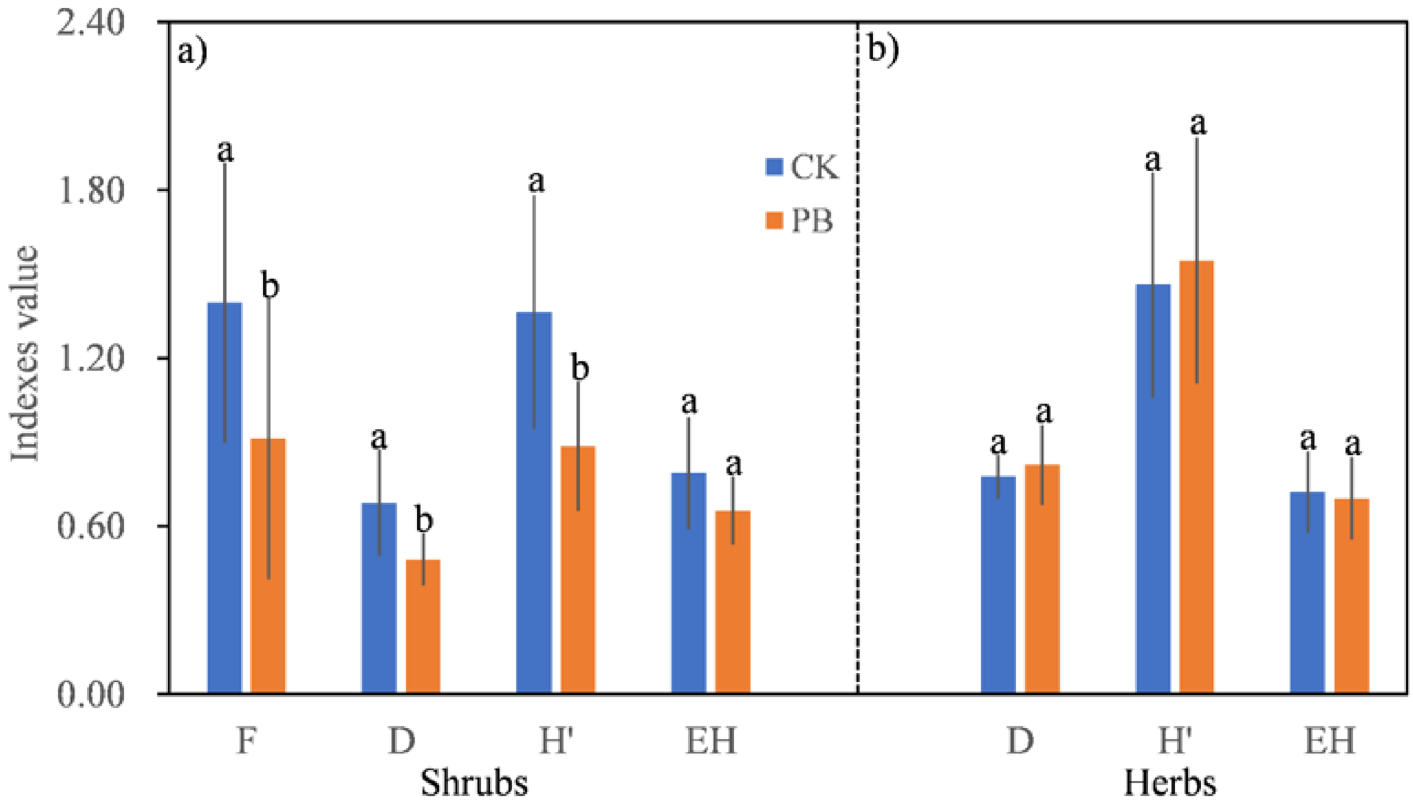

Figure 9

Fig. 8 Diversity indexes of understory in burned plots and unburned plots (*p*< 0.05 *, *p* < 0.01 **)

The same letter represents no significant difference, different letters indicate a significance level of α=0.05.

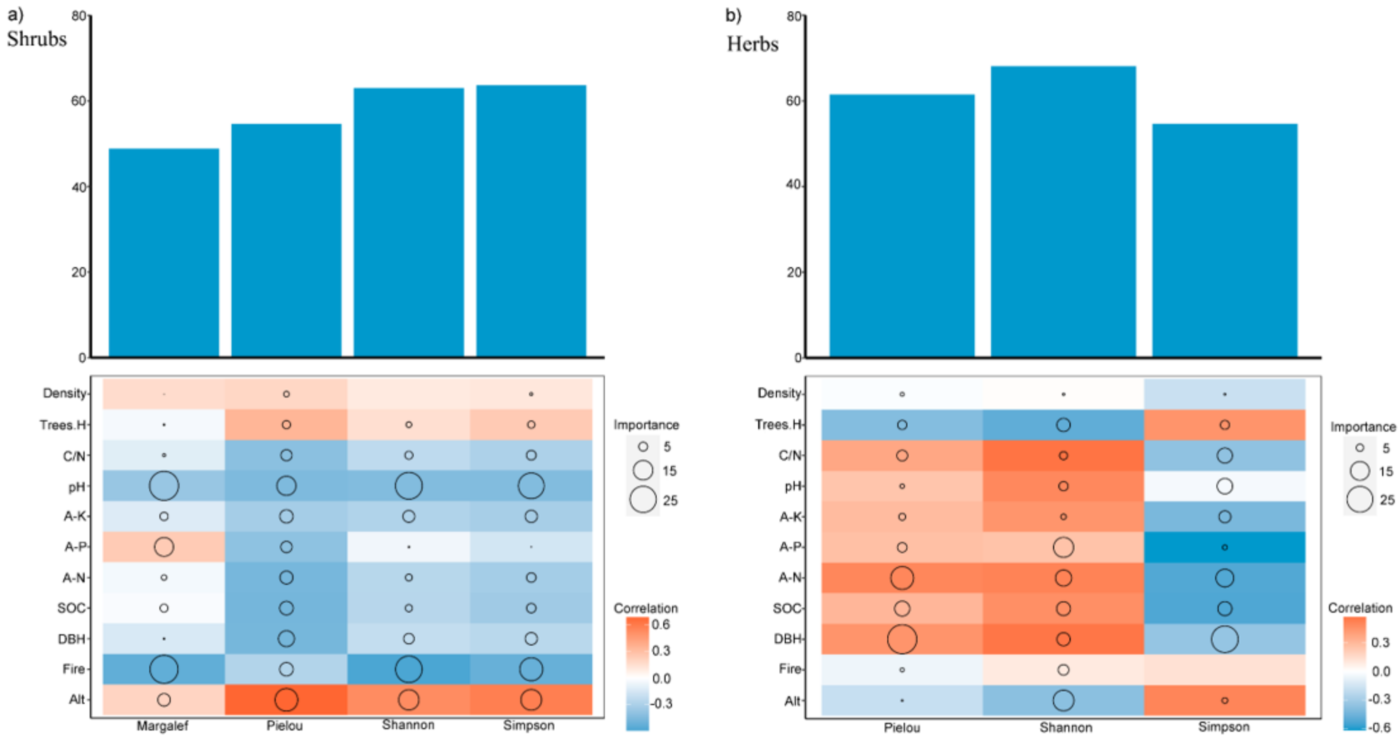

Figure 10

Fig. 9 Spearman's correlation coefficients between species diversity index and influencing factors

Density represents tree density, Trees.H represents tree height, C/N represents soil total carbon/total nitrogen, A-K represents soil available potassium, A-P represents soil available phosphorus, A-N represents soil hydrolyzable nitrogen, SOC represents soil organic carbon, DBH represents tree diameter at breast height, Fire represents prescribed burning, Alt represents altitude. The size of the circle represented the importance of each variable. Orange represented a positive correlation, blue represents a negative correlation. The darker the color, the stronger the correlation. The bar graph represents the total explanatory power of canopy structure factors, environmental factors, and soil nutrient factors on plant diversity variation.

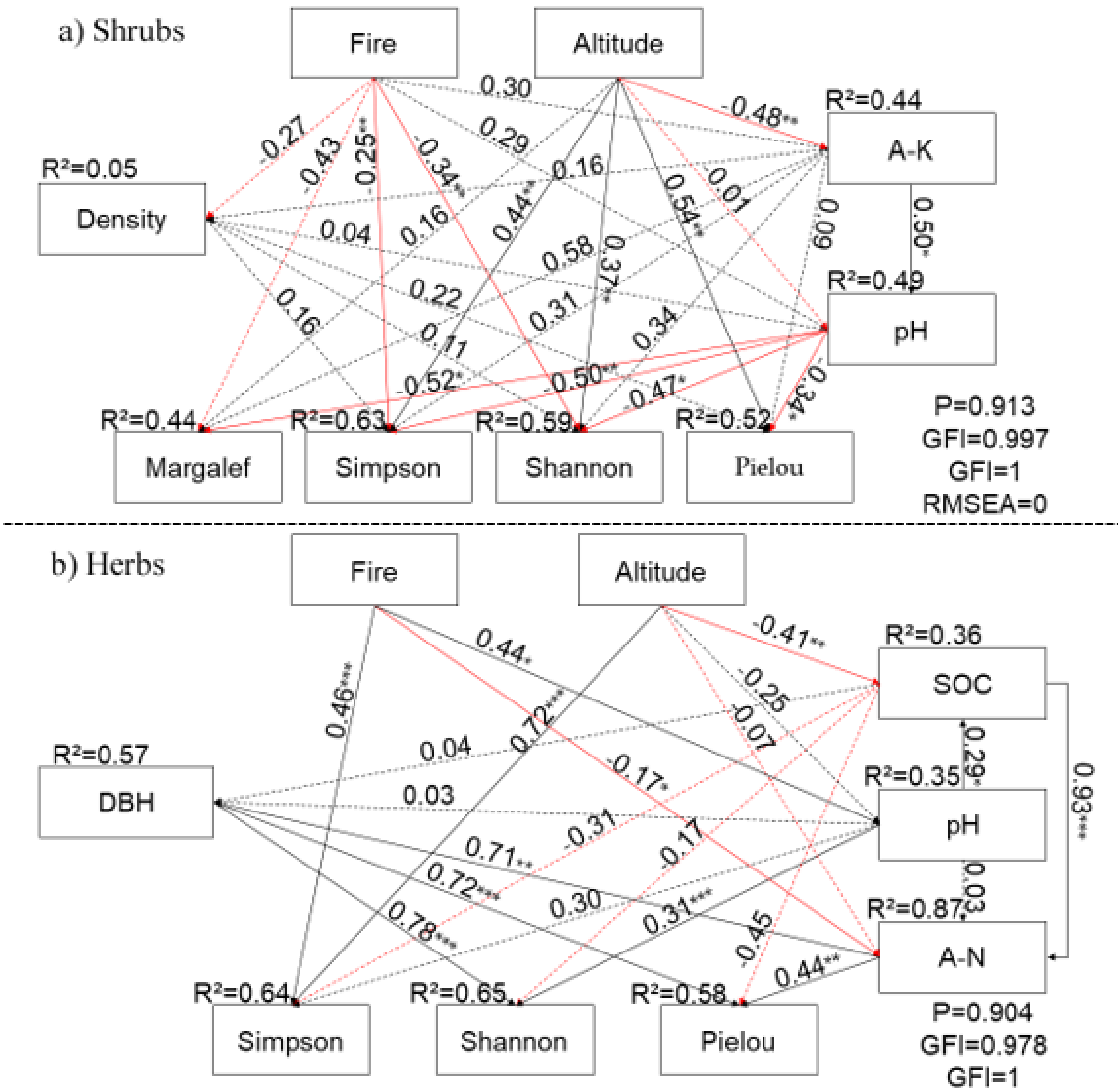

Figure 11

Fig. 10 Relationships among varied factors for the shrub layer and herb layer, respectively

Density represents tree density ofoverstory, DBH represents tree diameter at breast height, Fire represents prescribed burning, A-K represents soil available potassium, SOC represents soil organic carbon, A-N represents soil hydrolyzable nitrogen. Red represents negative correlation, black represents positive correlation, dashed lines represent insignificant correlations. Solid lines represent significant causal relationships between two variables, with significance levels of P<0.05 (*), 0.01 (**), and 0.001 (***)

Supplementary Files

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- supplementarymaterial.docx