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Post-Fire Sprouting Dynamics of *Quercus brantii* Lindl.: Assessing Stem Size Influence and Adaptive Responses to Recurrent Fires

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ABSTRACT

Aims: Persian oak (*Quercus brantii*) relies heavily on sprouting for post-fire persistence. However, the long-term influence of initial stem size and the impact of repeated fires on these sprouting dynamics require clarification. This study aims to (1) quantify the effect of initial stem size on sprout characteristics (number, diameter, height) over several years following a fire and (2) compare these regeneration responses after an initial versus a recurrent fire. This study offers novel insights by examining the dynamics of Persian oak regeneration over several years and across two fire events.
Materials & Methods: Post-fire regeneration of Persian oak was monitored in the Zagros forests, Iran. The study was conducted in the Berjue Protected Area. A total of 76 Persian oak trees were surveyed for four years after a 2019 fire. Sprout number, diameter, and height were measured annually. After a second fire in the fifth year, 18 surviving trees were re-evaluated. Sprouting trends were analyzed using ANCOVA and regression models. A Combined Growth Index (CGI) was developed to assess overall sprout performance.
Findings: Sprouting declined over time, with the number of sprouts per stem decreasing by more than 50% in trees with fewer than three initial stems. Initial stem size significantly influenced long-term regeneration ($P<0.01$). Trees with 7–9 initial stems showed the most remarkable diameter growth (up to 0.9 cm.y-1), while the tallest sprouts (averaging 170 cm) were found in trees with fewer stems. Following the second fire, the mean sprout count dropped from 9.6 to 5.1 per stem, indicating reduced regeneration capacity. However, sprout diameter, height, and CGI showed no significant decline, suggesting sustained growth performance despite recurrent fire exposure.
Conclusion: The initial number of stems, competition, and resource allocation determines the sprouting pattern. To support oak regeneration and ecosystem resilience, managers should implement selective thinning to reduce intra-stem competition and use low-intensity prescribed burns to minimize damage while promoting sprouting in fire-adapted individuals. It is essential to avoid recurring fires at short time intervals to allow adequate recovery time, preventing severe regeneration decline.

Keywords: Sprouting Dynamics; Stem Size Influence; Oak Forest Resilience; Fire Ecology; Coppice Regeneration.

CITATION LINKS

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Introduction

Wildfires are increasingly frequent in many forested regions worldwide, driven by climate change, land-use practices, and prolonged drought. These events trigger substantial environmental changes, affecting soil properties, hydrological cycles, atmospheric conditions, and patterns of biodiversity. These disturbances can drastically alter vegetation cover, disrupt ecosystem processes, and affect species regeneration dynamics [1]. Extensive research on forest regeneration after fire has focused primarily on seedling recruitment, while the role of sprouting as a strategy for persistence is increasingly recognized [2]. Among all woody species, oaks possess remarkable sprouting adaptations to frequent fires [3]. Recent studies have confirmed that vegetative regeneration through sprouting is a key mechanism enabling oak forests to recover and maintain their ecological function in fire-prone environments [4,5]. Consequently, understanding the dynamics of oak sprouting is crucial for the sustainable management and conservation of fire-prone forests [6,7].

Given this background, Persian oak (*Quercus brantii* Lindl.), an essential species in the Zagros forests, demonstrates exceptional sprouting capacity, allowing it to regenerate quickly after fire events [8]. Studies show that the rate of sprouting is influenced by several factors, including fire severity and pre-fire stem density [8-10]. In some cases, these oak stands recover rapidly and transition to younger stands dominated by sprouts [8,9]. However, fire-induced changes in forest composition have also been observed, with an increased presence of pioneer species such as hawthorn and wild almonds over time [10]. These observations underline the dual nature of fire, both as a regenerative force and as a driver of ecological change. These patterns align with broader observations of forest dynamics, where shifts in species composition and structural development have been reported [11,12].

Stem size, typically measured by trunk diameter and height, is a significant factor in post-fire regeneration, influencing both the initial sprouting response and the long-term survival of shoots [8,13,14]. Smaller stems often produce a higher number of sprouts immediately after fire due to their greater bud density and reduced bark thickness, which enables faster resource mobilization [8]. However, these advantages may be short-lived, as smaller stems are also more vulnerable to complete top-kill during high-severity fires and may lack the root carbohydrate reserves needed to sustain long-term growth [15]. In contrast, larger stems tend to produce fewer sprouts initially but have a greater capacity for sustained sprout development, thanks to their thicker bark, elevated bud positions, and deeper carbohydrate stores [16, 17].

This variability in sprouting response highlights the need to examine not only stem size but also how post-fire competition and resource allocation evolve. Over time, competition among sprouts leads to self-thinning, where only the most vigorous stems survive and continue growing. This dynamic results in a trade-off: trees with numerous initial sprouts may undergo more intense competition, while those with fewer but more robust stems may allocate resources more efficiently toward structural development [18]. Despite recent advances in sprouting ecology, few studies have evaluated the long-term effects of recurrent fires on stem performance in oak forests [13,19]. Furthermore, factors such as apical dominance and resource partitioning influence the direction of growth, favoring either height or diameter, depending on environmental conditions and fire history [20,21]. However, previous studies have predominantly focused on the effects of stem size following a single fire event, neglecting the impact of repeated fires (fire recurrence) on sprouting dynamics [13].

Fire recurrence is a key, yet little-studied, factor that significantly influences forest regeneration patterns [22]. While Persian oak forests show strong post-fire regeneration, their ability to persist with increasing fire recurrence remains uncertain. The resilience of oak populations depends on the ability of trees to maintain their regeneration capacity after several fires or on the progressive weakening of their reserves by successive disturbances, ultimately leading to resprouting failure [1,7,22]. Over time, recurrent fires can reduce oak dominance, facilitating the expansion of faster-growing, disturbance-adapted species [9,10,23]. Given the increasing frequency of fire events across the Mediterranean and West Asia, understanding species-specific thresholds for regeneration failure has become a critical research priority. Such changes are of growing concern in Zagros forests, where land-use change and disturbance have also been shown to alter biomass dynamics and carbon storage [24,25].

To better understand the resilience of oak forests in fire-exposed ecosystems, this study examines the long-term sprouting dynamics of *Quercus brantii* following initial and recurrent fire events. Based on existing literature, it is expected that stem size plays a decisive role in shaping sprouting behavior and that recurrent fires reduce regeneration potential by depleting reserves —a pattern especially relevant in sprouting-dependent species, such as Persian oak. Therefore, we hypothesize that (1) smaller stems will exhibit higher initial sprouting but reduced long-term performance compared to larger stems and (2) sprouting response after a second fire will be significantly lower than after the first, both in terms of sprout number and overall growth, due to resource depletion and structural damage. This study aims to (a) quantify the relationship between stem size and sprout traits (number, diameter, and height) across multiple years post-fire and (b) compare regeneration responses after initial and recurrent fire events to assess the long-term resilience of Persian oak stands.

Figure 1) The Berjue Protected Area, highlighted in green, is situated within the Zagros Mountains of central Iran. This site is close to the villages of Berjui and Kalamui and is adjacent to the Vanak River valley. The red dots indicate the approximate location of the initial fire.

Materials & Methods

Study Site

The Berjue Protected Area is located in central Iran, within the Zagros Mountains. It covers 55 hectares and is enclosed by a protective fence. The area features a sparse, south-facing coppice structure and is located near the villages of Berjui and Kalamui, overlooking the Vanak River valley. The average elevation is 2,120 meters. The region receives approximately 503 mm of rainfall annually, mostly in winter, and has a mean annual temperature of 12°C. According to the Köppen climate classification, the climate is classified as Csb (Mediterranean, dry summer). Soils in the area are deep calcareous clay loam, supporting around 40 native Irano-Turanian plant species. Among them are nine tree and shrub species, with Persian oak (*Quercus brantii*) being dominant and accounting for about 93% of the tree population.

Pre-fire stand characteristics, recorded as part of a B.Sc. final project conducted by forestry students at Shahrekord University, documented a tree density of 343 stems per hectare, a mean canopy cover of 66.25%, a mean diameter of 11.2 cm, a dominant height of 9.4 m and an average standing volume of 34.4 m^3 per hectare (unpublished institutional data).

Fire Events

In the first week of September 2019, a wildfire impacted a portion of the study area, consuming hundreds of trees and shrubs with varying intensities. Fire types ranged from crown fires in the foothills to surface fires on the hilltops, completely incinerating ground vegetation, including wild almond and daphne shrubs. Newly emerged shoots were entirely burned, while some trees suffered crown scorching, and a limited number exhibited trunk charring.

After the fire, 76 Persian oak trees, each comprising multiple stems (coppices), were marked for long-term monitoring. The fire primarily impacted the crowns, leaving the lower portions (stumps) largely intact. Sprouting dynamics of these trees were monitored annually through the fourth year post-fire. In the third year, a cleaning cut (topping) was performed to remove burned and dead crown branches. A second surface fire occurred in August 2023, five years after the initial 2019 fire. This fire was less intense and primarily affected the western portions of the previously burned area. It burned accumulated ground litter, herbaceous vegetation, and newly sprouted oak. Although fire intensity was lower than in the first event, some smaller oak stems experienced complete top-kill, resulting in total sprout loss and an inability to regenerate. Of the original 76 monitored trees, 18 individuals survived both fires with at least one living stem and were selected for continued monitoring. Resprouting measurements for these trees were taken two years after the second fire. Figure 2 depicts the resprouting stages following both fire events and the timing of crown topping.

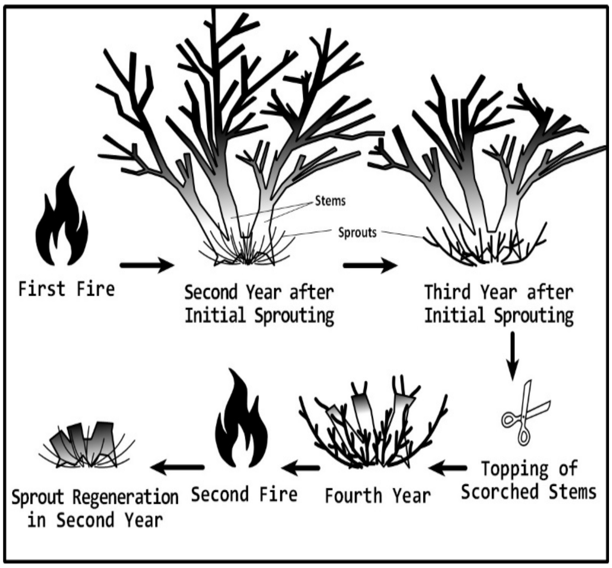

Figure 2) Sprouting stages of *Quercus brantii* following two fires and crown topping. The timeline shows initial sprouting after the first fire, topping of scorched stems in year three, and sprout regeneration after a second fire in year five.

Post-Fire Monitoring and Measurements

Sprouting was recorded at the end of each growing season, focusing on the number of vegetative sprouts emerging from each stem base. Sprout diameters were measured to the nearest 0.5 cm using calipers, and sprout height was measured to the nearest cm with a measuring rod.

Data Analysis

Temporal trends in sprout diameter, height, and number per stem from years two to four post-fire were evaluated using linear regression, reporting mean slope values across initial stem size classes. ANCOVA, with initial stem count as a covariate, analyzed variations in these sprout metrics. Resprouting probability was modeled using ordinal logistic regression, categorizing sprout numbers into three quartile-based levels, with sprouting response as the dependent variable and fire history as the predictor variables [19]. Sprout metrics were normalized using an $(X - Min)/(Max\text{-}Min)$ formula, where X represents sprout number, diameter, or height, with Min and Max denoting their respective range within each fire event [26]. A Combined Growth Index (CGI) was calculated as a weighted sum of these normalized values, with weights based on Pearson correlations between fire incidence and each metric [27]. ANCOVA, with individual trees as a covariate, compared sprouting dynamics and CGI between the first and second fires, followed by Fisher's LSD post hoc tests at 95% confidence to identify significant differences.

Findings

Temporal Dynamics of Sprout Growth

The temporal trends in sprouting dynamics from the second to fourth years post-fire showed variability across initial stem number classes. Sprout density per stem decreased progressively from Year 2 to Year 4, with the steepest declines observed in trees with fewer than three initial stems. The mean slope of sprout number per stem declined across all classes, indicating a decrease in sprouting density over time. Trees with fewer than three initial stems experienced the most significant reduction in sprout production, while those with the highest initial stem counts exhibited the least decline (Figure 3).

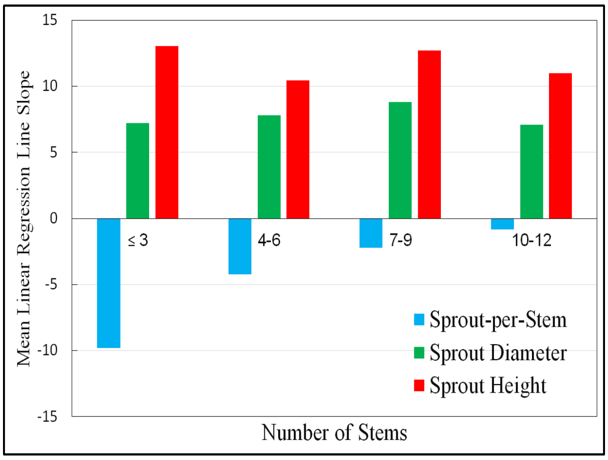

Figure 3) Temporal trends in sprout number, diameter, and height by initial stem number classes, based on the slope of linear regression.

Sprout diameter and height increases followed distinct patterns. The most remarkable diameter growth was observed in trees with 7–9 initial stems, while the highest height increase occurred in trees with the fewest initial stems and those with 7–9 initial stems (Figure 3).

ANCOVA confirmed significant effects of both year and initial stem count on all sprouting metrics (number, diameter, and height). Sprouting responses varied significantly across the years. The number of sprouts per stem showed a significant effect on year ($F = 6.11$, $p < 0.01$) and stem count ($F = 124.12$, $p < 0.001$). Post hoc comparisons (Fisher LSD) indicated that sprout numbers were significantly higher in Year 2 than in Year 4, while Year 3 was not significantly different from either group (Figure 4). Sprout diameter also differed significantly among years (F = 153.16, p < 0.001), with Year 4 producing the thickest sprouts, followed by Year 3 and Year 2 (Figure 4). Stem count was also a significant predictor of sprout diameter (F = 86.9, p < 0.001). Sprout height showed the most substantial interannual variation (F = 211.06, p < 0.001 for year and F = 93.16, p < 0.001 for stem count). Average sprout height increased progressively from Year 2 to Year 4, all differences being statistically significant (Figure 4).

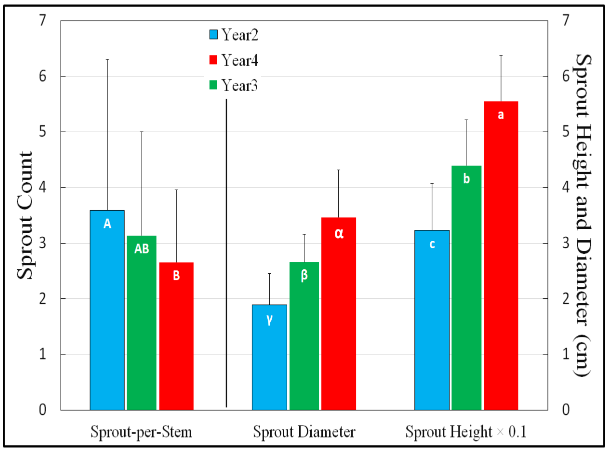

Figure 4) Temporal changes in post-fire sprouting traits. Means sharing the same capital, small, or Greek letters are not significantly different based on Fisher's LSD post hoc test (p < 0.05).

Sprouting Probability

Sprouting probability declined over time across all quartile groups, as indicated by ordinal logistic regression. Higher quartiles, representing greater sprout production per stem, consistently showed lower probabilities compared to lower quartiles. At Year 2 post-fire, the estimated probability of a stem falling into quartile 1 (lowest sprout number category) exceeded 80%, while probabilities for quartiles 2 and 3 were 57% and 30%, respectively. By Year 4, these probabilities further declined to 63%, 36%, and 15%, respectively.

Sprouting probability per stem declined over time across all measured factors, including initial stem count, diameter, and height. Regarding stem count, trees with three or fewer initial stems exhibited the highest sprouting probability, which progressively decreased as stem number increased, reaching its lowest in the 10–12 stem class (Figure 6A). Stem diameter also influenced sprouting probability, with larger stems generally displaying a higher initial likelihood of sprouting. Stems in the 20–25 cm diameter class had the highest probability, reaching up to 50%, whereas all other diameter classes did not exceed 22% in Year 2 (Figure 6B). Similarly, stem height played a role, with taller stems showing the most significant sprouting probability (up to 32% in Year 2). However, in the shortest stem height classes, this probability declined to 22% over the same period (Figure 6C).

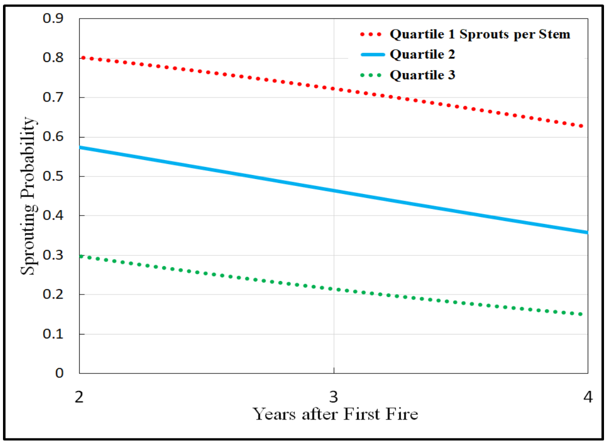

Figure 5) Sprouting probability over time across quartiles of sprout production per stem. Quartile 1 showed the highest probability, while Quartile 3 had the lowest.

Impact of Repeated Fires on Sprouting

The number of sprouts per stem was significantly influenced by fire history (F = 9.8, p = 0.004), while individual tree effects were non-significant (p = 0.893). Post hoc analysis indicated a significantly higher mean sprout count following the first fire compared to the second, suggesting that repeated fire exposure diminished sprouting potential. Sprout diameter showed no significant differences between fire events (F = 0.08, p = 0.774), nor was it influenced

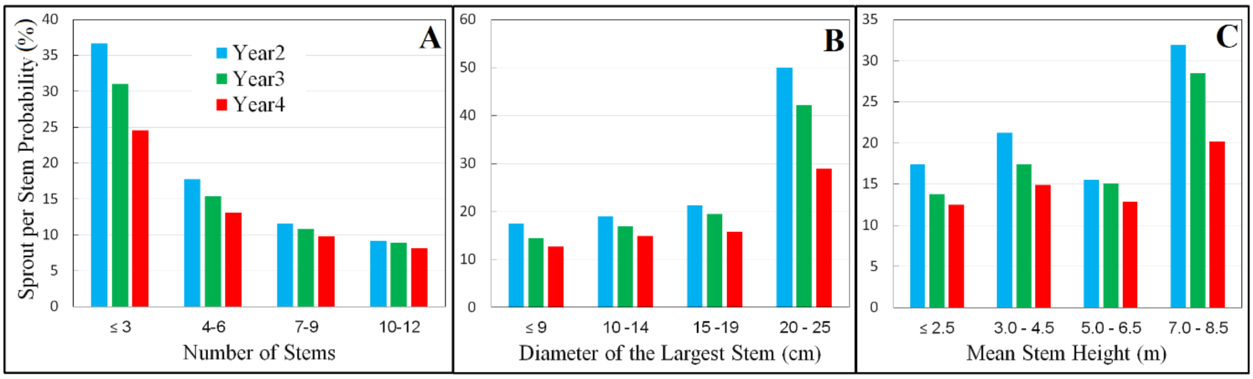

Figure 6) Sprouting probability per stem over time based on initial stem count (A), diameter (B), and height (C).

by individual tree variation (p = 0.163). Similarly, sprout height did not significantly differ between fire events (F = 0.03, p = 0.86); however, individual tree effects were significant (F = 5.42, p = 0.026), indicating that tree-specific factors contributed to height variation. Neither fire history (F = 0.6, p = 0.443) nor individual tree variation (F = 3.55, p = 0.068) had a significant effect on CGI, indicating that overall sprout growth, when normalized across all metrics, remained stable between the two fire events.

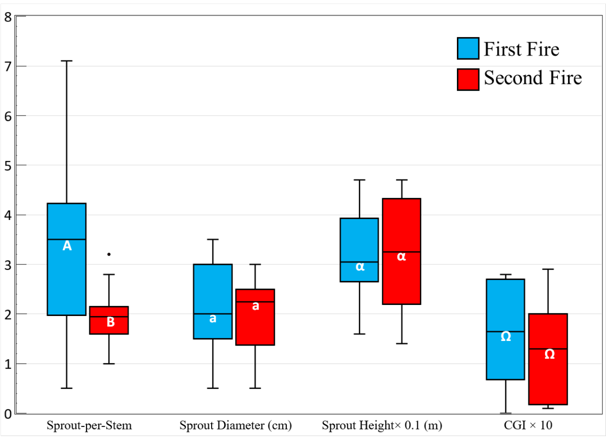

Figure 7) Comparison of sprouting traits after the first and second fires. Significant differences (p < 0.05) were determined using Fisher's LSD post hoc test. This means sharing the same letter is not significantly different.

Discussion

This study was designed to investigate two key objectives: (1) to assess how initial stem size influences sprouting traits (number, diameter, height) over several years after fire and (2) to compare regeneration responses after an initial versus a recurrent fire. Our findings support both objectives, providing new insight into the long-term regeneration dynamics of *Quercus brantii* in fire-prone environments.

Temporal Dynamics of Sprout Growth

Our results showed a noticeable decline in sprouting density over time, particularly in trees with fewer than three initial stems, indicating higher vulnerability in these individuals. This pattern supports the hypothesis that initial stem structure influences post-fire recovery and reflects a self-thinning process commonly observed in oak regeneration systems [3,13]. The rate of decline was closely linked to initial stem count, suggesting that competition among sprouts may be a key factor in determining long-term sprout survival. While sprout diameter and height increased over time, their relationship with stem number was non-linear: trees with 7-9 stems exhibited the most substantial diameter growth, whereas both the 1-3 and 7-9 stem classes showed the greatest height gains. These mixed patterns point to a complex resource allocation strategy, as reported in other oak coppice systems [23,28]. The vigorous resprouting capacity of oaks after the fire, documented in various ecosystems [2,29], underscores their resilience; however, our results suggest that the initial stem structure plays a decisive role in modulating this response.

Significant temporal variations in sprout characteristics have been observed, with a decline in sprout number over time, alongside a consistent increase in sprout diameter and height. This pattern suggests a transition from a high-density establishment phase to a phase of structural development [16,30-32]. The reduction in sprout number aligns with post-fire self-thinning dynamics, which likely facilitates resource allocation toward diameter and height growth. Notably, increased sprout diameter can enhance fire resilience [16,33]. However, maintaining a balance between height and diameter is crucial for overall stability [17,34].

Sprouting Probability

Post-fire sprouting probability exhibits a declining trend over time across all quartiles, with stems increasingly falling into lower categories of sprout production. By the second year post-fire, the probability of a stem being in the lowest quartile exceeded 80%, which decreased to 63% by the fourth year, indicating that a reduction phase often follows early, vigorous sprouting. This pattern aligns with well-documented post-fire self-thinning dynamics [13,35] and suggests that stems initially producing more sprouts may experience a steeper decline due to intra-stem competition. Factors such as apical dominance and resource allocation likely influence this trend, with surviving sprouts prioritizing height growth rather than new shoot production [20,36].

Our results indicate that the initial stem count, diameter, and height have a significant impact on the probability of sprouting. Specifically, trees with three or fewer stems had the highest probability of sprouting, while those with 10-12 stems showed the lowest. This inverse relationship suggests that increased stem number intensifies competition for limited resources, reducing the likelihood of successful sprouting, a trend also observed by Kim et al. [13], who reported reduced sprouting vigor in multi-stemmed oaks due to intra-stem competition. Similarly, Dey and Schweitzer [28] found that sprout survival and growth rates declined as initial stem density increased, further supporting the idea that high stem density can compromise resource allocation. Our findings confirm these patterns in *Quercus brantii*, indicating that initial stem architecture is a critical determinant of regeneration success following fire. Larger stems (20–25 cm in diameter) demonstrated the highest sprouting probability, supporting previous research linking thicker stems to greater carbohydrate reserves and enhanced fire resistance due to thicker bark [16]. Conversely, smaller stems showed notably lower sprouting probabilities, likely due to heightened susceptibility to fire-induced top-kill.

Taller stems exhibited the highest early sprouting probability, consistent with findings that critical tissues positioned above the heat zone of surface fires are less vulnerable to fire-induced mortality [30,37]. These patterns suggest a trade-off between initial sprouting vigor, driven by higher stem number or size, and long-term survival, which may be constrained by competition and resource limitations. This underscores the importance of balancing initial stem count, resource availability, and competitive dynamics for sustained post-fire recovery [6,31].

Impact of Repeated Fires on Sprouting

Our results showed a significant decline in sprout number following the second fire, with mean values dropping from 3.4 to 1.9 sprouts per stem, representing nearly a 43% reduction. This suggests that repeated fire exposure reduces the sprouting potential of Persian oak. In contrast, sprout diameter and height did not differ significantly between the first and second fire events, suggesting that although fewer sprouts were produced, those that emerged maintained similar structural development. This pattern may reflect a shift in resource allocation, where the tree invests more heavily in the growth of fewer, more competitive shoots rather than initiating widespread sprouting. Such a shift could be a strategic adaptation to conserve declining root carbohydrate reserves following successive disturbances, a phenomenon also reported in other oak species under repeated stress [7,38]. These findings support the idea that while Persian oak retains the capacity to resprout after multiple fires, its regeneration mode becomes more conservative, prioritizing structural resilience over shoot quantity.

The relatively stable CGI between fire events further supports this interpretation, suggesting that oak coppice systems compensate for reduced sprout numbers by reallocating available resources toward the remaining sprouts, effectively maintaining overall structural development. This pattern highlights a key trade-off in *Quercus brantii* regeneration. While an initial fire stimulates abundant sprouting to maximize early survival and competition suppression, subsequent disturbances promote a shift toward fewer, more robust stems capable of sustaining long-term growth. This adaptive strategy may reflect an ecological response, where early sprouting ensures immediate survival, while later disturbances favor the development of well-supported stems that contribute to forest stability [7, 39].

Environmental factors such as light availability may further modulate these sprouting responses. For example, improved recovery in canopy gaps [9,23] contrasts with potentially reduced sprout production in shaded conditions. Despite this adaptive capacity, repeated disturbances may eventually deplete root reserves, posing a risk to the long-term resilience of the coppice. The observed emphasis on structural stability over maximizing sprout count aligns with strategies that prioritize maintaining robust stems in fire-prone environments [6, 7, 40].

Conclusion

This study demonstrates that initial stem size significantly influences the long-term sprouting dynamics of *Quercus brantii* following fire. The most important outcome is that while smaller stems showed higher initial sprouting, larger stems exhibited greater persistence and structural development over time, supporting our first hypothesis. Additionally, recurrent fire exposure resulted in a significant reduction in sprout number without affecting sprout diameter, height, or overall CGI, partially confirming our second hypothesis. These findings suggest that Persian oak employs a conservative regeneration strategy after multiple fires, shifting from quantity to quality in sprout investment. These results highlight the importance of considering initial stem structure and fire history when developing post-fire management strategies. Encouraging the maintenance of well-structured stems and implementing controlled and low-intensity burns can improve regeneration and long-term resilience in these fire-prone oak ecosystems.

The following recommendations are proposed to guide future research and enhance fire management strategies for Persian oak forests:

- Implement Targeted Thinning Regimes: Introduce selective thinning practices to reduce intra-stem competition in multi-stemmed individuals. By prioritizing the removal of weaker sprouts, this strategy can improve resource allocation and promote the growth and vigor of the remaining stems.
- Establish Long-Term Monitoring Programs: Develop comprehensive monitoring initiatives to track changes in sprout density, diameter, and

height across sites with varying fire histories. Such data will provide critical insights into oak recovery dynamics and inform predictive models for post-fire regeneration.

- Develop Adaptive Management Plans: Design flexible management frameworks that integrate fire frequency, intensity, and post-fire interventions. By tailoring these strategies to local conditions, managers can enhance the resilience of Persian oak stands and improve their capacity to withstand future disturbances.

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