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Post-fire Sprouting Patterns of Oak Species in the Zagros Forests of Western Iran

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Abstract

This study examined post-fire sprouting patterns in three oak species (*Quercus brantii*, *Q. infectoria*, and *Q. libani*) in the Zagros forests of western Iran. It examined the number, type (root and stem sprouts), diameter, and height growth of sprouts over three post-fire intervals (2, 4, and 10 years), while analyzing differences among species and stump sizes. The results showed that root sprouts were the dominant regeneration mechanism, accounting for over 90% of post-fire sprouting and underscoring the importance of below-ground bud banks. Sprout density peaked two years after the fire and gradually declined thereafter, indicating a decrease in sprouting potential as the stands aged. Despite similar sprouting responses among species, likely due to shared physiological traits such as extensive root systems, variations in sprout density and growth were observed across different stands. A significant negative correlation was found between stump diameter and both sprout number and growth rates, with small to medium-sized stumps (5–35 cm) showing the highest sprouting potential. Rapid sprout growth occurred within the first two years post-fire, often surpassing mature tree growth rates, likely due to established root systems and enhanced nutrient availability. The study concluded that sprouting is vital for oak regeneration in fire-prone areas, especially where seed-based regeneration is limited. It supports coppice management strategies, including thinning and stump management, to encourage vigorous sprout growth. Recommendations include cutting burned trees (diameter >5 cm) during the dormant season, restricting grazing for 4–5 years, and thinning sprouts to enhance post-fire regeneration and ensure the long-term sustainability of these valuable oak forests.

Keywords: Fire, Oak, Sprouting, Zagros Forests, Post-Fire Regeneration

Introduction

Fire plays a vital role in shaping forest ecosystems, affecting their structure, composition, and regeneration. Fire stimulates the germination of fire-resistant species and enhances soil nutrient levels, thereby increasing ecosystem resilience (Barnes et al., 1997; Kolanek et al., 2021; Aguilar-Garavito et al., 2023; Trotta et al., 2024; Li et al., 2024; Chandra et al., 2025). However, the increasing frequency and intensity of fires—primarily driven by global warming and human activities—pose serious threats to ecosystem health, often causing long-lasting or permanent damage (Murphy et al., 2018; Kolanek et al., 2021; Rasooli et al., 2018). Large fires caused by human activity can lead to deforestation, habitat loss, soil sedimentation, and reduced carbon uptake, further intensifying global climate change (Atondo-Bueno et al., 2024; Jones et al., 2024; MacCarthy et al., 2023).

Wildfires stem from the intricate interplay of human and natural factors, with climate change serving as a key driving force (Lacey et al., 2024). Around half of the world's burned areas result from controlled, human-induced fires, often set for agricultural clearing (Perkins et al., 2024). Rising global temperatures have altered rainfall patterns and caused prolonged dry periods, creating a highly unstable atmosphere that fuels the occurrence and spread of fires. Human activities such as deforestation, land use changes, and agricultural expansion, particularly in densely populated areas, contribute to the increased frequency and spread of fires (Yu, 2021; Holonec & Holonec, 2012; Quan et al., 2022; Gaur et al., 2021).

The growing severity of wildfires has had extensive effects on forest ecosystems. In 2021, global forest cover loss amounted to 9.3 million hectares, with substantial losses observed in areas such as the western United States and Canada (Wang et al., 2024; Jones et al., 2024). The 2023–2024 fire season resulted in 3.9 million km² burned globally, contributing to 16% higher-than-average carbon emissions (Jones et al., 2024). In Iran's Zagros forests (study area), covering 3.5% of the country's land area, wildfires occur frequently with an average of 76.2 fires annually. Fire frequency in this area was highly variable between 2000 and 2021 as a result of climate change, elevated temperatures, and variations in wind speed (Sayahnia et al., 2024; Beygi Heidarlou et al., 2024). Forest fires are a significant factor in forest destruction, and they pose a serious threat, especially in dry and fragile ecosystems. Fires lead to the loss of trees, forest floor vegetation, and wildlife. However, some fire-prone species, such as oaks, respond to fires by producing sprouts and ensure their survival after the fire through sprouting. Wildfires have significant positive and negative impacts on ecosystems, human health, and the environment. On the positive side, they can promote the growth of new plants by clearing dead vegetation, enrich the soil with nutrients, and create habitats for fire-dependent species (Gajendiran et al., 2023; Chandra & Muchan, 2024). However, wildfires also pose serious risks, including loss of life, economic damage, air pollution, and disruption of ecosystems. Understanding these dual impacts is essential for the effective management and mitigation of wildfire risks (Gajendiran et al., 2023; Chandra & Muchan, 2024; Ying et al., 2024).

Resprouting is a crucial survival strategy for woody plants, particularly broadleaf trees, enabling them to withstand and recover from disturbances such as fire and cutting. This mechanism is based on a combination of traits, including resprouting ability, growth vigor, and sprout survival, type of disturbance, climatic conditions, and resource availability. These traits enable many species in fire-prone ecosystems to exhibit high resistance to fire (Nzunda, 2008; Hwang et al., 2011; Moreira et al., 2012; Pausas et al., 2016; Bond & Midgley, 2001). Heat and carbohydrate storage in the soil are essential for the sprouting process, while excessive disturbance can reduce resprouting potential—for example, in tropical dry woodlands, where intense fires decrease sprout density (Moreira et al., 2012; Ferreira et al., 2017; Umeki et al., 2018). Physiological and morphological resprouting strategies include lignotubers—subterranean carbohydrate storage structures capable of generating new shoots

after fire—deep root systems that provide access to water and nutrients, and resting buds that enable resprouting following fire disturbance (Souza et al., 2023; Cowan et al., 2023). These changes strengthen the resilience of oak species, allowing them to endure and recover from fire disturbances while highlighting their essential role in sustaining forest ecological stability.

The *Quercus* genus, the most taxonomically diverse group within *Fagaceae*, comprises nearly 50% of all *Fagaceae* species (Manos et al., 1999). Oak, with approximately 450 to 500 species, is dominant in the forest ecosystems of the Northern Hemisphere, particularly in environments influenced by fire regimes. Their remarkable ability to adapt to diverse climatic and soil conditions has enabled their widespread distribution across Asia, Europe, North America, and Africa (Nixon, 1993; Pang et al., 2019; Plomion et al., 2016).

Oak species (*Quercus* spp.) are vital for maintaining ecosystem stability, as they endure and recover from fire, logging, and other disturbances primarily through vegetative resprouting and seedling establishment. Their specialized physiological and morphological traits make them more resistant to disturbances, with strong resprouting capability serving as the dominant post-disturbance process, enabling rapid recovery. The success of resprouting after a fire in these species depends on intrinsic species traits, fire intensity, and environmental factors (Marais et al., 2014; Burrows, 2021; Dib et al., 2022; Camarero et al., 2024; Atondo-Bueno et al., 2024).

Certain oak species have the potential to yield up to 869 sprouts per hectare with indications of effective regeneration mechanisms to ensure ecosystem balance and carbon circulation (Shen et al., 2023; Verdaguer, 2020). Oak species vary in their sprouting after fire, depending on a combination of species traits, environmental conditions, and fire intensity. Research indicates that factors such as light intensity of fires, cutting frequency, and the ecological environment play significant roles in regulating sprouting dynamics. The sprouting capacities of oak species, particularly *Quercus serrata* and *Quercus acutissima*, vary notably under shaded conditions and after recurrent cutting. *Q. acutissima* exhibits exceptional sprouting ability, especially with repeated cutting, and maintains a higher survival and sprouting rate compared to other oaks, thriving even in shaded environments (Lee et al., 2017; Dinh et al., 2018). In contrast, species like *Q. serrata* and *Q. dentata* show limited resilience, with *Q. serrata* dying after the second cut and *Q. dentata* after the third (Lee et al., 2017). While shaded conditions reduce growth metrics such as height and biomass in *Q. acutissima*, it still sprouts effectively (Li et al., 2018). The limited sprouting ability of certain oak species could threaten the overall health of oak communities and reduce biodiversity in forest ecosystems. Sessile oak (*Quercus petraea*) ability to sprout reduced with increasing stump diameter in Central European coppices, while tree age was found to be the primary predictor for successful regeneration (Matula et al., 2012).

Fire-sprouting in oak species occurs through either root or stem sprouts, depending on fire severity and species characteristics. For example, *Quercus kelloggii* and most oaks are likely to produce root sprouts after a fire, which over time develop into multi-stem clumps, while stem sprouts also emerge, especially after high-severity wildfires (Ritchie et al., 2024). Comparative studies have revealed that *Quercus alba* shows higher sprouting vigor and survival rates compared to *Quercus stellata*, emphasizing the variations in post-fire regeneration abilities among oak species (Williams & Brewer, 2024).

A variety of ecological factors are responsible for impacting the oak sprouting success and number, such as site characteristics and species attributes. Environmental variables, post-fire sprout density, and species identity have complex interactions. For instance, *Quercus pubescens* and *Quercus frainetto* had similar sprouting trends following the fire (Milios et al., 2017). The variation in sprouting capacity between *Quercus alba* and *Quercus*

velutina highlights significant interspecific differences that influence forest regeneration. *Q. alba* has a moderate sprouting capacity that is essential for its persistence, although it is generally lower than that of other oaks (Weigel et al., 2011). In contrast, *Q. velutina* shows higher sprouting potential, particularly in disturbed environments, with its stump sprouts more likely to dominate after harvesting (Weigel et al., 2006; Weigel et al., 2011). Both species benefit from increased light, though *Q. velutina* shows a stronger response under high light conditions, indicating better adaptation to favorable regeneration environments (Petersson et al., 2020). Recognizing these differences is vital for forest management, as species-specific sprouting behaviors can inform predictive models to guide regeneration after disturbances (Weigel et al., 2011). Topography and other environmental conditions also play a crucial role in post-fire regeneration (Atondo-Bueno et al., 2024).

The referenced studies highlight the critical role of species traits, fire intensity, and environmental factors in influencing the success of oak sprouting. Certain oak species are highly fire resilient through strong sprouting reactions, whereas others are exposed to environmental constraints. These aspects are important for understanding successful forest management and restoration techniques.

A review of the literature on post-fire sprouting in oak species highlights great gaps in our knowledge about the oak species in the Zagros forests of Iran, where wildfire, occurring an average of 76.2 times a year, is one of the biggest threats (Sayahnia et al., 2024; Beygi Heidarlou et al., 2024). The present study aimed to address this gap by exploring the post-fire sprouting dynamics (i.e., vegetative regeneration) of pure pollarded stands of *Quercus brantii*, *Q. infectoria*, and *Q. libani* in the northern Zagros forests, western Iran. The research compares the number, type (stem and root sprouts), and growth (height and diameter) of sprouts at three post-fire periods (2, 4, and 10 years), and also investigates differences between species and among different burned stump diameters for sprouting capacity. By evaluating species-specific responses and trends over time in growth, this study contributes to the knowledge of the resilience of pollarded oaks and addresses sustainable fire and forest management in silvopastoral landscapes.

The Zagros forests are some of the most valuable natural Iran and the Middle Eastern systems, and they cover a total area of about 5.5 million hectares from northwestern Iran (West Azerbaijan) to southwestern Iran (Fars province) (Marvie Mohadjer, 2005; Sagheb Talebi et al., 2014). The Zagros forests play significant roles in water supply provision, maintaining the hydrologic cycle, soil conservation, climate mitigation, and biodiversity hosting. In addition to their economic value, the Zagros forests play a significant role in the livelihood and economy of nomads and villagers (Ghazanfari et al., 2004; Marvie Mohadjer, 2005; Sagheb Talebi et al., 2014; Valipour et al., 2014; Ghahramany et al., 2018).

Although these forests produce poor-grade wood, in the past, wood from trees such as oak, pistachio, wild pear, and wild almond was an important material for rural and local industries. Oak wood was once extensively utilized as fuel; however, its use has declined due to the reduction in forest reserves and the increasing availability of gas and other fossil fuels. The non-timber products of the Zagros are high value; wild pistachio, wild almond, hawthorn, and wild pear fruits not only serve as food and material for consumption but are also used in the preparation of medicinal herbs. Pistachio trees also produce resins used in the pharmaceutical and food industries. Much of the local communities in the region are dependent on livestock production and make use of the Zagros forests as the primary source of fodder for their livestock. Besides, the forests have high ecological tourism (ecotourism) potential, which can be a means of sustainable development and employment generation in the region

(Jazirehi & Ebrahimi Rastaghi, 2003; Gazanfari et al., 2004; Sagheb Talebi et al., 2014; Jamali & Haack, 2024; Sadeghi et al., 2024).

The examined oak species (*Quercus brantii*, *Quercus infectoria*, and *Quercus libani*) have also spread to the neighbouring countries of Turkey, Iraq, Syria, and Afghanistan, showing a broad ecological range (Jamali & Haack, 2024; Sadeghi et al., 2024; Shooshtari et al., 2024).

The key research questions in this study are as follows:

1. How do the dominant oak species of the Zagros forests respond to forest fires, and what are the variations in their sprouting abilities?
2. How do the number of post-fire root and stem sprouts, as well as the diameter and height growth of sprouts, differ among oak species, diameter classes of burned stumps, and over time since the fire?

By addressing these questions, this study provides important insights into the sprouting capabilities of oak species, contributing to our understanding of how pollarded oaks recover after fire. These findings are crucial for improving post-fire management strategies, enhancing oak regeneration, and guiding fire management practices to strengthen the resilience of oak ecosystems in silvopastoral management systems.

Materials and methods

Study area

The study area is located in Marivan County, Kurdistan Province, northwestern Iran in the Northern Zagros region of western Iran (35°16' to 36°13' N, 46°23' to 46°29' E) (Figure 1, Table 1). The study area of approximately 449,000 hectares encompasses part of the vast Zagros oak forests of western Iran. It has a semi-humid high-altitude climate, and its mean annual rainfall of 600 mm mainly occurs in the late autumn and early spring periods. The average temperature ranges from 18°C in August, the hottest month, to 1.5°C in February, the coldest (Kurdistan Meteorological Bureau, 2023).

Three dominant oak species, Lebanon oak (*Quercus libani*), Gall oak (*Qercus infectoria*), and Persian oak (*Qercus brantii*), cover the study area (Marvi Mohajer, 2005; Jazirehi & Ebrahimi Rastaghi, 2003; Ghahramany et al., 2018). In the study area, native communities practice a silvopastoral system, pollarding oak trees for livestock winter fodder and producing non-timber forest products such as oak acorns, galls, manna, and pistachio gum (Ghazanfari et al., 2004; Valipour et al., 2014; Ghahramany et al., 2018).

Table 1. Main characteristics of the studied oak stands.

Stand	Time elapsed since last fire (years)	Area (ha)	Aspect	Slope (%)	Altitude (m.a.s.l.)
2AF	2	4	Southwest	40	1300
4AF	4	4	South	35	1250
10AF	10	4	Southwest	35	1300

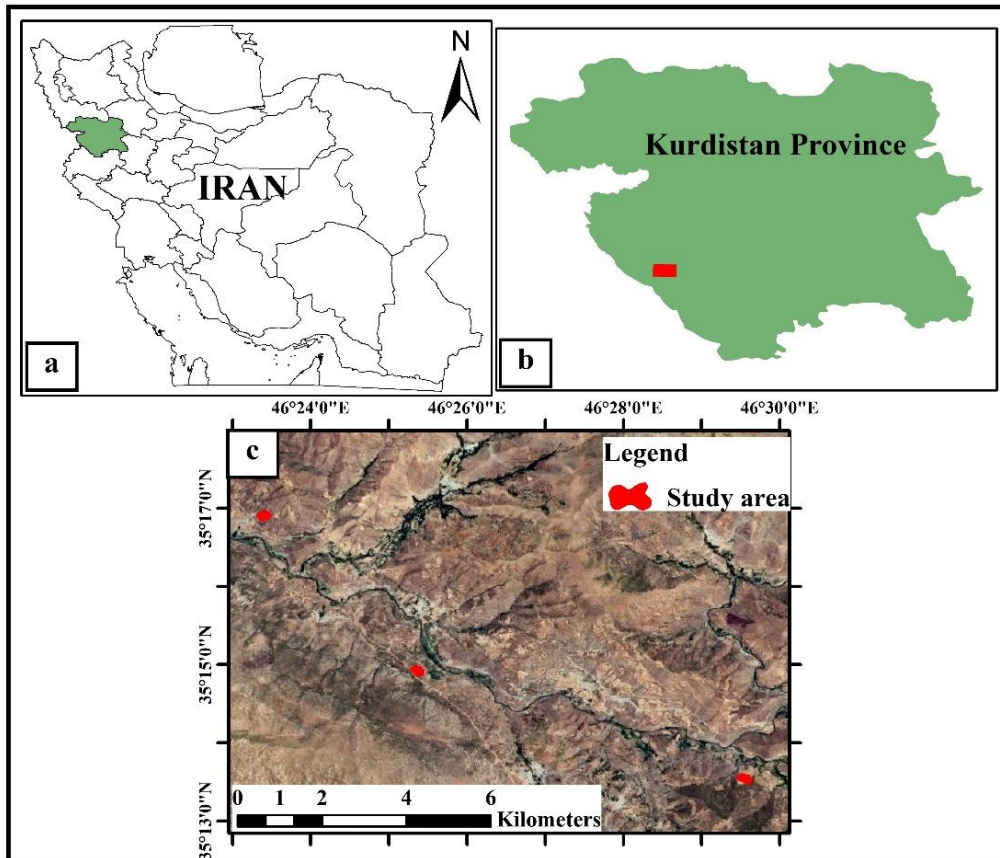


Figure 1. Location of the study area in Iran (a), Kurdistan Province (b), and the location of the studied stands (c).

Data collection

For this study, three natural oak forest sites, each spanning 4 hectares, were identified using satellite imagery analysis and field surveys. These sites represent different post-fire intervals—2 years (hereafter 2AF), 4 years (hereafter 4AF), and 10 years (hereafter 10AF)—while exhibiting similar physiographic features and having experienced moderate fire severity (Figure 1, Table 1). The locations and boundaries of the selected stands were individually mapped using Google Earth. Key stand attributes, including area (measured with GPS GARMIN 78S, accuracy: ± 10 m), average slope (using a Suunto clinometer), general aspect, and altitude (recorded via GPS), were documented (Table 1).

In each stand, a complete inventory was made to measure the collar diameter of burned trees and count the number of post-fire root and stem sprouts per burned stump by species. The largest post-fire root sprout's diameter and the tallest post-fire root sprout's height were measured for each sprout group (i.e., stool). There were 1,349 burned stumps measured, which included 505, 380, and 464 burned oak trees in the three forest stands at the 2AF, 4AF, and 10AF ages, respectively.

Data analysis

The number of post-fire sprouts was assessed based on sprout type (root and stem sprouts) for three oak species—*Quercus brantii*, *Q. libani*, and *Q. infectoria*—across different collar diameter classes of burned stumps. The diameter and height increments of the thickest and tallest post-fire root sprout in each stool were calculated. The average diameter growth was determined by dividing the diameter of the thickest post-fire root sprout by the number of years since the most recent fire, while the average height growth was calculated by dividing the height of the tallest post-fire root sprout by the time elapsed since the last fire.

The normality of the distribution of the data was tested using one-sample Kolmogorov-Smirnov test (Lilliefors, 1967). Quantities of post-fire stem and root sprouts within the examined stands were compared with the Mann-

Whitney U test. Post-fire root sprouts among the three stands, as well as sprouts number dynamics within different periods, were compared with the use of One-way ANOVA.

Since the data from each stand (2AF, 4AF, and 10AF) were not normally distributed, the sprouting ability of the oak species (*Quercus brantii*, *Q. libani*, and *Q. infectoria*) was compared based on the number of post-fire sprouts using the Kruskal-Wallis H test. One-way ANOVA was used to compare the diameter and height increment of post-fire sprouts at different times after the fire. Post hoc comparison by the Duncan test was carried out after ANOVA (for the diameter increment) while Tamhane's T2 test was performed following ANOVA for the height increment due to heterogeneity of variances. Levene's test was applied to assess the homogeneity of diameter and height increment variances before conducting ANOVA analysis.

Trend analysis was done in order to research variations in density of post-fire sprouts, and diameter and height growths of post-fire root sprouts, by various diameter classes and the studied stands (2AF, 4AF, and 10AF). The boundaries of the forest stands were determined by Google Earth. Statistical analysis was carried out by R software. The plots were obtained using Excel 2019.

Results and Discussion

Post-fire sprouting dynamics in pollarded oak species

Table 2 summarizes statistical data on burned stumps examined in the stands under study. The observations indicate that all of the investigated oak stumps sprouted successfully after the fire, primarily from root sprouts, with the lesser percentage accounted for by stem sprouts. The Mann-Whitney U test results (Table 3) reveal a significant statistical difference in the number of root and stem sprouts across all three stands (2AF, 4AF, and 10AF). The research indicates that root sprouts are the predominant mechanism of post-fire regeneration for oak species and account for over 90% of the resprouting. This serves to underscore the critical significance of below-ground bud banks, which are instrumental in the ability of oak species to regenerate after fire. The highest density of sprouts at 2,255 sprouts per hectare occurred with treatment 2AF and reflects an early vigorous response to the burning. However, 10AF treatment showed the least density of sprouts (1,349 sprouts/hectare), which may indicate that with the progress of time, there was a progressive decline in sprouting density, and this might have been due to the ageing of the stumps. The study shows that tree trunk and stump damage due to fire induces heavy sprouting as a compensatory response. These findings are consistent with previous research, for example, Leite et al. (2022) highlighted the importance of below-ground sprouting bud banks to fire-adapted species, and Petersson et al. (2020) stated that oak trees have a great potential for survival and sprouting even after the fire destroyed the crown of the tree. Thus, oak species' heavy reliance on below-ground stores is the key to their recovery from fire damage. Root sprouting provides enormous benefits, including greater stability, resilience, and strong growth, thereby improving oak species' capacity to recover from fire events (Gracia & Retana, 2004; Johnson et al., 2002). Sprouting following fire is one of the essential processes involved in forest restoration and regeneration, especially in areas with seed regeneration hampered (Bellingham & Sparrow, 2000; Swaim et al., 2016).

In addition to responding to fire disturbance, the oak species also respond to human activity and traditional exploitation by bearing abundant sprouts. The oaks in regions with intensive human intervention have developed and established vigorous sprouting mechanisms, which enable them to restore themselves following disturbance, as highlighted in past studies (Ghazanfari et al., 2004; Jazirehi & Ebrahimi Rastaghi, 2003; Pourreza et al., 2009; Pourhashemi, 2015; Schwilk et al., 2016; Iverson et al., 2017; Valipour et al., 2021; Verdaguer, 2020). The capacity of the oak species (*Quercus* spp.) to sprout has been recognized as an integral part of their regeneration and restoration, especially in woodlands that have undergone logging and other disturbances such as fire. Numerous researchers have stressed the significance of this trait (Ducrey & Turrel, 1992; Gardiner & Helmig, 1997; Lockhart et al., 2002; Lockhart & Chambers, 2007).

Figure 3 illustrates the distribution of post-fire root sprouts across stump diameter classes in the 2AF, 4AF, and 10AF treatments. The trend lines show a decline in sprouting as stump size increases. The negative slopes indicate

that smaller stumps contribute more to resprouting, indicating stump size as one of the determining factors of post-fire regeneration. In the 2AF and 4AF treatments, the number of sprouts increased with stump diameter up to approximately 15 cm before declining, whereas in the 10AF treatment, this increase continued up to 20 cm before decreasing. More than 90% of post-fire sprouts were observed on stumps of diameters 5-35 cm (diameter classes: 7.5-32.5 cm), which highlights the key role played by medium stumps in post-fire sprouting. The provided diameter class is a balanced one between energy reserves and sprouting capability. Previous research has documented the effect of stump diameter on sprouting in other oak species (Sands & Abrams, 2009; Jung et al., 2013). The results agree with Khan and Tripathi (1986), Sands and Abrams (2009), Pourreza et al. (2009), Matula et al. (2012), Affleck and Gaines (2023), and Paneghel et al. (2024), who concluded that sprouting potential declined with increasing stump size. Additionally, Harris et al. (2022) and Ruggirello et al. (2023) point to the significance of small fire-resistant stumps in the early stages of post-fire regeneration. Khan and Tripathi (1986) mentioned that, in *Quercus dealbata* and *Quercus griffithii*, mean sprout number per stump decreased as stump diameter increased. According to a study by Sadeghi et al. (2020), stump diameter is one of the primary variables that control sprouting capacity, and the ability to sprout reduces with an increase in stump diameter. Other research also points out the relationship between stump diameter and the ability to sprout. These declines are attributed to structural changes such as bark thickening, reduced carbohydrate storage, and reduced meristematic activity, although larger stumps with larger root systems can retain sprouting capacity and physiological vitality, as suggested by Johnson et al. (2002), Michelot-Antalik et al. (2019), Aguilar-Garavito et al. (2023), Weigel and Peng (2002), and Valipour et al. (2021). Larger, thicker trees are typically older and have more advanced root systems. Since sprouting ability is inversely related to tree age but directly related to root system size and development, the balance between these factors—depending on species and site conditions—plays a crucial role in determining sprouting potential. The interaction between stump size, tree age, and root system expansion plays a critical role in sprouting capacity (Valipour et al., 2021; Weigel & Peng, 2002).

Figure 3 is a diagram of post-fire root sprout distribution by stump diameter classes for the 2AF, 4AF, and 10AF treatments with trend lines showing a trend towards declining sprouting with increasing stump size. The downward slopes that show smaller stumps contribute more to resprouting emphasising the importance of stump size in post-fire recovery. For 2AF and 4AF treatments, the number of sprouts rose with the diameter of the stump until about 15 cm when it fell, whereas for the 10AF treatment, this behaviour continued up to 20 cm before falling. More than 90% of post-fire sprouts were on stumps with 5 to 35 cm diameters (diameter classes: 7.5-32.5 cm), which documents the important contribution made by stumps of intermediate sizes to post-fire sprouting. This diameter range provides an optimum maximum between sprouting capacity and energy reserves. The effects of stump diameter on sprouting in some oak species have been reported in previous research (Sands & Abrams, 2009; Jung et al., 2013). The result agrees with Khan and Tripathi (1986), Sands and Abrams (2009), Pourreza et al. (2009), Affleck and Gaines (2023), and Paneghel et al. (2024), where it was established that as stump diameter increased, sprouting potential reduced. As stem diameter increases, bark thickness also increases, enhancing fire resistance and reducing the sensitivity of dormant buds to sprouting (Masaka et al., 2000).

Table 4 presents the post-fire sprouting response per stump for the studied oak species (*Quercus brantii*, *Q. infectoria*, and *Q. libani*) in the different stands. The results indicated that all the species responded in the same way by sprouting, and there were no differences in the number of sprouts among them (Table 5 for comparison analysis). The result demonstrates that despite some species-specific variation, all three oak species respond in the same way by sprouting after fire. The uniform sprouting behaviour among these species is likely due to shared physiological adaptations, i.e., healthy belowground bud banks and effective sprouting capacity, that allow them to recover rapidly after the fire. Additionally, bark thickness, a key trait for tree survival and capacity to sprout after wildfire, also appears to be comparable among these species (Khanm and Tripathi, 1986; Pausas, 2016; Xue et al., 2013).

This study agrees with Milios et al. (2017) and Batziou et al. (2017), which found that oak species such as *Quercus pubescens* and *Q. frainetto* have similar sprouting responses after fires. Past studies also confirm that all three oak species being researched have massive underground bud stores and excellent sprouting capacity, which enable them to resprout after fire incidents (Ghazanfari et al., 2004; Valipour et al., 2021; Ghahramany et al., 2018). These fire-resistance traits are essential for the survival and regrowth of oak trees in the event of recurrent fires. Oaks possess robust underground structures, including expansive root networks and high bud numbers, from which they can rapidly regrow following fires to allow them to recover (Verdaguer, 2020). Such regeneration capacity is essential for oaks to survive and thrive in areas where fires are a recurring occurrence (Atondo-Bueno et al., 2024). Although these physiologically similar adaptations are comparable between species, they may differ based on interspecific competition and soil, humidity, and soil-type environmental conditions. They make regeneration a complex process to analyze and result in the specification of species-wise management to promote successful post-fire recovery (Milios et al., 2017).

The outcomes of the ANOVA test indicated that no significant difference was found in the number of post-fire root sprouts among the studied stands ($F = 1.072$; $P = 0.355$). It indicates that even ten years later, the number of post-fire sprouts was quite stable in different stands. The lack of significant sprouting ability variation shows that the oak species being researched possess a long-lasting ability to regenerate due to the belowground bud bank resistance and low influence of environmental conditions (Leite et al., 2022; Keyser et al., 2016).

Understanding the long-term sprouting ability can inform forest management decisions, such as if fire-killed trees need to be harvested to promote regeneration (Milios et al., 2017). Resistance of oak forests in fire-prone environments can be fostered with the right management measures (Keyser et al., 2016).

Seed regeneration in Zagros forests is highly restricted by factors such as pollarding in northern Zagros regions, collection of acorns by local people, the non-availability of healthy and pest-free seeds with active germination potential, poor establishment conditions, and depletion of naturally regenerated seedlings due to grazing by animals and clearing of forest for pasture. In these circumstances, oak sprouts developing as a result of environmental stresses such as fires or anthropogenic actions are a critical source of coppice regeneration and play a crucial role in the survival and stability of the forest (Ghazanfari et al., 2004; Ghahramany et al., 2018). The importance of coppice regeneration in the sustainability of forest stands and the regrowth of such an ecosystem has been elaborated upon in previous studies (Bellingham & Sparrow, 2000; Swaim et al., 2016).

Table 2. General statistics of burnt stumps in the studied stands.

Stand	Number of burnt stumps per stand	Number of burnt stumps per hectare	Median diameter of burnt stumps (cm)	Minimum diameter of burnt stumps (cm)	Maximum diameter of burnt stumps (cm)
2AF	505	126	14.0	5.0	57.0
4AF	380	95	15.0	5.0	55.5
10AF	464	116	15.5	6.0	61.0

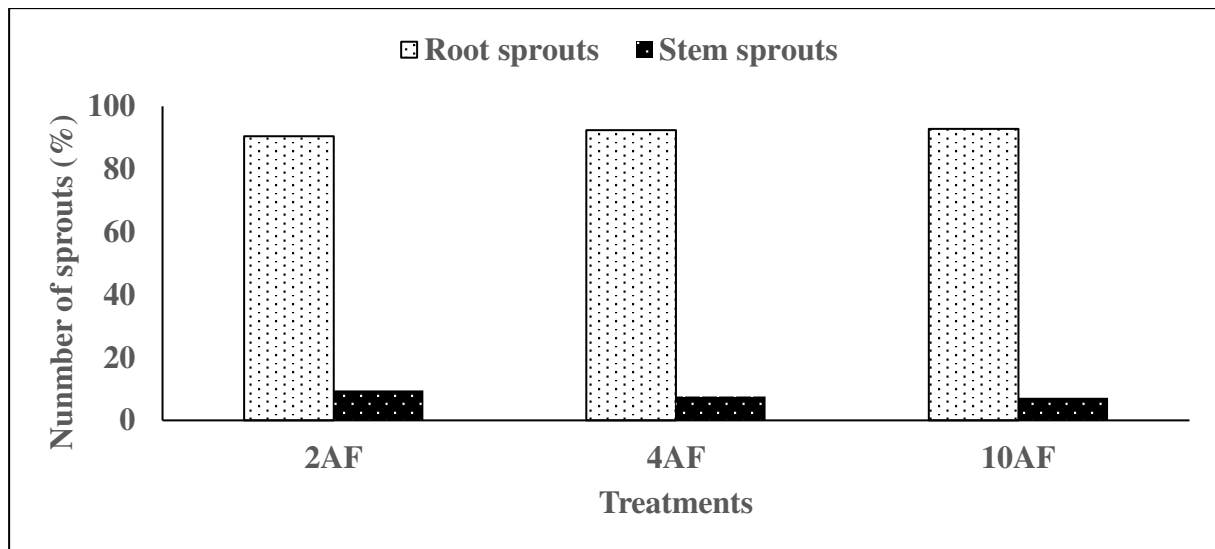


Figure 2. Comparison of the number of post-fire root and stem sprouts (all species) in the studied stands.

Table 3. Results of the Mann-Whitney U test comparing the number of root and stem sprouts (all species) in the studied stands.

Stands	Number of sprouts per hectare		Z	P-value
	Root sprouts	Stem sprouts		
2AF	2040	215	-3.151	<0.01
4AF	1257	104	-2.632	<0.01
10AF	1178	92	-2.532	<0.05

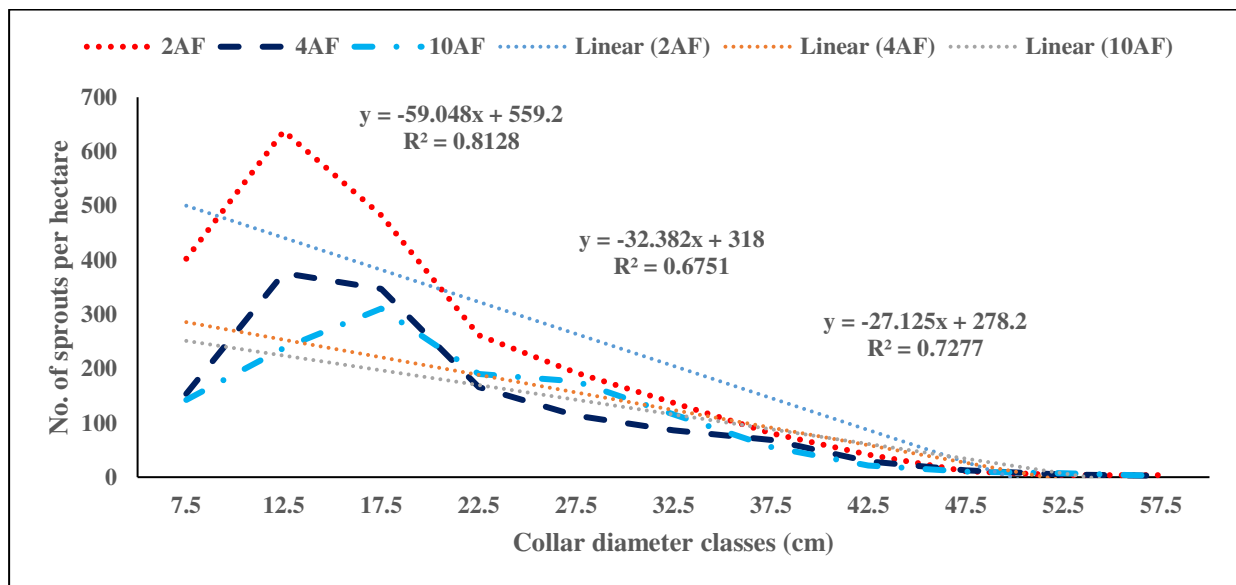


Figure 3. Distribution of post-fire root sprout numbers (all species) across diameter classes of burned stumps in the 2AF, 4AF, and 10AF treatments.

Table 4. General statistics of post-fire root sprout numbers per stump by species in the studied stands.

Stands	Mean (sprout per stump) $\pm$ Standard deviation (Minimum and Maximum)			
	<i>Q. brantii</i>	<i>Q. infectoria</i>	<i>Q. libani</i>	All oak species
2AF	18 $\pm$ 5(5-36)	18 $\pm$ 6(4-29)	17 $\pm$ 6(8-27)	18 $\pm$ 5(4-36)
4AF	14 $\pm$ 6(4-33)	15 $\pm$ 6(4-26)	13 $\pm$ 5(4-20)	14 $\pm$ 6(4-33)
10AF	11 $\pm$ 5(3-27)	11 $\pm$ 5(3-22)	9 $\pm$ 4(3-15)	11 $\pm$ 5(3-27)

Table 5. Results of the Kruskal-Wallis H test comparing post-fire root sprout number per stump among the oak species in the studied stands.

Statistical criteria	Stands		
	2AF	4AF	10AF
χ^2	0.072	2.772	0.904
df	2	2	2
P-value	0.965	0.250	0.637

Diameter and height increment of post-fire root sprouts

Table 6 shows the diameter and height growth of root sprouts post-fire across the treatments (2AF, 4AF, and 10AF). The 2AF treatment exhibited the highest diameter growth at 11.2 mm per year, suggesting robust initial growth. In contrast, the 10AF treatment showed the lowest diameter growth at 4.7 mm per year, indicating a slower growth pattern. The results of the ANOVA test revealed significant differences in diameter growth among the three stands at the 1% level of significance (Table 7, Figure 5). These differences can be attributed to increased competition among sprouts, the ageing of parent stumps and sprouts, and the gradual closure of the stand canopy (Karlsson, 2006), which progressively limits the availability of light and nutrients. The findings underscore the importance of early intervention management intervention, such as thinning sprouts within the initial years following a fire, to sustain conditions that favor the survival of high-quality sprouts.

Camarero et al. (2024) have reported that *Quercus ilex* and *Celtis australis* exhibited growth increments of 39.5% and 48.9%, respectively, in the first year after the fire. This positive impact was, however, temporary, with the radial growth rates declining in five years. The pattern reflects the initial benefits of reduced competition and enhanced nutrient availability that are eventually curbed by factors such as soil quality, water, and competition. The observed variations in sprout growth between stands and fire history emphasize the importance of site-specific conditions. Such dynamics are relevant to be understood for successful forest management and restoration (Li et al., 2024; Qin et al., 2024).

In comparison to the diameter increment of post-fire oak root sprouts in the current study (Table 6) with the growth rates of mature oak (2 mm yr⁻¹) in previous studies (Valipour et al., 2014; Rostami Jalilian et al., 2016; Iverson et al., 2017; Ghahramany et al., 2018; Oksari et al., 2019), it can be observed that sprouting oak seedlings exhibit higher growth rates than mature trees as well as non-sprouting seedlings (Iverson et al., 2017; Oksari et al., 2019). Early root growth of stump sprouts is the outcome of an extremely developed and widespread root system, which enhances fast growth using carbohydrate reserves and enhanced resource acquisition (Bond & Midgley, 2001; Johnson et al., 2002). This growth benefit positions stump sprouts in a more favourable competitive position compared to other forms of reproduction (Lockhart & Chambers, 2007).

These accelerated growths are possibly a consequence of increased soil nutrient levels (like phosphorus, potassium, calcium, and magnesium) in response to varied intensities of burn (Milios et al., 2017; Short et al., 2019; Vakili Tajareh et al., 2019; Roula et al., 2020; Yazadni et al., 2020).

Figure 4 illustrates the change in post-fire root sprout diameter growth along the burned stump diameter classes, with trendlines describing the growth tendency of the sprouts in the investigated stands. The negative slope of trendlines indicates that the diameter growth of root sprouts decreases as stump diameter increases at a gentle rate. Correlation coefficients for 2 years post-fire ($r = -0.956$, $p < 0.001$), 4 years post-fire ($r = -0.920$, $p < 0.001$), and 10 years post-fire ($r = -0.894$, $p < 0.001$) further confirm the negative correlation between stump diameter and the diameter growth of root sprouts.

This suggests that burned stumps with smaller diameters produce root sprouts with greater diameter growth. Stand conditions and stump size regulate growth rates, which vary depending on environmental factors. The results are consistent with previous studies by Khan and Tripathi (1989) and Pourreza et al. (2009), which reported decreased growth with increasing stump size.

This study recommends early silvicultural interventions in burned oak stands. Among these, thinning is particularly important as it provides favourable conditions for stronger and higher-quality sprouts, facilitating the regeneration and restoration of burned stands (Ebrahimi et al., 2019).

In addition to diameter increment, the height increment of post-fire sprouts serves as a crucial biometric indicator for evaluating oak trees' responses to fire.

The annual height increment of post-fire root sprouts varied across the treatments. The highest increment was recorded at 63.1 cm yr⁻¹ in the 2AF treatment, which was indicative of robust early post-fire growth. Conversely, the lowest rate of height increment of 21.3 cm yr⁻¹ was found in the 10AF treatment, indicating a decrease in height increment as the post-fire interval increased. As shown in Figure 6, oak sprouts had their highest rate of height growth in the first two years following the fire. Growth started to slow down in subsequent years as a result of canopy closure and increased competition.

ANOVA results confirmed the existence of significant statistical differences in height increment of the stands at a 1% level of significance (Table 8, Figure 7). Highly significant differences among stands suggest that, in addition to the time passed since the last fire, other conditions such as soil fertility, water supply, and light regimes also affect the growth of post-fire sprouts. These findings emphasize the importance of site-specific conditions in post-fire forest regeneration and could inform management strategies aimed at optimizing recovery and stand development (Woś et al., 2024; Semenyakin & Tikhonova, 2024; Zhu et al., 2024). The findings of Nemens et al. (2018) on the effect of repeated wildfires on the regeneration of mixed oak (*Quercus kelloggii*) and conifer forests (mainly *Pinus ponderosa* var. *ponderosa* C. Lawson) in northern California showed that the average height of post-fire sprouts after the first wildfire, 12 years post-fire, was about 4.1 m (with an annual height growth of 34 cm) and a maximum height of 7.9 m (66 cm yr⁻¹). However, after the second wildfire, the average sprout height after three years was about 2.2 m (73 cm yr⁻¹), with a maximum height of 4.2 m (140 cm yr⁻¹). According to Milios et al. (2017), after three growing seasons following the forest fire, the average height of the tallest sprout per stump was significant in both species, measuring 2.08 m for *Q. pubescens* and 2.29 m for *Q. frainetto*. Understanding these dynamics can guide the development of management strategies focused on optimizing recovery processes and promoting stand development following a fire (Mantero et al., 2023).

Figure 6 illustrates the distribution of height increments for post-fire root sprouts across different diameter classes of burned stumps, showing an inverse relationship between stump diameter and sprout height growth. The highest height increments—69.6 cm yr⁻¹, 38.6 cm yr⁻¹, and 23.3 cm yr⁻¹ in 2AF, 4AF, and 10AF, respectively—were observed in thinner sprouts within the 7.5 cm and 12.5 cm diameter classes of the corresponding treatments.

All trendlines have negative slopes, indicating that sprout height increment is reduced with increasing stump diameter. The correlation coefficients of stump diameter with height growth in the 2AF ($r = -0.886$, $p < 0.001$), 4AF ($r = -0.916$, $p < 0.001$), and 10AF ($r = -0.906$, $p < 0.001$) also attest to the negative correlation between tree growth and stump diameter in fire-scarred trees.

Pourreza et al. (2009) reported that the height growth of Persian oak under varying fire intensities was 22.4 cm yr⁻¹. Similarly, according to Kim et al. (2020), in the forests of the Republic of Korea, the average height of post-fire sprouts for *Q. variabilis*, *Q. serrata* and *Q. mongolica*, over 18 years was 9.6 m, 9.1 m, and 6 m respectively. According to Valipour et al. (2021), one-year old sprouts of *Q. libani* in northern Zagros, Iran, showed an average height growth of 60.9 cm. In that study, the average annual height growth of post-fire sprouts in *Q. variabilis*, *Q. serrata*, and *Q. mongolica* was estimated at 54 cm, 40 cm, and 33 cm, respectively. Compared to the results of the present study, the height growth of post-fire sprouts of studied oaks is more similar to that of *Q. mongolica*. Additionally, that study reported a direct correlation between height growth and sprout group density.

Many previous studies have pointed out that artificial thinning of sprouts in the early stage can not only increase the diameter, height, yield, and stem quality of the remaining sprouts (Cole, 1983; Mitchell et al., 1985; Dwyer et al., 1993), but also maintain the health of the stumps (McDonald & Tappeiner, 1996). Therefore, in the management of oak forests after fire, adjusting the number of sprouts in the first year after harvest may be

necessary. This strategy can prevent energy loss from stumps due to self-thinning and provide some small stems for firewood. However, further research is also needed to focus on how many sprouts should be retained in each stump to achieve the maximum biomass of sprouts and aid in stand recovery. The economic cost of this management should also be considered and calculated.

The results of this research confirm the fire resistance of the prevailing oak species of the Zagros woods. Therefore, these oak species can be good candidates for reforestation in fire-prone ecosystems that are subject to site conditions similar to those of the Zagros, especially those with a semi-humid climate.

Table 6. General statistics of diameter and height increments of post-fire root sprouts (all species) in the studied stands.

Indices	Mean $\pm$ Std. error (Minimum and Maximum)		
	2AF	4AF	10AF
Diameter increment (mm yr ⁻¹)	11.2 $\pm$ 0.7 (7.5-14.4)	7.2 $\pm$ 0.3 (5.9-8.5)	4.7 $\pm$ 0.2 (3.8-5.5)
Height increment (cm yr ⁻¹)	63.1 $\pm$ 1.8 (50.3-69.6)	35.9 $\pm$ 0.6 (33.1-38.6)	21.3 $\pm$ 0.5 (18.1-23.3)

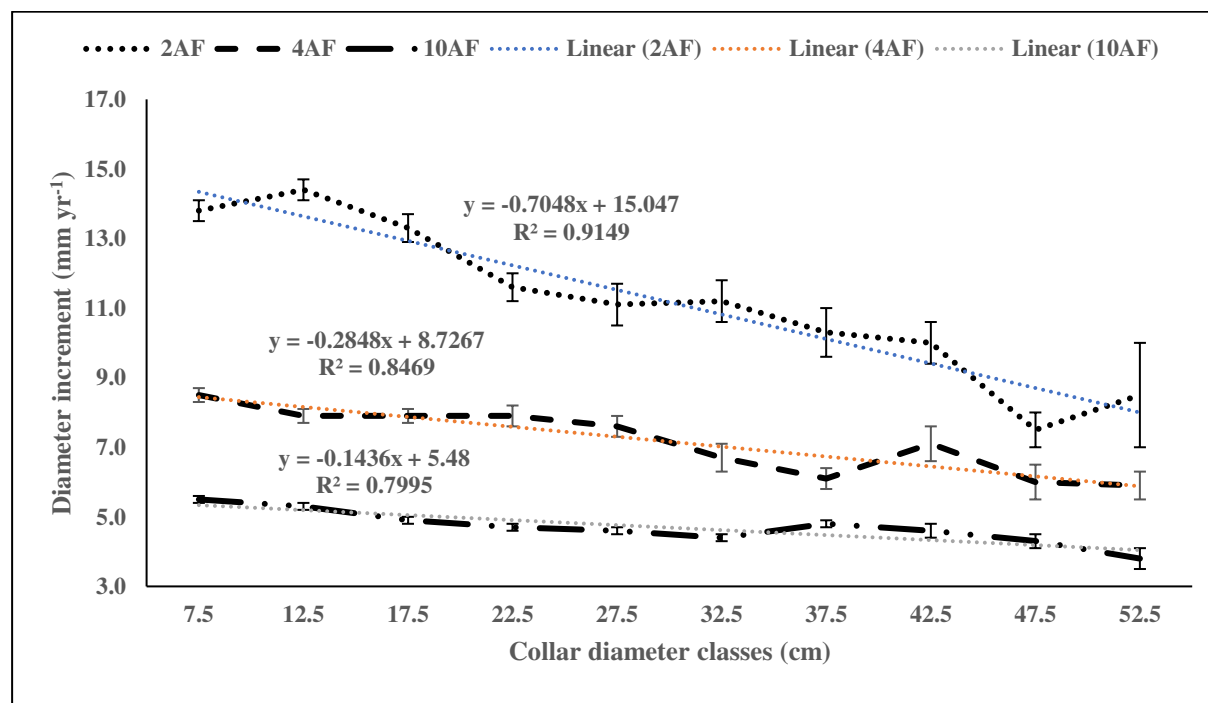


Figure 4. Distribution of diameter increment in post-fire root sprouts across diameter classes in the 2AF, 4AF, and 10AF treatments (vertical bars represent standard error).

Table 7. Analysis of variance for the diameter increment of post-fire root sprouts across the 2AF, 4AF, and 10AF treatments.

Source	Type III Sum of Squares	df	Mean Square	F	P-value
Stands	213.905	2	106.952	52.663	<0.01
Error	54.834	27	2.031		
Total	268.739	29			

R Squared = 0.796 (Adjusted R Squared = 0.781); CV%=18.5

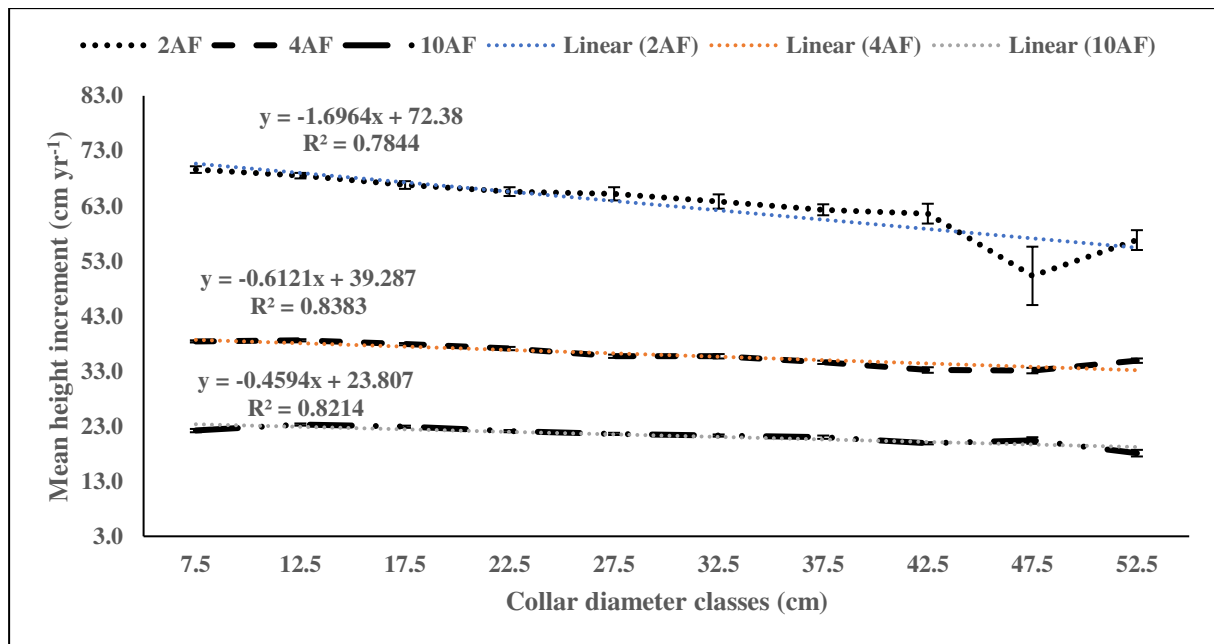


Figure 6. Average height increment of post-fire root sprouts across diameter classes in the 2AF, 4AF, and 10AF treatments (vertical bars represent standard error).

Table 8. Analysis of variance for the height increment of post-fire root sprouts across the 2AF, 4AF, and 10AF treatments.

Source	Type III Sum of Squares	df	Mean Square	F	P-value
Stands	8983.665	2	4491.832	336.218	<0.01
Error	360.717	27	13.360		
Total	9344.382	29			

R Squared =0.961 (Adjusted R Squared = .959); CV (%)=9.1

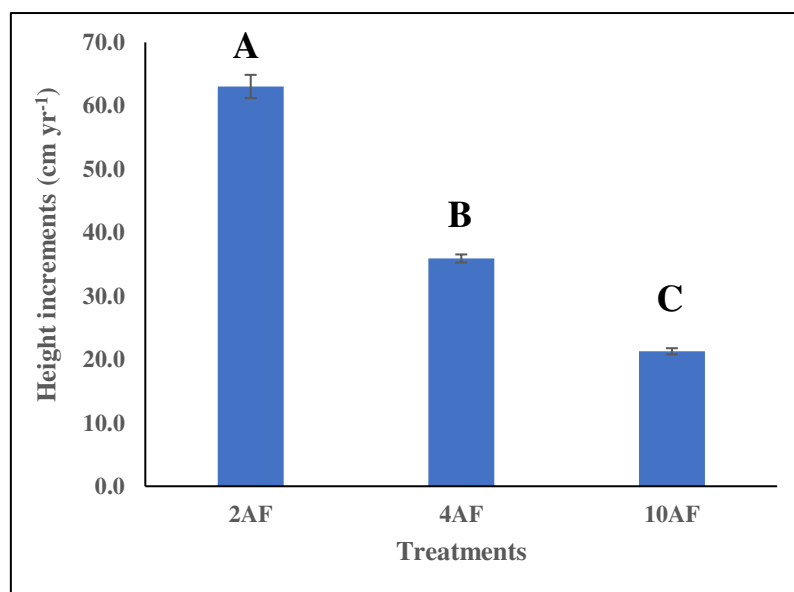


Figure 7. Post-hoc Tamhane's T2 test comparing the mean height increment of post-fire root sprouts across the 2AF, 4AF, and 10AF treatments (means with different letters indicate significant differences at the 1% level).

Conclusions and recommendations

This study provides valuable knowledge on the sprouting behaviour of three oak species—*Quercus brantii*, *Q. libani*, and *Q. infectoria*—in response to fire disturbance in the Northern Zagros forests of western Iran. The findings refer to the important contribution of post-fire root sprouting as one of the key mechanisms for forest regeneration and restoration. All three oak species showed vigorous sprouting capacity with a preference for root sprouts compared to stem sprouts, which play critical roles in forest regeneration, particularly in those ecosystems where seed regeneration is low.

Patterns of diameter and height increment of root sprouts showed early commencement of rapid growth, particularly during the initial two years following the fire, and referred to the resilience and fire tolerance of the species. More precisely, with the increasing diameter of burnt stumps, the diameter and height increments of post-fire sprouts decreased.

Our findings suggest that stump diameter plays a significant role in sprouting capacity, with smaller to mid-sized trees exhibiting the highest sprouting potential. The number of post-fire sprouts, along with both the diameter and height increment indices for post-fire root sprouts, followed similar trends across diameter classes, all declining as stump diameter increased. The negative slopes of the lines fitted to the distribution of the number of post-fire sprouts and the diameter and height increment curves across diameter classes further support the inverse relationship between these indices and stump diameter. This highlights that managing stump size through interventions like thinning can aid forest regeneration by promoting the growth of high-quality sprouts.

In conclusion, the findings highlight the crucial role of oak species' sprouting abilities in preserving the ecological integrity of Zagros forests, particularly in areas impacted by frequent fires and human activities like pollarding. The study supports the use of the coppice method for forest regeneration in the study area, which can be enhanced through traditional forestry practices such as thinning and stump management to promote high-quality sprout growth and facilitate faster regeneration. By encouraging natural regeneration through sprouting, these oak species provide a practical solution for restoring oak-dominated ecosystems, ensuring the long-term sustainability of these forest ecosystems, especially after fire.

Given these insights, we propose the following management recommendations to enhance post-fire regeneration and sprouting in oak forests:

1. Prioritize cutting burned trees with a diameter of at least 5 cm, especially during the dormant season, such as December, to increase the number of viable stumps and post-fire sprouts, thereby promoting the regeneration and recovery of burned oak forests. Cutting the burned trees during the dormant season, particularly in winter months such as December, to increase the number and vigour of post-fire sprouts.
2. Considering the annual height growth of post-fire sprouts, it is crucial to prevent livestock grazing for at least 4-5 years to allow sprouts to grow beyond the grazing horizon (over two meters), thus increasing their chances of successful establishment.
3. Given the abundance of sprouts following a fire, focusing growth potential on the most viable sprouts through thinning can enhance regeneration and reduce vulnerability to future fires. These insights are essential for developing sustainable forest management strategies that support the natural regeneration of oak forests and ensure their long-term ecological stability.

By implementing these strategies, forest managers can enhance the fire resilience of oak forests and ensure sustainable regeneration and long-term ecological stability in oak forests located in fire-prone areas.

496 **Statements and Declarations**

497 **Ethics approval:** All authors have read, understood, and complied as applicable with the statement on "Ethical
498 responsibilities of Authors" as found in the Instructions for Authors and are aware that, with minor exceptions,
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500 **Competing interests:** No, I declare that the authors have no competing interests as defined by Nature Research,
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502 **Dual publication:** No, the results/data/figures in this manuscript have not been published elsewhere, nor are they
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