

Elevational controls on deadwood carbon stocks in a semi-arid forest ecosystem related to longterm climate trends (1988–2024)

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Abstract

Aims

Climate change profoundly alters carbon cycling and poses major threats to forest ecosystems. Deadwood constitutes a critical carbon pool, yet quantitative data on its stocks remain scarce in semi-arid Zagros forests. This study aimed to quantify carbon stocks of standing (SDW) and fallen deadwood (FDW) along an elevational gradient (250–2355 m a.s.l.) in Qalajeh Protected Area, Iran, and to examine relationships with physiographic factors and climatic trends (1988–2024).

Materials & Methods

Standard forest inventory methods were employed, including the line-intersect method for FDW and allometric equations for SDW. Two-way ANOVA, Pearson's correlation, and the modified Mann–Kendall test were applied to analyze physiographic relationships and long-term climatic trends.

Findings:

Elevation showed significant negative correlations with SDW ($r = -0.65$) and FDW carbon ($r = -0.64$; $P < 0.01$), while slope and aspect had no significant effects. Highest FDW carbon ($17.03 \pm 2.30 \text{ t ha}^{-1}$) occurred at low elevations (1400–1500 m). Significant warming (Sen's slope = $+0.0697^\circ\text{C yr}^{-1}$, $P < 0.01$) and declining humidity and frost days ($P < 0.05$) were detected over the 37-year period.

Conclusion

Elevation emerged as the primary factor governing deadwood carbon distribution. Increasing temperatures and decreasing humidity at lower elevations likely intensify drought stress and tree mortality, enhancing deadwood accumulation. By addressing a critical knowledge gap in semi-arid forest carbon dynamics, these findings provide essential baselines for adaptive management strategies to enhance Zagros Forest resilience under ongoing climate change.

Introduction

Anthropogenic climate change has profoundly altered global carbon cycling, with forest ecosystems serving as both major carbon sinks and sources (IPCC, 2021). Among forest carbon pools, deadwood—comprising standing dead trees (SDW) and fallen deadwood (FDW)—plays a critical but often overlooked role. Although deadwood no longer sequesters carbon, it functions as a transient reservoir, storing carbon for decades to centuries while supporting biodiversity, nutrient cycling, and soil formation (Jandl et al., 2007, Russel et al., 2015). Recent global syntheses emphasize that deadwood dynamics are controlled by interacting biotic (insects, microbes) and abiotic (water, fire, freeze-thaw) drivers, yet Earth

system models currently capture only a fraction of these complexities (Wijas et al., 2024). Consequently, deadwood remains a major source of uncertainty in forest carbon budgets, particularly in understudied semi-arid ecosystems.

Semi-arid forests, such as the Zagros woodlands in western Iran, experience increasing drought stress, rising temperatures, and anthropogenic pressures including overgrazing and land-use conversion. These conditions can simultaneously increase deadwood inputs through drought-induced mortality and accelerate carbon losses through enhanced decomposition, creating considerable uncertainty in forest carbon cycling (Chowdhury et al., 2024). The Zagros region, the largest forested area in Iran covering approximately five million hectares, has recently witnessed unprecedented tree mortality driven by climate-induced drought and associated pathogens such as *Biscogniauxia mediterranea* (Azimi et al., 2023, Javanmiri Pour et al., 2023).

Studies confirm that oak decline in this region is fundamentally a drought-induced phenomenon, with mean annual maximum temperature and relative humidity being key risk factors (Mehri et al., 2024). Yet, quantitative information on deadwood carbon stocks and their spatial distribution remains almost nonexistent.

Three major research gaps currently hinder effective assessment and management of deadwood carbon in semi-arid Zagros forests. First, most studies have focused on living biomass or soil organic carbon, ignoring SDW and FDW as separate pools with distinct ecological functions. Even in well-studied tropical montane forests, deadwood carbon has only recently been quantified along elevational gradients (Komposch et al., 2022). Second, the effects of elevation, slope aspect, and slope gradient on deadwood carbon storage have never been systematically evaluated in this region, despite evidence from other semi-arid ecosystems suggesting that elevation can explain substantial variation in deadwood biomass, with lower elevations often accumulating more necromass due to climatic stress (Khan et al., 2024). Third, no study has quantitatively linked deadwood carbon dynamics to multi-decadal climatic trends such as temperature, precipitation, humidity, and frost days, despite evidence of regional warming and drying over recent decades [11,12].

To address these gaps, the present study tested three hypotheses. First (H1), deadwood carbon stocks of both SDW and FDW decrease significantly with increasing elevation, based on expected lower tree density and biomass at higher elevations as well as reduced drought stress and mortality compared to warmer low-elevation zones [10]. Second (H2), deadwood carbon stocks vary significantly among slope aspects and slope classes, with higher stocks expected on south-facing slopes due to greater drought stress and light-demanding species dominance, and on gentle slopes due to better water and nutrient retention compared to steep slopes (Mehri et al., 2024). Third (H3), the study region exhibits significant warming and drying trends over the 1988–2024 period, characterized by increasing temperature, declining relative humidity, and reduced frost days (Attarod et al., 2023 & 2024), and these trends are expected to correlate with patterns of tree mortality and deadwood accumulation.

Accordingly, the present study quantified SDW and FDW carbon stocks along a 1400–2100 m elevational gradient in the Qalajeh Protected Area, western Iran. Specifically, we aimed to: (i) estimate deadwood carbon storage across elevation classes, slope aspects, and slope gradients; (ii) test the relationships between deadwood carbon stocks and physiographic factors using Pearson correlation and analysis of variance; and (iii) evaluate long-term trends (1988–2024) in temperature, precipitation, relative humidity, and frost days using the Mann–Kendall test. The novelty of this study lies in the integrated assessment of SDW and FDW pools within an understudied semi-arid ecosystem and, more importantly, the first quantitative link between deadwood carbon and 37-year climate trends in the Zagros forests. Recent research confirms that abiotic factors including climate properties, topographic features, and land use collectively influence oak forest decline in this region [8], yet deadwood carbon has remained unquantified. The findings will provide essential baseline data for improving national carbon accounting under the United Nations Framework Convention on Climate Change and for developing climate-adaptive forest management strategies that recognize deadwood as an integral component of resilient forest ecosystems.

Materials and Methods

Site description

The present study was conducted in the Qalajeh Protected Forest, located in Gilan-e Gharb County, Kermanshah Province, western Iran (33°41'24" to 34°25'43" N latitude and 45°35'39" to 45°48'58" E longitude). The area is characterized by considerable topographic heterogeneity, with elevations ranging from 250 to 2355 m above sea level, and contains three distinct climatic zones (warm, temperate, and cold). The forest vegetation is dominated by *Quercus brantii* Lindl., accompanied by *Pistacia atlantica* Desf., *Crataegus* spp., *Pyrus* spp., *Cerasus microcarpa* (C.A. Mey.) Boiss., *Acer monspessulanum* L., *Amygdalus scoparia* Spach, and *Amygdalus* spp. The area also provides habitat for two ecologically valuable species, *Anagyris foetida* and *Myrtus communis* L.

Field Sampling and Deadwood Inventory

The study area was stratified into seven elevational classes at 100-m intervals from 1400 to 2100 m: 1400–1500, 1500–1600, 1600–1700, 1700–1800, 1800–1900, 1900–2000, and 2000–2100 m. Within each elevational class, three sampling plots of 100 × 100 m (1 ha) were established. For each plot, slope gradient (classified as 0–15%, 15–30%, 30–45%, and 45–60%) and slope aspect (north, east, south, west) were recorded.

For standing dead wood (SDW), diameter at breast height (DBH) and total height were measured for single-stemmed trees. For coppice trees, a composite diameter variable was calculated as the square root of the sum of squared diameters of all sprouts measured at 0.5 m above ground level (Pourhashemi et al., 2015). Tree height for coppice stools was estimated from four representative sprouts: the tallest

sprout, the thickest sprout, and the sprouts closest to the stool center on the northern and southern sides.

For fallen dead wood (FDW), the line-intersect method was applied (Zobeiry, 2000). Within each plot, ten parallel transects of 100 m length spaced 10 m apart were established. All fallen woody debris with a diameter ≥ 2 cm intersecting the transects was recorded following Iwashita et al. (2013). When a deadwood piece intersected a transect, its diameter was measured perpendicular to the longitudinal axis at the intersection point. If the transect crossed the end of a deadwood piece, the diameter was measured only when the central axis of the piece intersected the transect. Pieces whose longitudinal axis coincided with the transect line were excluded, and for curved or branched pieces, the average diameter of all intersections was used (Zobeiry, 2002). Diameters were measured using a diameter tape, lengths with a measuring tape, and SDW heights with a Suunto clinometer.

Determination of dry density and carbon fraction

To determine dry density, representative wood samples ($2 \times 2 \times 2$ cm) were collected and oven-dried at 105°C for 24 h (Henry et al., 2010). Dry density was calculated as the ratio of oven-dry mass to fresh volume (Vahedi & Mataji, 2014). Deadwood biomass was then estimated by multiplying dry density by deadwood volume.

The carbon fraction was determined using the loss-on-ignition method (Allen et al., 1986). Wood samples ($2 \times 2 \times 2$ cm) were combusted in an electric furnace at $500\text{--}600^\circ\text{C}$ for 3–4 h. After combustion, samples were cooled in a desiccator and weighed repeatedly until constant mass was achieved. Ash content and carbon fraction were calculated using Eq. (1):

$$\text{Ash (\%)} = ((W_3 - W_1) / (W_2 - W_1)) \times 100 \text{ Eq. (1)}$$

$$\text{C (\%)} = (100 - \text{Ash \%}) \times 0.58 \text{ Eq. (2)}$$

where:

- Ash (%) = ash content after complete combustion;
- W_1 = weight of the crucible (g);
- W_2 = weight of oven-dried sample plus crucible (g);
- W_3 = weight of ash plus crucible (g);
- C (%) = calculated carbon fraction.

The constant 0.58 represents the carbon content of organic matter (Allen et al., 1986). Finally, deadwood carbon stock (t ha^{-1}) was obtained by multiplying biomass by the calculated carbon fraction.

Deadwood volume estimation

The volume of standing dead wood (SDW) was estimated using Eq. (3) (Zobeiry, 2000):

Equation (2) – SDW volume

$$V = g \times h \times f \text{ Eq. (3)}$$

where:

- V = SDW volume (m^3);
- g = basal area (m^2);
- h = tree height (m);
- f = form factor (assumed to be 0.38); (Heidari Safari Kouchi et al., 2015)

The volume of fallen dead wood (FDW) was estimated using the line-intersect sampling Eq. (4); [16]:

$$V = (\pi^2 \times \sum d^2) / (8Lm) \text{ Eq. (4)}$$

where:

- V = FDW volume ($\text{m}^3 \text{ ha}^{-1}$);
- d = diameter of woody debris (cm);
- n = number of deadwood pieces in transect j ;
- m = number of transects;
- L = transect length (m).

Climatic data analysis

To evaluate long-term climatic variability, temporal trends in four climatic variables—annual precipitation, mean annual temperature, relative humidity, and number of frost days—were analyzed over the 1988–2024 period. Data were obtained from the nearest synoptic meteorological station with complete records.

The non-parametric Mann–Kendall test was used to detect monotonic trends in the time series. Because temporal autocorrelation can inflate the variance of the test statistic and lead to false significant trends, the modified Mann–Kendall test proposed by Hamed and Rao (1998) was applied. This method corrects for the effect of autocorrelation by removing the serial correlation components from the data before calculating the test statistic. The Z statistic was used to determine trend significance, with positive Z indicating increasing trends and negative Z indicating decreasing trends. The magnitude of the trend was estimated using Sen's slope estimator (Sen, 1986). All climatic trend analyses were performed using R software (version 4.3.1) with the 'trend' package.

Statistical analyses

Data normality was assessed using the Kolmogorov–Smirnov test, which confirmed that all data followed a normal distribution. Relationships between deadwood carbon stocks and environmental variables (elevation, slope gradient, slope aspect) were evaluated using Pearson’s correlation coefficient for continuous variables (elevation and slope) and the Eta correlation ratio for the categorical variable (aspect). Differences in carbon stocks among elevation classes, slope classes, slope aspects, and their interactions were analyzed using two-way analysis of variance (ANOVA). When significant differences were detected ($P < 0.05$), Duncan’s multiple range test was applied for pairwise comparisons among groups. All statistical analyses were performed using SPSS software version 25 (IBM Corp., Armonk, NY, USA).

Results

Two-way analysis of variance (ANOVA) revealed no significant effects of elevation classes, slope aspects, or slope classes on SDW carbon storage at the 95% confidence level (Table 1). Furthermore, none of the interaction effects (elevation $\times$ slope, elevation $\times$ aspect, slope $\times$ aspect) were statistically significant ($P > 0.05$ for all), (Table 1).

Similarly, ANOVA results for FDW carbon storage indicated that none of the physiographic factors—including elevation classes ($F = 1.64$, $P = 0.20$), slope aspects ($F = 1.11$, $P = 0.37$), or slope classes ($F = 1.75$, $P = 0.19$)—significantly affected carbon storage (Table 2). The interaction effects were also non-significant, although the slope $\times$ aspect interaction yielded the highest F-value ($F = 1.80$, $P = 0.20$) (Table 2).

Table 1
(Analysis of variance (ANOVA) summary for SDW carbon storage in relation to environmental factors

source of changes	df	mean of squares	F	P-value
Elevation classes	6	14	1.69	0.19
Slope aspect	3	12.62	1.32	0.30
slope classes	3	16.38	1.84	0.17
Elevation $\times$ slope	18	5.04	0.41	0.84
aspect $\times$ elevatoin	18	6	0.61	0.56
slopex aspect	9	11.51	1.52	0.25

Table 2
(Analysis of variance (ANOVA) summary for FDW carbon storage in
relation to environmental factors

source of changes	df	mean of squares	F	P-value
altitude classes	6	20.31	1.64	0.20
geographical directions	3	16.14	1.11	0.37
slope classes	3	23.23	1.75	0.19
altitude× slope	18	8.03	0.45	0.81
aspect× altitude	18	7.04	0.49	0.62
slope× aspect	9	20.55	1.80	0.20

Mean carbon storage of both SDW and FDW exhibited a clear decreasing trend with increasing elevation above sea level (Table 3). The highest values were observed in the lowest elevation class (1400–1500 m), reaching $17.03 \pm 2.30 \text{ t ha}^{-1}$ for FDW and $12.8 \pm 1.73 \text{ t ha}^{-1}$ for SDW. Conversely, the lowest values were recorded in the highest elevation class (2000–2100 m), with $9.8 \pm 2.02 \text{ t ha}^{-1}$ for FDW and $6.7 \pm 1.73 \text{ t ha}^{-1}$ for SDW. Across all elevation classes, FDW carbon stocks consistently exceeded those of SDW.

Table 3
(Mean carbon storage ($\pm$ standard error) of SDW and FDW
along the elevational gradient

elevation classes (m)	FDW (t. ha^{-1})	SDW (t. ha^{-1})
1400–1500	17.03 ± 2.30	12.8 ± 1.73
1500–1600	15.2 ± 2.02	11.06 ± 1.73
1600–1700	14.08 ± 1.45	10.2 ± 1.15
1700–1800	13.6 ± 0.88	9.04 ± 0.57
1800–1900	12.7 ± 3.05	8.9 ± 2.51
1900–2000	10.05 ± 1.76	7.5 ± 1.52
2000–2100	9.8 ± 2.02	6.7 ± 1.73

Although differences in carbon storage were observed among slope aspects, these variations were not statistically significant ($P = 0.37$). The highest values for both FDW and SDW were recorded on south-facing slopes (15.02 ± 1.28 and $11.4 \pm 1.06 \text{ t ha}^{-1}$, respectively), whereas the lowest values occurred on west-facing slopes (11.4 ± 1.30 and $7.2 \pm 1.2 \text{ t ha}^{-1}$, respectively) (Table 4).

Table 4
(Mean carbon storage ($\pm$ standard error) of SDW and FDW across slope aspects

Slope aspect	FDW (t. ha ⁻¹)	SDW (t. ha ⁻¹)
North	12.5 $\pm$ 1.46	8.04 $\pm$ 1.17
East	14.03 $\pm$ 1.98	9.07 $\pm$ 1.58
South	15.02 $\pm$ 1.28	11.4 $\pm$ 1.06
West	11.4 $\pm$ 1.3	7.2 $\pm$ 1.2

Across slope classes, the highest carbon storage values were recorded within the 15–30% slope class (FDW: 16.08 $\pm$ 1.25 t ha⁻¹; SDW: 11.5 $\pm$ 0.96 t ha⁻¹), while the lowest values were found in the 45–60% slope class (FDW: 10.06 $\pm$ 1.12 t ha⁻¹; SDW: 6.7 $\pm$ 1.2 t ha⁻¹). However, these differences were not statistically significant ($P = 0.19$) (Table 5).

Table 5
(Mean carbon storage ($\pm$ standard error) of SDW and FDW across slope classes

slope classes (%)	FDW (t. ha ⁻¹)	SDW (t. ha ⁻¹)
0–15	13.02 $\pm$ 1.83	9.08 $\pm$ 1.53
15–30	16.08 $\pm$ 1.25	11.5 $\pm$ 0.96
30–45	11.7 $\pm$ 1.35	8.4 $\pm$ 1.11
45–60	10.06 $\pm$ 1.12	6.7 $\pm$ 1.2

Pearson correlation analysis revealed significant negative relationships between elevation and carbon storage for both SDW ($r = -0.65$) and FDW ($r = -0.64$) at the 1% significance level ($P < 0.01$) (Table 6). This indicates a similar decline in carbon storage with increasing elevation for both deadwood pools. In contrast, the correlations between slope gradient and carbon storage were negative but not statistically significant for either SDW ($r = -0.31$, $P > 0.05$) or FDW ($r = -0.30$, $P > 0.05$). The Eta coefficient revealed no significant relationship between slope aspect (as a categorical variable) and carbon storage of either deadwood type (Table 6).

Table 6) Pearson correlation coefficients and Eta coefficients between deadwood carbon stocks and physiographic factors

	Pearson correlation coefficient		Eta coefficient
	Elevation	Slope gradient	Slope aspect
SDW	-0.65**	-0.31 ^{ns}	0.43 ^{ns}
FDW	-0.64**	-0.30 ^{ns}	0.40 ^{ns}

** : correlation is significant at the level of 1%, ^{ns} not significant at the 0.05 level

Climatic Trends

The highest annual precipitation (684 mm) was recorded in 1990, whereas the lowest value (21 mm) occurred in 2021. For annual temperature, the maximum mean (22°C) was observed in 2008 and during the period 2020–2023, while the minimum (18°C) occurred between 1990 and 1992. Annual temperatures during 2008–2024 were generally higher and exhibited greater fluctuations compared with the previous two decades. The highest annual relative humidity (53%) was recorded in 1991 and 1997, and the lowest (30%) in 2022, with generally higher humidity during the first decade than in subsequent decades. The maximum number of frost days (35 days) was recorded in 1992, whereas the minimum (0 days) occurred in 1998 and 2008, with a declining trend over time (Fig. 2).

The sequential forward (U) and backward (U') series derived from the non-parametric Mann–Kendall test for identifying change points over the 37-year study period graphically indicated negative trends in precipitation (B), relative humidity (C), and frost days (D), whereas temperature exhibited a positive trend (A) (Fig. 3).

The modified Mann–Kendall test, which corrects for autocorrelation effects [21], revealed statistically significant trends for all four climatic variables examined (Table 7; Fig. 3). Mean annual temperature exhibited a significant increasing trend with Sen's slope of + 0.0697°C yr⁻¹ (Z = 4.856, P < 0.01), indicating substantial regional warming. In contrast, annual precipitation (Sen's slope = - 0.038 mm yr⁻¹, Z = - 1.479, P < 0.05), relative humidity (Sen's slope = - 0.3297% yr⁻¹, Z = - 4.718, P < 0.05), and frost days (Sen's slope = - 0.571-day yr⁻¹, Z = - 3.953, P < 0.05) all exhibited significant declining trends. The greatest rate of decline was observed for frost days, indicating a pronounced reduction in cold-period occurrence throughout the study area (Table 7).

Table 7
(Modified Mann–Kendall trend analysis of climatic parameters (1988–2024)

Climatic parameter	Z statistic	P-value	Sen's slope	Trend type
Mean annual temperature	4.856	$P < 0.01$	+ 0.0697	Significant increasing trend
Annual precipitation	-1.479	$P < 0.05$	-0.038	Significant decreasing trend
Relative humidity	-4.718	$P < 0.05$	-0.3297	Significant decreasing trend
Frost days	-3.953	$P < 0.05$	-0.571	Significant decreasing trend

Discussion

Elevation as the primary control on deadwood carbon storage

The most prominent finding of this study was the strong and significant negative correlation between elevation and carbon storage in both standing dead wood (SDW) and fallen dead wood (FDW). This pattern indicates that deadwood carbon stocks decline consistently with increasing elevation across the semi-arid Zagros forests. Several ecological mechanisms may explain this observation.

First, lower elevations in the study area (1400–1500 m) are characterized by warmer temperatures, higher evaporative demand, and longer growing seasons, which collectively increase drought stress on *Quercus brantii* trees. Prolonged drought exposure weakens tree physiology, reduces hydraulic conductivity, and ultimately increases mortality rates, thereby contributing to greater deadwood inputs at lower elevations (Chowdhury et al., 2024, Allen et al., 2010). Second, lower elevations typically support higher tree density and aboveground biomass compared to higher elevations, providing a larger source pool for necromass production (Khan et al., 2024). Third, although decomposition rates are generally temperature-dependent and expected to accelerate under warmer conditions, the increased mortality rate at low elevations appears to outweigh carbon losses through decomposition, resulting in net deadwood accumulation. This balance between input (mortality) and output (decomposition) is a key determinant of deadwood carbon storage (Russell et al., 2015, Anderegg et al., 2020).

In contrast, higher elevations (2000–2100 m) experience lower mean annual temperatures, reduced drought stress, and consequently lower tree mortality rates. These conditions lead to reduced deadwood inputs. Furthermore, lower temperatures may slow decomposition, but the overall effect is a reduction in deadwood standing stocks due to lower biomass production and tree density at high elevations (Komposch et al., 2022). Similar findings have been reported from tropical montane forests, where deadwood carbon stocks declined sharply along elevational gradients due to decreasing productivity and tree size (Iwashita et al., 2013, Chambers et al., 2000).

Non-significant effects of slope aspect and slope gradient

Contrary to our second hypothesis (H2), neither slope aspect nor slope gradient significantly affected deadwood carbon stocks in this study. Although south-facing slopes exhibited the highest carbon storage values (15.02 t ha⁻¹ for FDW and 11.4 t ha⁻¹ for SDW) and west-facing slopes the lowest, these differences were not statistically significant.

The absence of significant aspect effects may be explained by several factors. First, *Quercus brantii* is a light-demanding species that can tolerate a wide range of solar radiation and moisture conditions, reducing aspect-related differentiation in growth and mortality (Pilehvar et al., 2014). Second, the semi-arid climate of the Zagros region, characterized by overall water limitation across all aspects, may override the moderating effects of aspect on microclimate. Third, anthropogenic disturbances such as livestock grazing and fuelwood collection are widespread across all slopes in the Qalajeh Protected Area, potentially masking natural aspect-related patterns (Sagheb-Talebi et al., 2104).

Similarly, slope gradient did not significantly influence deadwood carbon stocks, although a decreasing trend was observed from gentle (15–30%) to steep (45–60%) slopes. Steeper slopes typically experience enhanced surface runoff, reduced soil water retention, and lower nutrient availability, which can limit tree growth and biomass accumulation (Magnusson et al., 2016). However, the high spatial variability of deadwood distribution and the relatively small sample size within each slope class may have reduced statistical power to detect significant differences. Nguyen et al. (2012) similarly reported that physiographic factors significantly affect biomass carbon storage only under optimal site conditions, whereas under stressful conditions (such as water limitation), other factors like disturbance history and climate become more important.

Long-term climatic trends and their implications for deadwood dynamics

The Mann–Kendall trend analysis revealed significant climate shifts in the study region over the 37-year period (1988–2024). Mean annual temperature increased at a rate of + 0.0697°C yr⁻¹ ($P < 0.01$), equivalent to a total increase of approximately 2.6°C over the study period. Concurrently, relative humidity declined by – 0.3297% yr⁻¹, annual precipitation decreased by – 0.038 mm yr⁻¹, and frost days declined by – 0.571-day yr⁻¹ (all $P < 0.05$). These trends are consistent with regional climate change projections for the Middle East (IPCC, 2022, Attarod et al., 2023 & 2024).

The combined effects of rising temperature and declining humidity have likely intensified atmospheric evaporative demand and soil moisture deficits, particularly at lower elevations. Such conditions increase physiological stress on *Quercus brantii*, making trees more susceptible to drought-induced mortality and pathogen attacks, including the charcoal canker fungus *Biscogniauxia mediterranea* (Azimi et al., 2023). The substantial accumulation of deadwood observed at low elevations (1400–1500 m) may therefore represent a direct consequence of climate-driven tree dieback.

The declining trend in frost days is particularly noteworthy. Frost events typically limit the distribution of certain pests and pathogens, and reduced frost frequency may allow insect populations and fungal

pathogens to expand their ranges and activity periods, further contributing to oak decline (Azimi et al., 2023). Moreover, the absence or reduction of seasonal frost may alter the timing of phenological events, potentially disrupting the synchrony between tree growth and environmental conditions.

Under balanced climatic conditions, increasing elevation is generally associated with lower temperatures and higher precipitation, which would be expected to slow decomposition and enhance deadwood carbon storage (Zhu et al., 2010). However, the observed decline in deadwood carbon storage along the elevational gradient in this study suggests that regional warming has already reached a threshold where decomposition and mortality dynamics are substantially altered. Similar findings have been reported by Woodall and Liknes (2008) in United States forests and by Chambers et al. (2000) in Amazonian tropical forests, where temperature increases accelerated carbon emissions from deadwood pools.

Comparison with previous studies

The deadwood carbon stocks reported in this study (ranging from 6.7 to 17.0 t ha⁻¹) are comparable to values reported for other semi-arid and Mediterranean forests. For example, Amanzadeh et al. (2013) reported deadwood carbon stocks of 8–15 t ha⁻¹ in Caspian forests of northern Iran, while Sefidi et al. [33] found higher values (20–30 t ha⁻¹) in undisturbed temperate forests. The relatively lower values in our study reflect the semi-arid conditions of the Zagros region, where lower productivity and faster decomposition under warm, dry conditions limit long-term deadwood accumulation.

However, direct comparisons are complicated by methodological differences in deadwood inventory protocols (e.g., minimum diameter thresholds, transect length, and carbon fraction assumptions). The consistent use of standard methods (line-intersect for FDW; allometric equations for SDW) in our study ensures internal validity and allows future meta-analyses across semi-arid ecosystems.

Limitations of the study

Several limitations should be acknowledged. First, deadwood decomposition rates were not directly measured. While we infer decomposition dynamics from climatic trends, direct measurement of decay constants would improve mechanistic understanding of carbon fluxes. Second, climatic data were obtained from the nearest synoptic station rather than within forest plots; microclimatic conditions within the forest canopy may differ substantially from regional station records. Third, the study is observational and space-for-time substitution (elevational gradient) may not fully capture temporal dynamics of climate-driven deadwood accumulation. Fourth, anthropogenic disturbances (grazing, fuelwood collection) were not quantitatively assessed, although they likely influence deadwood distribution patterns. Fifth, the sample size (three plots per elevation class) limits statistical power to detect small but ecologically meaningful effects, particularly for slope and aspect interactions.

Future research should integrate direct decomposition measurements, high-resolution microclimatic sensors, and experimental manipulations to disentangle the relative contributions of climate, disturbance, and biotic factors to deadwood carbon dynamics in semi-arid forests.

Management implications

The findings of this study have several practical implications for forest management under climate change. First, the substantial carbon stocks stored in deadwood (up to 17 t ha⁻¹ for FDW) indicate that deadwood removal for fuelwood or sanitary purposes would not only reduce biodiversity associated with deadwood microhabitats but also cause immediate release of stored carbon, undermining climate regulation services provided by these forests. Therefore, retention of deadwood, particularly in low-elevation zones, should be prioritized in forest management plans.

Second, low elevations (1400–1500 m) and south-facing slopes were identified as high-risk zones for deadwood accumulation and climate-sensitive tree mortality. These areas should be targeted for monitoring and adaptive management, including assisted natural regeneration, reduction of additional stresses (e.g., grazing), and potential enrichment planting with more drought-tolerant genotypes or species.

Third, the significant climate trends documented here (warming, drying, reduced frost) provide an early warning that Zagros forests are undergoing rapid environmental change. Forest managers should integrate long-term climate trend monitoring into routine forest inventory programs. This integration would enable early detection of mortality hotspots and support proactive rather than reactive management responses.

Fourth, the data generated by this study provide a critical baseline for improving national forest carbon estimates in Iran and enhancing reporting accuracy under the United Nations Framework Convention on Climate Change (UNFCCC). Currently, deadwood carbon is often omitted from national greenhouse gas inventories in many developing countries, leading to substantial underestimation of forest carbon stocks (Wijas et al., 2024).

Conclusions

In conclusion, this study demonstrates that elevation is the primary physiographic factor governing deadwood carbon distribution in semi-arid Zagros forests, overriding the effects of slope aspect and gradient. The significant negative correlation between elevation and deadwood carbon stocks reflects a balance between drought-induced tree mortality (higher at low elevations) and reduced biomass production (at high elevations). The long-term climate trends—warming at +0.07°C yr⁻¹, declining humidity, and reduced frost days—confirm that the study region is experiencing rapid environmental change that likely exacerbates tree mortality and deadwood accumulation in vulnerable low-elevation zones.

By quantifying SDW and FDW carbon pools separately and linking them to 37-year climate trends, this study addresses critical knowledge gaps in semi-arid forest carbon dynamics. These findings provide an evidence-based foundation for adaptive forest management strategies that recognize deadwood as a dynamic, climate-sensitive, and ecologically valuable component of forest carbon balance. Under future climate scenarios, long-term warming and precipitation uncertainty may threaten the stability of

deadwood carbon reservoirs, underscoring the urgent need for integrated monitoring, modeling, and conservation efforts in the Zagros forests.

Declarations

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Mohsen Javanmiri Pour: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – Original Draft, Visualization.

Fardin Moradi: Methodology, Validation, Writing – Review & Editing, Project administration.

Ethical Permission

This study did not involve human participants, human data, or animal experiments. All field sampling was conducted in accordance with the environmental and forestry regulations of the Islamic Republic of Iran.

Consent to Publish declaration: not applicable

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AI Use Declaration

During the preparation of this work, the authors used DeepSeek solely for language polishing, grammar checking, and improving readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the final content of the publication. No generative AI was used for data analysis, interpretation, or scientific conclusion drawing.

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Figures

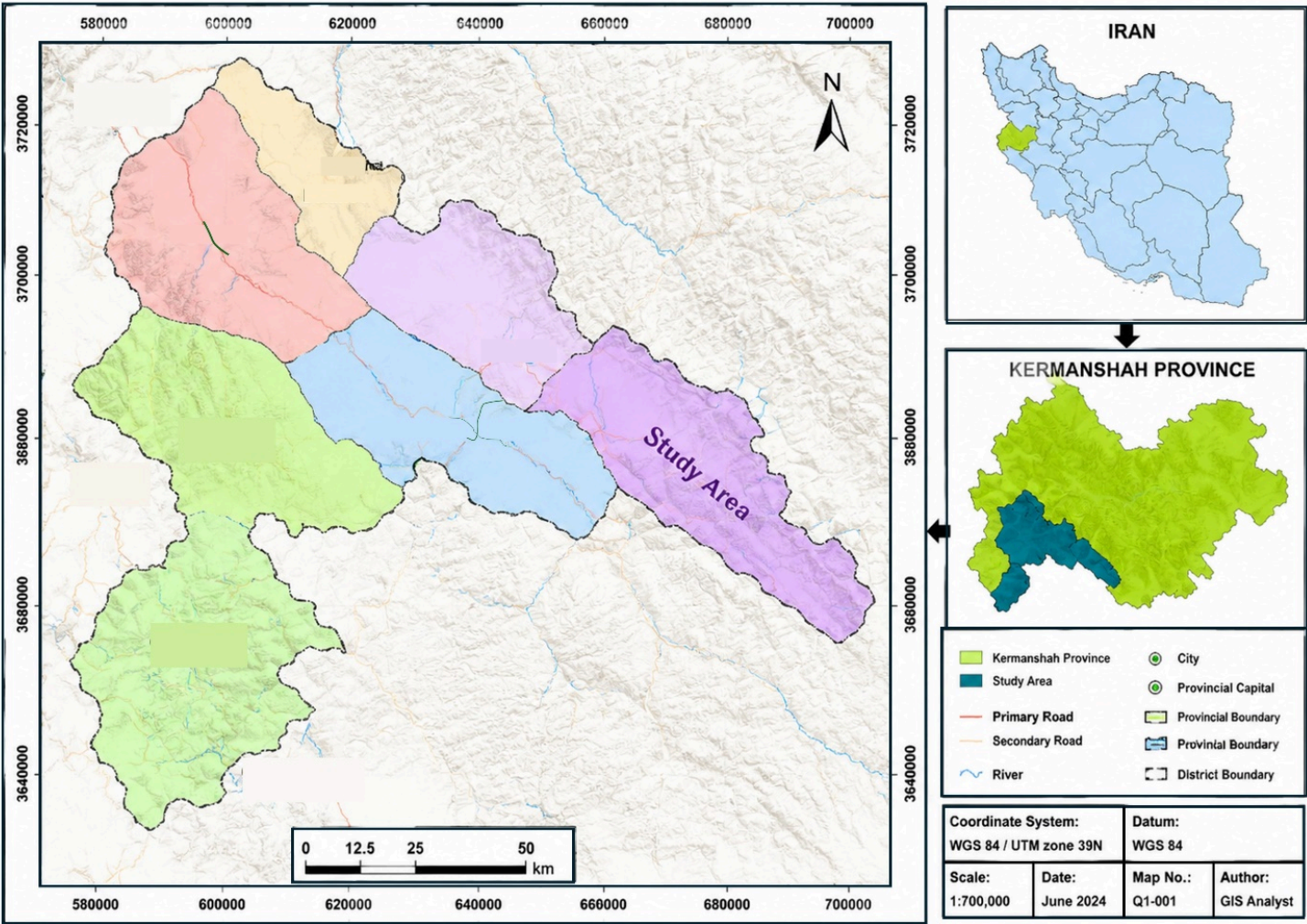


Figure 1

Geographic location of the study area in western Iran.

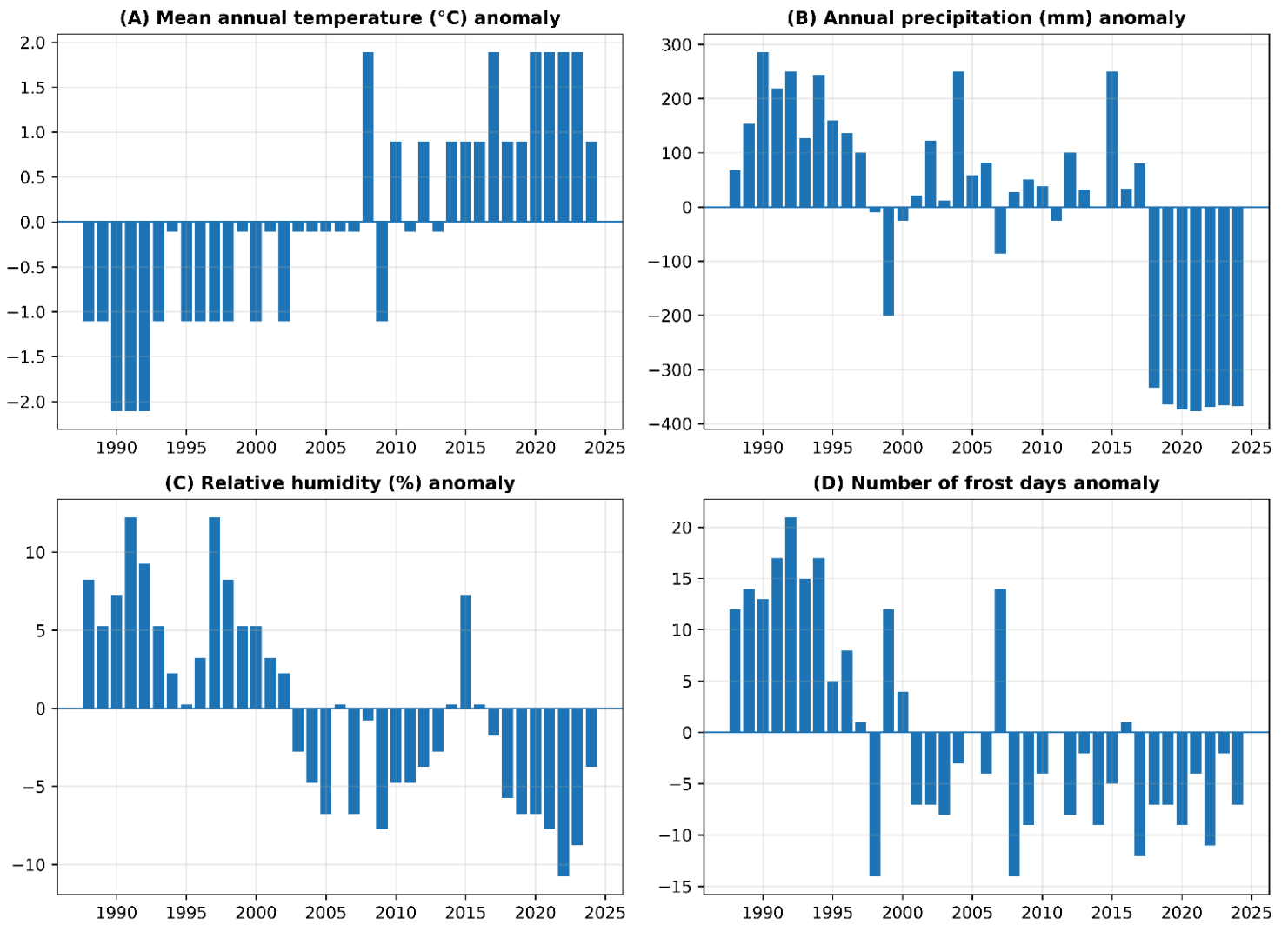


Figure 2

Annual precipitation, annual temperature, annual relative humidity, and annual frost days during the study period.

Mann-Kendall Trend Analysis — Gilangharb Meteorological Station (1988-2024)

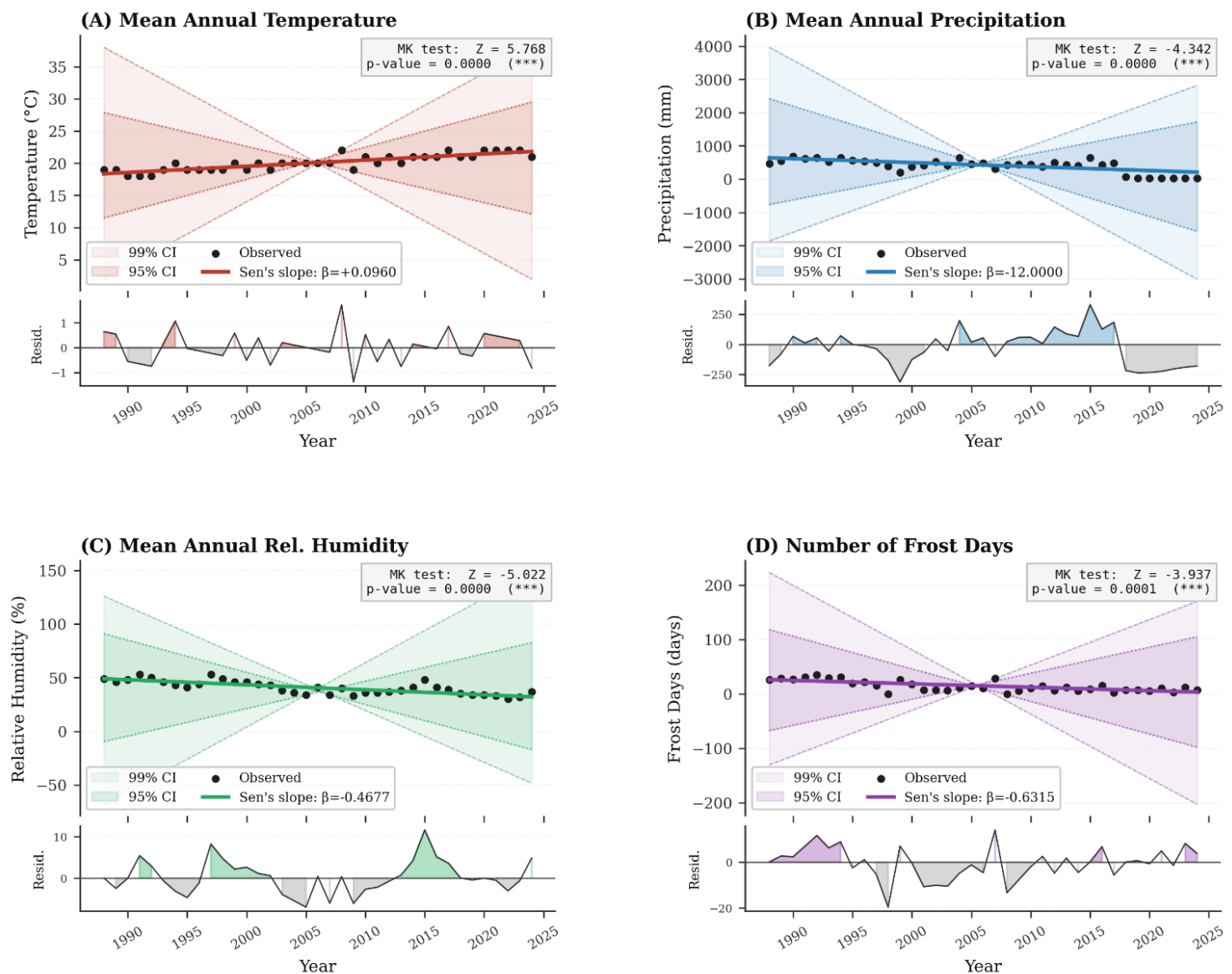


Figure 3

Mann–Kendall trend test for precipitation, temperature, relative humidity, and frost days over the 37-year study period in the study area.