



# Assessing the Effectiveness of Silvicultural Treatments on Fire Behavior in the Hyrcanian Temperate Forests of Northern Iran

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## Abstract

We implemented a fire modeling approach to evaluate the effectiveness of silvicultural treatments in reducing potential losses to the Hyrcanian temperate forests of northern Iran, in the Siahkal National Forest (57,110 ha). We compared the effectiveness of selection cutting, low thinning, crown thinning, and clear-cutting treatments implemented during the last ten years ( $n = 241$ , 9500-ha) on simulated stand-scale and landscape-scale fire behavior. First, we built a set of fuel models for the different treatment prescriptions. We then modeled 10,000 fires at the 30-m resolution, assuming low, moderate, high, very high, and extreme weather scenarios and human-caused ignition patterns. Finally, we implemented a One-way ANOVA test to analyze stand-level and landscape-scale modeling output differences between treated and untreated conditions. The results showed a significant reduction of stand-level fire hazard, where the average conditional flame length and crown fire probability was reduced by about 12 and 22%, respectively. The conifer plantation patches presented the most significant reduction in the crown fire probability (>35%). On the other hand, we found a minor increase in the overall burn probability and fire size at the landscape scale. Stochastic fire modeling captured the complex interactions among terrain, vegetation, ignition locations, and weather conditions in the study area. Our findings highlight fuel treatment efficacy for moderating potential fire risk and restoring fuel profiles in fire-sensitive temperate forests of northern Iran, where the growing persistent droughts and fuel buildup can lead to extreme fires in the near future.

**Keywords** Silvicultural treatments · Temperate forests · Siahkal National Forest · Fire modeling · Fire behavior

## Introduction

Temperate forests are characterized by moderate annual precipitation and large deciduous trees distributed across the Northern Hemisphere including eastern North America, western and central Europe, Northeast Asia, South-Eastern Australia, and southern South America (Gilliam 2016),

covering 16% of the world's forests (FAO 2020). These forests are under enormous pressure and declining mainly due to human activities, ongoing climate change, fires, pests and diseases, and other disturbances (Rawat et al. 2022). Although the knowledge about historical fire data in temperate regions remains limited, especially regarding fire sizes (Zin et al. 2022), forest fires are a permanent threat in these regions. According to the analysis of the MODIS burned area dataset (MCD64A1), between 2001 and 2018, approximately 63 million hectares of temperate forests were burned (Hislop et al. 2020). Large and severe forest fire occurrences are expected to grow as warmer temperatures, drier conditions, and longer fire seasons increase in frequency (Tran et al. 2020; Masinda et al. 2022). In temperature-fire-prone ecosystems, shifts in forest composition and structure will result from climate changes (Keenan 2015). Indeed, widespread impacts on forest ecosystems result from the observed increase in the frequency and intensity of extreme weather events such as hot extremes, drought, and fire weather (IPCC 2022). The fire-weather pattern within the dry temperate forests with

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intermediate moisture provides the best fire habitats (Lafon and Quiring 2012). Furthermore, vegetation productivity is high under high moisture and temperature conditions, resulting in more vegetation and hence heavier fuel loads (Adab et al. 2016), which dry quickly due to warmer temperatures and high evapotranspiration during the summer. In addition, land-use change and rural depopulation caused by urbanization are a general trend in temperate regions of Iran (Esfandeh et al. 2022) that have favored more homogeneous and flammable landscapes and make fire-landscape dynamics challenging to predict (Zin et al. 2022).

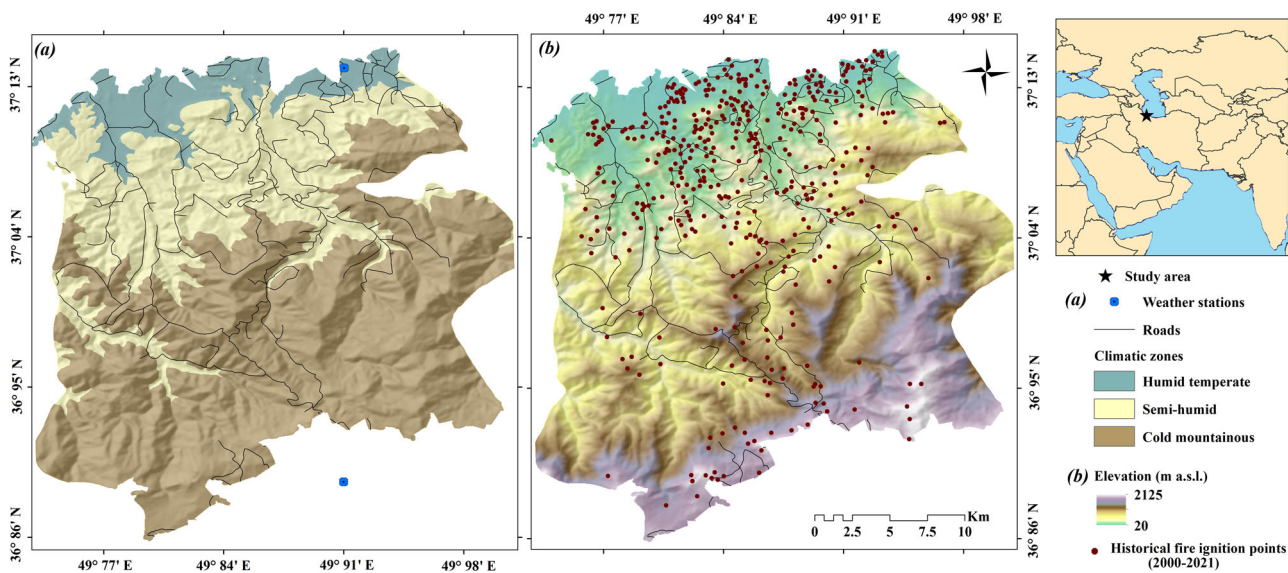
Forest fires are becoming more widespread in the Hyrcanian temperate forests of northern Iran (Ghorbanzadeh et al. 2019). According to the regional data cited by the Natural Resources and Watershed Management Organization (FRWO) of Iran (2022), Hyrcanian temperate forests (~18,400 km<sup>2</sup>) experienced an average of 400 fires per year which burned an average of about 2000 ha each year during 2000–2021. These forests are recognized as internationally significant and valuable ecosystems listed as UNESCO World Heritage Sites (Khare et al. 2021). Almost half a century ago, national forest management started in the forests with even-aged silvicultural systems like shelterwood systems, especially in pure and mixed oriental beech forests, and lasted for three decades (1970–2000; Sagheb-Talebi and Schütz 2002). These systems had socioeconomic and ecological problems, and since 2000, close-to-nature silvicultural selection systems have been implemented in the forests (Tavankar et al. 2022). There has also been a shift in forest management in the temperate zone globally from even-aged rotation management systems toward continuous-cover silvicultural approaches that support structural heterogeneity (Kováč et al. 2018). In general, three silvicultural treatment prescriptions (selection system, thinning, and clear-cutting) with the objectives of conserving diverse and mixed uneven-aged structures of the forests were carried out in 45% of the forests in northern Iran (Tavankar et al. 2021). In managed forests, industrial harvesting is done by a selection-cutting system under an intensive timber management regime. The total wood harvest was two times bigger than the natural potential of the forests (i.e., mean annual volume growth of ~2 m<sup>3</sup> ha<sup>-1</sup>) in the last decades (Sagheb-Talebi et al. 2014). Severe logging, along with agricultural activities, urbanization, and livestock grazing, caused severe damage to the forests, and because of the amount of land deforested annually (~12,000 ha; FAO 2014), industrial logging was ceased in 2017 in the name of the “forest rest” strategy (FRWO 2017). The exploitation of the forests for commercial and industrial purposes was prohibited for ten years.

Silvicultural treatments can help maintain healthy, diverse, and resilient forest ecosystems across multiple spatial and temporal scales. These effects vary by treatment

type, size, and age at the stand level, but their spatial arrangement and rate of implementation can alter outcomes at the landscape level (Barnett et al. 2016). Previous studies have shown the efficacy of stand-level treatment prescriptions for reducing surface and ladder fuels, as well as changing forest structural characteristics to increase landscape resilience to future climate change and fires in temperate coniferous forests of the western United States (Fulé et al. 2012; Johnson et al. 2007; Moghaddas et al. 2018). Moreover, the effectiveness of the treatments on several response variables, including vegetation and fire behavior, have been reported at the stand level by several authors in temperate forests of Northern Pacific (Mitchell et al. 2009), South-Eastern Australia (Keenan et al. 2021; Volkova et al. 2017), northeastern China (Zhu et al. 2022), and South America (Rago et al. 2020).

A fire modeling approach helps reveal a better view of the quantification of fire potential profiles (Salis et al. 2021; Alcasena et al. 2022), fire risk characterization (Mitsopoulos et al. 2015; Parisien et al. 2020), and the evaluation of fire and fuel management practices (Ager et al. 2020; Palaiologou et al. 2021). Studies in temperate forests have focused on fire potential, which concerns the general description of potential fire activity with social and ecological features (Stephens et al. 2014; Jahdi et al. 2020; Heisig et al. 2022). However, a need remains for further detailed studies for characterizing fire potential through fire spread simulations, which can guide efforts to improve the existing prioritization of fire protection and fuel management and compare different fuel treatment strategies in temperate forests.

Despite efforts of silvicultural treatments, the forest management effects in reducing wildfire risk are still poorly known in the Hyrcanian temperate forests. The silvicultural treatments implemented in the area generally included mechanical treatments to alter the forest structure (Parhizkar et al. 2021). In this study, we explored the effectiveness of different silvicultural treatments on stand-level fire hazard and overall effects on fire likelihood at the landscape scale within the Siahkal National Forest. The primary forest management objectives in northern Iran are conservation and protection, forest restoration, and timber production (Oghnoum et al. 2020). Appropriate interventions according to silvicultural prescriptions to achieve defined forest management objectives included a selection system for timber production, thinning for the restoration of even-aged stands, and clear-cutting as a regeneration method for plantations. We evaluated the effectiveness of the selection system, thinning, clear-cutting, and combined treatment in the historical fires (2000–2021). Under the five fire weather scenarios (low, moderate, high, very high, and extreme) mostly associated with large fires in the study area, we modeled potential fire behavior parameters for all



**Fig. 1** Map of the Siahkal National Forest (Siahkal County, N Iran) study area along with climatic zones, roads, and the weather stations (a), and spatial distribution of historical fire ignition points (2000–2021) in the study area along with terrain elevation (b). We

framed a 57,110-ha landscape file (LCP) containing the study area for fire modeling. Top-right insert, location of Siahkal County, northern Iran

treatments. Quantifying the effectiveness of the silvicultural treatments on fuel and fire dynamics can bridge critical knowledge gaps for forest managers in northern Iran and other temperate areas with similar forest management practices.

## Materials and Methods

### Study Area

The study area is a 57,110-ha heavily forested and mountainous region (ranging from 20 m along the Shemrood River to 2125 m at Deylaman Peak) located in the northern Siahkal in Guilan Province, Iran, with a geographical range of 36°80′–37°15′ N, 49°70′–50°01′ E (Fig. 1). The area along the southern coast of the Caspian Sea, northern Iran, has three main climate zones: humid temperate, semi-humid, and cold mountainous (Fig. 1a). In general, the study area has a humid and temperate climate with warm summers and moderate winters. The study area is influenced by local Foehn winds (Garmij), which are warm, dry, and gusty and occur throughout the Alborz Mountains (Mofidi et al. 2015). The Foehn winds, which are episodic drivers of potential fires (Sharples et al. 2010) generated across the northern parts of the Alborz Mountains, are the primary cause of the localized southerly wind maximum on the Alborz lee side (Mofidi et al. 2015).

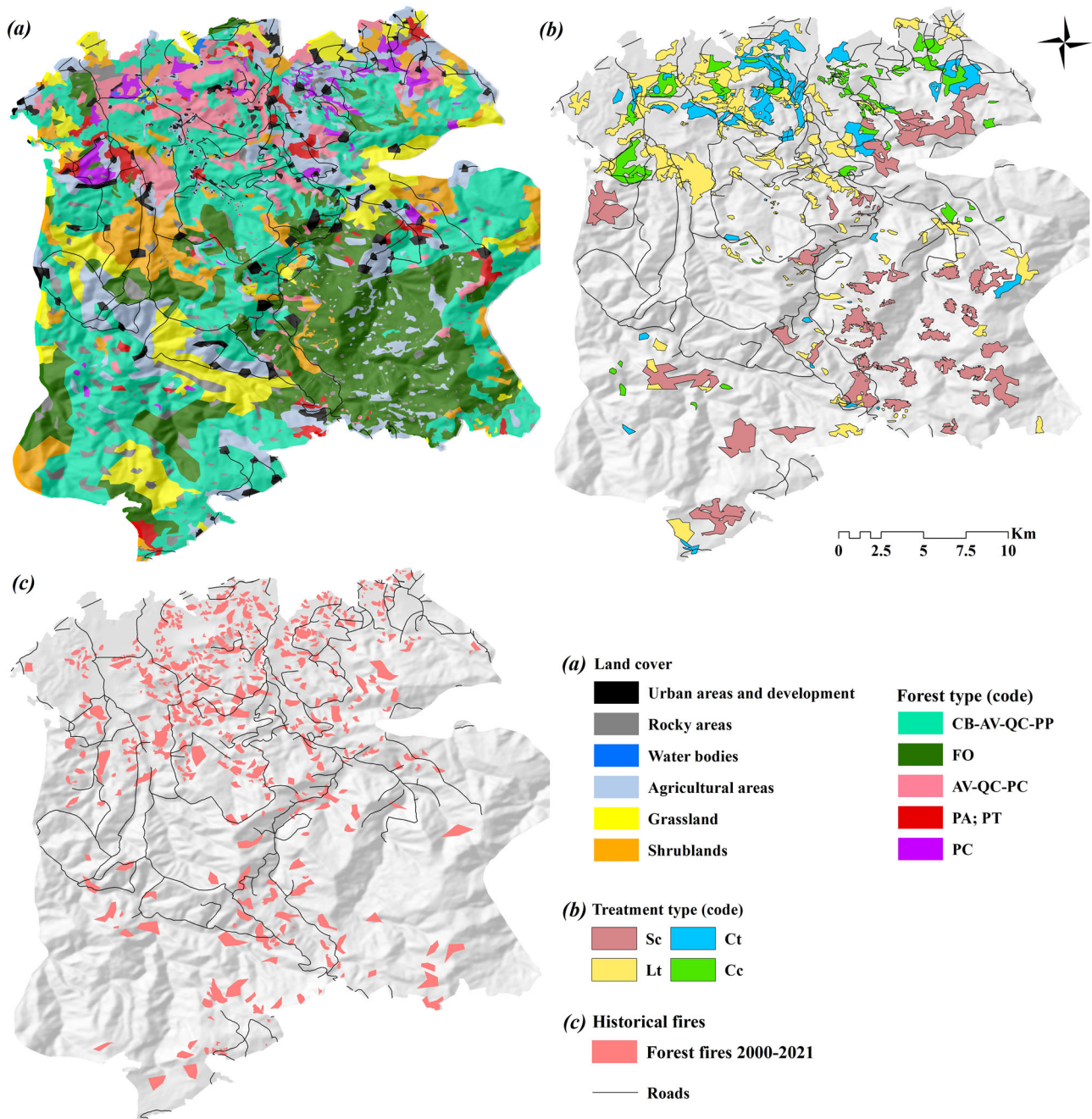
The dominant forest types include (i) mixed broadleaf forests of hornbeam (CB; *Carpinus betulus* L.), Persian maple (AV; *Acer velutinum* Boiss.), Chestnut-Leaved Oak

(QC; *Quercus Castaneifolia* C.A. Mey.), and Persian ironwood (PP; *Parrotia persica* (DC.) C.A.Mey.) with an area of 18,480 ha; (ii) oriental beech (FO; *Fagus orientalis* Lipsky) forests with an area of 11,850 ha; and (iii) mixed planted stands including Persian maple, Chestnut-Leaved Oak, Caspian poplar (PC; *Populus caspica* Bornm.), Norway spruce (PA; *Picea abies* L. Karst.), and Loblolly Pine (PT; *Pinus taeda* L.) with an area of 5880 ha (Fig. 2a). They accounted for 63.4% of the entire landscape area, followed by the agricultural areas (11.4%), grasslands (9.1%), shrublands (7.7%), and non-burnable areas (8.4%).

Siahkal is one of the largest fire-prone areas in the Hyrcanian forests. Summary statistics show that the total burned area during the 2000 to 2021 period was 5260 ha, while the minimum and maximum fire sizes were 0.05 ha and 115 ha, respectively (Fig. 1b). On average, 24 fires burn about 250 ha yr<sup>-1</sup>. More fires are reported in winter and spring (December to April) than in other seasons (322 out of 524). While previous studies reported a fire season length of about four months (Jahdi et al. 2014, 2015), conditions that allow fires to ignite and spread are growing in frequency in recent years, with an inherent increase in the fire season length (six to eight-month spans). Most fire ignitions (>95%) were confirmed to be the result of human activity (Jahdi et al. 2020).

### Silvicultural Treatments

In this study, we considered four silvicultural treatments, including selection cutting, low thinning, crown thinning, and clear-cutting to achieve forest management objectives



**Fig. 2** Maps of the land cover (a), silvicultural treatments (b), and the perimeters of the forest fires in the period 2000–2021 (c) in the study area. Forest types: CB hornbeam, AV Persian maple, QC chestnut-

leaved oak, PP Persian ironwood, FO beech, PC Caspian poplar, PA Norway spruce, PT loblolly pine. Treatment type: Sc selection cutting, Lt low thinning, Ct crown thinning, Cc Clear-cutting

(i.e., timber production, natural habitat restoration, and wood farming). Although treated stands were not specifically treated for fire resiliency, we evaluated the potential for silvicultural treatments to reduce fire risk across the forest landscape using fire potential modeling. The silvicultural treatments included the following (Table 1):

- Selection cutting (Sc). Harvests single trees or small groups of trees to create an uneven-aged stand structure.

In uneven-aged mixed broadleaf (CB-AV-QC-PP) and oriental beech (FO) stands in the study area, mature, over-mature, diseased, or damaged trees with at least 20 cm dib (diameter inside bark) top were harvested such that basal area was not reduced below 20 m<sup>2</sup> ha<sup>-1</sup> to maintain the complexity and heterogeneity of the natural forests. Tree marking was completed in September 2009, and they were felled by chainsaw in March 2010.

**Table 1** Summary table of the silvicultural treatment prescriptions implemented in the Siahkal National Forest (northern Iran) between 2007 and 2017

Forest type (code)	Stand structure	Management objective	Treatment prescriptions			Treated stands	
			Type (code)	RBA (%)	Interval (yr.)	Number	Avg. area (ha)
CB-AV-QC-PP and FO	Uneven-aged	Timber production and habitat conservation	Sc	80	10	70	22
AV-QC-PC, PA, and PT	Even-aged	Timber production	Lt	80	4	67	18
AV-QC-PC, PA, and PT	Even-aged	Timber production	Ct	60	6	83	16
PC	Even-aged	Wood farming	Cc	n.a.	10	21	3.5

The treatments are weighted proportionately by the residual basal area (RBA, i.e., basal area after treatment). The total area treated during the ten years was 9500-ha. See Appendix 1 for stand descriptors after the treatment implementation by forest type

Forest types: *CB* hornbeam, *AV* Persian maple, *QC* chestnut-leaved oak, *PP* Persian ironwood, *FO* beech, *PC* Caspian poplar, *PA* Norway spruce, *PT* loblolly pine, Treatment type: *Sc* selection cutting, *Lt* low thinning, *Ct* crown thinning, *Cc* Clear-cutting

- Low thinning (Lt). Removes suppressed and sub-dominant trees. The remaining stand is composed of evenly distributed dominant and codominant trees. Low thinning was implemented with 10% of the basal area removed at four-year interval and a 15-cm upper dbh (diameter at breast height) limit in the even-aged mixed broadleaf (AV-QC-PC) and pure conifer (PA; PT) plantations (2007–2017).
- Crown thinning (Ct): removes some dominants and co-dominant trees. The remaining stand consists of more open stands than low thinning, and very large trees are more valuable. Crown thinning with 30% removal of the basal area at six-year interval with a 15-cm upper dbh limit was implemented in the even-aged mixed broadleaf (AV-QC-PC) and pure conifer (PA; PT) plantations (2007–2017).
- Clear-cutting (Cc): a whole forest area is completely felled and harvested. Clear-cutting creates gaps in forest stands and contributes to subsequent regrowth. As a wood production system, clear-cutting has successfully regenerated poplars in the study area. All trees with at least 5 cm dib top were harvested in the even-aged polar (PC) plantations during 2011–2017.

In this study, as a first step, we generated five silvicultural treatments, which consisted of the no-treatment (NT) and four treatment types, including Sc, Lt, Ct, and Cc. The treatments were implemented in 241 stands corresponding to six forest types (Table 1 and Fig. 2b). No-treatment stands were established in six adjacent forest types. It is worth mentioning that surface fuels were reduced slightly by all treatments in the study area (Supplementary Table S1). In the second step, in addition to the separate analysis of each treatment type, we used a combination of the four treatment types (Sc, Lt, Ct, and Cc) in a new “TREAT” scenario to better analyze fire behavior at a landscape level. Finally, this combined scenario (TREAT) was also compared to the NT.

## Fuel Models

In this study, to represent dominant landscape land use types (e.g., forest, agricultural, urban areas and development, grasslands, and shrublands), we used the land cover map of the Guilan region (FRWO 2017). Moreover, to represent the stands of the forest landscape, we used the already existing forest formation map of Siahkal produced from the field survey utilizing a systematic randomized sampling method (with 3.3% sampling intensity) based on circular plots of 1000 square meters in size (Natural Resources Office (NRO), Guilan province, Iran, 2019). Basic variables associated with the condition of forest stand such as species name, number of trees per ha, diameter at

breast height (dbh; cm), tree height (m), canopy cover (%), canopy height (m), and crown base height (m) in each plot were recorded. Stand-level data were collected from sample plots ( $N = 353$  plots) in 2007 (no-treatment). After silvicultural treatments (2007–2017), remeasurements of these plots occurred in this study in 2019–2020 from the treated stands and untreated stands across the landscape. Average values of the measurement variables describing the forest stand structures after treatments in the study area are presented in Supplementary Table S1.

Vegetation types (basic fuel models) were organized into five groups (natural forest, plantation, shrubland, grassland, and non-burnable) according to the fuel load characteristics to facilitate fuel model assignment for the study area. All the stratified areas were then surveyed on-site, and 88 ( $1 \times 1$  m) sampling plots with similar fuel conditions for each area were randomly selected. In each sampling plot, the following fuel parameters were measured in the summer and fall of 2020: 1-h ( $\varnothing < 0.64$  cm), 10-h ( $0.64 < \varnothing < 2.54$  cm), and 100-h ( $2.54 < \varnothing < 7.62$  cm) fuel load (kg), live foliage (green and woody twigs  $\varnothing < 6$  cm with attached leaves (kg), fuel depth (cm). We created customized fuel models for each measured plot. Supplementary Table S2 shows the inputs to develop these field-validated fuel models.

### Fire-Weather Scenarios

We simulated potential fire behavior under five weather and fuel moisture scenarios for comparative purposes. We used low, moderate, high, very high, and extreme weather scenarios across the landscape (Table 2). The FireFamily Plus (FFP, v. 4.0; Bradshaw and McCormick 2009) was used to create weather scenarios, incorporating historic daily meteorological datasets of Deylaman and Ezbaram weather stations from 2000 to 2021 as reference (IRIMO 2021).

Wind speed is also an essential driver for fire behavior outputs in each weather scenario in fire behavior modeling. The historical average wind speeds of  $5\text{--}35 \text{ km h}^{-1}$  were determined for all weather scenarios (Table 2). Furthermore, for each weather scenario, we considered three wind

directions (SW ( $225^\circ$ ; 0.35 probability), W ( $270^\circ$ ; 0.5 probability), and NW ( $315^\circ$ ; 0.15 probability)) associated with the dominant wind direction in the study area during the fire season (Table 2).

### Fire Simulation Modeling

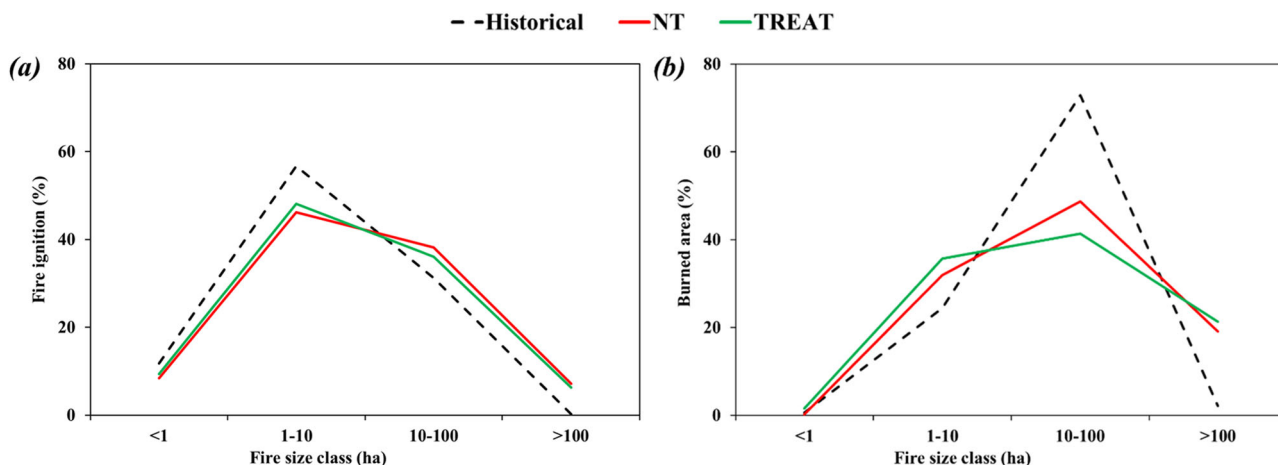
To determine fire potential for each pixel of the study area for a given condition, we created the no-treatment landscape and each of the treatment landscapes and used them as inputs for the Minimum Travel Time (MTT) fire spread algorithm (Finney 2002), embedded in the FlamMap program (v. 6.1; Finney 2006). For model calibration, we compared the historical and simulated (NT and TREAT landscapes) fire size distribution (Fig. 3). We used a burning period of 6 h for the simulations, which replicated the average observed fire size distributions in the study area. In general, the simulated fire size distribution was similar to the historical fire size distribution between 2000 and 2021. The fire size histograms peaked at 1–10 ha and 10–100 ha for fire ignition and burned area, respectively. The largest differences were observed for the 10–100 ha class, where fire size was underestimated, and an apparent overestimation for fires larger than 100 ha. The fire ignition and burned area distribution by fire class size were similar for the two treatment landscapes (NT and TREAT). Simulated fires between 10 and 100 ha had a higher number of ignitions and burned areas, accounting for about 40% of all ignitions.

We simulated 10,000 fires of historically based ignitions for a fixed burn period. We selected all fire ignitions for 2000–2021 in the study area and derived a smoothed historical fire ignition density map, which was constant for all fire simulations. For the simulations, the weather scenarios were set to the five-fuel moisture and weather scenarios, and three wind directions (Table 2). Simulations were performed at a resolution of 30 m, consistent with the landscape input data (topography, surface fuel, and canopy metric grids).

**Table 2** Fire weather scenarios are used for fire behavior simulations

Weather scenario	Fuel moisture content (FMC, %)					Wind condition		Probability
	1-h	10-h	100-h	LiveH	LiveW	Wind speed ( $\text{km h}^{-1}$ )	Wind Direction ( $^\circ$ )	
Low	13	14	16	110	130	5	225, 270, 330	0.38
Moderate	11	12	13	90	110	10	225, 270, 330	0.35
High	9	10	11	70	90	15	225, 270, 330	0.16
Very high	5	7	9	50	70	30	225, 270, 330	0.09
Extreme	3	5	7	30	50	35	225, 270, 330	0.02

Three wind directions (SW ( $225^\circ$ ; 0.35 frequency), W ( $270^\circ$ ; 0.5 frequency), and NW ( $315^\circ$ ; 0.15 frequency)) are associated with the dominant wind direction in the fire season in the study area



**Fig. 3** Comparison between historical and simulated fire size distribution regarding the effectiveness of different silvicultural treatments in distributions of ignition (a) and burned area (b). NT non-

treatment landscape, TREAT a treatment landscape that combines all treatment types implemented in the study area (See Table 1 for treatment types)

**Table 3** Stand-level fire behavior analyses (avg. (standard deviation under parenthesis)) for the different forest types and treatment types in the study area

Forest type (code)	Treatment type (code)	BP	CFL (m)	FS (ha)	CFP
CB-AV-QC-PP	NT	0.0032a (0.0014)	0.39a (0.12)	123.31a (27.60)	0.0477a (0.0082)
	Sc	0.0032a (0.0010)	0.34b (0.11)	128.15a (27.91)	0.0397b (0.0076)
FO	NT	0.0009a (0.0005)	0.30a (0.09)	126.60a (28.12)	0.0332a (0.0065)
	Sc	0.0009a (0.0003)	0.26b (0.10)	127.99a (28.42)	0.0292b (0.0061)
AV-QC-PC	NT	0.0041a (0.0019)	0.44a (0.19)	143.31a (32.16)	0.0547a (0.0143)
	Lt	0.0042a (0.0020)	0.39b (0.21)	149.75a (35.46)	0.0447b (0.0112)
	Ct	0.0042a (0.0020)	0.41b (0.20)	152.38b (34.72)	0.0421c (0.0116)
PA; PT	NT	0.0062a (0.0023)	0.79a (0.24)	226.39a (67.41)	0.0733a (0.0229)
	Lt	0.0066b (0.0025)	0.68b (0.26)	229.51a (68.50)	0.0500b (0.0124)
	Ct	0.0068b (0.0020)	0.74c (0.29)	232.30b (69.17)	0.0444c (0.0118)
PC	NT	0.0026a (0.0014)	0.38a (0.10)	86.83a (23.28)	0.0253a (0.0051)
	Cc	0.0028a (0.0016)	0.31b (0.08)	91.35a (22.86)	0.0227b (0.0046)

Different lower-case letters indicate a significant difference among different treatments ( $p$ -value < 0.05) We performed an ANOVA test to identify significant differences ( $p$ -value < 0.05) in simulation outputs NT non-treatment. See forest type and treatment type abbreviation codes in Table 1. BP burn probability, CFL conditional flame length, FS fire size, CFP crown fire probability

### Statistical Analysis

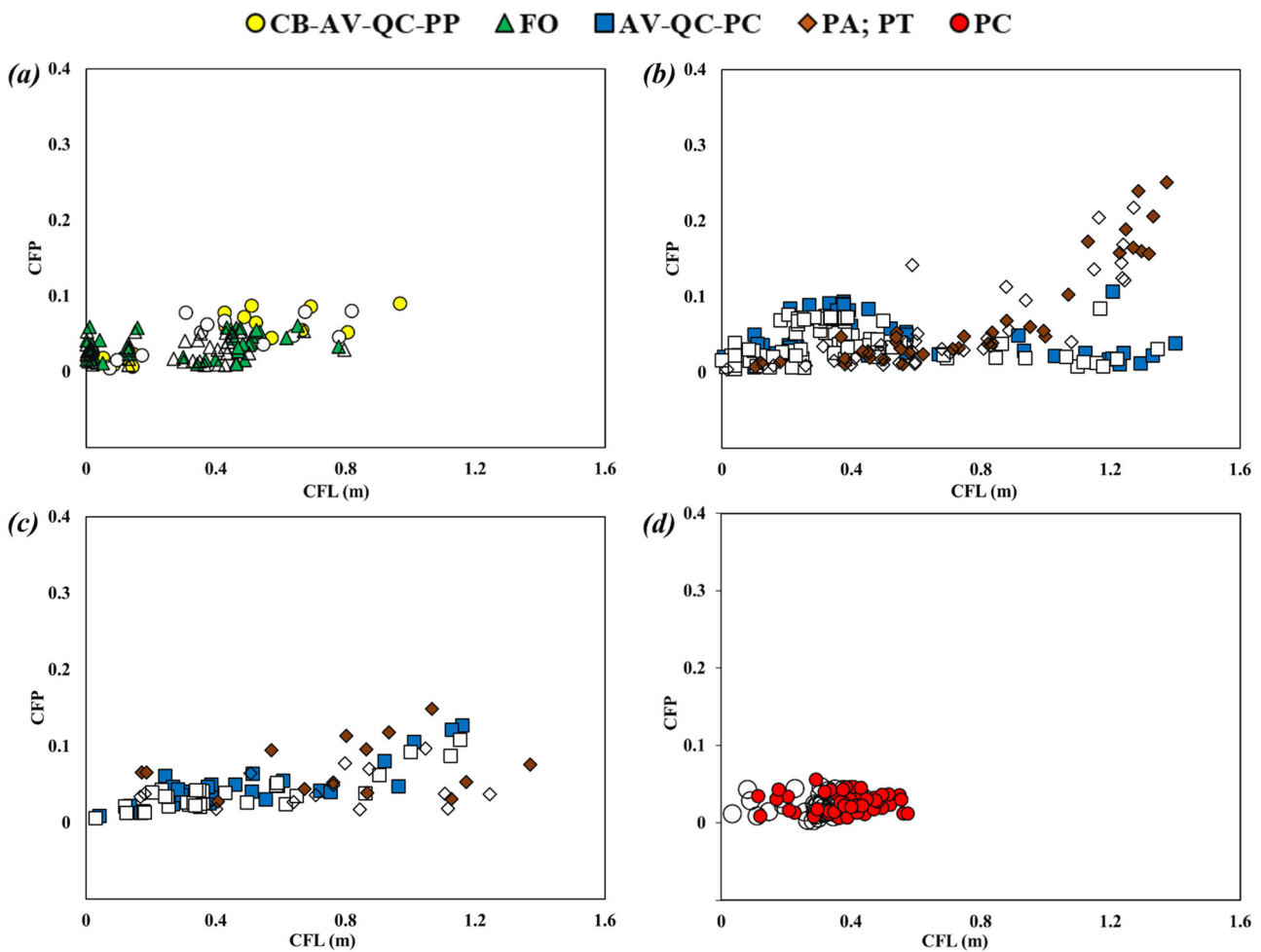
Pairwise comparisons of transformed mean responses were performed assuming an analysis of variance (ANOVA) model to assess the effectiveness of silvicultural treatments on different forest types using the XLSTAT software in Excel. One-way ANOVA post hoc test of multiple comparisons was applied to test for differences in means of the pixel-level fire potential parameters. The data were tested for normality with the Kolmogorov–Smirnov test to maintain ANOVA assumptions. Data were normalized, and unbiased estimators were used in the statistical analysis if variables were significantly non-normal. Furthermore, the statistically significant differences in simulation outputs

between treatments were obtained using a one-way ANOVA test (95 % confidence level).

### Results

#### Fire Potential at Stand-Scale

We presented stand-scale quantitative assessments of treatment effectiveness on fire potential metrics within the six forest types coupled with the treatments, regardless of the weather scenario (Table 3). Sc treatment did not produce significant differences in BP compared to the NT stands when treating the natural CB-AV-QC-PP (0.0032) and FO



**Fig. 4** Scatter plots of average conditional flame length (CFL (m)) versus average crown fire probability (CFP) estimated for each treatment type (Sc, **a**; Lt, **b**; Ct, **c**; Cc, **d**) in individual polygons or stands.

See forest type and treatment type abbreviation codes in Table 1. Note that unfilled and filled polygons show treated and untreated stands, respectively

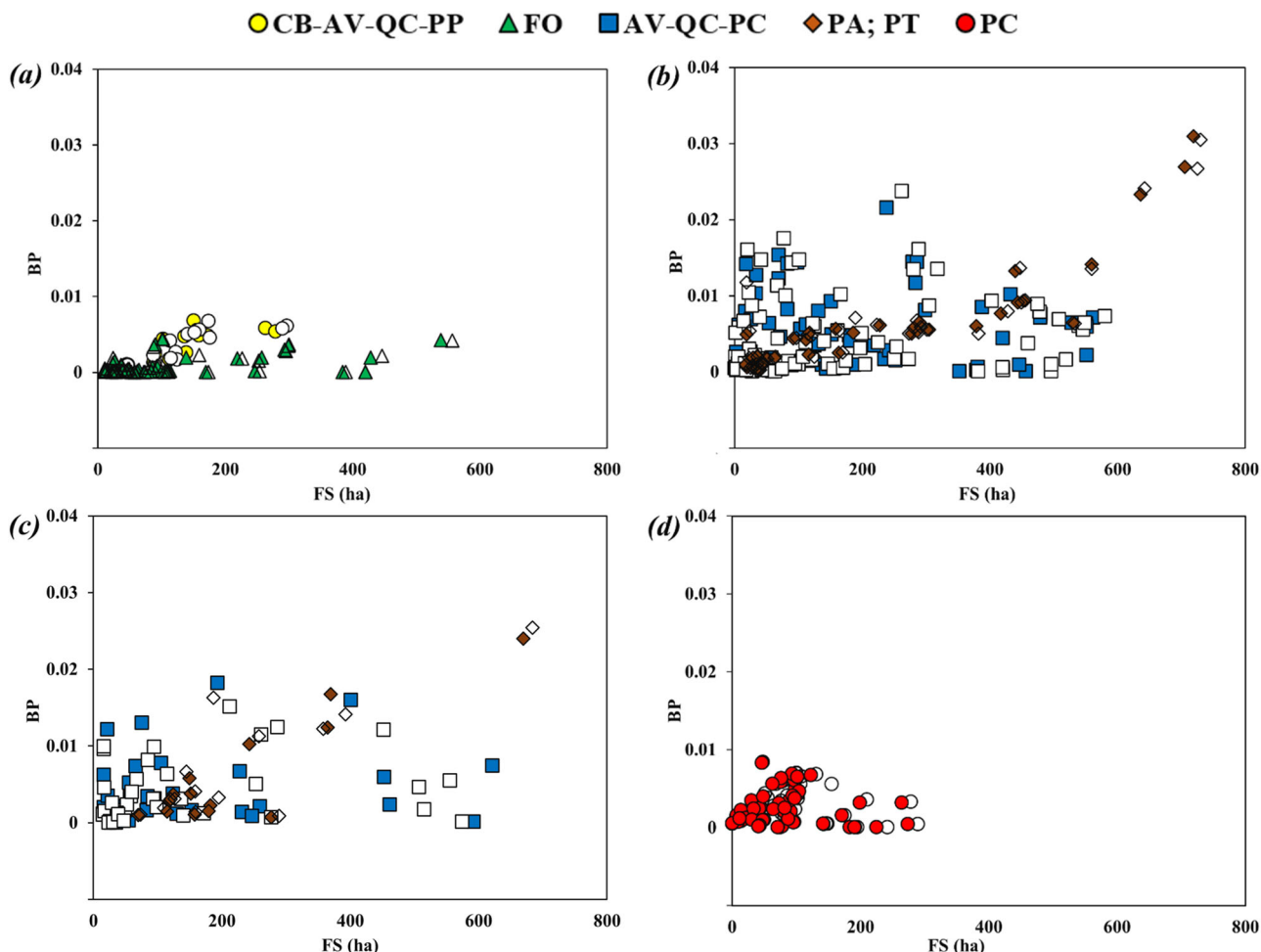
(0.0009). Across broadleaf plantations (AV-QC-PC), the mean BP was 0.0041 for NT and 0.0042 for Lt and Ct treatments. Contrast analysis confirmed that BPs in the treated stands were not statistically different from NT stands. Across PA and PT plantations, the mean BP in the NT stands was 0.0062, which was higher in the treated stands (Lt = 0.0066 and Ct = 0.0068). Although, the increase for Lt treatment was not statistically different from NT. When just Cc treatment was considered, for BP, there was an increase of 7% for PC plantations (0.0028) compared to the NT stands (0.0026). Again, there was no significant difference between BP values in treated and NT stands (Table 3).

For all of the treatments tested in the study area, focusing on the CFL values, we found that the average CFL decreased compared to the NT stands (Table 3). Treating CB-AV-QC-PP stands by Sc treatment reduced the average CFL from 0.39 m to 0.34 m. For FO stands treated, the average CFL was reduced by 15% for Sc treatment.

Therefore, the Sc treatment resulted in a significant reduction in CFL. In AV-QC-PC plantations, the mean CFL for NT stands was 0.44 m. Compared to the NT stands, CFL were 0.39 m and 0.41 m for Lt and Ct treatments, with almost 11 and 7% reduction. The rate of decrease in CFL for the Ct was not significantly different from NT. Across PA and PT plantations, the NT stands produced mean CFL that peaked at 0.79 m. The mean CFL values in the Lt and Ct treatments were 0.68 m and 0.74 m, with almost 14 and 6% reduction compared to NT, respectively. In addition, Cc treatment guaranteed a reduction in average CFL values close to 19% for PC plantations (0.31 m) compared to the NT stands (Table 3).

Evaluating the FS, mean values increased for all treated stands compared to the NT stands (Table 3). The increases at the treated stands were somewhat similar to the BP. The increases were not statistically significant for CB-AV-QC-PP and FO treated stands. In AV-QC-PC plantations, the treated stands (Lt = 150 ha and Ct = 152 ha) had a larger





**Fig. 5** Scatter plots of average fire size (FS (ha)) versus average burn probability (BP) estimated for each treatment type (Sc, **a**; Lt, **b**; Ct, **c**; Cc, **d**) in individual polygons or stands. See forest type and treatment

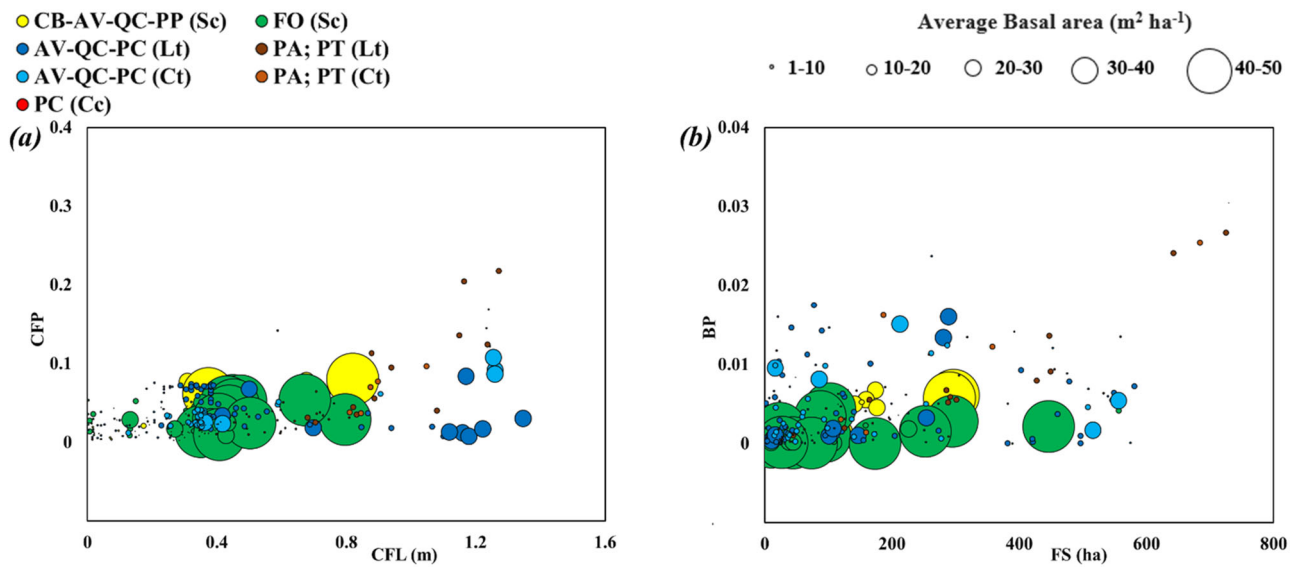
type abbreviation codes in Table 1. Note that unfilled and filled polygons show treated and untreated stands, respectively

mean FS than NT stands (143 ha). We did not observe a significantly greater difference in FS by treated stands for Lt treatment than the NT stands. In PA and PT plantations, mean FS values revealed an increase of 1.4% in Lt (229 ha) and 2.6% in Ct (232 ha) when compared to the NT stands (226 ha). Again, no significant differences were registered when comparing Lt treatment with NT. Moreover, the effect of Cc treatment did not reach significance for PC plantations compared to the NT stands (Table 3).

More variability was exhibited among treatments in the CFP (Table 3). Here we found a significant effect of Sc treatment, such that CFP was reduced by about 17 and 12% for CB-AV-QC-PP and FO treated stands, compared to the NT stands. For AV-QC-PC plantations, CFP in the NT stands had the highest mean (0.055), and a smaller mean was observed for treated stands (Lt = 0.045 and Ct = 0.042). CFP was significantly less on treated stands (on average, 21% reduction) than on NT stands. Again, the highest pixel-level variability within treatment alternatives was found for the

CFP across PA and PT plantations, where the difference between the NT stands and treated stands was higher than 30%. Within the conifer plantations, the mean CFP was reduced from 0.073 (NT) to less than 0.05 under the Lt and Ct treatments. Under Cc treatment, mean CFP was reduced from 0.025 to 0.023 (10%) for PC plantations, compared to the NT stands, reflecting a significant treatment effect (Table 3).

Scatter plots of average BP, CFL, FS, and CFP simulated values for individual stands illustrated variations among and within the different classes (Figs. 4 and 5). Considerable reduction in CFL and CFP was observed for all treated stands (Fig. 4). For instance, the effect of the treatments can be observed in the shifting of the CFL for individual stands to the left (lower CFL). The difference between treatment types is also evident in the plots. The highest CFP values were recorded in untinned PA and PT stands (Fig. 4b). When comparing BP and FS differences between individual stands, most treated stands showed an increasing trend compared to NT stands (Fig. 5). The highest values were



**Fig. 6** Average conditional flame length (CFL (m)) versus average crown fire probability (CFP) (a) and average fire size (FS (ha)) versus average burn probability (BP) (b). The average basal area ( $\text{m}^2 \text{ha}^{-1}$ ) is

related to the bubble size and is presented for each treatment and forest type. See forest type and treatment type abbreviation codes in Table 1

**Table 4** Landscape-scale fire behavior analyses (avg. (standard deviation)) under different weather scenarios for the study area

Weather scenario	Treatment type (code)	BP	CFL (m)	FS (ha)	CFP
Low	NT	0.0010a (0.0001)	0.36a (0.11)	93.00a (23.68)	0.0180a (0.0029)
	TREAT	0.0010a (0.0001)	0.31b (0.10)	91.92a (20.90)	0.0145b (0.0015)
Moderate	NT	0.0020a (0.0001)	0.51a (0.18)	154.89a (39.93)	0.0210a (0.0041)
	TREAT	0.0020a (0.0001)	0.46b (0.18)	153.21a (37.21)	0.0179b (0.0035)
High	NT	0.0065a (0.0002)	0.92a (0.30)	444.07a (123.86)	0.0259a (0.0050)
	TREAT	0.0066b (0.0002)	0.87b (0.31)	456.31b (127.69)	0.0231b (0.0043)
Very high	NT	0.0361a (0.0161)	1.73a (0.52)	2498.14a (841.61)	0.0315a (0.0062)
	TREAT	0.0368b (0.0172)	1.68b (0.58)	2587.00b (853.49)	0.0290b (0.0059)
Extreme	NT	0.0555a (0.0248)	2.12a (0.69)	4106.30a (1011.09)	0.0400a (0.0087)
	TREAT	0.0567b (0.0250)	2.06b (0.66)	4268.08b (1040.21)	0.0375b (0.0076)
Total	NT	0.0013a (0.004)	0.13a (0.04)	93.51a (27.75)	0.0044a (0.0008)
	TREAT	0.0013a (0.004)	0.11b (0.04)	95.95b (27.80)	0.0038b (0.0006)

Different lower-case letters indicate a significant difference between NT and TREAT ( $p$ -value < 0.05)

Total mean values were derived from the combination of the five fire behavior maps by applying the weights determined for each weather scenario (Table 2)

We performed an ANOVA test to identify significant differences ( $p$ -value < 0.05) in simulation outputs

NT non-treatment landscape, TREAT a treatment landscape that combines all treatment types implemented in the study area (See Table 1 for treatment types). BP burn probability, CFL conditional flame length, FS fire size, CFP crown fire probability

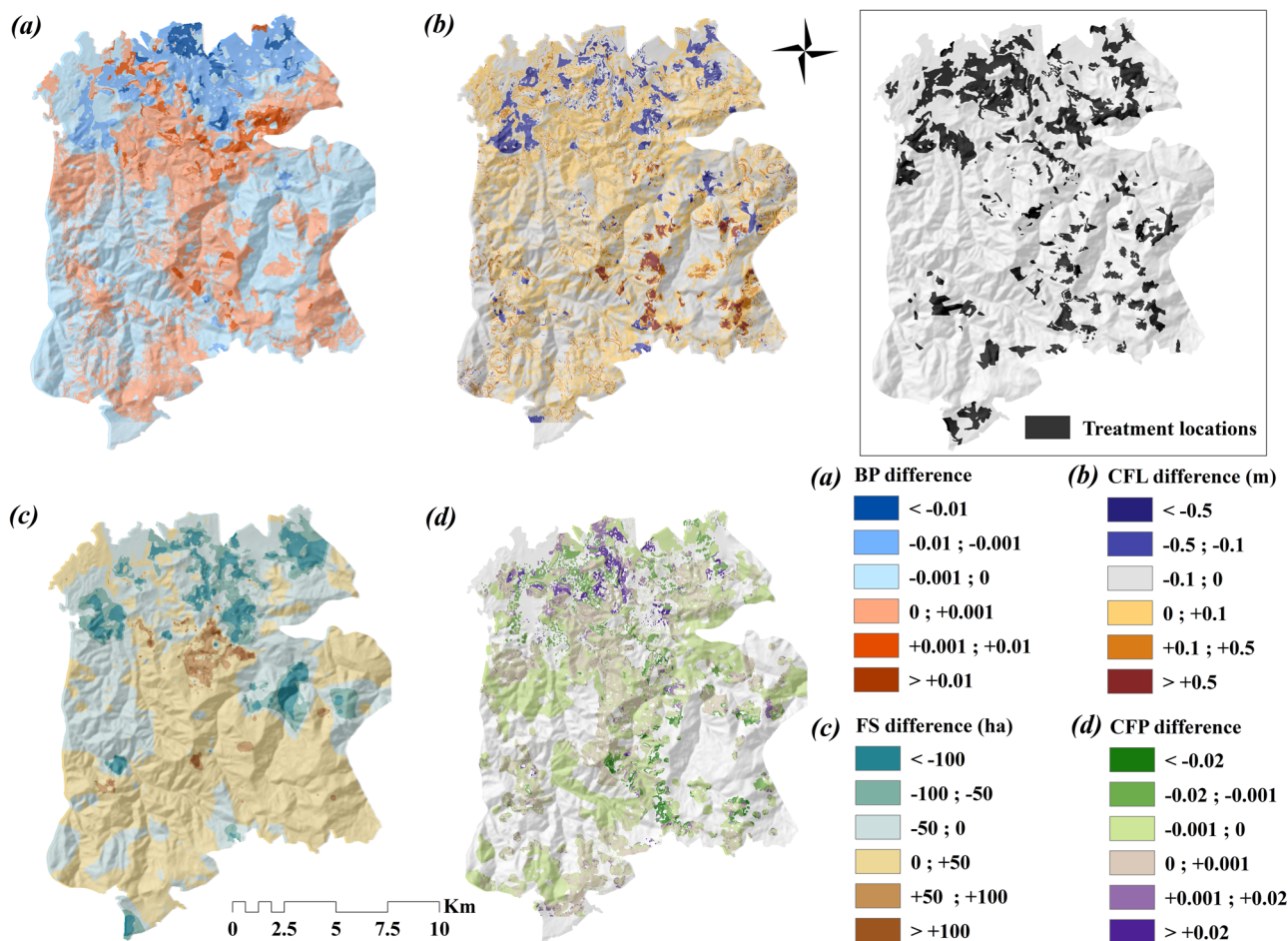
found in AV-QC-PC, PA, and PT planted stands with  $BP > 0.02$  m and  $FS > 600$  ha (Fig. 5b, c).

Fire potential differences between the individual stands were depicted graphically in bubble plots, considering the average basal area ( $\text{m}^2 \text{ha}^{-1}$ , bubble size) values within stands (Fig. 6). In total, 241 stand-level basal area observations were available for this analysis. According to the plots of average CFL, CFP, and basal area, high CFL ( $> 0.4$  m) was positively related to high basal area values (i.e., large bubble size; Fig.

6a). CFP also increased with larger basal areas. While there is a different influence of the basal area on the average BP and FS, stands with higher basal area values showed lower average BP ( $< 0.01$ ) and FS ( $< 500$  ha).

### Fire Potential at Landscape-Scale

We simulated fire with the combined silvicultural treatment alternative (TREAT), which integrates thinning (Lt and Ct)



**Fig. 7** Difference in burn probability (BP, **a**), conditional flame length (CFL (m), **b**), fire size (FS (ha), **c**), and crown fire probability (CFP, **d**) between NT and TREAT conditions at landscape-level. Positive values can be observed in the areas that benefit from treatments. Top-right

insert, location of the silvicultural treatments in the study area. NT non-treatment landscape, TREAT a treatment landscape that combines all treatment types implemented in the study area (See Table 1 for treatment types)

methods with the Sc and Cc treatments. Considering the observed frequency for the fire weather scenarios (Table 2), we assessed fire potential metrics for each landscape (Table 4). Figure 7 also shows the changes in the metrics due to implemented treatments in 2007–2017 in the study area. Within the TREAT landscape as well as the NT landscape, the simulated fire potential metrics (BP, CFL (m), FS (ha), and CFP) were highest in the extreme weather scenario. In this scenario, for the NT landscape, BP averaged 0.055, given an average CFL of 2.12 m, mean FS of 4106 ha, and average CFP of 0.04. While, in the low scenario for the NT landscape, BP averaged 0.001, given an average CFL of 0.36 m, mean FS of 93 ha, and average CFP of 0.018 (Table 4). See maps of fire potential metrics for the NT (non-treatment) condition at the landscape level in Appendix 2 for further details (Supplementary Fig. S1).

According to Table 4, the one-way ANOVA test on BP in the low and moderate scenarios (combined within treatments) had  $p$ -values  $> 0.05$ , indicating a non-significant

difference between NT and TREAT landscapes. Nevertheless, the model showed increased BP concerning the high, very high, and extreme scenarios ( $p$ -values  $< 0.05$ ) within the TREAT landscape compared with the NT landscape. In total, it has been shown that within the NT landscape mean BP was 0.0013, while the overall percentage increase was about 1.5% in the TREAT landscape, for all-weather scenarios considered here. Regarding CFL, the TREAT landscape had significantly lower values than the NT landscape, in all-weather scenarios. Considering the five weather scenarios, the mean CFL was 0.13 and 0.11 m for NT and TREAT landscapes (7.5% reduction), respectively. Regarding the impact of the treatments on FS, we obtained significantly larger values in the TREAT landscape than the NT landscape for the high, very high, and extreme scenarios, similar to those predicted for BP in these scenarios. In the low and moderate scenarios, our analysis produced a lower mean FS for the TREAT landscape than the NT landscape, while the treatments had no statistically

significant effect. In total, the NT landscape had a mean FS of 93.5 ha, while in the TREAT landscape it was about 96 ha (2.6% increase), considering all weather scenarios. The predicted CFP in the TREAT landscape was significantly lower than in the NT landscape in all-weather scenarios. Based on the average CFP from all-weather scenarios, CFP was 0.0044 and 0.0038 for NT and TREAT landscapes (14.4% reduction), respectively.

## Discussion

### Fire Potential At Stand-Scale

This work evaluated how various fuel treatment strategies affected fires in the Siahkal National Forest. We compared the fire potential metrics between the treated and untreated stands (Table 3). The simulation results were completely different in these treatments by order of magnitude. The differences in the fire potential metrics confirmed our expectations regarding the effects of Sc (selection cutting) treatment. When compared to uncut stands (NT), cut stands had a higher BP, a larger FS, a lower CFL, and a minimum CFP. The high BP and low CFL for the cut stands were confirmed in the study of Ager et al. (2012). This is likely attributed to a strong track record in cutting and the environmental condition of the forest ecosystem. Cutting affects fires depending on which trees are removed and the fuels left behind (Pollet and Omi 2002). Cutting without treatment of the unmerchantable material will leave the canopy base height unchanged, potentially increasing surface fuel loads and fire intensity and risk (Ager et al. 2017). Since the logging removed large rather than small trees in the study area, we observed high BP and FS simulated values. However, the treatment can reduce the risk of fire (i.e., CFL and CFP values in this study) by increasing fragmentation of fuel continuity to make the fire spreading more difficult and by providing safe anchor points with fuel breaks for firefighting activities (Palma et al. 2007).

In our study, consistent with the previous study by Agee and Skinner (2005), low thinning (Lt) was a more efficient fuel management strategy for creating fire-resilient stands than crown thinning (Ct). Moreover, Omi (2015) highlighted the effectiveness of thinning treatments followed by significant changes in canopy fuels, more large-diameter trees, and slash disposal methods. Thinning with prescribed burning has been accepted as the most effective fuel treatment (Fulé et al. 2012; Willms et al. 2017). However, the Iranian Forest Authority is not allowed to conduct prescribed fires, including slash pile burning to manage harvest or thinning residues and subsequently mitigate fire risk on public or private lands. The main reason for mechanical treatments was ecological restoration, but according to the results of this study, they can somehow help reduce fire hazards. The

model results indicated a significant reduction in CFP and surface modeled fire behavior (i.e., CFL) through thinning alone. The finding is consistent with previous studies (Safford et al. 2009; Prichard et al. 2020; Johnston et al. 2021; Taylor et al. 2021), demonstrating that thinning alone can be somewhat effective at reducing fire severity. This process is probably responsible for the substantial differences in the ground and surface fuels between thinned and unthinned stands. Arellano-Pérez et al. (2020) highlighted that thinning alone can minimize the potential crown fires in conifer plantations in NW Spain. However, thinning alone did not significantly reduce the fire severity. Similar findings were found in this study, where thinning alone resulted in a slight increase in the BP and FS values, including the Lt and Ct.

On the other hand, clear-cutting (full over-story removal) treatment in PC plantations increased average BP and FS, like other fuel treatments in this study. The resulting fire potential metrics are likely related to the added fuels, the altered microclimate, and the removed small trees (Weatherspoon and Skinner 1995). However, clear-cutting can act as a fuel reduction treatment by reducing canopy fuels and breaking up stand canopy continuity in dense forests (Chung 2015; Agee and Skinner 2005). The latter point can be attributed to lower CFL and CFP values in PC stand containing fuel treatment with regeneration cuts (i.e., small clear-cuts with young regenerating forests).

Results showed that fire potential metrics are associated with the stand basal area (Fig. 6). However, the association varies with forest types and fuel treatments. In this study, when examining the CFL and CFP values, it appeared that stands characterized by high basal areas would have high CFL and CFP values. Similar results were found by González et al. (2006), in which CFP on a forest stand increased with larger basal areas. This is associated with thicker structures and higher densities, which were more influential on crown fires. However, there is a clear indication that stands with the higher average basal area had a smaller fire size. This might occur since greater basal areas prevent understory growth, reducing the risk of fires occurring and spreading (Fonseca and Duarte 2017). The result is consistent with that reported by Nunes et al. (2019), that the stand basal area had a clear effect on the occurrence and spread of fires on the Iberian Peninsula. In addition, several studies have found that basal area is the most crucial variable in estimating the vertical structure of forest stands and the profiles of surface and canopy fuels such as canopy fuel loads and canopy bulk density (Fernández-Alonso et al. 2013; González-Ferreiro et al. 2017), which affect the fire behavior.

### Fire Potential at Landscape-Scale

Modeled fire behavior confirmed that the treatments influence fire activity, particularly in high, very high, and

extreme weather scenarios (Table 4 and Fig. 7). Silvicultural treatments increased BP and FS. At the same time, CFL and CFP decreased on the TREAT landscape. Increased BP has also been observed in some pixels of the TREAT landscape in other modeling studies based on the FlamMap MTT (Salis et al. 2018; Alcasena et al. 2018; Palaiologou et al. 2020). This is probably a result of the changes in the rates of spread and fire spread pathways across the treated landscape (Thompson et al. 2017). For reference fuel (NT) conditions, we found lower BP under different fire weather scenarios. Unlike low and moderate weather scenarios, the increase in BP was statistically significant in higher weather scenarios in the TREAT landscape compared to the NT. Previous studies have also shown increases in fire behavior associated with dry fuel moisture and higher wind scenarios across the treated landscapes (Parsons et al. 2018; Marshall et al. 2020). The increase in weather severity can cause an increase in the extent of high-intensity fires and highly connected fuel patches in the landscape (Sá et al. 2022).

The treatments effectively reduced CFL in the study area, as the sparse understory decreased available fuel load, resulting in low flame length and intensity. Nevertheless, it is less effective within extreme fire weather scenarios. Relatively low CFL for the TREAT landscape, which influences the effectiveness of firefighting operation, and case studies in fire modeling support that mechanical and thinning treatments of forests reduce fire intensity in terms of CFL. For example, Cruz et al. (2017) found the effectiveness of thinning treatment for changing forest structure and reducing fire severity in South Australia. Chiono et al. (2017) have similarly pointed to the decreased CFL in the treated landscape due to the influence of treatments on fire spread and intensity.

The highest FS values were associated with the TREAT landscape. In low and moderate weather scenarios, similar to BP, there was insufficient statistical evidence to demonstrate a difference in mean FS between the NT and TREAT landscapes. However, FS increased significantly in higher weather scenarios in the TREAT landscape. Our findings show similarities to earlier studies (Parsons et al. 2018; Banerjee 2020), which show some increases in fire behavior relating to higher wind and weather conditions within the landscape following thinning and cutting fuel treatments. In the TREAT landscape, for some pixels, the increase in FS value is replicated in some localized increases in BP, which is consistent with the previous study by Thompson et al. (2017).

CFP was generally low in the study area, likely reflecting low tree density and CBD. In addition, CFP decreased in the TREAT landscape compared to the NT landscape. Although the treatments reduced CFP, the likelihood of crown fire initiation may reduce by lowering CBD, and increasing CBH is achieved (Agee and Skinner 2005). Reducing the CFP in the treated forest was also observed by

other authors (Agee and Lolley 2006; Jiménez et al. 2016; Taylor et al. 2021). This reduction generally requires a decreased amount, density, and continuity of surface fuels and removed ladder fuels (Graham et al. 2004).

## Conclusions

Business-as-usual silvicultural treatments affected stand-level and landscape-scale fire behavior and spread very variably within the Siahkal National Forest (northern Iran). Uneven-aged structures showed a moderate hazard (i.e., fire intensity and crown fire probability) and emphasized the high vulnerability of temperate forest ecosystems where burn probability is low (and therefore, wildfires are still rare events), but would cause high mortality and adverse effects in high-elevation natural ecosystems. On the other hand, treated conifer stands with low and crown thinning showed a very significant reduction in crown fire probability, and we can thus conclude by recommending those management prescriptions when the objective is mitigating extreme wildfire behavior. While the low-thinning treatments remove ladder fuels and prevent tree torching, high-intensity crown thinning in even-aged plantations can reduce active and independent crown fires. Nevertheless, none of the thinning treatments showed a substantial stand-level fire intensity reduction, emphasizing the need to implement a mechanical mastication treatment over the surface fuels after the thinning if we want to generate low-hazard fire-resilient forest ecosystems. Yet, surface fuel reduction mechanical treatments are costly, and future studies should evaluate the optimal allocation design so that few treatments implemented in strategic areas of the landscape (e.g., high burn probability spots such as those shown in our maps) could effectively reduce large fire spread. Likewise, evaluating prescribed fires' effectiveness in conifer forests may be an interesting option for future studies.

## Compliance with ethical standards

**Conflicts of Interest** The authors declare no competing interests.

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