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ORIGINAL PAPER

Effect of fire severity on physical and biochemical soil properties in Zagros oak (*Quercus brantii* Lindl.) forests in Iran

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Abstract Fire affects the physical and chemical properties and soil biological activity of natural ecosystems. This study was conducted in the Miyan Tang region, Ilam Province in western Iran. The study site was 110 hectares, where we sampled soils in areas that were classified by fire severity: low (LS), high (HS) and medium severity (MS), and unburned (UB), which served as the control. In each severity class, 25 transect points were randomly selected for measurement. Around each transect plot center, 3 soil samples were selected randomly and soils collected from the 0 to 20 cm depth were combined into a composite sample that was used in laboratory analysis to represent conditions at that point. Plots in the UB and LS fire classes had similar soil conditions and had higher values of factors such as saturated moisture, organic carbon, carbon dioxide, and silt and clay content. In contrast, plots in the HS and MS fire severity classes were clustered in the positive direction along the first axis that represented gradients in soil acidity, electrical conductivity, cation exchange capacity, accessible phosphorus, accessible potassium, bulk density, and sand. Soil attributes were similar in areas of HS and MS fire severity classes, whereas soil conditions in the LS class and UB controls were most similar. Fire in the LS areas either did not significantly alter the physical–chemical soil properties and microbial basal respiration, or soils were able to recover quickly after being burned.

Keywords Fire severity · Oak · Soil respiration · Physical and chemical soil properties

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Introduction

Forests play a vital role in the continuity of human communities, especially in Iran, which is among the most arid of countries in the world (Heydari and Mahdavi 2009; Sagheb-Talebi et al. 2004). Thus, it is important to preserve forest ecosystems and ensure their stability through sustainable management. Fire is an important disturbance in the functioning of many forest ecosystems, including oak forests and woodlands (Zald et al. 2008; Neary and Overby 2006; Johnson et al. 2007, 2009). However, fire also has the potential to be one of the most destructive agents to soil and vegetation in the Zagros forests, Iran (Heydari et al. 2012). The study of fire and its effects on the present and future conditions of ecosystems is of great interest (Stoof et al. 2010). Annually, hundreds of fires occur in the forests and plains in Iran and they burn thousands of hectares (Banj Shafiei et al. 2010; Heydari et al. 2012). Fire severity is a measure of the ecological effects of fire and the degree of change in ecosystem components (DeBano et al. 1998; Neary et al. 2005). The degree of degradation in ecosystem structure and function due to fire varies over landscapes as differences in fire severity occur from local to regional scales (Wright and Heinselman 1973). Site-specific rehabilitation or restoration management plans are needed depending on the fire severity or degree of degradation caused by fire (Barnes et al. 1998). Fire directly affects the physical and chemical properties, and biological activity of soils in natural ecosystems, and indirectly causes soil changes by changing successional pathways and modifying the floral community (DeBano et al. 1998; DeBano 2000; Arocen and Opio 2003; Hebel et al. 2009; Aref et al. 2011). For example, fire effects soil respiration through the modification of soil physical and chemical properties (Weber 1990; Wüthrich et al. 2002; Tang et al. 2005). Soil respiration is a common measure of soil biological activity, and is measured by the amount of CO_2 released by plant roots, soil microbes, and to a lesser extent oxidation of root exudates, plant detritus and humified organic matter (Raich and Schlesinger 1992). Fire also affects soil nutrient availability and cycling, and can damage soil structure by consumption of organic matter and alteration of mineral elements in the soil (Duran et al. 2008). The amount of nutrient loss is, in part, determined by fire severity. During a fire, the energy released (i.e., temperature, radiant energy, duration of heating) can effect chemical changes that control soil acidity, moisture, and the concentration of soil nutrients (Hamman et al. 2008). Fire affects the physical properties of the soil such as the amount of surface soil permeability (Imeson et al. 1992).

Research on fire effects on soils report mixed results on changes in chemical and physical soil properties. Although fire generally increases the amount of nitrogen and carbon in burned regions compared to unburned regions, Banj Shafieia et al. (2010) found that there was no significant difference when comparing nitrogen and carbon content in burned and control regions in Hyrcanian mixed forests in Iran. Heydari et al. (2012) investigated the effect of fire severity on physical and chemical properties of soil in Zagros forest ecosystems in Iran and found that edaphic properties varied with degree of fire severity. They showed that in general, chemical properties were more affected by fire severity than physical soil attributes. Granged et al. (2011) investigated the gradual changes in soil properties in Mediterranean areas and reported that soil organic matter, acidity and electrical conductivity returned to their original levels within one year after a fire. Rau et al. (2009) concluded that burning increases nitrogen, phosphorus, calcium, magnesium, manganese, and zinc in semi-arid ecosystems. Neff et al. (2005) investigated the effect of fire on organic matter, composition and soil nutrients in north Alaska and concluded that severe fire destroys the surface profile of the soil and increases the amount of elements such as carbon, phosphorus, potassium, calcium, and nitrogen in the region. Ketterings and Bigham (2000) pointed out that low-severity fires have a minor effect on chemical and biological properties of soil. However, in high-severity fire, it is possible that the main and fundamental soil properties such as the texture and cation exchange capacity are changed (Ketterings and Bigham 2000).

Thus, fire effects on soil properties vary by fire severity, ecoregion and time since fire. Few studies have been reported on the fire ecology of the Zagros Oak Forest Region. In this study we evaluated the early effects of various degrees of fire severity on soil respiration and some physical and chemical soil properties. Our objectives were to provide information that can be used to manage Zagros oak ecosystems, to monitor changes in key soil attributes that determine long-term productivity, and to provide input for adaptive management where fire is used in the sustainable management of oak forests.

Materials and methods

Study site description

This study was conducted on 110 hectares in Miyan Tang region, Sarabele county, Ilam, Iran (Fig. 1). Average annual precipitation in this area is 632 mm, average daily temperature is 9.8 °C, average maximum temperature is 18.4 °C, average minimum temperature is 6 °C, and average frost season is 42 days each year. According to umbroje climate classification, Miyan Tang region has a Mediterranean climate (Arekhi et al. 2010). The elevation range in this region is between 1105 and 2000 m and slope gradients generally range from 20 to 40 %.

Oak (*Quercus brantii*) is the main tree species in the Zagros forest and it is also a widely distributed species in other middle eastern countries (Turkey, Iraq, Syria and Lebonan). Maximum forest canopy coverage in the study area was 35 %, diameter at breast height (DBH) averaged 27 cm, and there were 133 trees per ha on average. Other tree and shrub species included *Celtis australis* L., *Prunus mahaleb*, *Pistacia atlantica*, *Crataegus pontica* and *Prunus tottuesa*.

Experimental design and treatment selection

The region was burned by a fire in late July 2012 and data were collected one year later in July 2013. During and immediately after the fire, 20 sampling points were selected randomly from within the region. Transects of varying length were run in perpendicular north–south directions from each sample point. Along each transect, sample plot centers were established at 100 m intervals. Maximum range of elevation along these transects was 100 m and maximum difference in slope gradient was 10 %. At each

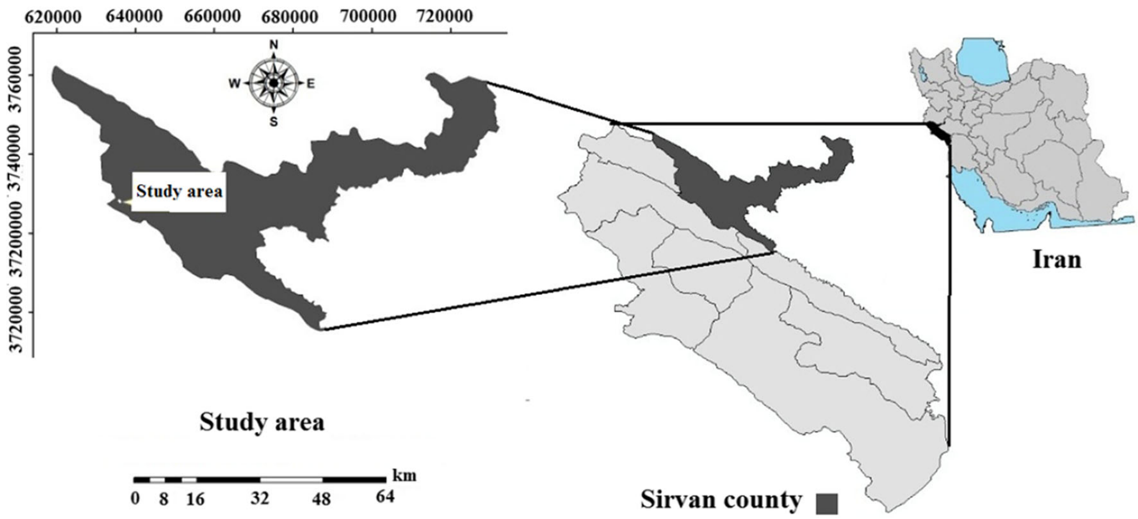

Fig. 1 Location of the study area

sample plot we visually assessed fire severity within an area of 100 m^2 and assigned it to one of four classes (treatments) as defined by Heydari et al. (2012), viz. low severity (LS), medium severity (MS), high severity (HS), and unburned or control (UB) (Table 1). From the total number of sample plots assigned to each severity class we randomly selected 25 plots for detailed measurements as described below.

Soil sampling and laboratory analysis

Around each transect plot center, 3 soil samples were selected randomly from 0 to 20 cm depth and a composite sample was used in laboratory analysis to represent conditions at that point. Soil texture, bulk density and moisture were measured using the hydrometric method (Bouyoucos 1962), cylinder method (Blake and Hartage 1986), and gravimetric method (Famiglietti et al. 1998), respectively. Soil acidity and salinity were determined by pH meter and electrical conductivity meter, respectively (Kalra and Maynard, 1991). Organic carbon (OC) and cation exchange capacity (CEC) were measured using the Walkley–Black method and by taking soil extracts using ammonium chloride, washing with ethanol, and using ICP-AES apparatus (Kalra and Maynard 1991). Accessible phosphorus and absorbable nitrogen (NO_3^-) were determined following Bray and Kurtz (1945) by extracting the samples (soil proportion of 1:10) with 2 mol potassium chloride using an Autoanalyzer machine (Bray and Kurtz 1945). Soluble potassium and CO_2 were measured using the extraction method of 1 M ammonium acetate with an acidity of 7 (Thomas 1982), and incubating humid soil in the vicinity of NaOH and titration with HCL, respectively.

Statistical analysis

The Kolmogorov–Smirnov (K–S) test was used to test for data normality. Non-normal data were subjected to logarithmic transformation. This was done for bulk density, organic carbon and cation exchange capacity. Homogeneity of variances was assessed using the Leven test. One-way analysis of variance (ANOVA) was used to investigate

Table 1 Criteria indicators for classifying the fire severity in the sampling area

Fire severity	Indicators (in the next growing season after fire)
a. Unburned (UB)	No evidence of fire, Litter accumulation (depth ≈ 15 cm), Soil surface covered by litter, High cover of herbaceous, Sprouts survived
b. Burned with low severity (LS)	No obvious evidence of fire (only the scorched collar of burned grasses and annual plants), No litter, High cover of herbaceous
c. Burned with medium severity (MS)	Obvious evidence of fire, litter consumed, Soil surface bare or covered by ash, low cover of Herbaceous cover, Sprouts survival
d. Burned with high severity (HS)	Obvious evidence of fire, litter consumed, Soil surface bare or covered by ash, no cover of Herbaceous cover, Sprouts consumed or dead (no survival)

the effect of fire severity on each one of the studied parameters. In addition, Duncan's multiple range test was used to compare means of fire severity classes for these parameters. Analyses were performed using SPSS16® software. Principal components analysis (PCA) was employed to summarize the environmental data and investigate whether they could explain the change in patterns of response variables. Multivariate analysis was conducted using PC-ORD version 3 software.

Results

Change in soil properties by fire severity class

Soil physical properties, viz. saturated moisture content (SP), clay, sand and silt percentage, bulk density (BD), and carbon dioxide (respiration), varied with degree of fire severity (Table 2). Soil chemical properties, viz. pH, electrical conductivity (EC), accessible phosphorus (P_{ava}), accessible potassium (K_{ava}), organic carbon (OC), nitrate nitrogen (NO_3–N), and cation exchange capacity (CEC) also varied with fire severity (Table 2).

The lowest values for CO_2, silt, and SP were recorded severely burned (0.18, 29.6 and 28.36 respectively) and moderately burned plots (0.19, 29.8 and 30.4 respectively). The highest values for these parameters were recorded in UB (0.246, 44.72 and 43.72, respectively) and low-severity plots (0.236, 44.64 and 41.84, respectively). Parameter values were similar for the control and low-severity plots. Bulk density and sand percentage were highest and were similar in MS (BD = 1.29; Sand = 42.68) and HS plots (BD = 1.3; Sand = 44.28), and lowest and similar in UB and LS plots. The highest and lowest clay content were recorded in LS (27.44) and HS (25.28) plots, respectively. Clay content was similar in UB and LS plots (Fig. 2).

Greatest amount of OC was found in UB plots (5.92), followed by LS (4.92) and MS (4.8) plots. Least amount of OC was found in HS plots (4.22). LS and MS plots contained similar amounts of OC, EC, NO_3–N, P_{ava}, and CEC were similar across all fire intensity categories. Soil acidity (pH) and K_{ava} were highest in HS plots (pH 7.17; K_{ava} = 197) and lowest and similar in UB (pH 6.71; K_{ava} = 57.12) and LS plots (pH 6.72; K_{ava} = 60). MS plots were intermediate in value for these parameters, and were significantly lower than HS plots and significantly higher than UB and LS plots (Fig. 3).

Principal component analysis (PCA)

The first and second primary components with eigenvalues of 6.6 and 1.69, respectively, justified 47.74 and 12.1 %, respectively, of the changes in environmental properties. UB and LS plots were clustered in a negative direction along the first axis, which represents factors such as SP, OC, CO_2, and silt and clay. In contrast, HS and MS plots were clustered in the positive direction along the first axis. The positive direction of the first axis represents gradients of pH, EC, CEC, P_{ava}, K_{ava}, BD, and sand. This analysis indicates that edaphic conditions were similar in HS and MS plots, whereas soil conditions in LS and UB were most similar (Fig. 4 and Table 3).

Table 2 Analysis of variance significance levels (one-way ANOVA) for treatment effects (different fire severity) on physical, chemical and biological soil properties

Soil properties	Variables	F	df	Sig
Physical and biological properties	SP (%)	52.96	3	0.02*
	BD (g cm^{-3})	12.1	3	0.01*
	Sand (%)	103	3	0.03*
	Silt (%)	210.5	3	0.01*
	Clay (%)	52	3	0.001**
	CO_2 (mg/g/dry soil/day)	8.9	3	0.04*
Chemical properties	pH (1:1 H_2O)	52.96	3	0.03*
	EC (ds m^{-1})	11.5	3	0.02*
	P_{ava} (mg kg^{-1})	13.14	3	0.04*
	K_{ava} (mg kg^{-1})	86.88	3	0.001**
	OC (%)	8.9	3	0.03*
	NO_3–N (mg kg^{-1})	34	3	0.000**
	CEC ($cmol^{(+)}$ kg^{-1})	13.1	3	0.03*

ns difference not significant

* Significant difference at $\alpha = 0.05$

** Significant difference at $\alpha = 0.01$

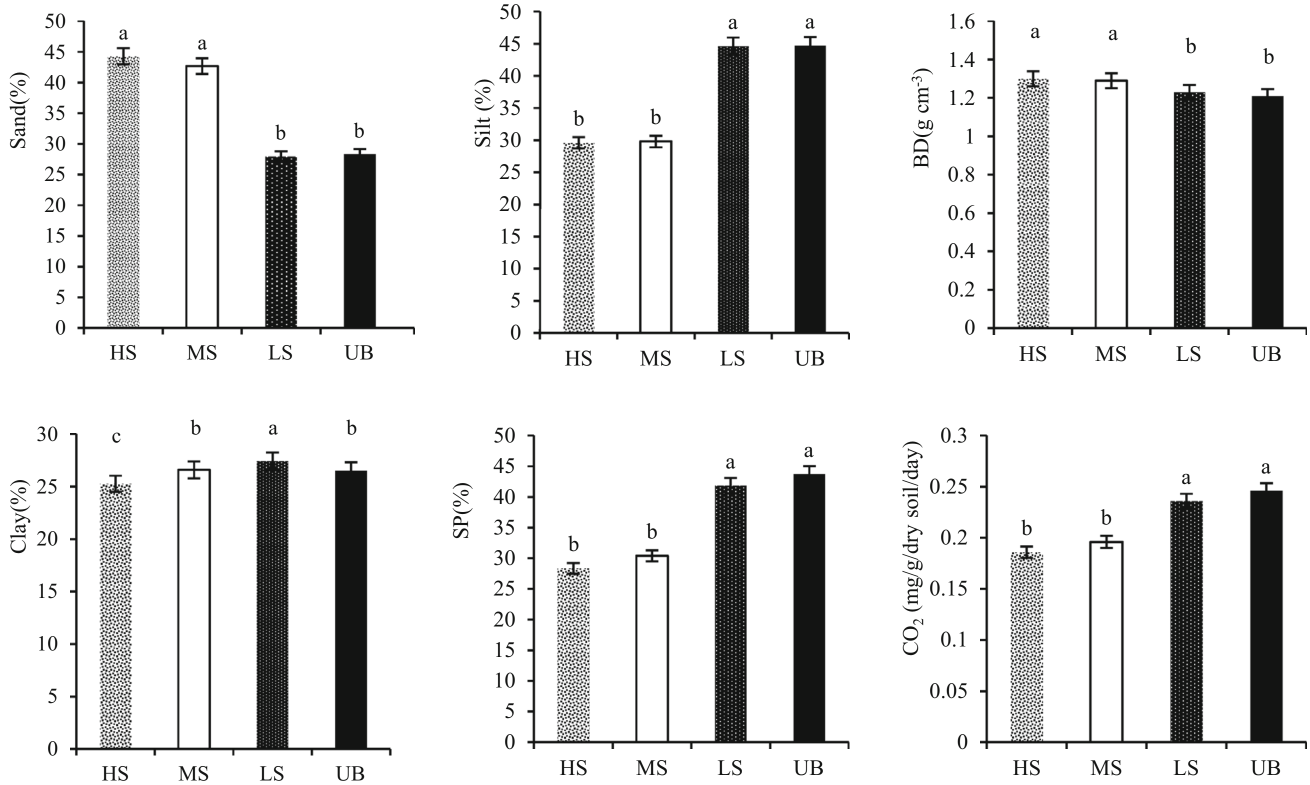

Fig. 2 Mean values of soil physical properties in four fire severity classes. Means with different letters in a column differ significantly. *HS* High-severity fire, *MS* Medium-severity fire, *LS* low-severity fire, *UB* Unburned or control)

Discussion

Response of physical and biological properties to fire severity

Sand percentage in HS and MS plots was higher than in UB and LS plots. In contrast, silt content in HS and MS plots was lower than in UB and LS plots. The change in clay content in relation to fire severity was directionally similar to the change in silt content, i.e., it declined significantly in HS plots. Severe fire can alter fundamental soil properties such as texture and mineralogy (Ketterings and Bigham 2000). Clays are the most susceptible texture class to modification by high temperatures through the irreversible deletion of hydroxyl ions (OH) and destruction of crystalline structure. On the one hand, high temperatures during fire could cause better aggregation of clay particles to the size of sand, thus increasing sand-sized particles, but at the expense of clay content (DeBano et al. 2005). The increase of sand after fire, especially HS fire, could be the result of Al and Si oxides and hydroxides, which are produced during Kaolin destruction, that cause particle cementation and formation of aggregates in the size of sand (Duriscoe and Wells 1982; Dyrness and Youngberg 1957; Ulery et al. 1993).

Significant increase in coarse soil texture (sand) after severe fire could indirectly lead to erosion and resulting decline in content of fine particles such as clays and silts (Granged et al. 2011). In Cameroon, Obale-Ebanga et al. (2003) reported that fire increased the percentage of coarse particles at the soil surface. Saturated moisture content is often used as an index of soil texture, which is determined by the proportional distribution of soil minerals, i.e., sand, silt, and clay because soil texture largely determines soil water holding capacity (Saxton and Rawls 2006). In this study, the saturated moisture content (SP) declined significantly after HS and MS fires. Low-severity fire did not change the saturated moisture content. The reduction of water holding capacity in HS and MS plots might be related to the decrease in soil permeability that resulted from the decrease in organic matter, as suggested by Rastad (2009). The complete destruction of the organic layer by HS fires decreases the water permeation and storage capacity of the soil (Imeson et al. 1992). Robichaud (2000) reported that the discharge coefficient decreased by 40 % as a result of fire in soils under *Psuedotsuga menziensii* and *Pinus contorta*. Granged et al. (2011) reported that the saturated moisture content of the soil declined to 44 % after high-severity fires. In soils with higher clay content (for instance in LS and UB areas in this study),

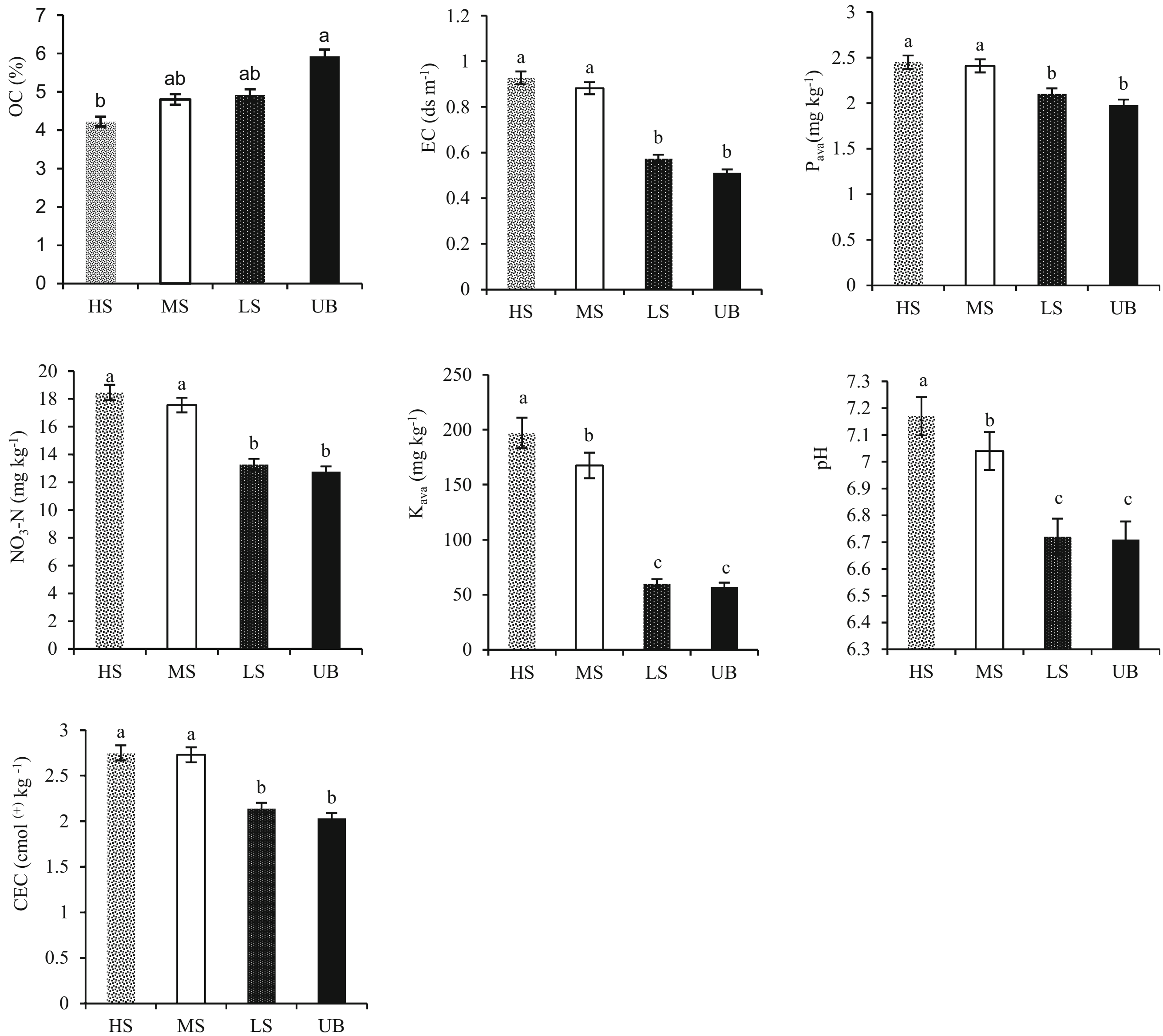

Fig. 3 Mean values of soil chemical properties by fire severity classes. Values with different letters in a column differ significantly. *HS* High-severity fire; *MS* Medium-severity fire; *LS* low-severity fire; *UB* Unburned or control)

water holding capacity is high because of the high capability of clay particles to hold water. In contrast, the high percentage of coarse sand particles in HS plots reduced the water holding capacity (Heydari et al. 2012). High temperatures are also capable of breaking the cements that bind soil minerals, thus significantly decreasing soil stability (Badia and Marti 2003). Destruction of organo-mineral compositions that occur in high-severity fires leads to the increased closure of soil pores by ash and released clay minerals. This reduces the capacity of soil to retain water, and increases the likelihood of runoff and surface erosion (Martin and Moody 2001). We observed that bulk density (BD) in LS plots ws unchanged after low-intensity fire, but it increased as fire severity increased to high and medium levels. The increase in BD following fire is driven by the destruction of the structures and pores within the soil profile (Badia and Marti 2003; Seymour and Tecle 2004; DeBano et al. 2005) and decrease in organic matter, especially noticeable after high-severity fires (Giovannini et al. 1988).

Hubbert et al. (2006) reported that bulk density in mineral soil increased after a fire. Seymour and Tecle (2004) argued that high-severity fire in ponderosa pine (*Pinus ponderosa*) forests would result in the destruction of soil aggregate structure and increase the bulk density in the surface horizons.

Fig. 4 Classification of sample plots based on environmental variables using Principal Component Analysis (*Filled circle* High-severity fire, *filled inverted triangle* Medium-severity fire, ⅄ Low-severity fire, *filled triangle* Unburned)

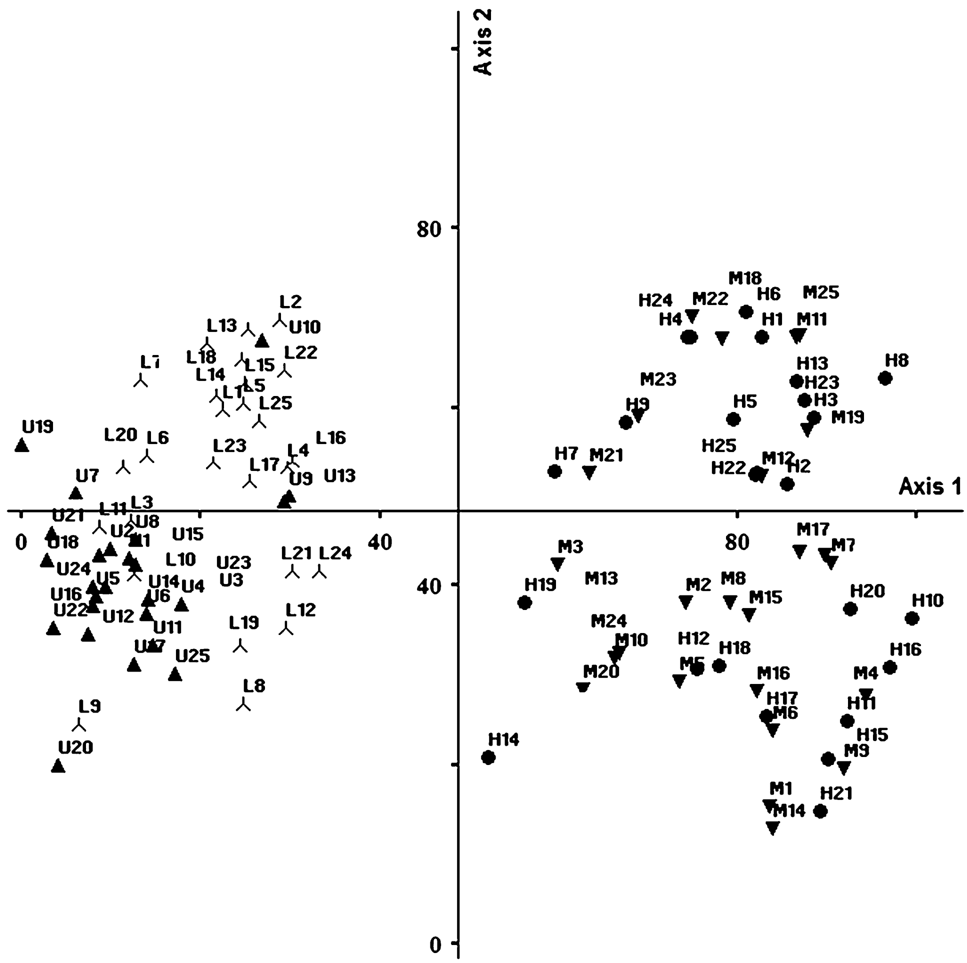

Table 3 Pearson correlation between axes 1 and 2 PCA and environmental variables

Environmental variables	Axis 2	Axis 1
pH (1:1 H_2O)	0.32*	0.69**
SP (Saturated moisture) (%)	−0.499**	−0.542**
EC (Electrical conductivity) (ds m^{-1})	0.04 ns	0.503**
P_{ava} (Accessible phosphorus) (mg kg^{-1})	0.249*	0.423**
K_{ava} (Accessible potassium) (mg kg^{-1})	0.430**	0.621**
OC (Organic carbon) (%)	0.321**	−0.741**
CO_2 (Carbon dioxide)(mg/g/dry soil/day)	−0.232**	−0.415**
Nitrate nitrogen (NO_3–N) (mg kg^{-1})	0.03 ns	0.869**
(CEC) Cation exchange capacity (cmol$^{(+)}$ kg^{-1})	0.201 ns	−0.796**
BD (Bulk density) (g cm^{-3})	0.03 ns	0.731**
Clay (%)	−0.04 ns	−0.8**
Silt (%)	−0.251*	−0.681**
Sand (%)	0.251*	0.593**
Eigenvalues	1.69	6.6
Percentage of variance explained	12.11	47.74

ns not significant

* Significant correlation at $\alpha = 0.05$

** Significant at $\alpha = 0.01$

The lowest values of CO_2 were found in HS and MS plots and the highest values were recorded in UB and LS plots. The significant decline in soil respiration in HS plots is similar to the results of Holden et al. (2016), who showed a significant decrease in soil respiration with high severity burning, a slight to no decrease with fires of moderate severity, but no significant decrease with low severity burning.

Response of chemical properties to the severity of fire

Soil pH increased significantly with increasing fire severity. The highest pH value was recorded in high-severity plots. Increases in soil pH after a fire may be due to the burning of accumulated organic matter on the ground surface, which leads to the release large quantities of basic cations (DeByle 1976). Certini (2005) reported that the significant increase in pH occurs only at higher temperatures (>450–500 °C) coincident with the complete combustion of fuel and the consequent release of bases. Ash production and its accumulation may increase soil pH due to the high pH of ash (Molina et al. 2007).

Ulery et al. (1993) suggested that increases in soil pH in surface profiles after fire may result from the formation of oxides, hydroxides and sodium and potassium carbonates. In a study conducted in pine-oak forests, Neill et al. (2007) reported that soil pH increased in burned areas compared to unburned control areas.

We observed that electrical conductivity was higher in high- and medium-severity plots compared to UB and LS plots. This might have resulted from the release of mineral ions generated by the burning of organic matter (Hernandez et al. 1997; Certini 2005). Heydari et al. (2012) obtained similar results in western Iran.

In this study, organic carbon content decreased with increasing fire severity. In general, increase in the carbon content of soil has been observed after medium-severity fires (Gonzalez-Perez et al. 2004). However, frequent or high-severity fires reduce the thickness of the organic layer of the soil profile (Neill et al. 2007). Heydari et al. (2012) reported reduced organic matter after a high-severity fire in oak forests in the Zagros region. Our results confirmed those of Khanna et al. (1994) and Liang et al. (2006), who also noted a release of basic cations from the burning of organic matter on the forest floor, and a subsequent increase in soil reaction, electrical conductivity, and cation exchange capacity. We noted that soluble phosphorus increased with increasing fire severity. The amount of absorbable phosphorus in nature is higher in soils after a fire compared to that in unburned soils (DeBano and Conrad, 1987). This results from both the accumulation of ash from burnt plant material and the transformation of organic phosphorus into mineral orthophosphate. Banj Shafiei et al. (2010) reported similar results and showed that in areas experiencing high-severity fire the amount of phosphorus increased. Nitrate nitrogen generally increased in high-severity fire plots compared to other fire severity plots in this study. Since the largest source of nitrogen is litter, more nitrate nitrogen is released into the soil as leaf litter decomposes or is burnt (Moreno et al. 2011).

Covington et al. (1991) reported that one year after fire the amount of nitrate nitrogen increased significantly. Although ammonium is the organic form of nitrogen that is produced after a fire in the short-term, it is transformed into nitrate nitrogen through nitrification (Covington and Sackett 1992). We found that fire has a significant effect on soil potassium. Highest content of potassium was observed in high-severity fire plots and lowest content was recorded in unburned plots. Increased potassium may result from the consumption of organic matter in severe fires, as suggested by Adams and Boyle (1980).

Conclusion

We found that most of the soil physical–chemical and microbial basal respiration properties studied, especially nitrate nitrogen and soluble or accessible potassium, were significantly altered one year after HS and MS fire. Some changes led to increased availability of nutrients such as soluble phosphorus, nitrate nitrogen, potassium, and increases in pH that may be beneficial to plant growth after burning, especially in the Zagros region where soil fertility is often limiting to plant growth (Fattahi and Ildoromi 2011). But other changes induced by moderate to high severity fires could lead to reductions in soil productivity due to increased bulk density, decreased organic matter, loss of fine particle sizes (clays), loss of soil structure, and reduced moisture infiltration and moisture holding capacity. Collectively, these changes could cause soil erosion problems after high severity fires. In contrast, LS fire did not significantly alter the physical or chemical properties or the microbial respiration in soils. Based on the results of this study, we recommend the use of low severity prescribed fire when it is ecologically appropriate to promote oak regeneration and stand development. LS fire does not significantly alter the physical–chemical or microbial basal respiration soil properties. Some properties, such as nitrate nitrogen increased slightly (insignificantly) one year after in low-severity fire. Based on the positive role of nitrogen in plant growth, it can be important for soil fertility in most parts of the Zagros forest. In the Zagros forest, controlled low-severity fires can be prescribed as a management tool.

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