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The Effect of Forest Fires on Physical Properties and Magnetic Susceptibility of Semi-Arid Soils in North-Eastern, Libya

G. S. Eldiabani, W. H. G. Hale, C. P. Heron

Abstract**—**Forest areas are particularly susceptible to fires, which are often manmade. One of the most fire affected forest regions in the world is the Mediterranean. Libya, in the Mediterranean region, has soils that are considered to be arid except in a small area called Aljabal Alakhdar (Green mountain), which is the geographic area covered by this study. Like other forests in the Mediterranean it has suffered extreme degradation. This is mainly due to people removing fire wood, or sometimes converting forested areas to agricultural use, as well as fires which may alter several soil chemical and physical properties. The purpose of this study was to evaluate the effects of fires on the physical properties of soil of Aljabal Alakhdar forest in the north-east of Libya. The physical properties of soil following fire in two geographic areas have been determined, with those subjected to the fire compared to those in adjacent unburned areas in one coastal and one mountain site. Physical properties studied were: soil particle size (soil texture), soil water content, soil porosity and soil particle density. For the first time in Libyan soils, the effect of burning on the magnetic susceptibility properties of soils was also tested. The results showed that the soils in both study sites, irrespective of burning or depth fell into the category of a silt loam texture, low water content, homogeneity of porosity of the soil profiles, relatively high soil particle density values and there is a much greater value of the soil magnetic susceptibility in the top layer from both sites except for the soil water content and magnetic susceptibility, fire has not had a clear effect on the soils' physical properties.

Keywords**—**Aljabal Alakhdar, the coastal site, the mountain site, fire effect, soil particle size, soil water content, soil porosity, soil particle density, soil magnetic susceptibility.

I. Introduction

FIRE is a physical process as well as an ecological process. The heat it produces, the rate at which it spreads and the effects it has on other ecosystem components are all part of the physical process. Watersheds, soils, air, plants, and animals are affected in one way or another by fire. Water quality and quantity, soil erosion, smoke and plant and animal mortality are some of the more obvious effects [1].

The main forest type in Libya is the natural forest occurring in Aljabal Alakhdar. These forests have been exposed to significant damage mainly through mismanagement and fires. Fire may alter several physical soil properties, such as soil structure, texture, porosity, wet ability, infiltration rates, and water holding capacity. The effect of fire on soil physical properties varies considerably depending on: fire intensity, fire severity, and fire frequency. In general, most fires do not cause enough soil heating to produce significant changes to soil physical properties. This is particularly true for low intensity fires. Even where fires do cause direct changes to soil physical properties, their indirect effects on soil hydrology and erosion will vary greatly depending on the condition of the soil, forest floor, topography and climate [2].

According to [3], soil structure degradation by fire can persist for a year to decades after a fire and is often responsible for reduced infiltration and increased runoff. Reference [4] also pointed out that intense burns may have a detrimental effect on soil physical properties by consuming soil organic matter which holds sand, silt and clay particles into aggregates, leading to loss of soil structure, and consequently increased soil bulk density, and reduced soil porosity [5], mostly through the loss of macropores (> 0.6mm diameter). Furthermore, [6] and [7] have concluded in their studies that particle size distribution remains unchanged until 300-400^{o}C but above this temperature range silt and clay aggregates and the sand fraction of soils increases.

The effects of fires on soil bulk density have been observed by many authors. References [8] and [9] showed that wildfires in Nothofagus glacua forests in Chile, which has similar climate characteristics to the Mediterranean region, did not affect soil bulk density. They suggested that this is a result of rapid re-establishment of vegetation following a fire. However, [4] found that burning increased bulk density of the soil where fire varied in intensity and degree of soil heating.

Magnetic susceptibility occurs in most soils, and is due to the presence of iron oxides which are may converted from weakly magnetic iron oxides such as Haematite (αFe_2O_3) to strongly magnetic oxides such as Magnetite (Fe_3O_4) and Maghaemite (γFe_2O_3). Generally soils are weakly magnetic, i.e. only haematite is present. However, haematite may be converted to the strongly magnetic forms of iron oxides, magnetite and maghaemite by reduction and reoxidation processes, respectively. Reference [10] mentioned two possible mechanisms for this conversion: (a) the effect of domestic fires on soils and vegetation matter and (b) the decay of organic material associated with human habitation.

The use of soil magnetic susceptibility was very important in determining the depth of soil that has been subjected to fire and thus assess the potential impacts of these fires on the physical properties of the studied soils.

G. S. Eldiabani is with Faculty of Science, University of Omar Almukhtar, Derna, Libya (e-mail: sfmag5@yahoo.com).
W. H. G. Hale and C. P. Heron are with School of Life Science, Division of AGES, University of Bradford, Bradford, UK (e-mail: w.h.g.hale@bradford.ac.uk, c.p.heron@bradford.ac.uk).

II. Methods and Materials

A. Study Area, Site Selection, and Sample Collection

This study was conducted in the Aljabal Alakhdar (Green Mountain) region, Libya. This mountain range is roughly oval in shape, trending North-east and extending over most of the Cyrenaic Peninsula. It rises to 882m above sea level and its character is mostly that of a slightly undulating plateau, with intermittent valleys [11].

The climate in the study area is semi-arid, being hot and dry in the summer, warm and wet in the winter. Most of the precipitation falls during the period from October to April at an annual rate of between 275-660mm. The annual minimum and maximum temperatures are approximately 10 and 35°C, annually [12].

The first site that has been used in this study lies in the coastal region (Fig. 1). It is in an area called Ras Alhelal; subsequently, this site will be referred to as the coastal site.

According to the American soil classification system, the soils in the area are classified as Lithic Hapeloxeralf [13]. The second site used in this study is located in an area called Marawah, approximately 150 km South-West of the first site. Throughout the rest of this study it will be referred to as the mountain site. Soils in this site are classified as Typic Haploanthrepts [13].

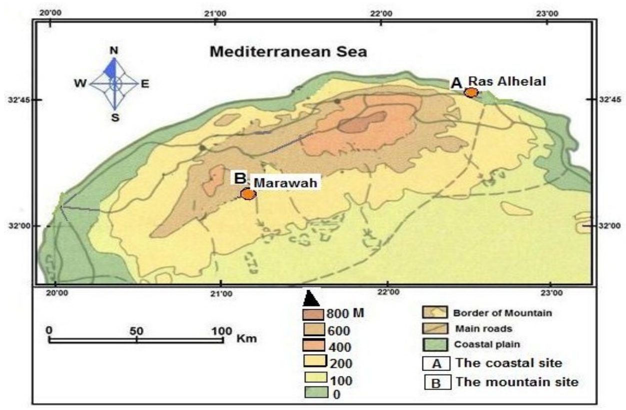


Fig. 1 Map showing the distance between the locations of the two study sites (coastal and mountain) [11]

These sites occur in the same region (Aljabal Alakhdar) and in convergent climatic conditions, however they lie in different geographical units (coastal and mountain), have a different vegetation density and were chosen so that the potential impacts of fire on their soils could be assessed based on exposure to fire at different periods of time, and therefore by comparing the results obtained it may be possibly to identify whether these soils are capable of regaining their pre-burn status over time.

After selection of the study sites, the locations for soil profiles were chosen to allow samples of each soil horizons to be obtained. The soil profiles were described according to the methods of [13]. At each of the two sites sampled (coastal and mountain), two areas (burned and unburned) were studied. According to the soil profile description in the two sites, which were consistent in their soil characterizations for burned and unburned areas, the soil samples from the coastal site in the burned and unburned areas were collected from following horizons that were identified in the field, i.e. from the centre of the following layers: 0-15, 15-35, and 35-60cm depth. Samples from the second site (mountain) in the burned and unburned areas were taken from the centre of the horizons: 0-15, 15-45, and 45-70cm depth. A total of fifty four soil samples were therefore collected from each site (3 depths × 9 replicates × 2 areas), and the total number of samples for both sites was 108. Each sample weighed approximately 1kg, and was placed in labeled sample plastic bags and tightly closed to retain moisture.

B. Soil Physical Properties Estimation

1. SOIL WATER CONTENT

After collection in 24 hours, a sub-sample from each sample was taken and used to establish the water content. This determination was made using the method of loss of weight which is shown in [14]. This involves a drying of 50gr from each sample in an oven at 105°C for 24 hours and re-weighing, to determine the loss of weight. The difference gave weight of moisture as a percentage of the original wet soil weight.

2. SOIL PARTICLE SIZE ANALYSIS

Has been determined using the pipette-sedimentation method [14].

3. SOIL PARTICLE DENSITY

Was calculated using the density bottle method [14].

4. SOIL POROSITY

The soil porosity was estimated after establishing the soil particle density, as shown in [14], using the following formula:

$$S_t: 100\,[(p_p - D_b) / p_p]$$

where: S_t: soil porosity, p_p: assumed value of 2.65g cm^{-3} for particle density of mineral soils. And D_b: particle density of the soil sample.

5. SOIL MAGNETIC SUSCEPTIBILITY

Estimation of magnetic susceptibility of the soil samples was achieved by using the device (Bartington ms2 B, 2 frequency), according to the method of [15].

6. STATISTICAL ANALYSIS

A 3-factor analysis of variance test with replications was undertaken in order to statistically verify the results of this study. The factors used related to sample values obtained from the site (coastal and mountain), the soil type (burned and unburned) and the depth (0-15, 15-35, 35-60cm for the coastal site and 0-15, 15-45, 45-70cm for the mountain site). MINITAB Release 16 Statistical Software has been used for

Windows on CD-ROM, 2010 edition for all data analysis, both statistical and graphical.

III. Results and Discussion

A. The Physical Properties

1. Soil Particle Size

Field observations of the soil profiles of both study sites indicated that these profiles were characterized by a granular structure in the surface layers and sub- angular soil structures in the sub-surface layer horizons. The results (Table I and Fig. 2) show that there is a relatively low clay content (particles of < 2μm in diameter), compared to the contents of silt and sand, in both study sites and burned and unburned areas, but especially in the mountain site. This is may be attributed to the reduced quantity of vegetation in the mountain site which may have affected the erosion of soil and therefore the selective movement of the clay particles, leaving the large particles of sand and silt *in situ.* This also reflects on the quantity of clay within the studied soil profiles, where the quantities of clay were accumulated in the middle depth. These results reinforced by the ANOVA results which indicate that the differences were highly significant ($p < 0.001$) between the study sites in the clay, silt and sand contents, however the differences were highly significant between different depths in clay content (Table I). The silt fraction (particles 2μm - 50μm in diameter) forms the highest percentage of the three particle size fractions, and there are considerable amounts of sand particles (50 – 2000μm in diameter) in the soil profiles. Thus, all the soils in both study sites, irrespective of burning or depth fell into the category of a silt loam texture [13]. The fires were presumably induced not enough to change the soil fractions and therefore the type of texture. ANOVA results strengthened that when indicate that there were no significant differences ($p > 0.05$) between the burned and unburned depths in the soil fractions sizes in the two studied sites.

These results are consistent with those found in field studies by [6] and [16], who recorded that most forest fires do not result in enough heat to change the texture of the soil. On the other hand, these results contrast with and [17] and [18] who found a sharp increase in the amount of sand and a decrease in silt and, especially, clay even when the fires generated only low temperatures. However the observed changes were mostly limited to the surface layer of soil (0-5cm depth), and also these observations were, laboratory based studies, whereas conditions in the field may be influenced by other factors such as different levels of moisture, and the presence of vegetation.

TABLE I
Results of Soil Particle Size Analysis in the Two Study Sites (Coastal and Mountain), for Both Burned And Unburned Areas at Three Depths. each Value Represents the Average of 9 Replicates

Site	Soil depth (CM)	Sample area	Percentage of soil particles within each size fraction		
			Clay	silt	sand
Coastal***	0-15	burned	^{a}21.0^{a}	^{a} 52.0 ^{a}	^{a} 27.0 ^{a}
		unburned	^{a}21.3^{a}	^{a} 51.4 ^{a}	^{a} 27.3^{a}
	15-35	burned	23.7 ^{b}	51.7 ^{a}	24.6 ^{b}
		unburned	24.2 ^{b}	51.2 ^{a}	24.6 ^{b}
	35-60	burned	24.0 ^{b}	51.0 ^{a}	25.0 ^{c}
		unburned	22.4 ^{c}	51.0 ^{a}	26.6 ^{c}
Mountain***	0-15	burned	^{a} 8.4 ^{a}	^{a} 62.2 ^{a}	^{a}29.4 ^{a}
		unburned	^{a} 8.2 ^{a}	^{a} 61.8 ^{a}	^{a} 30.0 ^{a}
	15-45	burned	13.2 ^{b}	61.3 ^{a}	^{a} 25.5^{a}
		unburned	13.5 ^{b}	61.0 ^{a}	^{a}25.5^{a}
	45-70	burned	^{C} 12.4	61.0 ^{a}	26.6 ^{c}
		unburned	12.0 ^{c}	60.0 ^{a}	28.0 ^{c}

***Symbol means the differences were highly significant ($p < 0.001$) between the two study sites in each of the soil particle size analysis results. The litters who are on the upper left side of the values represent the statistical analysis results between the three studied depths in the two sites of the study area, while those who are on the upper right side of the values represent the statistical analysis results between the burned and unburned depths. Across each column, values followed by a different letter are significantly different ($p < 0.001$) while those followed by a same letter are not significantly different ($p > 0.05$).

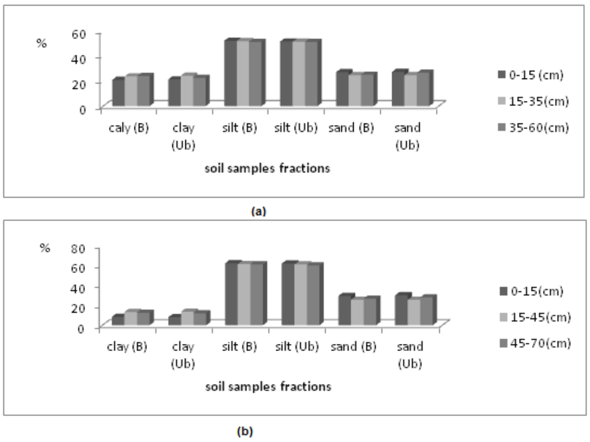


Fig. 2 Histogram showing the study area soil samples fractions percentages at three depths (a = the coastal site and b = the mountain site; B = burned and Ub = unburned)

2. Soil Water Content

The results of soil moisture content show that the studied soils had a low water content, between about 1 and 5% (Table II). This may be because the period in which the samples were collected (in August) is the period where the air temperature is at its highest (about 30 and 35°C at the coastal and mountain sites, respectively), thus increasing the evaporation rates from the soil. The data obtained from this study also indicate that there is a strong link between the percentage of moisture in the soils and the soil's clay content (Fig. 3). This relationship was present at both study sites and for both the burned and unburned areas. The soil moisture present increased with depth at the four study areas so, the results also show highly significant differences ($p < 0.001$) between the mean values of the water content at different depths, being lower in the top layer. This is may be consistent with the pattern of increase in the proportion of clay particles with depth (Fig. 4), as greater percentage clay concentration will lead to increased water retention, thus provide an opportunity to provide the humidity needed for the growth of vegetation. Thus, due to the proportion of clay being higher in the coastal site which increases the capacity of the soil to retain water, results also indicated that water content is lower in the mountain site samples compared to the samples from the coastal site. This difference between sites was significant at the $p < 0.001$ level (Table II).

TABLE II
RESULTS OF VARIOUS PHYSICAL PROPERTIES IN THE BOTH STUDY SITES FOR BOTH BURNED AND UNBURNED AREAS AT THREE DEPTHS
EACH READING REPRESENTS THE AVERAGE OF 9 REPLICATES

Site	Soil depth (CM)	Sample Area	Soil water content (%)	Soil porosity (%)	Soil particle density (gcm^{-3})
Coastal***	0-15	burned	$^{a}2.42^{a}$	$^{a}28.7^{a}$	$^{a}1.88^{a}$
		unburned	$^{a}4.33^{b}$	$^{a}30.3^{b}$	$^{a}1.89^{a}$
	15-35	burned	$^{b}3.50$	$^{b}21.6$	$^{a}1.85$
		unburned	$^{b}4.83$	$^{b}28.4$	$^{a}1.84$
	35-60	burned	$^{c}3.39$	$^{c}24.8$	$^{a}1.85$
		unburned	$^{c}4.82$	$^{c}28.6$	$^{a}1.89$
Mountai**	0-15	burned	$^{a}1.05^{a}$	$^{a}33.1^{a}$	$^{a}1.76^{a}$
		unburned	$^{a}1.85^{a}$	$^{a}32.0^{b}$	$^{a}1.80^{a}$
	15-45	burned	$^{b}2.34$	$^{b}31.7$	$^{a}1.81$
		unburned	$^{b}2.55$	$^{b}31.1$	$^{a}1.83$
	45-70	burned	$^{c}2.30$	$^{c}31.8$	$^{a}1.80$
		unburned	$^{c}2.23$	$^{c}31.4$	$^{a}1.81$

***Symbol means the differences were highly significant ($p< 0.001$) between the two study sites in each of the soil particle size analysis results. The litters who are on the upper left side of the values represent the statistical analysis results between the three studied depths in the two sites of the study area, while those who are on the upper right side of the values represent the statistical analysis results between the burned and unburned depths. Across each column, values followed by a different letter are significantly different ($p < 0.00$) while those followed by a same letter are not significantly different ($p>0.05$).

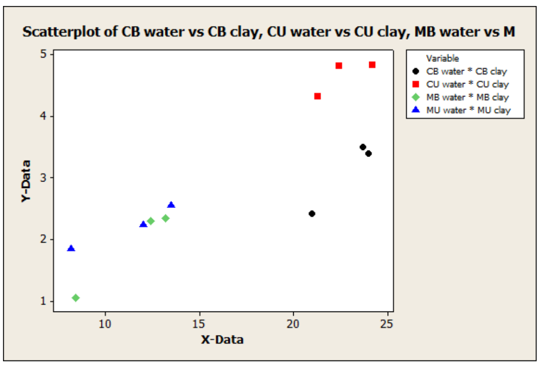
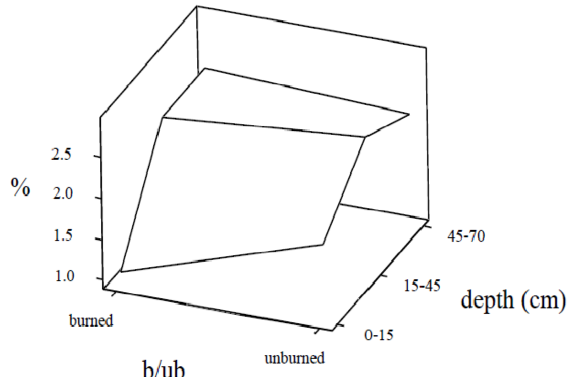
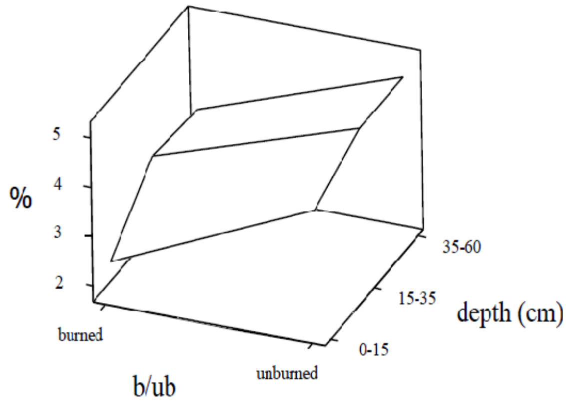


Fig. 3 Scatter plot of the relationship between soil water content (Y-Data) and soil clay content (X-Data) using mean data for all depths and burned and unburned area, from coastal and mountain sites, the different symbols indicate the four areas sampled (CB is burned coastal, CU is unburned coastal, MB is burned mountain and MU is unburned mountain)



(A)



(B)

Fig. 4 Surface plot showing the variation in the percentage of the water content at three depths in burned (b) and unburned (ub) soils from (A) the coastal site and (B) the mountain site

Moreover, the results of the statistical analysis by three-factor ANOVA (Table II) indicate that the differences between burned and unburned areas at the two study sites were also highly significant ($p < 0.001$) which may indicates to the effect of fire. On the other hand, from looking at the results in Table II, it would appear that the soil moisture is most reduced in the burned mountain site in the top soil layer, this may be due to that the period of burning was more recent than at the coastal site, and therefore the immediate effects of burning driving off moisture might still be in evidence.

The data obtained from the sites match the findings of [9] who noted increased evaporation rates from burned forests where the litter layer has been eliminated and as a consequence the soils in the burned areas were drier than those in unburned areas where the litter layer was intact.

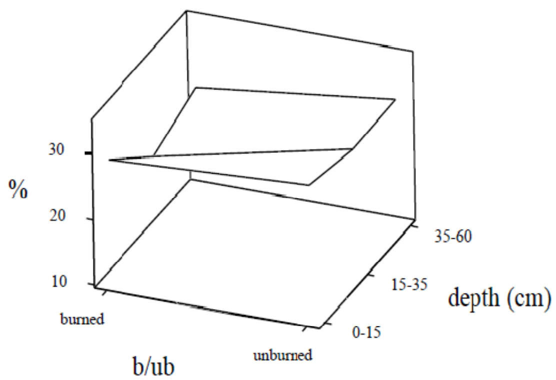
3. SOIL POROSITY

It follows from the data (Table II) that, although there is only a modest impact of fire on the porosity of the sampled soils (a weaker but still significant ($p < 0.05$) effect of burning compared to unburned areas) these soils appear to be characterized by the quality of internal drainage despite the low rates of moisture, i.e. the soil porosity is such that it will allow free movement of water without restriction. This is reinforced by the results of the electric conductivity (EC) measurements of the soil sample extracts (Table III) which indicate that the concentrations of soluble salts were greatest in the uppermost layers of the four study areas due to the soil solution rising up through the soil layers by capillarity.

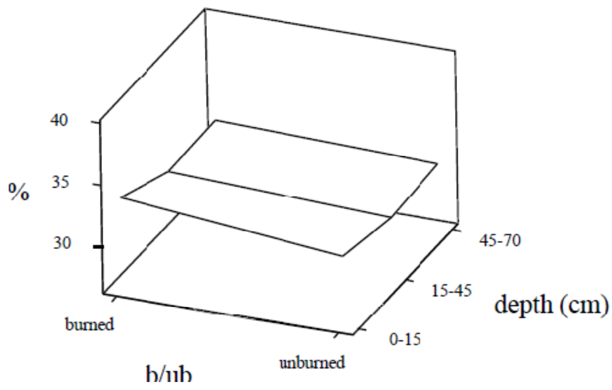
Although the absolute values of soil porosity do not vary greatly between the different study areas when they are analyzed by three-factor ANOVA (Table II) they are shown to be highly significantly different ($p < 0.001$) when comparing the coastal and mountain sites, with the latter having higher values possibly due to there being a higher content of silt and sand and lower content of clay in the mountain site. The results also show there is a strongly significant ($p < 0.01$) effect of depth, with higher values in the top soil layer (Fig. 5) due to an increase in the amount of clay and a relative decrease of sand and silt quantities with depth in the two study sites.

TABLE III
MEAN VALUES OF SOIL EC IN THE COASTAL AND MOUNTAIN SITES FOR BOTH BURNED AND UNBURNED AREAS AT THREE DEPTHS. EACH READING REPRESENTS THE AVERAGE OF 9 REPLICATES

Site	Type of sample	Depth (cm)	EC mS cm-1 at 25°C
Coastal	Burned	0-15	1.42
		15-35	1.16
		35-60	1.32
	Unburned	0-15	1.35
		15-35	1.05
		35-60	1.20
Mountain	Burned	0-15	2.22
		15-45	1.56
		45-70	1.72
	Unburned	0-15	1.84
		15-45	1.59
		45-70	1.64



(A)



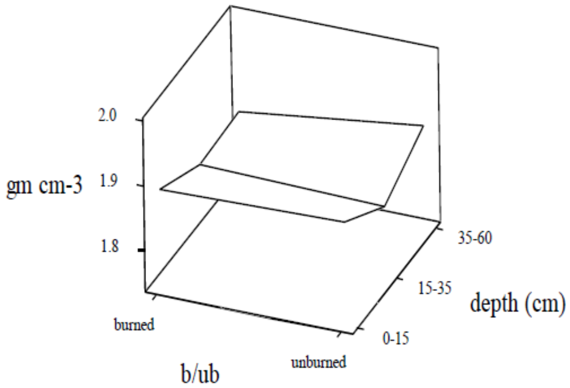
(B)

Fig. 5 Surface plot showing the variation in the percentage of the soil porosity at three depths in burned (b) and unburned (ub) soils from (A) the coastal site and (B) the mountain site

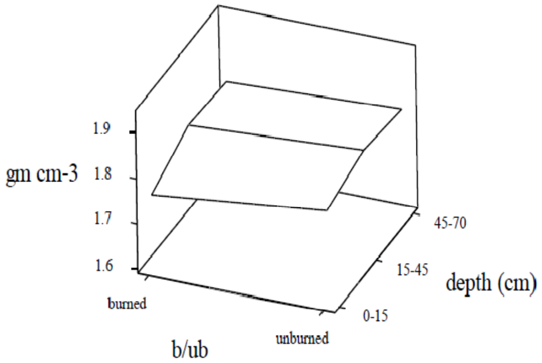
These results indicate that the intensity of the fire was not enough to produce any observable effect on the soil porosity in this ecosystem. This may be consistent with the study of [10], despite the fact that they observed an increase of total porosity with temperature of > 600°C either in sandy and clay soils, if the fire temperatures in the study sites were lower than this. Other studies, such as those of [19] and [20], do not accord with the results of the mountain site soil porosity estimation while they agree with the coastal site results.

4. SOIL PARTICLE DENSITY

Soil particle density of soils of the study sites are characterized by relatively high values ranging from 1.76 to 1.89 g cm^{-3} (Table II). This is probably due to the relatively high content of sand and silt particles compared to clay particles in both study sites. However, the two sites are statistically significantly different ($p < 0.001$) from each other with higher values in the coastal site. Furthermore, the illustrated surface plots in (Fig. 6) show that the mean values of the soil particle density do not vary much within each site, with the one exception that there is a slight reduction in the values in the middle depth in the coastal site only. The results of the three-factor ANOVA statistical analysis also indicated that there were no significant differences ($p > 0.05$) in the soil particle density values between burned and un-burned areas or between their depths at each study site. This may reflect that this important physical property at those sites which were subjected to fire has not been affected and that the soils under study were still characterized by homogeneous profiles. This study supports the ideas expressed by [6] and [7] who hypothesized that particle size ratio remains unchanged until temperatures of 300-400°C are reached. This also may agree with [21] who found in their study that an increase in particle density can result in deeper heat transfer into the soil profile. The implication of this is that the fires involved in burning the sites used in this study may not have reached temperatures above 300°C.



(A)



(B)

Fig. 6 Surface plot showing the variation in the values of the soil particle density at three depths in burned (b) and unburned (ub) soils from (A) the coastal site and (B) the mountain site

B. MAGNETIC SUSCEPTIBILITY

This study has used the technique of magnetic susceptibility for the first time in Libyan soils. Using this technique provided information that was particularly helpful in developing logical explanations for many of the results obtained from this study. In particular it assisted in identifying the depth of the soils that are believed to have been affected by fire and so helped to track the potential effects of fire on the physical and chemical properties within the soil profiles.

The results of magnetic susceptibility of soil samples (Table IV) have given values that slightly increase with depth in the unburned soil profiles; this may be attributed to the increase of percentage of clay with depth in these profiles (Table I), where clay has a capability to become magnetized due to the presence of iron oxides.

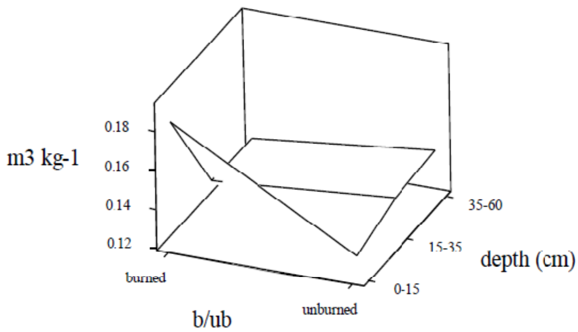
In the burned areas, however, there is a much greater value in the top layer from both sites (Fig. 7). The two sites are also different, with greater values in the coastal site may be due to the percentage of clay particles in the coastal site which was higher than in the mountain site. Therefore, the differences between the two study sites, between burned and unburned areas and their soil profiles depths are highly significant ($p < 0.001$) in the ANOVA (Table IV).

TABLE IV
MAGNETIC SUSCEPTIBILITY RESULTS IN THE TWO SITES (COASTAL AND MOUNTAIN), FOR BOTH BURNED AND UNBURNED CONDITIONS AT THREE DEPTHS. EACH READING REPRESENTS THE AVERAGE OF 9 REPLICATES

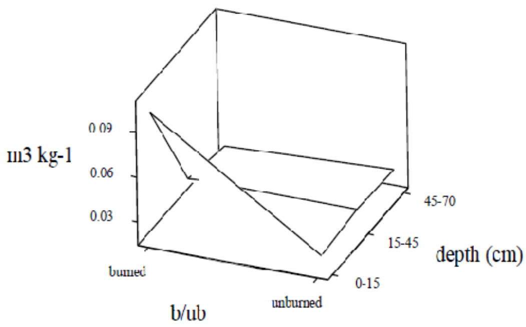
Site	Type of sample	Depth (cm)	Magnetic Susceptibility ($m^3\ kg^{-1}$)
Coastal	Burned	00-15	0.183×10^{-8}
		15-35	0.131×10^{-8}
		35-60	0.131×10^{-8}
	Unburned	00-15	0.131×10^{-8}
		15-35	0.139×10^{-8}
		35-60	0.141×10^{-8}
Mountain	Burned	00-15	0.101×10^{-8}
		15-45	0.029×10^{-8}
		45-70	0.023×10^{-8}
	Unburned	00-15	0.026×10^{-8}
		15-45	0.029×10^{-8}
		45-70	0.028×10^{-8}

There does appear to be a close relationship between the magnetic susceptibility of the soils and its clay content. It is worth noting that there is a major effect of burning evident on the magnetic susceptibility even in the coastal site which was burned 8 years ago. Therefore, this parameter does not appear to return quickly to its pre-burn levels.

The fact that the magnetic changes in the soils are confined to the surface layers accords with numerous studies that have indicated that the effect of fires in woodland is confined to the surface layers of the soils (e.g. [9]; [22]).



(A)



(B)

Fig. 7 Surface plot showing the variation in the values of the soil magnetic susceptibility at three depths in burned (b) and unburned (ub) soils from (A) the coastal site and (B) the mountain site

IV. Conclusion

The overall outcome from the results of the analysis of the soil physical properties from the two study sites emphasizes the point that, except for the measurements of the soil water content, the other soil physical properties tested were not affected very much by fire; there were a more differences associated with the site or the depth of the soil sample. However, although the soils of the two studied sites were subjected to fire at different periods of time, the results of the measurements of the magnetic susceptibility did show major differences as a result of burning, affecting the uppermost layer of these soils, and these effects were still very evident 8 years after burning in the coastal site.

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