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IMPACT OF FOREST FIRES ON SOIL DEGRADATION − CASE OF CORK OAK FOREST IN ALGERIA

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Abstract

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The Mediterranean forest ecosystem has a reputation for being subject to very high fire risks. In Algeria, this ecosystem is seriously threatened and suffers considerable damage every year due to wild and uncontrolled fires. Vegetation and soil are severely affected. The importance of the issues raises the need for a diagnosis of the vulnerability of soils subjected to fire and a reflection on the restoration of the quality of the burnt soils. Being aware of the consequences of the fires, we conducted a study on the impact of fires on the forest cover and, particularly, on the soil. The results showed that soil organic and mineral losses were greater than those of unburned soil, with erosion being 34 times higher. Sloping soils, after fire, degrade more quickly and becomemore vulnerable to erosion and drying out. A high frequency of fires alters the potential of the soil to such an extent that the resilience of the forest and soil could be compromised. The recurrence of fires creates a disturbance of vegetation and ground cover. Forest formations are degraded by fires and gradually replaced by secondary formations; the soil is often eroded. In some places, it has reached the threshold of irreversibility.

Key words: forest fires, erosion, soil, organic carbon, southern Mediterranean, Algeria.

Introduction

The Mediterranean forest ecosystem has the reputation for being subject to very high fire risks. Fires have disastrous impacts mainly in the south of the Mediterranean basin; they remain a major concern for all. Some authors (Paulo, 2013; Pausaset al., 2008; Bond et al., 2005) consider fires as natural processes; however, others reported that they can have effects that are more catastrophic on the forest landscape than on soil (Francos et al., 2024; Zavala et al., 2014; Arnan et al., 2007; Rodrigo et al., 2004; Marquès, Mora, 1992; Martin De Luís et al., 2005). Several cases have been reported where fire can engender significant changes in the hydrologic dynamics and lead to erosion by altering the physical, chemical, and microbial processes of the soil, as well as by reducing or eliminating the above-ground biomass. It usually takes 50 years to recover the qualitative aspects that are modified by fire (Vennetier et al., 2008); these aspects are key factors in replenishment of the ecosystem (Young et al., 2005).

In Algeria, a country located in the south of the Mediterranean basin, wildfire problems are almost unknown by the scientific community despite its devastating impacts (Meddour-Sahar, Bouisset, 2013). Forest fires have become a widespread phenomenon, posing a serious threat to our environment; forest fires seriously threaten the forest ecosystem and, more generally, the natural world. The upward trend in the number of fires and burned zones can only be worrying. Fires burned a total forest area of about 1million ha between 1985 and 2016; note that Algeria has a forest area of only 4.1 million ha. The frequency of fires is increasing in some forest regions; they may have a return interval of less than 10 years. Every year, forests in Algeria are subjected to considerable damage because of wild and uncontrolled fires; the vegetation and soil cover are, therefore, greatly affected. Repeated fires have severe negative impacts on the soil; they can affect the rehabilitation of the ecosystem and even its resilience. The ecosystem is not necessarily resilient in mountain areas where soils are highly threatened by accelerated erosion (Dupuy et al., 2015). It should be noted that very high fire frequency could indeed affect the vegetation in terms of diversity and richness; also, the resilience of forests could even be compromised (Borsali et al., 2014). The capacity of reconstituting the forest ecosystem, under repeated fires, must be explained through assessment of the vegetal and pedological dynamics (fertility of the physical, chemical, and biological soil).

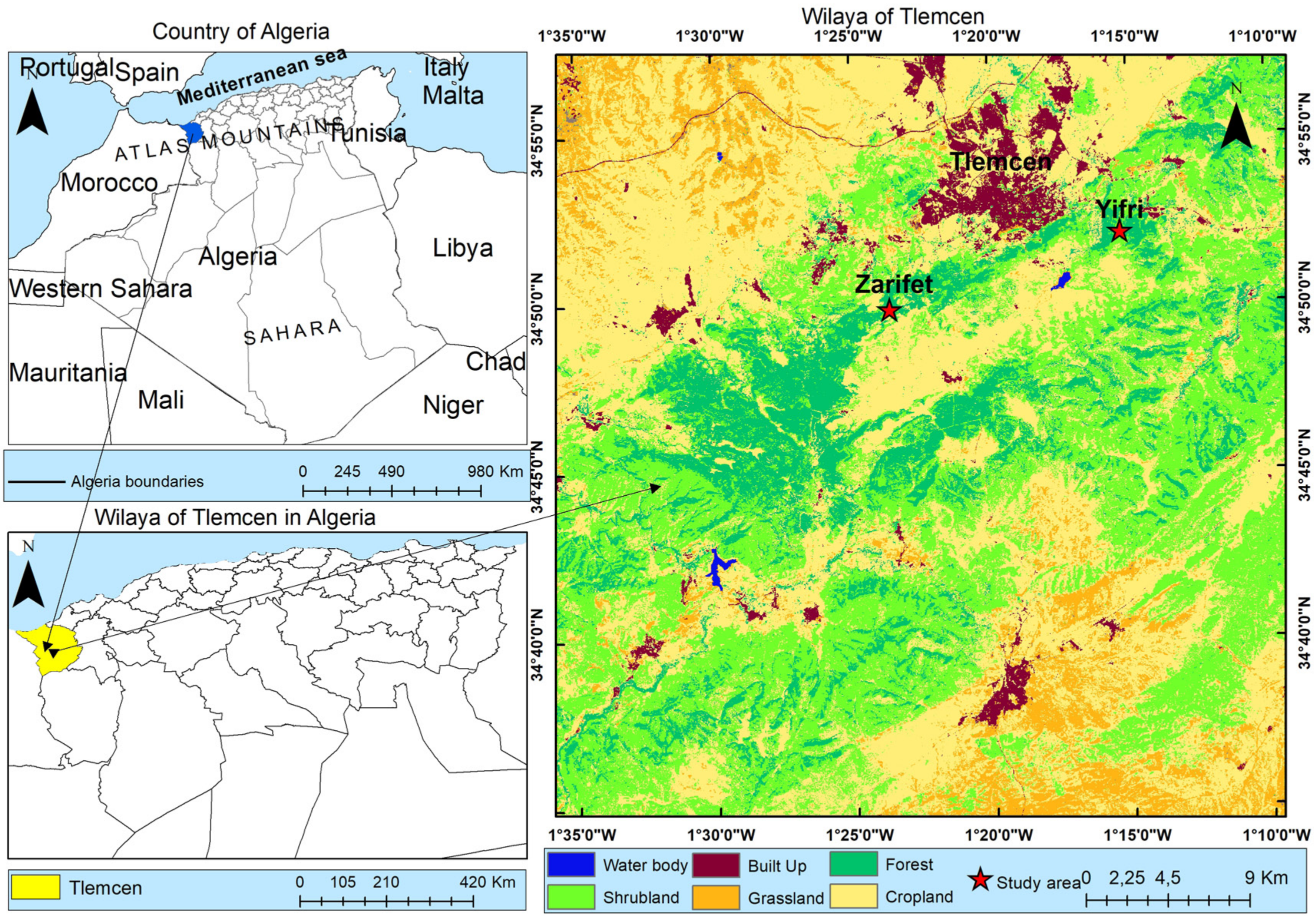

Fig. 1. The study area.

The increase in the number of fires becomes problematic for the dynamics of long-term resilience of soil (Guénon, 2010).

The importance of these issues raised the need for a diagnosis of soil vulnerability and dynamics after fires as well as restoration of the quality of burnt soils. Research work on this subject is rare in the region located south of the Mediterranean Sea; however, many studies have contributed to enrich the knowledge on the dynamics of vegetation and biodiversity after a fire. The present work aims to study the relationship between forest fires on the one hand and soil degradation and vulnerability on the other. Soil losses are probably the best indicator of post-fire disasters, as soil remediation becomes particularly slow (Pausaset al., 2008). The Forests of Tlemcen Mountains in Algeria, highly affected by fires, are the subject of our study.

Material and methods

Study area

The study area is located in the mountain range of Tlemcen, a town located in the western part of Algeria (Fig. 1). The climate is mainly characterized by dry summers and strong winds. The presence of highly combustible plant species promotes the initiation and progression of fires in the forest. The mean maximum temperature of the hottest month (August) is 30 °C, and the mean minimum temperature of the coldest month (January) is 3 °C. The average annual rainfall is around 550 mm. According to the Emberger classification, this area is characterized by a cool sub-humid Mediterranean climate and a lithology composed of sandstone, with medium to steep slopes. This site is part of the western region of the country; it has a very rich flora that was estimated to be consisting of 25,000 species by Quezel and Barbero (1990). However, the forest formations that covered the whole area are continuously declining from one year to another. The forest ecosystem has become fragile and vulnerable, with significant impacts on vegetation and soil. The anthropogenic disturbances, particularly fires, are largely responsible for the current state of vegetation (Quezel, Barbero, 1990). The study area is among the regions that are most affected by fires in Algeria, leading to an intensification of soil erosion processes and, consequently, degradation of the ecosystems.

Two sites were studied: the forests of Yfri and Zarifet (Fig. 1). These two sites are composed mainly of cork oak (*Quercus suber*). This type of cork oak forest is subjected to a gradual degradation by fires, with the appearance of a tree bush of green oak. The cork oak which covered 426,000 ha in Algeria (Boudy, 1948) has been reduced to only 230,000 ha.

The methodology employed in this study combines both descriptive and experimental techniques to comprehensively as-

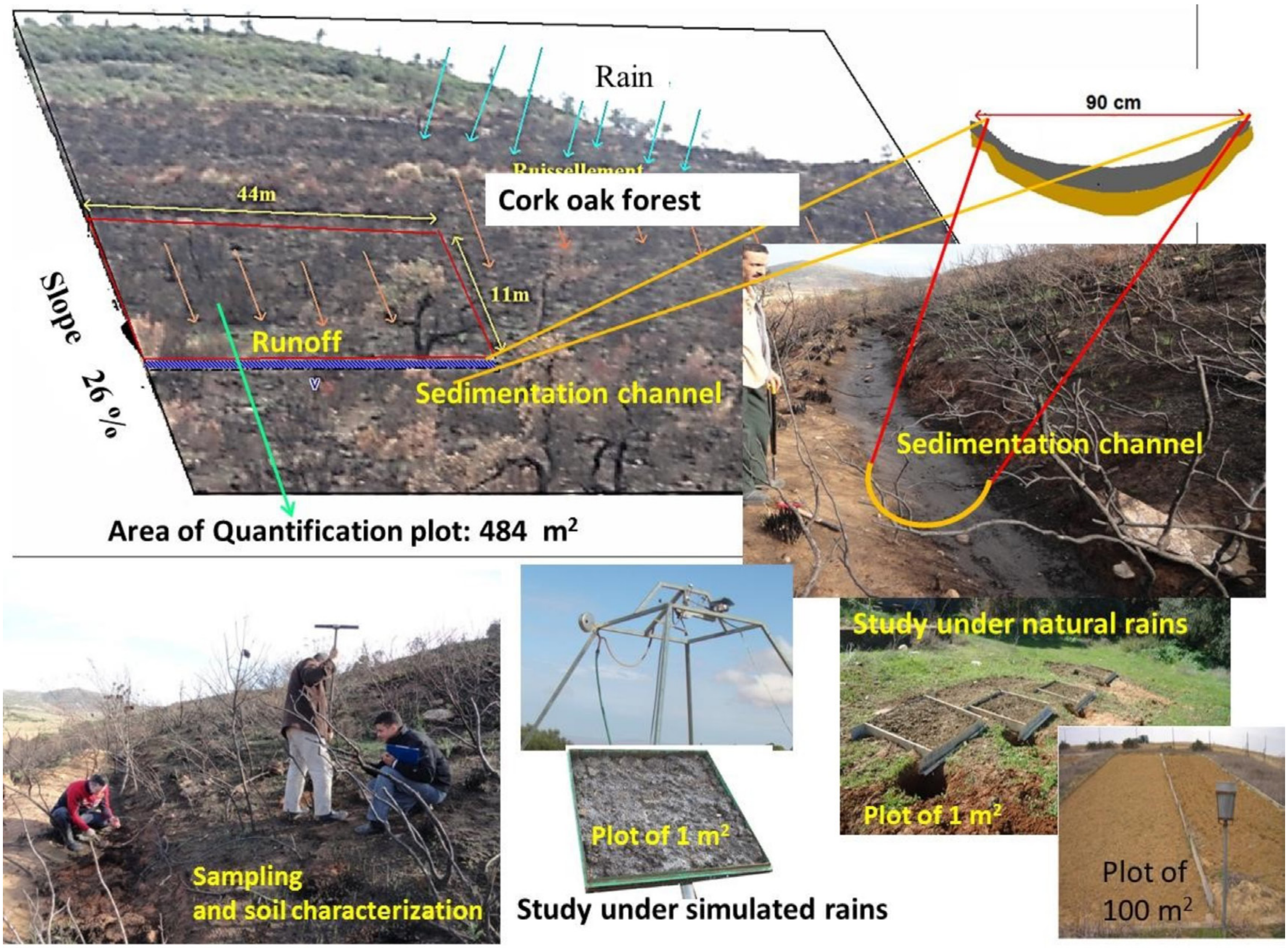

Fig. 2. Methods used in the study of soil and erosion assessment after fire.

sess the impacts of wildfires on soil properties and forest cover dynamics. Descriptive field observations were conducted to capture critical changes in the landscape, vegetation structure, and soil surface conditions following fire events. Soil characterization was performed using specific morphological and analytical criteria, such as texture, organic matter (OM) content, and structural stability, which are essential for evaluating post-fire soil quality. These characterizations helped to identify fire-induced alterations in soil properties, including compaction, loss of OM, and reduced infiltration rates, which play a crucial role in post-fire hydrological responses.

To further investigate the hydrodynamic behavior of the soil, the study employed experimental plots of 1 m², designed to simulate erosive dynamics and analyze surface conditions under controlled rainfall scenarios. Using an ORSTOM (Office of Scientific and Technical Research Overseas)-type rain simulator, we recreated post-fire rainfall conditions to assess how soil surfaces respond to intense precipitation events, mimicking real post-fire conditions. Erosion rates were measured at different spatial scales of 1 and 480 m² under both simulated and natural rainfall conditions to evaluate runoff generation and soil loss severity. This multi-scale approach allowed for the detailed quantification of soil degradation, runoff, and sediment transport processes across varying terrain and fire severity levels, providing a robust understanding of fire-induced erosion and its long-term effects on landscape stability and ecosystem recovery.

Two distinct study sites were selected to investigate the effects of wildfires on soil and forest cover: the Yfri Forest and the Zarifet Forest. In the Yfri Forest, the direct impacts of a single fire event were examined through comprehensive soil characterization and erosion quantification conducted on a 480-m² plot (Fig. 2). The study focused on assessing changes in soil properties, such as texture, compaction, and OM loss, which are critical indicators of post-fire soil degradation. Erosion measurements were carried out under natural rainfall conditions to evaluate the severity of soil loss and the vulnerability of sloping terrains to post-fire erosion. These assessments provided valuable data on how a single fire event can alter the hydrological and erosive behavior of soils, particularly on slopes.

In contrast, the Zarifet Forest, which experienced multiple fire events, was chosen to analyze the cumulative effects of recurring fires on both soil and forest cover. At this site, field observations, soil hydrodynamic behavior, and erosion quantification were conducted using smaller, 1 m² experimental plots. The focus was on understanding how repeated fire events affect soil structure, runoff dynamics, and vegetation recovery over time. This approach aimed to shed light on the long-term impacts of recurring fires,

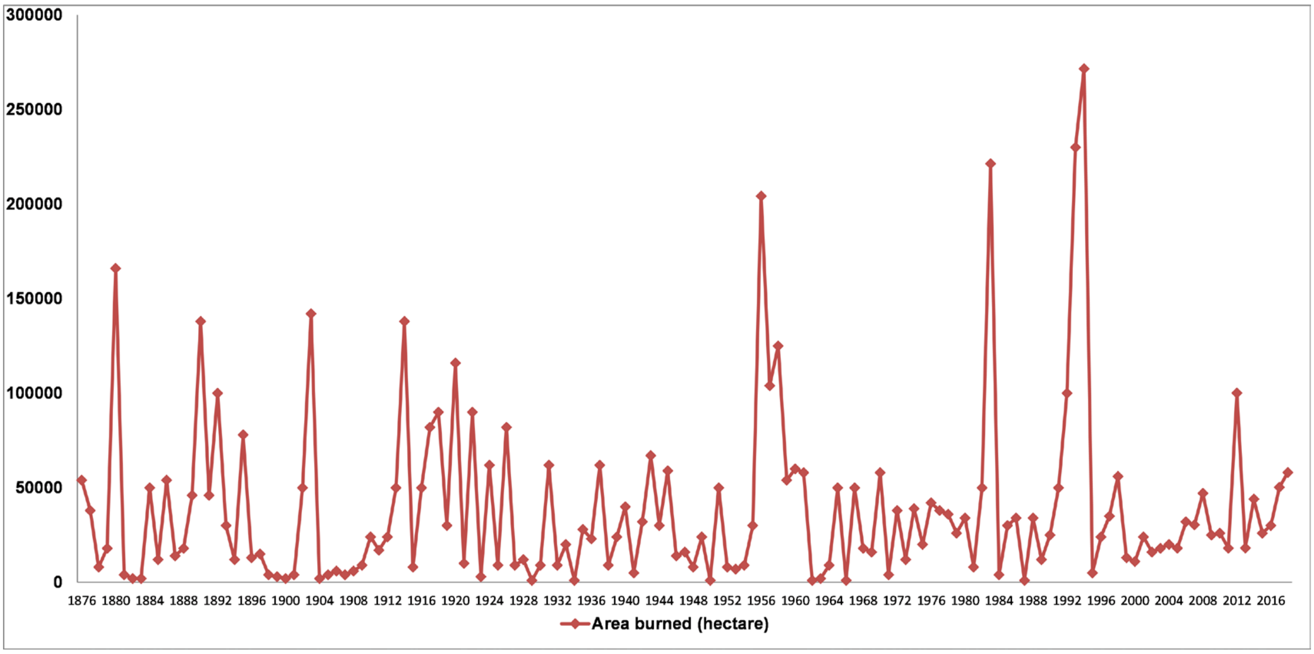

Fig. 3. Burned areas from 1876 to 2018.

particularly regarding soil stability, OM depletion, and ecosystem resilience. The combination of these methods enabled a detailed analysis of the vulnerability of sloping soils to erosion following recurrent fires and offered insights into the challenges of ecosystem regeneration under continuous fire disturbance.

Results and discussion

Drought is the major climatic event that slows down the evolution of the Algerian forest; its development is strongly dependent on the climate. Every year, the forest has been experiencing numerous wildfires (Fig. 3), which transform it into maquis and scrub. However, there are some local exceptions where forests burn seldom because they are more or less protected. The risk of forest wildfires, together with the risks of drought and desertification, has become a serious problem. Available statistics indicate that over a 126-year period, 4,834,874 ha of vegetation cover were burned, which represents 118% of the total forest area. Despite some enhancement measures regarding fire safety and fire prevention systems, the number of fires still cannot be significantly reduced. Northwestern Algeria is experiencing a high number of forest fires. The region of Tlemcen, where our study site is located, is affected by a large number of fires and, therefore, constitutes an ideal zone for studying the impact of fires on soil and forest cover.

The forest of Yfri

The first site, located in the forest of Yfri in the Wilaya (province) of Tlemcen, is characterized by sandy-loam soil. The presence of cork oak in this forest indicates the siliceous nature of the substratum. This forest consists mainly of cork oak. The undergrowth is very rich; it consists essentially of *Olea europaea*, *Phillyrea angustifolia*, *Cistus heterophyllus*, *Erica arborea*, *Rosmarinus tournefortii*, *Lavandula dentata*, *Thymus ciliatus*, *Genista tricuspidata*, *Calycotome intermedia*, *Arbutus unedo*, *Pistacia lentiscus*, and *Cistus monspeliensis*. The last two species are signs of a pronounced degradation of the cork oak forest, mainly due to fires (Godron, 1981). As this forest is too often burned, it is gradually replaced by the maquis, which is characterized by its much closed structure with the predominance of very fire-sensitive plant species (pyrophytes) such as the *Calicotome*, *Arbutus,* and *Rockrose*. According to Boudy (1948), cork oak forests are the most sensitive to fire. In addition, the herbaceous and shrub strata (*Erica arborea*, *Arbutus unedo*, etc.) present the ideal relay for fire to reach cork oak trees, especially on steep slopes where fire can gain strength, as is the case of the two forests under study.

Hydric behavior and soil erosion

The area of Fouazez in the forest of Yfri, which mainly consists of cork oak, was completely burned in August 2012. After the fire, the forest cover and OM of the soil surface horizon (litter and humus) were totally combusted and destroyed (Fig. 4), leaving a bed of ash very easily mobilized by water and wind. Monitoring erosion immediately after the fire gave alarming figures (Table 1 and Fig. 5) compared to erosion in unburned soil (Table 2).

These data indicate that sloping soils remain highly vulnerable to erosion after fire. The rains of the first months remove large quantities of earth, scraping most of the surface horizon (mineral elements, charred materials, ashes, etc.). In just 3 months, erosion reached 27.2 t/ha on the slopes. Sheet erosion is 34 times greater than the erosion in unburned ground, which confirms the very strong acceleration of erosion following the fire. Erosion increased from 0.8 t/ha for underground soil to 27.2 t/ha for burnedsoil. The average annual soil losses due to erosion in this type of landscape are less than 2t/ha/year (Morsli et al., 2004, 2005). Erosion may remain very high for periods ranging from a few months to a year or even longer after a fire. The duration of this period of soil vul-

Fig. 4. Forest completely burned by fire and ground totally burned and destroyed.

Table 1. Erosion after fire after 3 months only (September, October, and November 2012 and after a cumulative rainfall of 313 mm on a plot of 484 m2).

Quantity of eroded elements	1.32 t for a plot of484 m^2
Quantity of eroded elements per hectare	27.2 t/ha
Erodedelements >2 mm	4.2 t/ha (15,5%). Partially burned plant residues, charred matter, pebbles, stones
Erodedelements <2 mm	23 t/ha (84.5%). Carbonized matter and mineral matter (sands, silts, and ashes)

Table 2. Erosion of soil not burned (quantification of erosion under natural rain).

Eroded elements	**Erosion**			
	Min.	**Max.**	**Med.**	**Coefficient of Variation**
Quantity of eroded elements on a plot of 100 m^2 (erosion in sheet under forest, measures over 10 years) (t/ha/year)	0.5	1.2	0.8	0.2
Quantity of eroded elements on a plot of 100 m^2 (erosion in sheet on bare soil, measurements over 10 years) (t/ha/year)	0.8	7	5	0.2
Quantity of eroded elements on a plot of 1 m^2(erosion (detachment, measurements over one year) (t/ha/year)			4	
Loss of SOC (kg/ha/year)	20	150	40	0.3

Note: SOC – soil organic carbon.

nerability depends on the regeneration capacity of the vegetation cover; this regeneration is directly linked to the climatic conditions and soil quality. In our case, this period of erosion sensitivity co-occurred with exceptional rainfall events (Fig. 5). Extreme events were observed especially during that period. The maximum daily rain observed during the 3months after the fire was 140 mm (November 13, 2012), with a maximum intensity of 30 mm/h for 30 min. In Ain Fares (northwestern Algeria), Morsli and Habi (2014) recorded, during a 15-year period, the following maximum intensities for a period of 5 min: IM5 = 150 mm/h, IM10 = 120 mm/h, IM15 = 100 mm/h, IM30 = 30 mm/h, and IM60 = 20 mm/h. Sediments were generally transported by intensive and/or continuous rains. In the present case, sediments were mainly carried away by rains in two periods, that is, on September 27 (7 t/ha) and November 13 (16 t/ha), as indicated in Fig. 5.

The highest erosion rates are recorded during intense rain events (Table 3). The highest erosion rates and spectacular damage are due to exceptional rains (extreme events), very violent storms, long and saturating rains causing up to 30% of runoff, with erosion of more than 1ton/ha on vulnerable soils, such as the burned areas. An intense rainfall event can produce more than 30% of the annual erosion (Morsli, 2015).

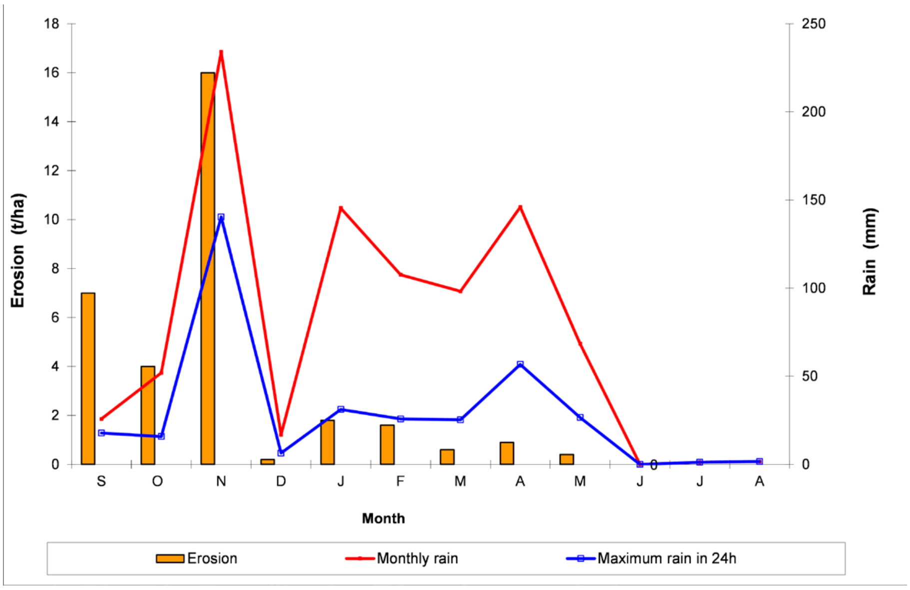

Fig. 5. Dynamics of erosion after fire.

Table 3. Erosion and runoff for some aggressive rains on bare plots of 100 m^2.

Date	Rain (mm)	Runoff(Kr) (%)	Erosion(kg/ha/year)	Situation of the sites
01/1990	80	38.6	5700	Tlemcen mountains in the far west of Algeria
01/1990	22	29.3	1322	Tlemcen mountains
05/1993	49	26.5	1621	Tlemcen mountains
05/12/1995	45	18.5	1800	Mascara mountains in western Algeria
28/02/1996	54	15.1	2000	Mascara mountains
10/11/2001	70	35.0	3400	Mascara mountains

The heavy rains that occurred after the exposure of soil following the fire increased the risk of erosion and caused considerable damage. But after 4months, when most of the deposits left by the fire were evacuated by erosion, the soil surface started to be covered by herbaceous vegetation that is favored by moist soil (consecutive rains) and is rich in mineral elements (OM mineralization). This stimulation of the herbaceous vegetation, which is manifested at the beginning, starts declining in the short term following consumption of the stock of elements released by combustion. Then, the *Cistus* invaded the land after the fire, which increases the vulnerability even more.

The ash bed, much of which has been mobilized by water, indicates that fire has led to rapid mineralization of the biomass, litter, and humus; this affects the soil organic carbon (SOC) stocks in soils, which are considered as carbon reservoirs. The organo-mineral layer at the soil surface, an essential source of soil fertility, is burned and gradually eliminated by erosion. After the fire, this layer is very much affected by erosion (loss of 4 t/ha), which profoundly modifies the water dynamics at the superficial horizons and reduces the infiltration, as well as the stability of aggregates. Henin'sindex of structural instability varies between 2 and 4, and the correlation between structural instability and the soil OM (MOS) is significant (r = 0.76). There is, therefore, a reduction in soil rainwater storage, a deficit in water balance, a reduction in soil productivity, and, consequently, a problem of regeneration of the plant cover with an increase in vulnerability of soils to erosion (27.2 t/ha). The erodibility varies between 0.3 and 0.4 for degraded sandy soils, which are mostly stripped on sandstone (Roose, Sarrailh,1989; Morsli, 2015); these soils may, therefore, be classified as very sensitive to erosion. It is worth noting that fire accelerates the erosive process in a significant manner.

Hence, the risk of erosion for sandy soil is greater than for clay soil. On this type of sandy and compact soil, OM-accumulated undergrowth is not well incorporated into the soil, which facilitates its incineration and evacuation by erosion. However, this OM is fairly well incorporated into clay soils, especially in vertic soils. The studies conducted in the present work on clay soils showed that these soils, due to their particular behavior (swelling and shrinkage), allow a good storage of carbon; the water infiltrated through the slits resulting from soil shrinkage takes considerable quantities of fine earth, which is very rich in OM, from the surface to the depths. The variation of carbon in the soil profile is less important than that of the sandy and compact soil. Vertic soils have a high potential for carbon sequestration and can thus constitute a large reservoir for carbon (Morsli et al., 2005). Clays exhibit a high stabilization of SOC by protecting OM from decomposers (Six et al., 2002).

Table 4. Soil characteristics of different sites of the toposequence –Forest Zarifet.

Site	Occupation	Slope%	Surface state	MOS(%)	Depth(cm)	Texture	Pebbles(%)	Pi(mm)	Erosion
S1	DM	>20	Litter	2 to 3	50	LSA	2 to5	10 to 20	Erosion traces
S2	DSM	>20	Compacted	1,5 to 2	30	LS	15 to 20	5 to 10	Stream and channel erosion
S3	(SDS)	>20	Compacted	1 to 2	40	SL	15 to 30	3 to 5	Stream and channele-rosion
S4	(DL)	>20	Compacted	1 to 1,5	< 30	LS	20 to 50	2 to 3	Stream and channel erosion
S4	forest (DF)	3 to 10	Litter	3 to 4	50	SL	10 to 15	>25	--

Notes: Pi - Impregnation rain corresponds to the wetting phase of the soil during which the volume of infiltration is greater than rain and where no runoff is observed (threshold for triggering runoff). Pi is used to determine the rainfall thresholds needed to trigger runoff and to assess soil response. (Simulated rain of 50 mm/h for 30 min on dry soil.) DM - dense maquis; LSA - loam-sablo-clay; LS - silt-sand; SL - sand-silt; MOS - organic matter of the soil; depth - soil thickness; pebbles - stony load on the soil surface; DSM - Degraded sparse maquis; SDS - Sparse diss steppe; DL - degraded land; DF - Dense forest.

Therefore, it would be necessary to intervene more quickly, just after the fire, to reduce the erosion that remains a threat for this type of soil and which could have serious consequences on rehabilitation of the burned zones. This is mainly attributed to the climate change and pedogenesis that is caused by aridity, which reduce the potential for rehabilitation of these burned areas.

Lands removed from slopes by erosion are redistributed in the fields or driven into the Thalwegs. Part of the eroded material remains trapped in the slopes. The amount of soil retained in the slopes depends on the topographic conditions and soil management practices. Significant deposits are observed in the slowdown parts, such as recesses, concavities, etc. Understanding this dynamic can help to better manage this heterogeneity of potentialities and also to restore SOC stocks in the soil, both for sustainability and for environmental purposes.

The forest of Zarifet

The second site is located in the forest of Zarifet in Tlemcen (northwestern Algeria). This sub-humid climate zone is characterized by a fragile and vulnerable ecosystem, with a lithology composed of sandstone and medium to steep slopes. This transect consists essentially of red soils mainly composed of sandstone. These are relics of ancient fersiallitic red soils, which are characteristic of the Mediterranean region [Rhodoxeralfs (according to the soil taxonomy classification); Mediterranean red soils (according to the Higher Council for Agronomic Research's soil classification (CPCS))]. In this zone, soils are generally non-carbonated; most of them are degraded due to overgrazing, erosion, and fire. On this transect, successive shrubby and bushy formations appeared, which generally caused repetitive fires. The forest formations that covered the entire area are declining from year to year. It is worth noting that the anthropogenic disturbances, especially fires, are largely responsible for the current state of vegetation in the region (Quezel, Barbero, 1990).

Due to repetitive fires, this forest has been transformed into matorrals and scrubs. This transformation was stimulated by anthropic practices; it was also favored by the climate of the region that is characterized by drought, which is a factor that hinders the evolution of the forest. The very short fire return intervals generate a regressive dynamics of the vegetation. Today, this issue constitutes a major problem for the countries having a Mediterranean climate (Fleur, 2003). In addition, it is important not to neglect the negative impacts of human practices that permanently disrupt forest systems (Missoumi et al., 2002).

On this transect, where shrubs and bush formations occur following repeated fires, there is also a change in the pedological parameters. Soil spatial variability is mainly due to water erosion, which can be explained by the degradation of the vegetation cover following recurrent fires. The results obtained show that the red soils, which used to cover the entire versant, changes facies on this transect. The morphological and analytical characters that differentiate the soils in this sequence include color, texture, OM content, thickness, horizon differentiation, and stone content. The different variations are presented in a synthetic form in Table 4.

Hydric behavior and soil erosion

For many years, fires and overgrazing have led to the disappearance of the primitive oak grove, which was replaced by shrub formations called matorrals. Under the dense formations, where relics of cork oak still remain, the red soil could relatively be preserved by the vegetal cover, but it is not out of reach of the erosion. In some bare, much localized land, the soil is stripped with the disappearance of the superficial horizon (truncated red soil). Under the fire-degraded matorral, which consists of not too covering secondary species (discontinuous plant cover) on steep slopes, the soil is bare and weakened. As soon as the soil is uncovered, erosion usually accelerates its stripping due to the high declivity of the ground. Soil stripping by erosion is corroborated by the stone content (15-50%), soil thickness (E <50 cm), and rock stripping (decalcified sandstone outcrop). It is commonly admitted that on a partially vegetated slope, bare areas are likely to be subject to erosion (Reid et al., 1999). On these sites, which are highly affected by repetitive fires, complete and regular profiles are rarely observed; the soil is compacted and the infiltration is very weak, which enhances runoff. One can clearly note the existence of areas of superficial depletion. Accelerated erosion can, therefore, cause not only the loss of land, but also the loss of fertility and water. However, well-covered soils (degraded matorrals) are relatively better preserved even in the presence of steep slopes.

The matorral of secondary species, resulting from the primitive oak degradation, in turn impoverishes and deteriorates under the action of repeated fires and is transformed into sparse Diss steppe (Clear Diss, range zone), which represents the ultimate phase of degradation of this forest (degradation facies). This Diss formation consists essentially of bushy plant species of *Ampelodesma mauritanica* of the *Poaceae* family. Although cork oak is one of the most fire-resistant species, well adapted to fire, this formation has suffered severe degradation and tends to regress more and more, as a result of repetitive fires. Due to the continuous degradation of the vegetative cover (DL), the soil is severely affected by sheet erosion, and therefore undergoes profound changes. This causes asurface horizon stripping, large stone content (stone content>50%), soil compaction, and decrease in biological activity. Soil truncation is so important that erosion can eventually cause the outcrop of pebble tessellations and the appearance of the sandstone bedrock at the surface, thus significantly impeding the infiltration of water and regeneration of plants of the primitive plant cover in particular; this can occur mainly in an unfavorable climate.

In some sections of the steep slope, the soil was burned so much that it could almost reach the threshold of irreversibility. The ground was stripped and the bedrock outcropped. In this case, soils are in precarious balance and remain very sensitive to changes in the vegetation cover which constitutes a major protection for these soils.

On the same transect, reforestation of *Pinus halepensis* (LR), carried out on a ground degraded by fire, allowed, after 45 years, forming a regular and highly covered forest (cover rate>80%) in an area where soil formed in colluviums. However, the land surface that was severely damaged by erosion, due to repeated fires, did not change much. Although the ground was covered by a 5-cm-thick litter (needles), it did not change much compared to the degraded soil. The successful reforestation is mainly attributed to the gentle slope, thick soil that formed in colluviums, litter-covered soil, OM-rich soil and water balance improvement (Pi>25mm). However, this reforestation could not rehabilitate either the primitive oak or the degraded soil cover.

Synthesis

The results from the study of these two sites suggest that sloping soils are very much affected by repetitive fires. On the first site, erosion was very apparent on the ground which remained bare for more than 5 months after the fire. The destruction of soil cover (plant cover and litter were entirely destroyed), decrease in soil resistance (OM of the highly carbonized superficial horizon, loss of stability of the aggregates), and its impermeability, which is due to the formation of a hydrophobic film, increased the risk of runoff and erosion in these areas. Erosion, which increased 34-fold, carried away the most fertile superficial organo-mineral layer of the soil. It removed most of the carbon stock that was concentrated in the first few centimeters of the ground.

Similarly, the results obtained from the second site indicate that the fire recurrence caused a disturbance and variation in the vegetal and soil cover. Early oak was degraded and has gradually been replaced by increasingly clear secondary formations. Soil was often eroded and depleted; in some places, it reached the critical irreversible threshold. The status of the Mediterranean soils shows accelerated degradation, with sometimes a threshold limit already reached or even exceeded (Lahmar, Ruellan, 2007). In a region like ours, where soils are shallower and pedogenesis is hindered by aridity (morphogenesis outweighs pedogenesis), it is highly recommended to review the tolerance thresholds; for sheet erosion and under a temperate humid climate, they range from 2.5 t/ha/year for shallow soils to 12.5 t/ha/year for deep and moderately permeable soils with a balanced texture (Klingebiel, Montgomery, 1966; USDA, 1951). Tolerance is likely to be lower in western Algeria because pedogenesis in this region is much slower and soil is mostly shallow. Moreover, the tolerance threshold does not take into account the phenomenon of sheet erosion selectivity. The sediments reveal the selectivity of fine particles, especially of organic carbon, with a selectivity index between 1.3 and 4.

The results obtained indicate that the close frequency of fires (recurrence <10 years) on sloping areas can have a catastrophic ecological and environmental impact. Global warming will certainly increase the vulnerability of forests and soils. Repeated droughts (drought occurrence: one year out of three) and heat waves (maximum temperatures in recent decades exceeding 40 °C) led to increased fire risk and reduced soil rehabilitation and resilience of forests. Drought years are usually associated with a rise in the frequency of intense fires. In Algeria, a temperature increase, between 1 and 2 °C, has been recorded, which is twice that of the entire planet, which is 0.74 °C (Tabet Aouel, 2008). This temperature rise, already predicted for the next few years (GIEC, 2007), is likely to increase the risk of forest fires and therefore increases soil erosion vulnerability. Soils in the northern Mediterranean region (wetter climate and soil with higher OM content) do not have the same sensitivity to climate disturbances and fluctuations as the southern soils that are exposed to extreme temperatures and droughts.

In general, in the south of the Mediterranean, fires are generally followed by the most sensitive period to erosion. Maximum erosivity of storms and maximum fragility of the environment are mostly observed in the season of fall. The fire may be followed by heavy rainfall events before a vegetative cover can be put in place; this represents a serious threat to soil due to abrupt erosion. This was observed in the forest of Yfri after the fire.

Conclusion

The Mediterranean forest ecosystem has the reputation of being subject to very high fire risks. However, in the southern Mediterranean basin, the fires have a disastrous impact and remain a major concern for all the countries concerned. In Algeria, forest fires have become a widespread and serious phenomenon; they represent a severe threat to the forest ecosystem and to the whole environment. In addition to the destruction of the vegetation cover, forest fires can also be the cause of serious land degradation phenomena, especially for shallow soils such as those of the forests of Yfri and Zarifet.

This study suggests that the onset of runoff is faster and sediment production is higher compared to unburned soils; erosion is multiplied by 34 times. Quantification of erosion indicates that soil organic and mineral losses are significant. The availability of nutrients and their loss after fires are controlled by erosion phenomena. The results show that sloping soils are more rapidly OM-depleted and become more vulnerable to erosion and to drying out after fire. A high frequency of fires (recurrence <20 years) could alter the edaphic potentialities (decreased fertility, lower resistance, weaker structural stability, and soil permeability) to a point where the resilience of forest and soil cover is impaired. The results obtained have repeatedly shown that the recurrence of fires leads to vegetation and soil cover disruption. Moreover, forest formations are degraded by fires and are progressively replaced by increasingly clear secondary formations. The soil is often eroded and depleted and, in some places, it may reach the threshold of irreversibility. Global warming (occurrence of drought in one year out of three, heat waves, temperature increase between 1 and 2 °C) increases the risk of fire and the vulnerability of forests and soils and reduces the rehabilitation of soil and forest resilience. Therefore, protecting forests against fire risks and restoring soil quality are essential. The establishment of precautionary measures for soils, just after fire, represents an important phase. A number of perspectives can be considered, namely monitoring the dynamics of long-term edaphic properties, studying the possibilities of remediating degraded soils, and identifying relevant monitoring indicators.

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