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Acceptance Letter

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Dear Dr. Guerine
It's a great pleasure for us to inform you that above mentioned manuscript has been accepted as the research and full paper for publication in "***Journal of Rangeland Science***" on the recommendation of the reviewers.

Best regards

Chief Editor
Professor Ali Ashraf Jafari

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Ecodendrometric Characterization of *Atlas pistachio* (*Pistacia atlantica Desf*)

Stands in the Ain Ben Khelil Region (Southwestern Algeria)

The Atlantic Pistachio (Pistacia atlantica Desf) forest has a valuable pioneering species heritage in the arid and semi-arid regions. It is described as the most original and remarkable species in the high steppes for both ecological and social value. The results of ecodendrometric characterization of this species in Ain Ben Khelil region show the dominance of big and very big woods, about 62% of the studied population. The natural regeneration of Atlantic Pistachio is closely related to the nurse plant effect (Jujube -Atlantic Pistachio). The rates recorded are respectively: 6.7% (grove 1), 8.3% (grove 2), 12.6% (grove 3) and 23.7% for the 4th grove. The floristic diversity of the Atlantic pistachio is characterized by three strata, namely a tree strata, shrub strata and a herb strata containing a significant floristic richness.

Key words: Atlantic Pistachio, Ain Ben Khelil, Ecodendrometric, Regeneration, Floristic richness.

The ecodendrometric characterization of the Atlantic Pistachio in Ain Ben Khelil region shows the predominance of big and very big woods. The natural regeneration of the Atlantic Pistachio is closely related to the nurse plant effect (Jujube - Atlantic Pistachio).

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Introduction

The present work is designed to respond to concerns closely related to the conservation and management of Atlantic Pistachio stands in Ain Ben Khelil steppe region (South-western Algeria) by the appreciation of some dendrometric and ecological parameters that will be used in the various rehabilitation plans for this species.

Pistacia atlantica Desf, Anacardiaceae, Sapindales, Magnoliopsida, Atlas Pistachio or "Betoum", are located in Northern Africa (Morocco, Algeria, Tunisia), and in the Canaries, Libya (Cyrenaica), Cyprus and the Near East (Médail and Quézel, 2003). A powerful species can reach up to 20 m in height, with a well-individualized, deciduous trunk (Benhssaini and Belkhodja, 2004; Fennane *et al*., 2007).

Pistacia atlantica, known as free-range, adapts to all soils except sand. It has low rainfall of about 150 mm and sometimes less (Benhssaini and Belkhodja, 2004; Benhssaini and Belkhodja, 2007). The growth of *Pistacia atlantica* is very slow, but it has the advantage of being the only tree north of the organizing power of forest ecosystems in arid and semi-arid bioclimates (Yaaqobi *et al*., 2009).

In Algeria, the species is included in the list of wild species protected by executive decree 12-03 of 4th January 2012. The Atlantic Pistachio finds its optimum in arid and semi-arid regions, particularly the high plains where it thrives in the talwegs and dayas (depressions). Stands more or less vast are found, here and there, in the Hoggar and the Atlas, where the *Pistacia atlantica* is limited in its expansion by the competition that opposes it to other species much more adapted to the cold and to moisture (Harfouche *et al*., 2005; Daget, 1980).

However, the Atlantic Pistachio in its range is in an alarming state of degradation because of its abuse by the rural population to meet their needs of firewood. Other factors such as pests, diseases and

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prolonged drought contribute to its degradation (Mseguem, 2017).

Studies on this species have focused on botanical, biogeographic, taxonomic and ecological aspects (Emberger, 1938; Monjauze, 1980; Zohary, 1996; Belhadj, 1999; Médail and Quézel, 2003; Belhadj, 2008; Amara, 2014). In addition, we noted that previous studies have never addressed the ecodendrometric aspect of Atlantic Pistachio stands.

Material and Methods

Presentation of the study area

The steppe region of Ain Ben Khelil (Fig. 1) occupies an area of 3741 km². It is located about 45 km south-west of the capital of the wilaya of Naâma. It is spread over the western end of the highlands southwest of Chott El Gherbi (Boudjadja, 2011). The province is characterized by its rural aspect where the nomads represent the majority of the population of about 63% (Mansour, 2011).

Ain Ben Khelil has two large geological assemblages, namely large areas of erosion (Bouzenoune, 2003) and mountainous terrain consisting of Middle Jurassic dolomites (Benkheira *et al.*, 2005). The pliocene plains occupy the rest of the pudding landscapes and lake limestones.

The climate in this study area is semi-arid, characterized by a dry summer season with increasing aridity from north to south (Mseguem, 2017; Mansour, 2011). The annual average of precipitation in the study area is 250 mm. The rainfall regime characterized by a long period of drought that extends from April to October. The aridity of climate, prolonged drought, fragility of the soil and overgrazing constitute the main causes of degradation of the natural vegetation. The proliferation of therophytes and chamaephytes, characterizes the major features of the vegetation cover of the region like other steppe regions (Aidoud, 2005; Amghar and Kadi Hanifi, 2008; Hamada *et al.*, 2004; Kaabeche, 1990; Kaabeche *et al.*, 1993).

Methodological approach

A systematic sampling that takes into account the variability of the Atlantic Pistachio stands has been carried out on a few groves (Fig. 2) in the Ain Ben Khelil region. The dendrometric measurements made within these groves concern the total height and the diameter of 1.30 m of all the subjects encountered, which numbered 361 trees. These measurements constitute a basic element in order to characterize the diametric and vertical distribution of the studied stands.

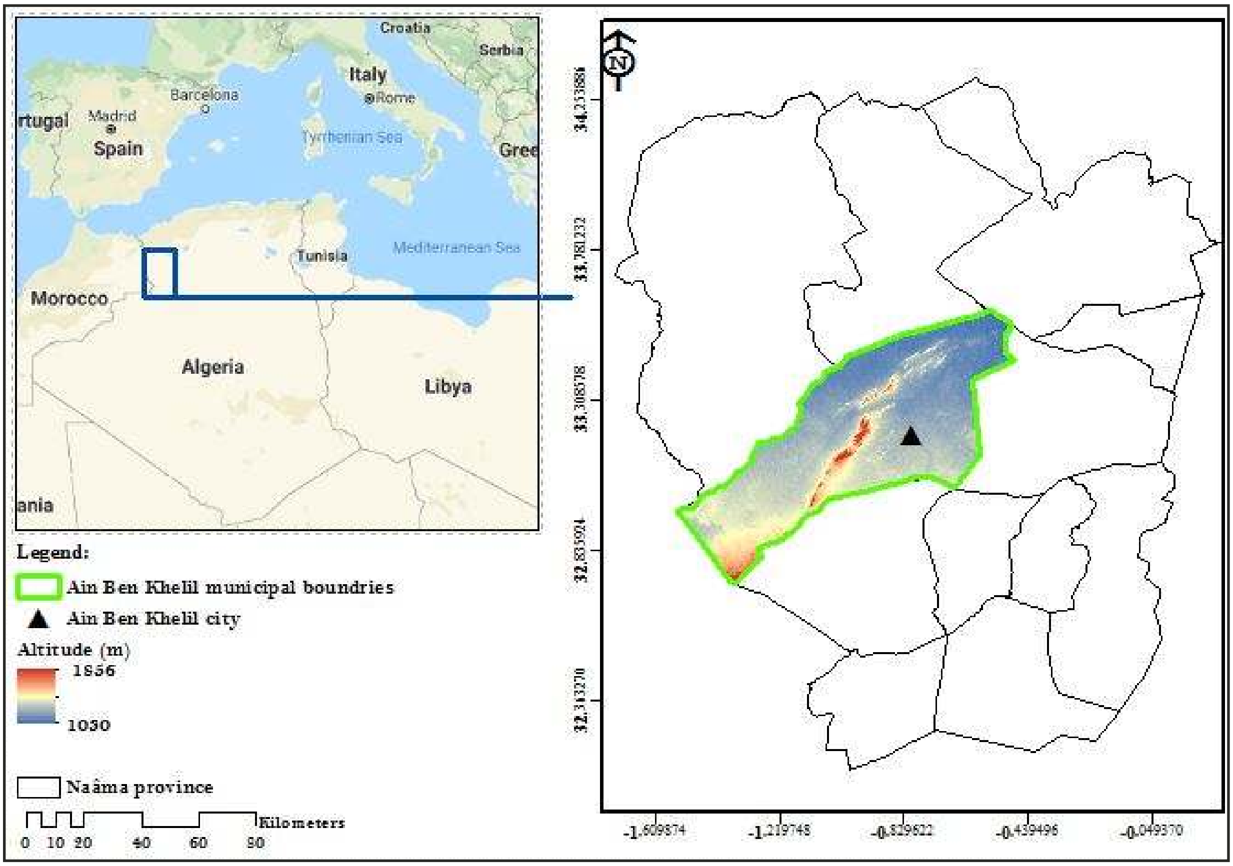

Fig. 1: Geographical location of the study area

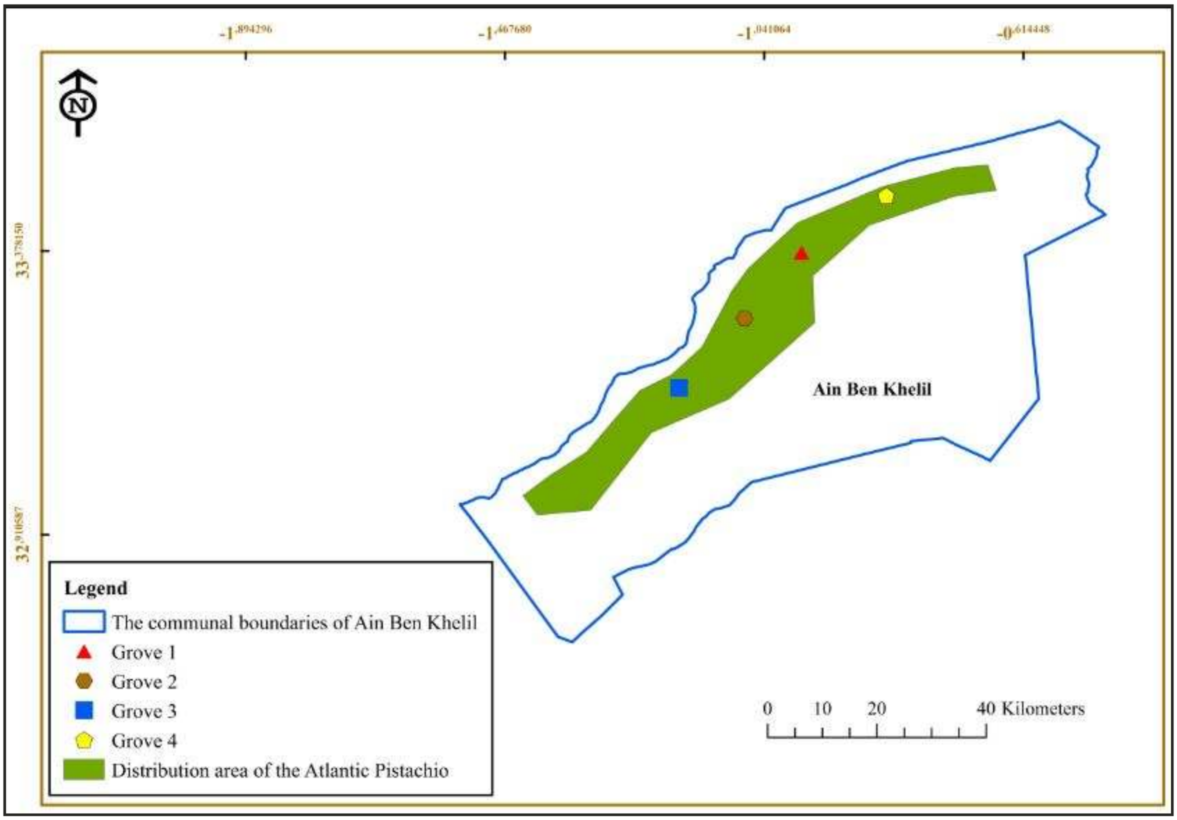

Fig. 2: Location of the studied groves

In order to characterize the floristic diversity of Atlantic Pistachio, 20 surveys of 100 m^2 were made at the rate of 5 surveys per groves. The species were identified according to the new flora of Algeria and the southern desert regions (Quézel and Santa, 1962-1963), the flora of North Africa (Maire, 1952-1987), Flora and vegetation of the Sahara (Ozenda, 2004) and the practical flora of Morocco, volume 3 (Fennane *et al*., 2014).

Different statistical methods make it possible to analyze data tables (quantitative and qualitative) and to look for possible links between variables. Among these last AHC (Ascending Hierarchical Classification) and FAC (Factorial Analysis of Correspondence) were used. These techniques are recommended by many authors (Guinochet, 1973; Boraud, 2000; Lebreton and Le Bourgeois, 2005; Touré, 2010; Meddour, 2011).

Results and Discussion

Diameter distribution of the Atlantic Pistachio

In any forest management, the determination of the structure and the way in which trees are distributed according to their diameters at 1.30 m is essential in forest planning. The total diameter distribution, or distribution of stems by diameter classes, is established taking into account all inventoried individuals (Roullet, 1974; Gaudin, 1996).

Given the high number of trees measured, represented by 361 trees, the grouping of trees by diametric classes is a very relevant choice (Table 1). The established classes are distributed as follows:

Ø <7.5 cm: Perchs (PER)

7,5 <Ø <22,5 cm: Small wood (SW)

22.5 <Ø <42.5 cm: Medium wood (MW)

42.5 <Ø <62.5 cm: Big wood (BW)

> 62.5 cm: Very big wood (VBW)

Trees with diameters up to 22.5 cm are considered natural regeneration (perch and small wood).

The overall analysis of the diameter distribution (Fig. 3) of the four groves highlighted a clear dominance of the very big wood category in groves 2 and 3 with respectively 66.7% and 75.7%. This category of diameter represents 36.7% in the grove 1 and 25.4% in the grove 4. In general, we are in presence of an old stand because the number of trees with diameters greater than 42.5 cm, namely big wood and very big woods, represents 62% of the stand. This irregular distribution is defined by a heterogeneous aspect of the dimensions of the trees. This heterogeneity can also be characterized by a majority of trees in one or two categories of diameter. The density parameters remain largely variable from one class to another.

Table 1: Number of stems per diameter category and per grove

Diameter class	Perchs	Small wood	Medium wood	Big wood	Very big wood	Total	Area (Ha)
Number of stems (Grove 1)	4	8	17	9	22	60	7,33
Number of stems (Grove 2)	6	0	8	10	48	72	10,74
Number of stems (Grove 3)	14	6	2	5	84	111	10,91
Number of stems (Grove 4)	28	20	24	16	30	118	36,46
General total						**361**	

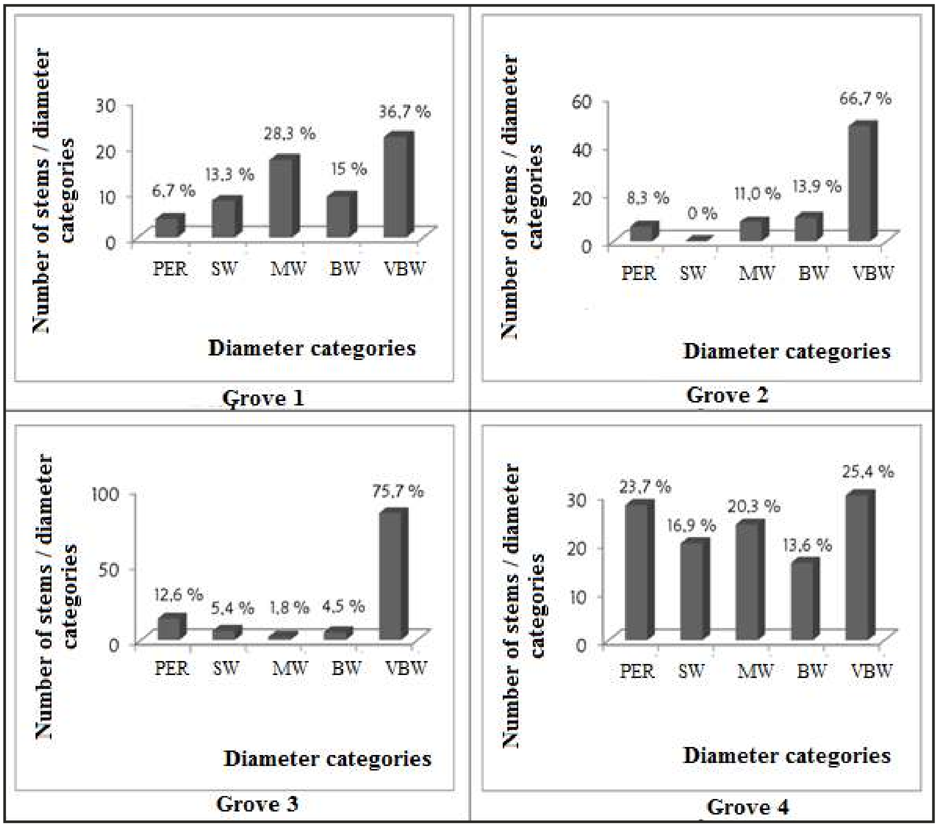

Fig. 3: Diameter distribution of Atlantic Pistachio tree in the four studied groves

Atlantic Pistachio regeneration "Nursing plant effect"

We found that all regenerated feet grew inside the *Zizuphus lotus* (Fig.4). The estimated natural regeneration rate (sum of perch and small wood) is low in groves 1, 2 and 3 with 6.7%, 8.3% and 12.6%. However, the grove 4 has a high regeneration rate of around 23.7%.

The seeds disseminated by the wind in the Jujube (*Zizuphus lotus*) find a favorable habitat to germinate (nursing plant effect). Monjauze (1980), reports that "the Jujube tree is the mother of Pistachio" which attests the protective nature jujube to the local flora. In addition, the soil where the leaves of *Zizuphus lotus* fall would become acidic and facilitate the germination of Atlantic Pistachio seeds. This natural phenomenon is primordial element of reconstitution of Atlantic Pistachio stands.

The growth and development of Atlantic Pistachio is at the expense of Jujube. When the Pistachio reaches certain dimensions, the Jujube tree dies (Fig.5).

We still report the presence of a large number of female subjects (61%). These female subjects ensure seed production and the sustainability of this native species. This shows that our study area can be a favorable site for the development of Atlantic Pistachio, in condition that Forest Service and High Commission for the Development of Steppe (HCDS) should control overgrazing.

Vertical distribution of the Atlantic Pistachier

The vertical structure represents the distribution of individuals by height class; it provides an indicator of site richness (Letreuch-Belarouci, 2009).

The tree sample heights (Table 2) in the 4 groves are grouped according to their diametric classes already requested above.

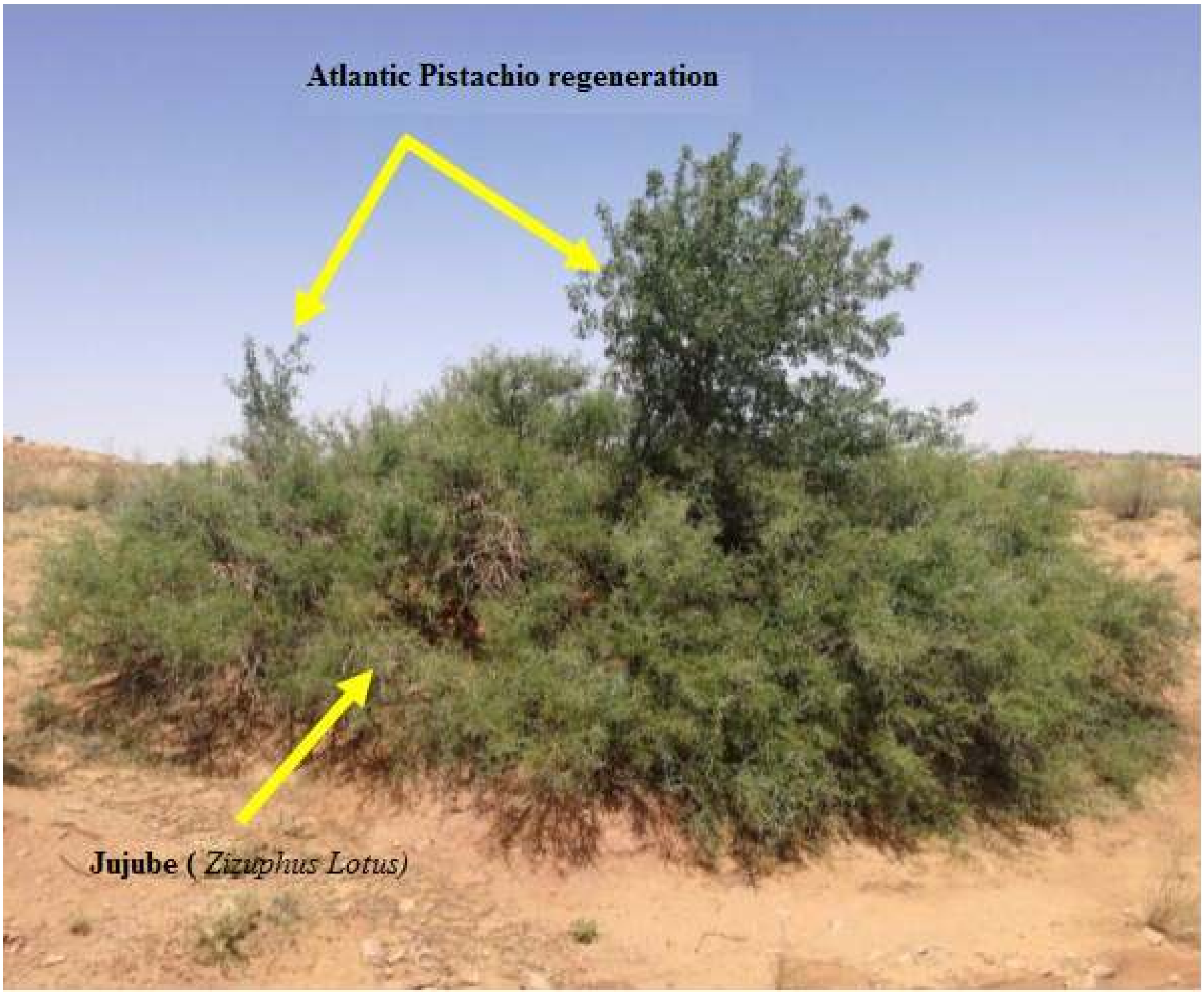

Fig. 4: Natural regeneration of Atlantic Pistachio inside Jujube tree

(a) Atlantic Pistachio regeneration (b) Begining disappearance of Jujube (c) Final disappearance of Jujube

Fig. 5: Atlantic Pistachio growth at the expense of Jujube tree

The average height (Fig. 6) of the stand varies from 2.10 m to 15.20 m. The average value for all the groves is 7.20 m. Behind these variations between diameter classes hides a real difference in vertical structure.

Atlantic Pistachio floristic richness

The inventory of the accompanying Atlantic Pistachio vegetation in the studied groves shows the presence of the following strata

Table 2: Average height by diameter class

Diameter class	Average height (m) (Grove 1)	Average height (m) (Grove 2)	Average height (m) (Grove 3)	Average height (m) (Grove 4)
Perchs	2,40	2,30	2,10	2,60
Small wood	6,90	0	2,31	5,20
Medium wood	7,70	6,80	7,5	7,40
Big wood	9,60	9,20	7,80	8,40
Very big wood	15,20	15,10	12,40	12,20

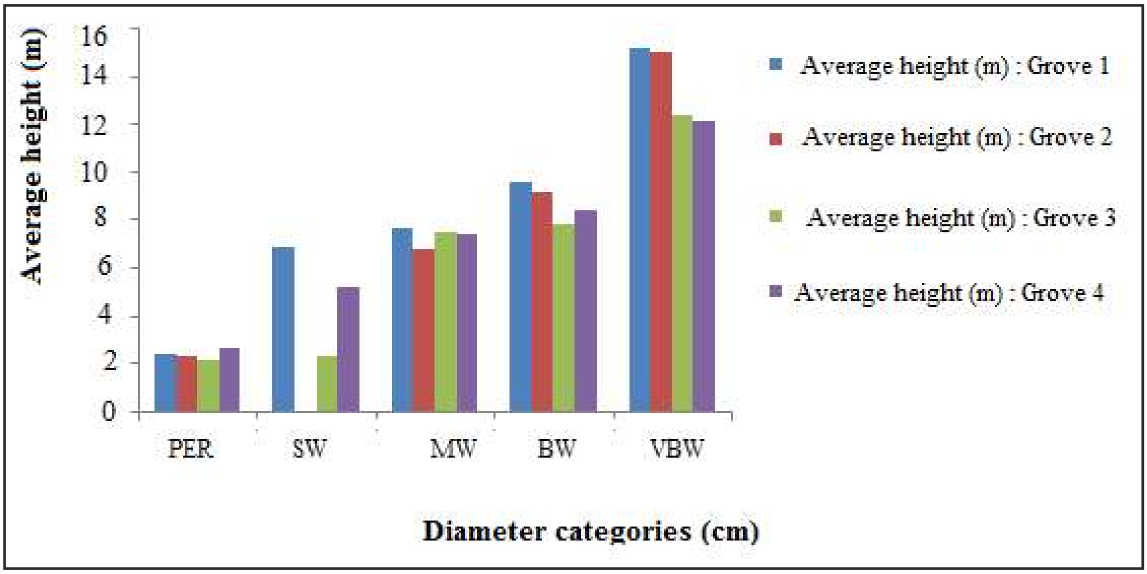

Fig. 6: Vertical distribution of Atlantic Pistachio tree in the four studied groves

Tree strata: *Pistacia alantica*

Shrub strata: *Ziziphus lotus*

Herb strata: *Pistacia alantica, Ziziphus lotus, Aristida pungens, Peganum harmala, Salsola vermiculata, Adonis dentata, Hordeum murinum, Herniaria fontanesii, Cutandia divaricata, Astragalus tenuifoluis, Malva lavatera, Marrubium deserti, Micropus bombycinus, Onopordon acaule, Atractylis humilis, Atractylis serratoides, Thymelea microphylla, Stipa tenacissima, Lygeum spartum* L, *Citrullus colocynthis* (L.) Lugwig*. Noaea mucronata.*

Ascending Hierarchical Classification (AHC)

The ascending hierarchical classification (AHC) allowed us to distinguish 03 groups that are well individualized (Fig.7).

Group A

Pistacia alantica; Ziziphus lotus; Atractylis serratoides; Peganum harmala; Salsola vermiculata; Thymelea microphylla; Atractylis humilis; Marrubium deserti.

This group contains sylvatic species, reflecting a good soil structure.

Group B

Aristida pungens; Stipa tenacissima; Lygeum spartum; Citrullus colocynthis; Hordeum murinum; Astragalus tenuifolius; Noaea mucronata.

This group is of major floristic importance because it includes characteristic steppe species

Group C

Adonis dentata Malva lavatera, Herniaria fontanesii ; Micropus bombycinus ; Cutandia divaricata ; Onopordon acaule.

This group is characterized by the presence of cosmopolitan species.

Factorial Correspondence Analysis (FCA)

Ecological significance of the axis

Factorial plan 2/1

A large number of xerophytic species settle on the negative side of axis 1, they are: *Astragalus tenuifolius, Malva aegyptiaca, Herniaria fontanesii, Citrullus colocynthis*. The prolonged periods of scarcity impose a strong evapotranspiration on vegetation and reshape the landscape with the installation of xerophilic vegetation.

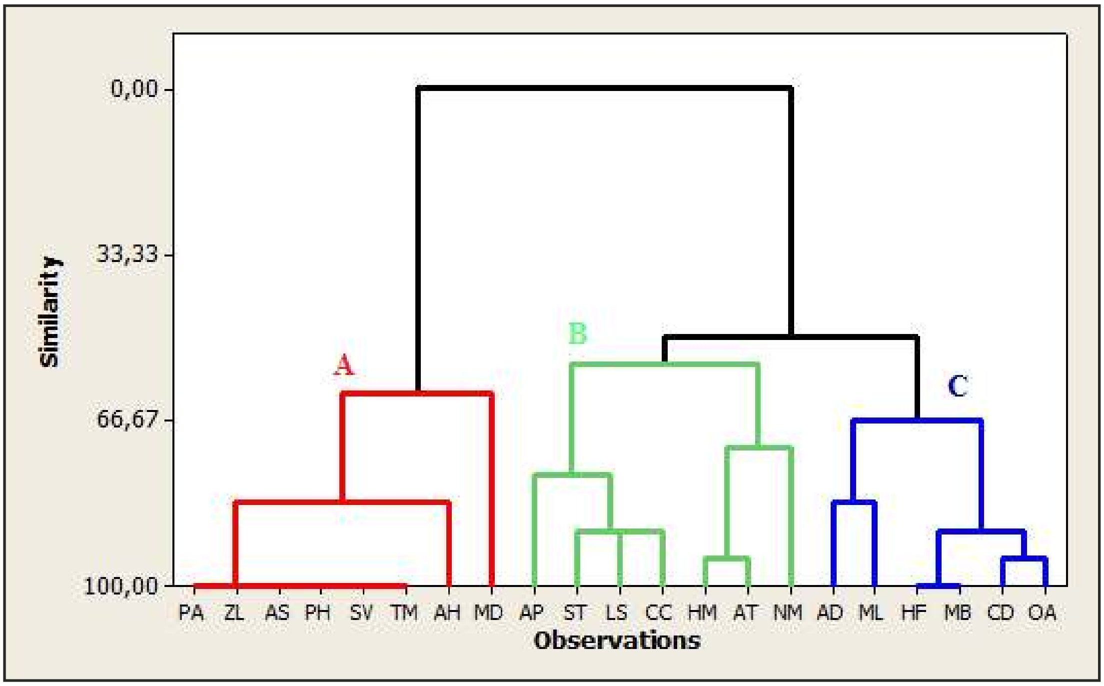

Fig. 7: Atlantic Pistachio floristic richness dendrogram in the study area

Negative side of axis 1		Positive side of axis 1	
Astragalus tenuifolius	-0,50134	*Pistacia alantica*	1,31975
Hordeum murinum	-0,63872	*Marrubium deserti*	0,92779
Aristida pungens	-0,72662	*Atractylis humilis*	0,98923
Noaea mucronata	-0,89148	*Ziziphus lotus*	1,31975
Citrullus colocynthis	-0,99505	*Atractylis serratoides*	1,31975
Stipa tenacissima	-0,8582	*Salsola vermiculata*	1,31975
Lygeum spartum	-0,82767	*Thymelea microphylla*	1,31975
Adonis dentata	-1,00354	*Peganum harmala*	1,31975
Malva aegyptiaca	-0,70586		
Onopordon acaule	-0,69651		
Cutandia divaricata	-0,60378		
Herniaria fontanesii	-0,69336		
Micropus bombycinus	-0,69336		

Factorial plan 2/2

Negative side of axis 2		Positive side of axis 2	
Lygeum spartum	-0,25831	*Astragalus tenuifolius*	1,83196
Adonis dentata	-0,54886	*Hordeum murinum*	1,63144
Malva aegyptiaca	-0,65954	*Aristida pungens*	1,21426
Onopordon acaule	-0,98273	*Noaea mucronata*	0,89217
Cutandia divaricata	-1,44581	*Citrullus colocynthis*	0,73994
Micropus bombycinus	-1,42012	*Stipa tenacissima*	0,20493
Herniaria fontanesii	-1,42012	*Marrubium deserti*	1,68306
Atractylis humilis	-0,48923		
Ziziphus lotus	-0,16217		
Pistacia alantica	-0,16217		
Peganum harmala	-0,16217		
Thymelea microphylla	-0,16217		
Atractylis serratoides	-0,16217		
Salsola vermiculata	-0,16217		

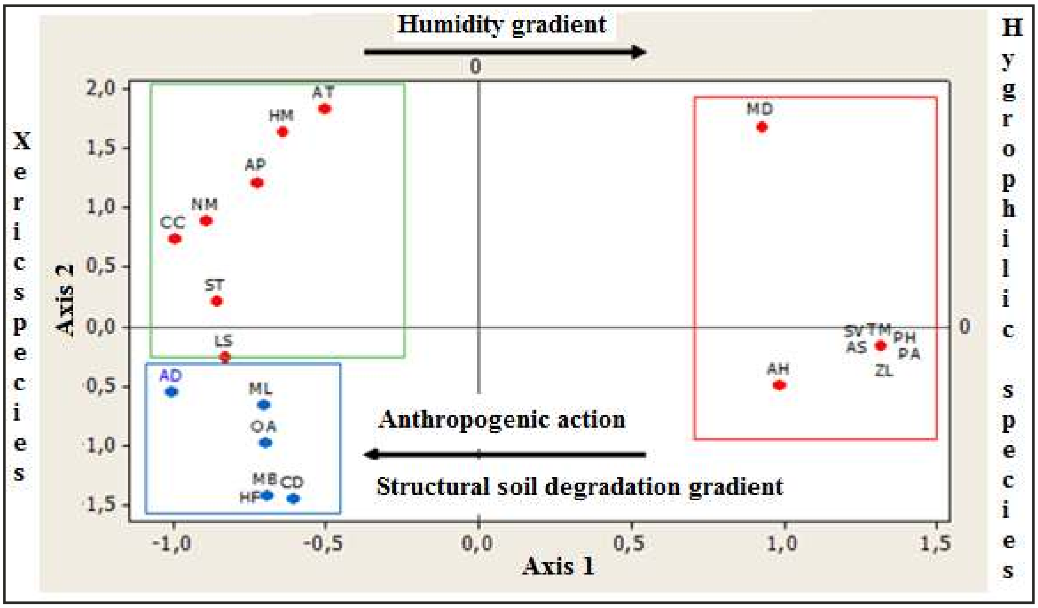

Fig. 8: Species factorial plan in the study area (axis 1 and axis 2)

The positive side represents the majority of species associated with Atlantic Pistachio. These taxa that grow on moist soils have a strong contribution to the factorial plane.

This analysis (Fig. 8) allowed us to highlight the influence of different environmental parameters on the floristic composition of *Pistacia atlantica* and to analyze the interrelations that may exist between species and environmental factors. This approach was possible for the first two axes, whose knowledge of the ecology of the taxa, the most contributory, allowed the demonstration of relevant ecological gradients involved in the structuring of the plant species of the study area. We were able to highlight the following gradients:

- Humidity
- Anthropogenic action
- Structural soil degradation

Conclusion

In the light of the results obtained, we find that the Atlantic Pistachio stands in the Ain Ben Khelil region are characterized by the dominance of very large and large wood, which indicates the state of aging of these stands. From an ecological point of view, the species is mainly accompanied by thermophilic and xerophilic taxa.

The Atlas Pistachio is an essential species for maintaining and restoring soil fertility, the floristic diversity of marginal lands and the softening of microclimates in the steppe region of Ain Ben Khelil.

Overgrazing is the main factor limiting the natural regeneration of Atlantic Pistachio in the region, in addition to climatic hazards that negatively affect germination.

We underline that the studied groves were selected by FAO (United Nations Organization for Food and Agriculture) for the rehabilitation of the Atlantic Pistachio in the region of Ain Ben Khelil.

इन बेन खलिल क्षेत्र (दक्षिण पश्चिम अल्जीरिया) में *एटलस पिस्टेचिओ* (*पिस्टेसिया अटलांटिका डीस्फ*) स्टैण्डों का इकोडेन्ड्रोमेट्रिक अभिलक्षण

गुरीन लखदर और हदिजएदज कोइदर

सारांश

अटलांटिक पिस्टेचिओं (*पिस्टेसिया अटलांटिका डीस्फ*) वन के शुष्क तथा अर्ध शुष्क क्षेत्रों में एक बहुमूल्य पुरोगामी प्रजाति विरासत है, इसे पारिस्थितिकीय और सामाजिक दोनों मानों के लिए उच्च घास के मैदानों में सबसे मौलिक और उल्लेखनीय प्रजाति के रूप में वर्णित किया गया है। इन बेन खलिल क्षेत्र में इस प्रजाति के इकोडेन्ड्रोमेट्रिक अभिलक्षण के परिणाम ने बड़े और बहुत बड़े काष्ठों, जो अध्ययन की गई आबादी के करीब 62% है, की प्रधानता को दर्शाया। अटलांटिक पिस्टेचिओं का प्राकृतिक पुनर्जनन नर्स पादप प्रभाव (*जूजूबी–अटलांटिका पिस्टेचिओं*) से घनिष्ठ रूप से सम्बद्ध है। अभिलिखित दरें क्रमशः 6.7% (ग्रोव 1), 8.3% (ग्रोव 2), 12.6% (ग्रोव 3) और चौथे ग्रोव के लिए 23.7% है। अटलांटिक पिस्टोचिओं की पादपी विविधता को तीन संस्तरों, यथा– वृक्ष संस्तर, झाड़ी संस्तर और शाक संस्तर द्वारा लक्षण वर्णन किया गया है, जिसमें महत्वपूर्ण पादपी समृद्धता है।

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The estimation of dendrometric characteristics of cork oak crown: a tool for sustainable management of Hafir forest (western Algeria)

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ABSTRACT

The study of the descriptive parameters of the cork oak crown in Hafir forest (western Algeria) was carried out on 14 sample plots of 10 ares. Projection area, diameter, volume, maximum area, vital spacing quotient, crown competition factor, and ideal density were determined for each plot. The results obtained show that the studied settlements were composed mainly of small wood whose diameter varies between 7.5 and 22.5 cm. The cork oak crown is characterized by a diameter ranging from 1.85 m to 5.08 m, a projection surface ranging between 4.77 m^2 and 35.28 m^2, a volume of 3.50 m^3 to 45.08 m3 and a maximum surface ranging from 4.48 m^2 to 32.88 m^2. Plots 7, 11 and 12 represent respectively 37%, 36% and 40% span scales, which results in a very strong competition between crowns. The ideal densities calculated for plots 1, 2, 3, 4, 5, 6, 8, 9, 10, 13 and 14 are higher than the current densities, so it is essential to practice reforestation operations. The opposite case is recorded for plots 7, 11 and 12 which have an excess of stems, hence the interest of starting thinning work.

INTRODUCTION

The cork oak is a species of the western Mediterranean and Atlantic sides. It is found spontaneously on the western perimeter of the Mediterranean from the Strait of Messina to Gibraltar: Sicily, Italian Peninsula, Sardinia, Corsica, France (Alpes-Maritimes, Var and Eastern Pyrenees), Spain (Catalonia, Andalusia) and along the Mediterranean coast of North Africa. In addition, the most extensive stands are located in Algeria and Tunisia (Saccardy 1938; Quezel and Medail 2003). The cork oak, calcifuge species, it structures an original ecosystem, recognized of community interest by the "European directive habitat" (Amandier 2006). The forest formations of the Algerian cork oak extend over all the north of the country between the littoral in the north and the telliens chains in the south. In 2008, the area of cork oak stands is estimated at 357,582 ha (D.G.F 2008; Bouchaour-Djabeur and al. 2011; Bouchaour-Djabeur 2013). Actually this area is under constant threat mainly related topests, fire, illegal grazing and woody cuts.In western Algeria, the area occupied by cork oak forests was estimated at 9,400 ha (Thinton 1948), but in 2003 this zone was regressed at only 6,500 ha (Bouhraoua 2003).

In addition to the factors contributing to the regression of cork oak forests, the occupation of airspace can be considered as a factor limiting the growth of this species. An effect exerted on cork oak by the associated shrubs and trees has an action that results to space competition. In this context, we are interested to estimate the dendrometric characteristics of the cork oak crown in order to evaluate the air competition between crowns and to provide the best densities for a balanced airspace in the Hafir forest located in Tlemcen national park in western Algeria.

MATERIALS AND METHODS

Study area

Hafir forest covers an area of 9872 ha; it is an essential part of Tlemcen national park in western Algeria (Figure1). The forest rests on a massif dating from the upper Jurassic, mainly composed of sequanian sandstones and quaternary alluvial deposits (Letreuch-Belarouci 2009). This forest massif is located at an altitude ranging from 1000

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to 1418 m (T.N.P 2000). The slopes vary from 12,5 to 25 % (Gaouar 1998; Letreuch-Belarouci and al. 2010). The hydrographic network is relatively dense but characterized by low flow (Otmani 2013). The climate is Mediterranean, marked by its summer drought which manifests itself as early as June. Annual rainfall ranges from 650 mm to 1000 mm (Medjahdi 2010).

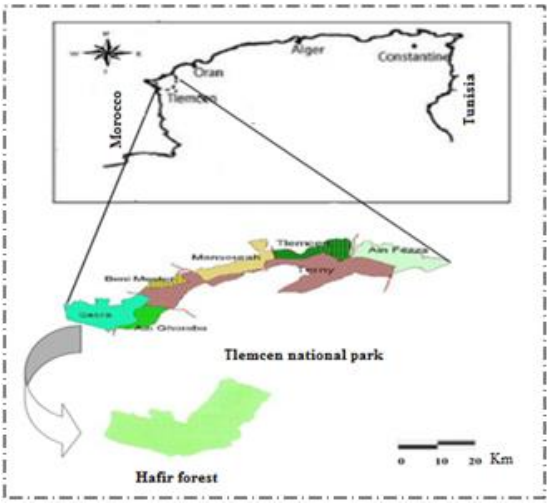

Figure 1 .Geographical situation of Hafir forest

The forest massif of Hafir as a whole offers a quite remarkable floristic diversity, directly related to the climate, soil and terrain conditions (Bouchaour-Djabeur 2001). It is mainly composed by *Quercus suber* on siliceous substratum, sometimes associated with *Quercus ilex*, while *Quercus faginea* is found in ravines (Valbuena and al. 2014; Letreuch-Belarouci et al. 2009; Mahboubi 1995). The shrub layer is composed by *Arbutus unedo*, *Erica arborea*, *Phyllarea angustifolia*, *Crataegus oxycantha*, *Juniperus oxycedrus*, *Rosa canina*, *Genista tricuspidata*, *Calycotome spinosa*, *Cistus monspeliensis*, *Chamerops humilis ...* (Belgherbi and al. 2015).

Fieldwork

Random sampling that takes into account the variability of cork oak stands has been carried out in a few cantons that make up the Hafir forest. The experimental plan we have put in place involves the following steps:

- Installation of circular plots of 10 ares of surfaces, and 17.84 m of radius.

- Measurement of total height and diameter at 1.30 m of all trees in the plot.

- Horizontal projection of the crowns which consists according to Parde and Bouchon (1988) and Rondeux (1993) to locate a point most often close to the foot of the tree, on the side where the summit with the greatest amplitude, this point will be considered as radiation center. The radii should then be measured in cardinal directions (Figure 2).

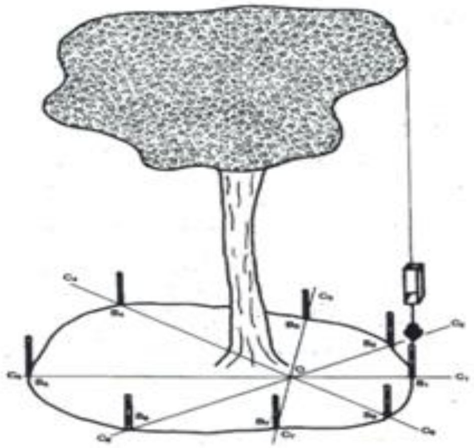

Figure 2. Principle of horizontal projection of the crown

Data analysis

After compiling the field data on a total of 348 cork oaks trees, calculation of dendrometric parameters relating to competition between crowns was carried out according to Rondeux, 1993 (Table 1):

Table 1. The calculated dendrometric parameters and their formulas.

Dendrometric parameters	Formula
Crown projection area	$Sp = \pi . \sum_{i=1}^{n} ri^2 / n$
Crown diameter	$dh_0 = \sqrt{\frac{4}{\pi} \bullet sp}$
Crown Volume	$Vh_0 = \frac{1}{6} \bullet \pi \bullet dn_0^3 / 2$
Vital spacing quotient	$TAR = \sum_{i=1}^{N} (Sp)$
Maximum crown area	$MCA = \frac{\pi(a_0 + a_1 d_i)^2}{4}$
Competition factor crowns	$FCC = \frac{1}{S} \bullet (\sum_{i=1}^{n} MCA_i) \bullet 100$
Ideal density of cork oak: It is commonly accepted that the optimal recovery of cork oak stands is 50 to 60% (ODARC 2002). The calculation of the ideal density Di for a cover of 50% obeys the following relation	$Di = 5000 / Sm$ $Di = (5000x4)/(3{,}14xdh^2)$

RESULTS AND DISCUSSION

Diameter structure of cork oak trees

Given the high number of trees sampled (348 trees), the cork oak was grouped into 5 diametric classes (Figure 3):

Ø <7.5 cm: Perchs (PER).

7.5 < Ø < 22.5 cm: Small woods (SW)

22.5 < Ø < 42.5 cm: Medium woods (MW)

42.5 < Ø < 67.5 cm: Big woods (BW)

> 62.5 cm: Very big woods (VBW)

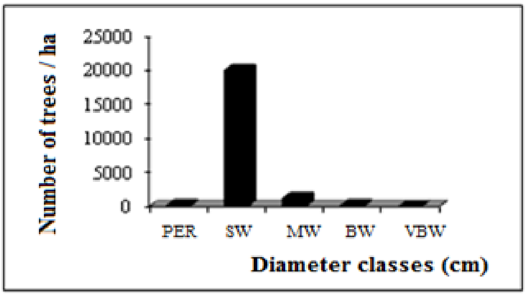

Figure 3. Diametric structure of cork oak in Hafir forest.

It appears clearly (Figure 3), that the studied stand is young, since the majority of this stand is composed by small woods. This structure results from post fire consequence, it produces for the moment very little reproduction cork. Regeneration by stump reject is ubiquitous in Hafir forest, this is largely due to the passage of fire. However, it seems difficult to rely solely on stump rejects to guarantee the regeneration of this forest (Letreuch-Belarouci and al. 2010). The ability of the species to reject strains decreases with age. Regeneration by stump reject is only a palliative; the maintenance of this forest will be ensured only by the assisted regeneration (Belghazi and al. 2001).

Vertical structure of cork oak trees

Figure 4 revealed the dominance of the heights of the first, second and third classes. The fourth class is moderately represented, while the fifth and sixth classes are composed of a relatively low number of trees.

Description of the dendrometric characteristics of the crown

The descriptive parameters of the calculated cork oak crown constitute a basic model established specifically for our forest. The results obtained highlight (Table 2):

- Crown diameter ranging from 1.85 m to 5.08 m

- Crown projection area oscillating between 4.77 m2 and 35.28 m^2

- Crown volume ranging from 3.50 m3 to 45.08 m^3

- Maximum crown area ranging from 4.48 m2 to 32.88 m^2

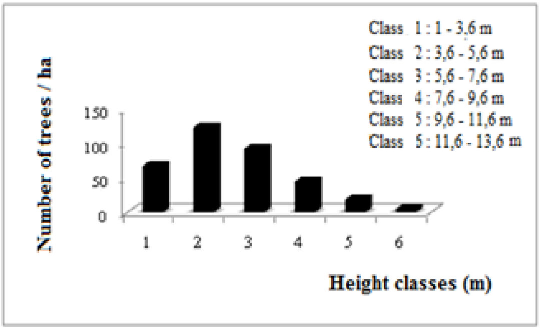

Figure 4. Vertical structure of cork oak in Hafir forest

The span degree of crown that corresponds to the ratio expressed as a percentage between the crown diameter and the total height of the tree, is an effective parameter for measuring stem competition (Lemaire 2010). The author estimates that the aerial competition between cork oak is very high when the diameter of their crown is less than one third of their total height. The optimum is to maintain a large crown whose crown diameter is half the total height, which means 50% crown span.

Table 2. Descriptive parameters of 6 cork oak in Hafir forest (average values)

Plots	Ht (m)	d_{h0} (m)	d_{h0}/ Ht (%)	S_p (m^2)	V_{h0} (m^3)	MCA (m^2)
1	6.35	4.58	72	20.14	42.23	15.06
2	5.07	3.60	70	17.38	21.86	11.47
3	4.32	3.92	90	13.93	23.20	12.97
4	4.15	3.15	75	9,75	15.03	8.26
5	5.37	3.54	65	10.94	16.39	9.39
6	3.85	2.35	61	4.77	4.39	4.48
7	5.15	1.85	37	32.98	21.42	11.83
8	4.52	2.96	65	8.31	3.50	7.26
9	5.2	3.8	73	16.68	33.82	15.73
10	7.46	5.07	68	22.59	45.08	21.78
11	7.63	2.82	36	35.28	25.89	25.67
12	6.75	2.75	40	33.82	44.20	32.88
13	4.90	3.75	76	13.95	24.36	11.16
14	7.14	5.08	71	22.04	43.96	20.77

In our case, we find that the competition between cork oak crowns is practically very high in plots 7, 11 and 12 which respectively represent a span degree of crown of 37%, 36% and 40%. The trees of the other plots are developing without competition.

Vital spacing Quotient and Crown Competition Factor

Plots 1, 2, 3, 5, 6, 9, 10, 13 and 14 have a crown competition factor approaching to100 (Table 3). These trees are developing without much competition and have reached the stage of complete closure of the canopy (medium and big wood). We believe that cork oak seedlings need sufficient light forest ablishment and growth. This assumes that crown cover competition is moderate and that cover is open or clear. These results are consistent with those reported by Letreuch-Belaruci (2002). Thus these plots are most likely in the near future to a progressive competition and to a very limited natural regeneration if the stand is allowed natural grow.

Table 3. Vital spacing Quotient and Crown Competition Factor

Plots	TAR	FCC %
1	0.94	84
2	1.04	79
3	0.92	77
4	0.95	71
5	0.96	81
6	0.98	64
7	0.93	115
8	1,13	65
9	1,12	93
10	0,91	95
11	1,07	122
12	0,95	105
13	1,11	93
14	1,08	97

Strong crown competition was found in plots 7, 11 and 12 with present a crown competition factor exceeding 100.

Table 4. Determination of ideal density in Hafir forest

Plots	S_m	Ideal density (cover of 50%)	Current density	Surplus /Deficit	% Preserve / thinning
1	20.14	248	140	-108	100
2	12.56	398	270	-128	100
3	13.94	358	160	-198	100
4	9.76	512	250	-262	100
5	10.95	456	350	-106	100
6	4.77	1048	120	-928	100
7	14.36	348	480	+132	73
8	8.31	609	330	-279	100
9	16.7	299	260	-39	100
10	22.59	221	200	-21	100
11	35.15	142	290	+148	49
12	33.8	148	180	+32	82
13	13.70	365	330	-35	100
14	19.62	255	180	-75	100

Ideal density of cork oak in Hafir forest

Table 4 demonstrated the percentage of trees to be conserved and / or possibly to be thinning in the silvicultural management of the forest.

As an example (Figure5), for plot 7, it seems to us imperative in theory to conserve 73% of the standing trees and to thinning the 132 trees in excess. The same statement is made for the plots 11 and 12.

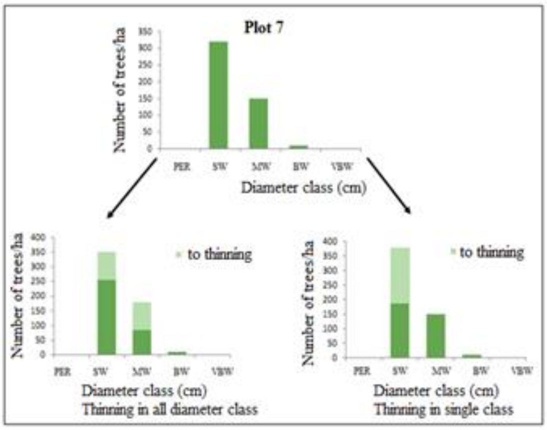

Figure 5. Options for thinning excess trees

Moreover, for the rest of the plots namely 1, 2, 3, 4, 5, 6, 8, 9, 10, 13 and 14, it is obvious that the stand is in deficit of stems. It is essential then to practice artificial plantations or assisted regeneration in clearings spaces.

CONCLUSIONS

The results obtained in this study confirmed the effect of crown competition on cork oak growth in Hafir forest. The tool set up through the crown tables contains all the criteria for estimating or predicting the density or vital space ideal for stand growth. The interest in Hafir's unmanaged forest is to have quantitative data available to determine the effect of improvement operations, including thinning on cork oak growth.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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To
Lecturer **GUERINE LAKHDAR**
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We hereby certify that the paper entitled "***Quantification de l'erosion hydrique sur les sols marneux des Alpes de Haute Provence (Region de la Motte du Caire), France***" (Author: Guerine Lakhdar) was published in the *Romanian Journal of Geography – Revue Roumaine de Géographie,* volume 61, no. 1, 2017.

Sincerely,

Prof. Dan Bălteanu
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back »»»

QUANTIFICATION DE L'EROSION HYDRIQUE SUR LES SOLS MARNEUX DES ALPES DE HAUTE PROVENCE (REGION DE LA MOTTE DU CAIRE), FRANCE

GUERINE LAKHDAR[*]

Key-words: Quantification, erosion, marls, TCSP, Southern French Alps, Motte du Caire, ablation, deposition.

Hydric erosion quantification on the marly soils of the Southern French Alps (la Motte du Caire region). A study on marly soils erosion quantification as undertaken in the Motte du Caire region (Southern French Alps) to quantify erosion rates on different types of marl. Measurements of ablation and deposition rates were made using a dense network of stakes covering the study area. The mean annual ablation values calculated over a period of 3 years of study were: 3.04 cm / year on Oxfordian marl, 1.67 cm / year on Bathonian marl and 1.9 cm / year on Callovian marl. The Oxfordian marl are most affected by erosion phenomena. There is a positive correlation between erosion rates and vegetation cover. The 'TCSP' model developed in this study offers a considerable advantage in identifying areas of ablation or sedimentation in order to treat and reduce erosion rates.

1. INTRODUCTION

L'érosion des terres noires est un problème à la fois dynamique et endémique en montagne méditerranéenne et en particulier dans les Alpes françaises du sud. Les terrains marneux sont exposés à de graves problèmes d'érosion qui se manifestent sous forme de ravinement et de glissement de terrain. Pour lutter contre les méfaits de l'érosion, les hommes font appel à toute une panoplie de moyens anti-érosifs (reboisements, gabionnage). L'efficacité de ces moyens nécessite un suivi permanent et d'importants moyens financiers. Dans la plupart des cas, la mauvaise connaissance du fonctionnement de l'érosion peut être l'une des causes principales d'exaspération de l'érosion. Cependant il est primordial de bien analyser le processus d'érosion, par le biais des dispositifs expérimentaux; afin d'adopter des solutions adéquates à mettre au point.

L'estimation de l'érosion implique la manipulation d'une somme considérable d'informations pour décrire l'environnement du bassin versant et l'emploi de modèles mathématiques complexes pour simuler les processus hydrologiques et sédimentologiques en jeu. Le recours aux modèles informatiques d'érosion hydrique est alors de mise. Dans le présent travail nous exposerons les résultats de notre étude sur la quantification des taux d'érosion sur différents types de marnes du bassin versant du Saignon (Fig. 1) dans les Alpes de Haute Provence.

L'érosion actuelle des marnes noires dans les Alpes du Sud est de taille. L'érosion sur les marnes est réputée comme le plus important taux d'érosion mesuré (Delannoy et Rovéra, 1996). En dépit de ce taux, les déserts de marnes et de cailloux ne sont pas un climax abiotique en Haute – Provence (Vallauri, 1997). Ils constituent uniquement le niveau ultime de la perturbation «érosion», suite à une crise climatique forte et /ou à l'action humaine. La restauration de l'environnement en montagne demeure possible et demande réflexion, effort et persévérance afin d'imiter au mieux les processus naturels dans leurs dynamique.

Les phénomènes d'érosion sur les marnes noires constituent un enjeu pour la région sur le plan hydraulique et agricole. Selon le service départemental «RTM[1]» des Alpes de haute Provence, la commune de la Motte du Caire, illustre par ailleurs très bien dans son ensemble l'étendue des

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problèmes d'érosion. L'envasement de la retenue du Saignon à vocation hydro–agricole fournit une bonne illustration des dégâts occasionnés par l'érosion sur les marnes noires. Le volume initial de la retenue est de 120000 m^3, le bassin versant est d'une surface de 360 hectares, dont 144 hectares de terrains nu. La retenue s'est envasée en 18 ans, le barrage n'ayant pu être utilisé pour l'irrigation que 5 ans (1964 à 1669).

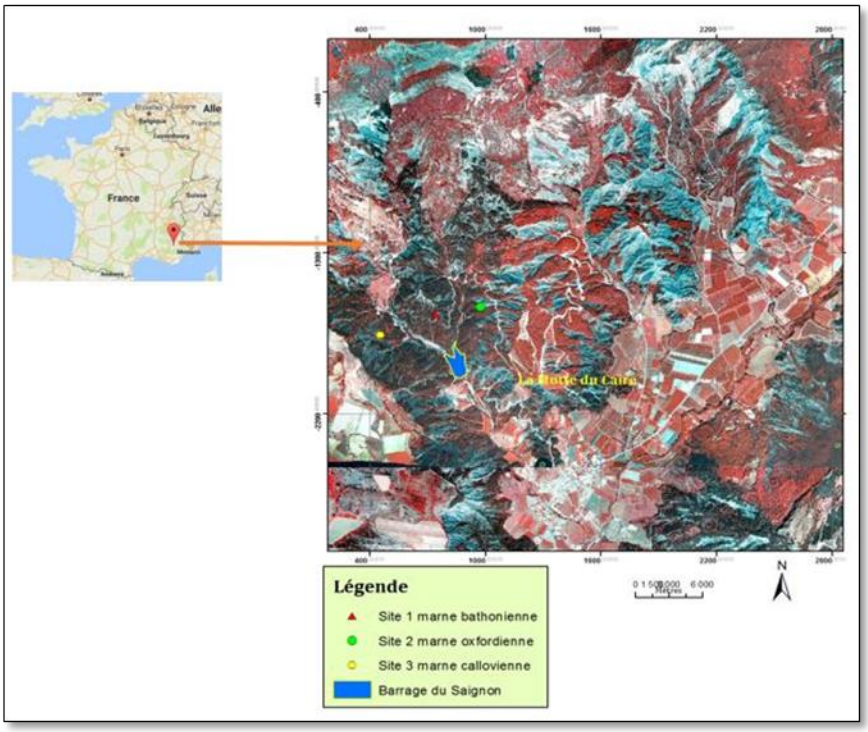

Fig. 1 – Localisation de la zone d'étude.

2. MÉTHODOLOGIE

1. Description de la zone d'étude

Une majeure partie de la Motte du Caire est constituée d'une couche épaisse de terres noires qui date du Jurassique (moyen et supérieur, Fig. 2). Ces terres noires sont consolidées par une couche calcaire tithonique qui date du Jurassique supérieur, on trouve aussi une couche de calcaires marneux appartenant au Crétacé inférieur. La région d'étude présente une succession de marnes noires épaisses de 1500 à 2000m. Ces marnes sont modérément feuilletées et assez tendres, dans la quasi – totalité des cas à patine brunâtre (Gidon *et al.*, 1991).

Les formations géologiques rencontrées dans la région d'étude se présentent comme suit:

Bathonien «moyen»: à l'Ouest de la Motte du Caire on rencontre des marnes à faciès de terres noires. Elles sont composées de fines plaquettes, l'épaisseur de ces dernières décroît vers le haut.

Bathonien supérieur: formé de plaquettes «médianes», de calcarénites rousses très bioturbées, caractérisées par l'abondance de petits bancs centimétriques. Leur épaisseur est de l'ordre de 50 à 150 m. Ils peuvent se dédoubler.

Bathonien – Callovien: cette formation est constituée de bancs de calcaire brun, d'une épaisseur décamétrique. Ils forment des bancs isolés épais de 0,2 à 0,5 m et espacés de 5 m environ. Ces bancs sont caractérisés par un calcaire brun à pâte fine et à patine jaune ocre. Ces bancs de calcaires reposent directement sur les plaquettes du Bathonien supérieur, à l'Ouest de la Motte du Caire et de la vallée de la Sasse.

Callovien inférieur: On rencontre à l'Est de la Motte du Caire et de la vallée du Sasse, la partie supérieure des plaquettes «médianes», formée de marnes qui présentent un aspect boursouflés, d'une épaisseur de 150 m.

Callovien inférieur-moyen: On constate à l'Est du transect, qui passe à l'Ouest de Melve, la Motte du Caire et la vallée du Sasse, le développement de bancs gris clair à dominance calcaire au sommet des plaquettes. Ces bancs ont une épaisseur de 10 à 30 cm espacés tous les 1 à 5 m dans les marnes.

Callovien moyen: cette formation se distingue par sa couleur brune ocre, sa richesse en plaquettes d'ordre centimétrique voire millimétrique. L'épaisseur de cette formation est de 100 m, ces plaquettes sont rares de manière progressive vers le haut comme le bas.

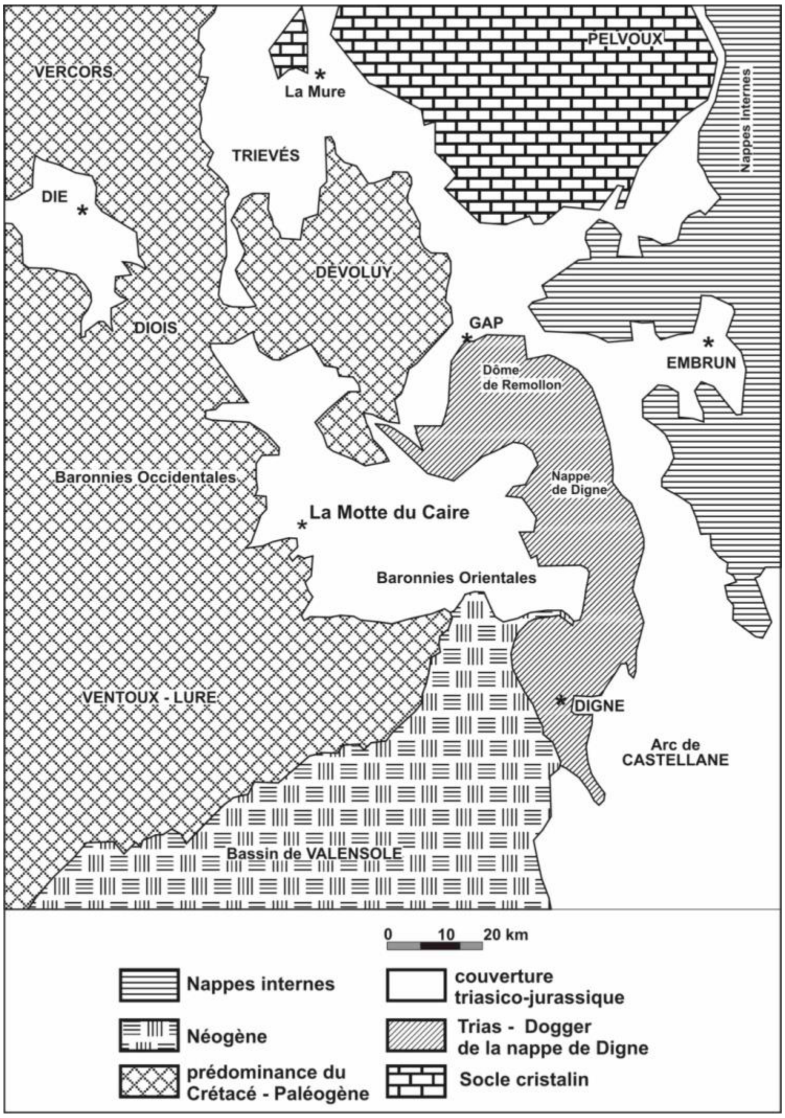

Fig. 2 – Schéma structural des Alpes externes méridionales,
d'après Guidon *et al.* (1990).

Callovien supérieur: on distingue à l'Est de la Motte du Caire, des marnes feuilletées caractérisées par l'abondance de petits amas de miches grises. Cette formation à une épaisseur de 100m, elle est relativement pauvre en fossiles.

Oxfordien inférieur: on remarque que les marnes de cette formation sont de couleur grise sombre, un peu bleutées, elles contiennent un nombre important des miches décimétriques. Ces miches sont alignées en lits espacés de 0,5 à 2 m, vers le haut des plaquettes les miches deviennent graduellement importantes. Elles ont une couleur de brique d'où leur appellation «galettes rouge».

La région d'étude est dotée d'un climat subméditerranéen, caractérisé par la concentration des pluies à l'époque froide de l'année, la coïncidence de la sécheresse avec les mois chauds qui présentent des températures élevées et contrastées. Cette région est caractérisée par une pluviométrie annuelle moyenne de l'ordre de 714,3 mm et une température moyenne mensuelle maximale de 29,6°C du mois le plus chaud. La moyenne des températures du mois le plus froid est de – 4,2°C. L'hiver thermique dure pendant 4 à 5 mois où la moyenne des températures à 7°C. Nous avons noté que l'hiver dans cette région est caractérisé par une longue période de temps ensoleillé, sec et froid avec gel la nuit et dégel en journée, entrecoupée de courtes périodes de précipitation. Dans un hiver classique on compte de 70 à 100 cycles gel – dégel (Vallauri, 1997).

2. Végétation de la zone d'étude

Après plus d'un siècle de restauration des terrains en montagnes, les marnes noires du bassin du Saignon sont aujourd'hui en majorité recouvertes de forêts composées principalement du pin noir d'Autriche (*Pinus nigra*). Quelques roubines sont encore en activité. Les marnes nues et peu colonisées représentent 13,77% de la surface du vallon. 46% de sa surface est boisée, 32% en Pin noir et 14% en feuillus (chênaie et hêtraie). Le reste de la surface est composé de terrains non érodés (pelouses et landes). On constate que la pinède de pin noir a occupé la quasi-totalité du substrat marneux, les sols se sont développés en un temps assez court.

La végétation sur les adrets est constituées d'un cortège floristique varié: *Juniperus communis, Ononis spinosa, Thymus vulgaris, Aphyllanthes monspeliensis, Calamagrostis argentea.*

3. MATERIEL ET MÉTHODE

L'objectif de ce travail est de quantifier l'érosion des sols marneux, en utilisant les données les plus précises disponibles pour la région de la Motte du Caire et en s'appuyant sur les connaissances les plus récentes des différents processus impliqués dans les phénomènes d'érosion hydrique des sols. La quantification de l'érosion devrait à la fois rendre compte de l'intensité de l'aléa et des types érosifs correspondants, afin de faire ressortir les spécificités de la région. Enfin, une autre spécificité de ce travail réside dans la **différenciation saisonnière de l'aléa** qui permet de rendre compte de la réalité du régime climatique de la région.

Cette approche saisonnière permet en outre de prendre en considération les interactions entre facteurs climatiques et occupation des sols de manière beaucoup plus précise que dans une approche annuelle et donc de mieux prendre en compte les différents types d'aléas érosifs.

3.1. Dispositif expérimental: le dispositif de mesure micrométrique

La technique de mesure adoptée pour notre travail est celle utilisée par de nombreuses équipes de recherche (Lecompte *et al.*, 1998; Coubat, 1998; Lecompte *et al.*, 1997; Robert, 1997). Une estimation de la variation de la hauteur du piquet permet donc une mesure de l'ablation ou du dépôt. Parmi les avantages de cette technique, nous pouvons citer la précision des mesures avec la jauge micrométrique, la mesure étant de l'ordre du demi-millimètre. La taille fine des piquets perturbe moins les conditions du milieu. La tête du piquet sert comme base pour la jauge qui permet d'effectuer les mesures, la tête est considérée comme une surface de référence. Pour un meilleur suivi de l'évolution du paysage à l'échelle millimétrique quatre mesures sont réalisées pour chaque piquet suivant les quatre directions cardinales. À la fin une moyenne des quatre mesures est prise. Les transects de piquets sont installés en différentes situations données par le Tableau 1.

Tableau 1

Les caractéristiques des sites d'étude.

	Zones	Taux de couverture végétale % (TC)	Pente % (S)
Site 1 Marne bathonienne	Z1	25	20
	Z2	55	25
	Z3	30	20
	Z4	25	20
Site 2 Marne oxfordienne	Z1	25	30
	Z2	25	35
	Z3	35	30
	Z4	20	35
	Z5	25	15
	Z6	30	25
Site 3 Marne callovienne	Z1	15	45
	Z2	30	30
	Z3	35	20
	Z4	20	30
	Z5	60	25

4. RÉSULTATS ET DISCUSSION

4.1. Évolution de la vitesse d'ablation selon le type de marne

Les valeurs d'ablation moyenne annuelle calculées sur une période de 3 années d'étude sont les suivantes: 1,67 cm/an sur le Bathonien, 1,9 cm/an sur le Callovien et 3,04 cm/an sur l'Oxfordien. Il s'avère que le suivi des phénomènes d'ablation et de sédimentation est plus intéressant sur une période de 3 années, car les dispositifs expérimentaux nous ont permis de cerner le phénomène d'érosion sur les terrains marneux de la commune de la Motte du Caire. Les différents taux de couverture végétale et positions topographiques sont bien représentés grâce à l'implantation de réseaux de piquets sur les différents types de marnes. Il en résulte d'ailleurs une erreur – type moins importante sur ce substrat marneux.

4.1.1. Variation de la vitesse d'ablation et de sédimentation sur marne bathoniene

Le suivi régulier des taux d'ablation et de sédimentation a mis en lumière les nombreuses difficultés pour la quantification des taux d'érosion sur ce type de substrat. Les zones Z1, Z2 et Z3 (Fig. 3) présentent des taux d'ablation important ce phénomène peut s'expliquer par les quantités de sédiments déplacées par le ruissellement de l'amont de la roubine. Nos résultats concordent avec ceux de plusieurs auteurs (Corona *et al.*, 2011; Mathys *et al.*, 2003; Rovéra *et al.*, 1999). Les mécanismes d'érosion sont dominés par le dépôt des sédiments dans les zones Z1, Z2 et Z3. La zone Z4 présente des taux d'ablation importants sur une année, il est intéressant de souligner que la concentration du ruissellement dans cette zone a engendré l'apparition de nombreuses griffures et rigoles. Les zones Z1 et Z4 enregistrent des taux d'ablation importants, ces derniers sont en nette augmentation. Nous enregistrons des valeurs moyennes annuelles d'ablation de 1,67 cm et 0,43 cm respectivement pour les zones Z1 et Z4. Nous notons que les mécanismes de sédimentation sont dominants dans les zones Z2 et Z3, ces mécanismes s'expliquent par l'importance du taux de couverture végétale et la position topographique (Gärtner, 2007).

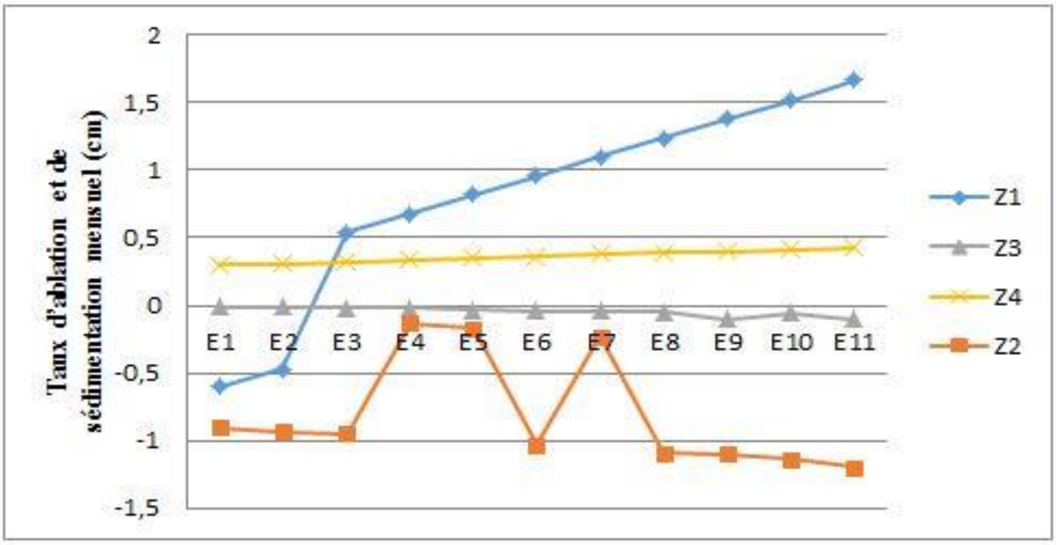

Fig. 3 – Variation de la vitesse d'ablation et de sédimentation mensuelle sur marne bathonienne.

4.1.2. Variation de la vitesse d'ablation et de sédimentation sur marne oxfordienne

Site équipé de 80 piquets pour mieux représenter les différents taux de couverture végétale et positions topographiques (Tableau 1). Les zones (Z1, Z2 et Z3) expriment des taux de sédimentation important, ceci s'explique par l'importance du couvert végétal qui joue un rôle énorme dans le piégeage des sédiments (Lecompte *et al.*, 1998) Au cours de notre étude, nous avons augmenté le nombre de piquets pour affiner les résultats de la campagne de mesure et aussi mettre en exergue le rôle de la strate herbacée comme de lutte anti – érosive.

Les zones Z4 et Z5 enregistrent des taux forts d'ablation, il est évident que les taux de couverture végétale et les positions topographique (pente) en sont responsables. Nous enregistrons la valeur de 5,3 cm pour la zone 4 caractérisée par un taux de couverture de 20% et une pente de 45%. Les zones Z1, Z2 et Z3 (Fig. 4) enregistrent des taux d'ablation important, cette tendance résulte du fait que la couche superficielle de la marne commence à se désagréger sous l'effet des facteurs climatiques tels que le gel –dégel et les précipitations (Coubat., 1998). Pour la zone Z6 dont le couvert végétal est constitué d'une strate herbacée *(Ononis spinos, Aphyllanthes monspeliensis*) la sédimentation est prédominante comme processus d'érosion. Sur 9 mois, la zone Z6 a enregistré 0,6 cm comme taux de sédimentation. La strate herbacée dissipe l'énergie des eaux de ruissellement et stabilise les sédiments transportés de l'amont de la roubine (Lecompte *et al.*, 1998; Lhenaff *et al.*, 1993).

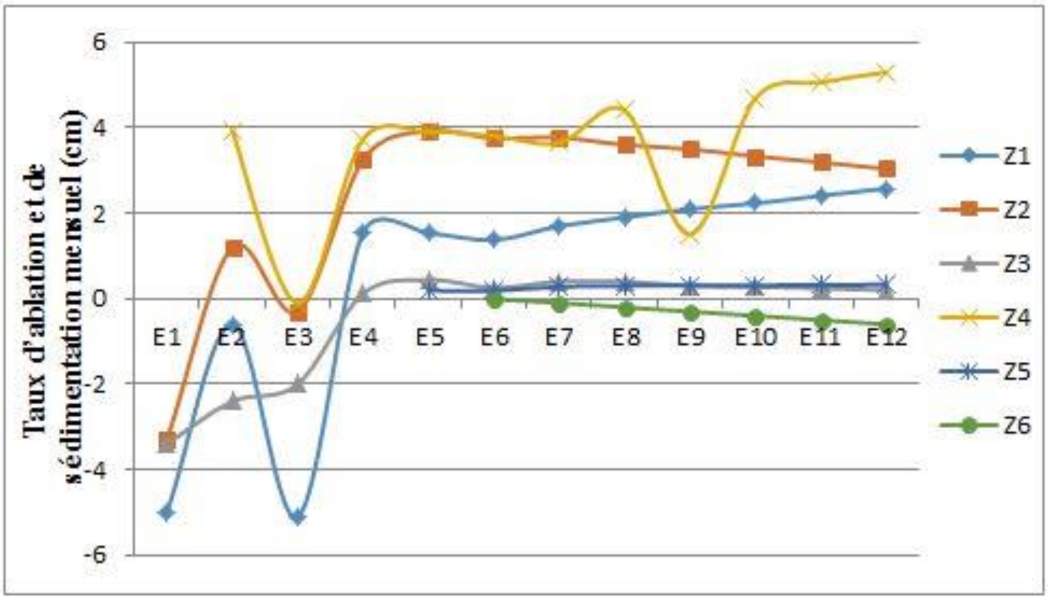

Fig. 4 – Variation de la vitesse d'ablation et de sédimentation mensuelle sur marne oxfordienne.

4.1.3. Variation de la vitesse d'ablation et de sédimentation sur marne callovienne

Les zones Z1, Z2, Z3 et Z4 enregistrent des taux d'ablation en augmentation. Une autre zone (Z5) a été équipée pour prendre en compte les différents taux de couverture végétale et positions topographiques. Pour les zones Z1, Z2, Z3 et Z4 les mécanismes d'ablation sont dominants (Fig. 5). Le taux d'ablation moyenne annuelle enregistré est de 1 cm/an. Les sédiments des zones pourvoyeuses de particules sont piégés par la strate herbacée de la zone (Z5) nous enregistrons un taux de sédimentation égale à (–3,8 cm/an).

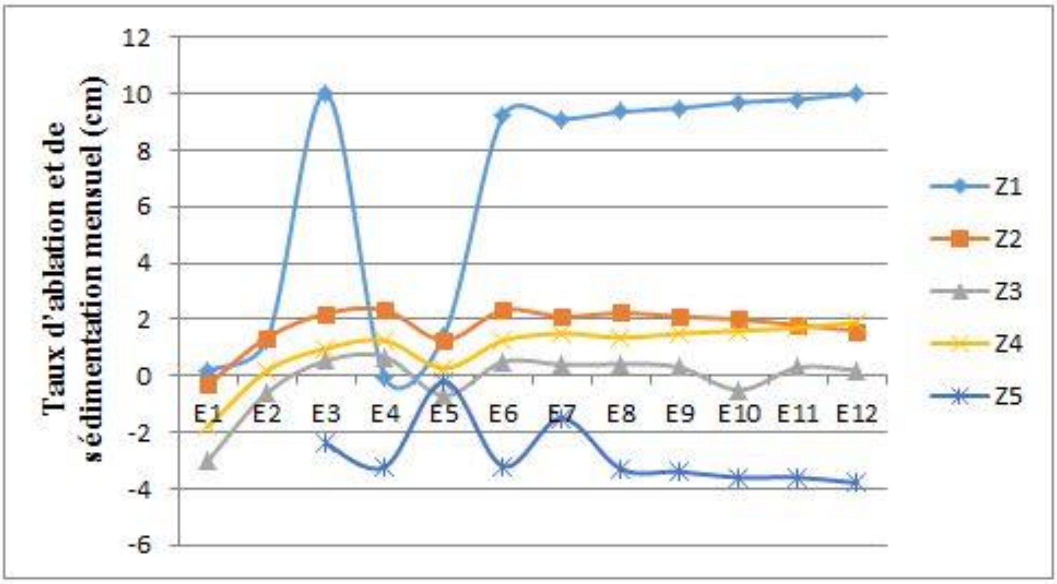

Fig. 5 – Variation de la vitesse d'ablation et de sédimentation sur marne callovienne.

4.2. Corrélation entre taux d'ablation – sédimentation et pluviométrie moyenne mensuelle

Les diverses formes d'écoulement engendrées par les précipitations jouent un rôle important dans l'ablation des marnes dans la commune de la Motte du Caire. Il est important de constater que toutes les intensités enregistrées sur une année sont susceptibles de déclencher une ablation et ou un dépôt fort et généralisé. Nos résultats rejoignent ceux de (Chodzko et Lecompte, 1992), ils notent qu'une averse de 250 mm/h durant 10mn) peut provoquer l'incision généralisée des roubines, avec l'apparition de nombreuses rigoles. Les coefficients de corrélation sont positivement significatifs (Tableaux 3, 4 et 5).

Tableau 2

Coefficient de corrélation entre taux d'ablation – sédimentation et pluviométrie moyenne mensuelle site 1.

Site1/zones	R^2 Pluviométrie- Ablation/sédimentation
Z1	0,82
Z2	0,34
Z3	0,79
Z4	0,82

Tableau 3

Coefficient de corrélation entre taux d'ablation – sédimentation et pluviométrie moyenne mensuelle site 2.

Site2/zone	R^2 Pluviométrie- Ablation/sédimentation
Z1	0,76
Z2	0,69
Z3	0,78
Z4	0,39
Z5	0,8
Z6	0,79

Tableau 4

Coefficient de corrélation entre taux d'ablation – sédimentation et pluviométrie moyenne mensuelle site 3

Site3/zone	R^2 Pluviométrie- Ab/sédimentation
Z1	0,88
Z2	0,51
Z3	0,55
Z4	0,77
Z5	0,48

Tableau 5
Coefficient de corrélation entre ablation/sédimentation, couverture végétale et pente.

Eléments de corrélation	R^2
Ablation/sédimentation vs Couverture végétale	0,67
Ablation/ sédimentation vs pente	0,75

Il est important de souligner que les intensités enregistrées par la station météorologique de la commune de la Motte du Caire sont fortement supérieures à celles citées par de nombreux auteurs. Des intensités de 5 mm/h sur sol sec et 1,7 mm/h sur sol humide peuvent déclencher un ruissellement sur les terres noires (Bufalo, 1989). Certains seuils expérimentaux sont fixés par des études (Brochot et Meunier, 1993), 12 mm sur sol sec et 5mm sur sol humide. La réponse du sol à la pluie dépend de sa teneur en eau en d'autre terme son état hydrique initial. L'état hydrique du sol, intervient dans la résistance contre l'érosion hydrique.

L'apparition du ruissellement dépend en grande partie de la teneur du sol (Collinet et Valentin, 1985; Casenave, 1989; Le Bissonnais et Le Souder, 1995). La réponse du sol à la pluie est en étroite relation avec l'humidité de la couche superficielle (Roose, 1996). Selon (Langdale *et al.*, 1975), la teneur du sol en eau réduit la dispersion des agrégats et la formation d'une croûte de battance.

Les travaux de certains auteurs ont mis en lumière l'importance de l'état hydrique initial du sol dans la résistance au ravinement et à l'incision, (Guerif, 1990; Guerine, 1998) ont mis en évidence le rôle principal de la cohésion du sol, cette dernière dépendante des caractéristiques texturales et de l'état hydrique du sol. En climat tempéré une pluie tombant sur un sol sec favorise davantage l'encroûtement superficiel et l'érosion, qu'une pluie survenant en hiver sur un sol humide (Bajracharya et Lal, 1992).

4.3. Relation entre ablation/sédimentation, couverture végétale et la pente

Les différents tests et analyses mettent en exergue les interactions existantes entre les taux d'ablation – sédimentation, la couverture végétale et la pente. L'analyse de la Figure 6 révèle des résultats intéressants: l'augmentation du couvert végétal engendre une diminution de l'érosion des marnes. L'érosion et le ruissellement sont toujours négligeables sous couvert dense, la forêt avec sa frondaison dispersée sur plusieurs étages, couvre le sol et le protège contre l'énergie des gouttes de pluie.

Parmi les facteurs qui conditionnent l'érosion, le couvert végétal est certainement le facteur le plus important puisque l'érosion passe de 1 à 1000 tonnes lorsque toutes les choses étant égales par ailleurs, le couvert végétal d'une parcelle diminue de 100% à 0% (Roose, 1994). Les résultats (Tableau 4) qu'on a obtenus de la corrélation «taux d'ablation – sédimentation et couvert végétal», présentent un coefficient de corrélation de 0,67. L'équation de la régression est de type logarithmique ceci explique l'influence de la végétation dans la diminution des taux d'érosion. Plusieurs auteurs indiquent le rôle indispensable du couvert végétal dans la lutte anti – érosive, ce rôle ne se restreint pas à la protection du sol des gouttes de pluie mais il intervient aussi dans le maintien de l'humidité du sol qui conditionne son comportement vis à vis du ruissellement (Fransen *et al.*, 2001; Weltz *et al.*, 1987; Laflen *et al.*, 1985; Mutchler *et al.*, 1982).

Nous constatons (Fig. 6) que les mécanismes d'ablation interviennent quand l'inclinaison de la pente dépasse le seuil de 20%. Au-dessous d'une inclinaison de 25% on assiste à des mécanismes de sédimentation. Les mécanismes d'ablation sont dominants quand la pente est supérieure à 25% (Foster *et al.*, 2000). Les résultats obtenus des corrélations entre taux d'ablation/sédimentation et pente présentent un R^2 positivement significatif égal à 0.75 (Tableau 5).

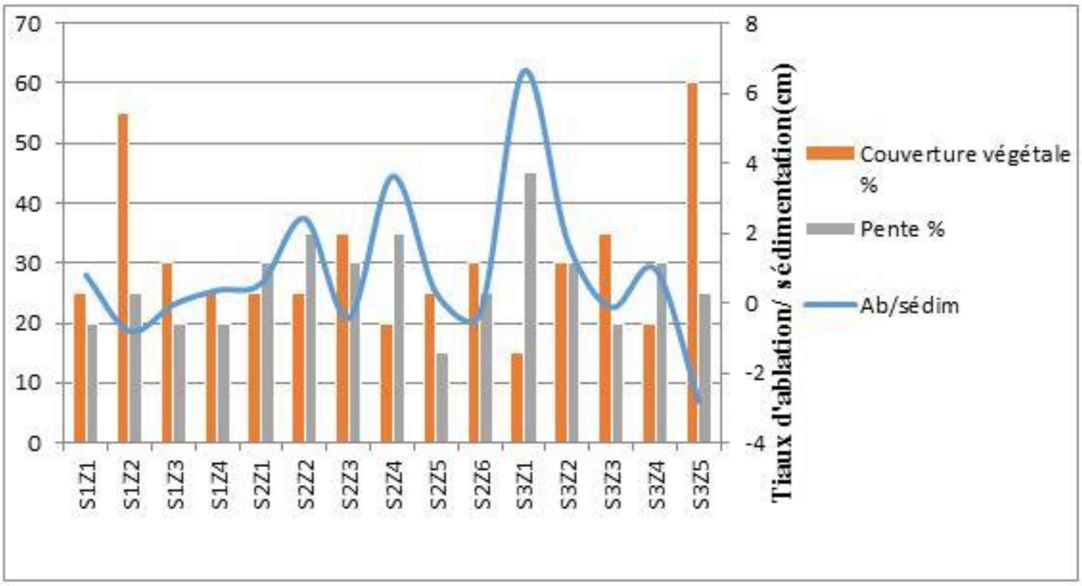

Fig. 6 – Relation entre ablation/sédimentation, couverture végétale et la pente.

4.4. Elaboration d'un modèle explicatif du phénomène d'érosion sur terrain marneux

Parmi les objectifs de cette étude est la compréhension des phénomènes d'érosion sur les terres noires (marne), et leur corrélation avec différents facteurs (pente, taux de couverture végétale et pluviométrie). L'élaboration d'un modèle d'érosion est l'aboutissement de 3 années de mesures dans la région de la Motte du Caire (Alpes du sud). La conception d'un modèle d'érosion constitue une étape importante dans l'aménagement du territoire et un outil d'aide à la décision. Le modèle «TCSP» développé au cours de cette étude est basé sur le traitement des taux d'ablation – sédimentation collectés des trois sites.

Cependant, pour les objectifs de notre étude, les taux d'ablation, de sédimentation moyens mensuels, les taux de couverture végétale, les classes de pentes et les moyennes mensuelles de pluviométries enregistrées sur le terrain au cours de 3 années ont fait l'objet d'un traitement sous le logiciel 'MATHLAB'. Nous avons élaboré un modèle qui explique le phénomène d'érosion sur les terrains marneux de la localité de la Motte du Caire. Le modèle en question, offre une idée précise sur le phénomène d'érosion, tout en identifiant s'il s'agit de processus d'ablation ou bien de sédimentation.

$$E = -10.3176\ TC + 4.5963\ S - 0.0293\ P + 4.0089$$

A savoir:
E: érosion [avec E (+) ablation / E (–) sédimentation]
S: pente
P: pluviométrie
4.0089: constante

5. CONCLUSION

Le présent article propose une nouvelle méthode permettant de réfléchir sur la manière de cibler les zones problématiques (ablation / sédimentation) sur les terrains marneux de la commune de la Motte du Caire. Nous avons adopté une nouvelle approche, qui considère les processus d'érosion comme étant le résultat d'une interaction de plusieurs facteurs du milieu (type de marne, topographie, pluviométrie et taux de couverture végétale) et dont la distribution spatiale est le fruit d'une organisation dans l'espace et le temps.

D'après les résultats obtenus au cours de cette étude, il ressort que les valeurs d'ablation moyenne annuelle calculées sur une période de 3 années sont les suivantes: 1,67 cm/an sur le Bathonien, 1,9 cm/an sur le Callovien et 3,04 cm/an sur l'Oxfordien. Il s'avère que le suivi des phénomènes d'ablation et de sédimentation est plus intéressant sur une période de 3 années. Ainsi, les marnes de l'Oxfordien sont les plus touchées par le phénomène d'érosion. Ces résultats expliquent l'envasement du barrage du Saignon dans un laps de temps très court (5 ans).

Parmi les objectifs de notre étude est d'élaborer un modèle de quantification d'érosion. Le modèle 'TCSP' développé au cours du présent travail est le fruit du traitement des données (moyennes mensuelles d'ablation / sédimentation en incluant celles des taux de couverture végétale, de pluviométrie et des classes de pentes) collectées sur le terrain durant 3 années. Le modèle 'TCSP' offre la possibilité d'identifier les zones problématiques pourvoyeuses de sédiments dans le but de les traiter ainsi réduire les taux d'érosion.

Lors de notre étude, nous avons observé que la présence d'une strate herbacée était capable de réduire les taux d'érosion en piégeant les sédiments provenant des zones en amont. Les corrélations entre taux d'ablation – sédimentation et taux de couverture végétale sont positivement significatifs.

Les phénomènes de ruissellement et d'érosion touchant les terres noires de la commune de la Motte du Caire ne peuvent pas être correctement analysés sans intégrer les effets du couvert végétal, de la pente et de la pluviométrie sur la genèse et la circulation du ruissellement. La complexité des phénomènes étudiés impose aussi un recours à la modélisation pour estimer l'efficacité des aménagements et pour trouver les mesures adaptées à chaque situation.

La prise en compte du taux de couverture végétale et de la pluviométrie a permis de distribuer spatialement les paramètres contrôlant les mécanismes d'ablation – sédimentation ainsi que les facteurs à l'origine des processus de détachement et de transport des particules solides. Par ailleurs, l'intégration des différents facteurs tels que le taux de couverture végétale et des classes de pentes a contribué à une nette amélioration des résultats de quantification par rapport à celles effectuées en n'intégrant que la topographie comme paramètre orientant la circulation du ruissellement.

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Paludification dynamics in the boreal forest of the James Bay Lowlands: effect of time since fire and topography

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Abstract: In many northern forest ecosystems, soil organic matter accumulation can lead to paludification and forest productivity losses. Paludification rate is primarily influenced by topography and time elapsed since fire, two factors whose influence is often confounded and whose discrimination would help forest management. This study, which was conducted in the black spruce (*Picea mariana* (Mill.) BSP) boreal forest of northwestern Quebec (Canada), aimed to (1) quantify the effect of slope and time since fire on paludification rates, (2) determine whether soil organic layer depth could be estimated by surface variables that can potentially be remotely sensed, and (3) relate the degree of paludification to tree productivity. In this study, soil organic layer depth was used as an estimator of the degree of paludification. Slope and postfire age strongly affected paludification dynamics. Young stands growing on steep slopes had thinner organic layers and lower organic matter accumulation rates compared with young stands growing on flat sites. Black spruce basal area and *Sphagnum* cover were strong predictors of organic layer depth, potentially allowing mapping of paludification degree across the landscape. Tree productivity was negatively related to organic layer depth (R^2 = 0.57). The equations developed here can be used to quantify forest productivity decline in stands that are undergoing paludification, as well as potential productivity recovery given appropriate site preparation techniques.

Résumé : Dans plusieurs écosystèmes forestiers nordiques, l'accumulation de matière organique peut mener à la paludification des sols et entraîner des pertes de productivité forestière. Le taux de paludification est principalement influencé par la topographie et le temps écoulé depuis le dernier feu, deux facteurs dont l'influence est souvent confondue et dont la séparation aiderait à l'aménagement forestier. Cette étude réalisée dans la pessière noire (*Picea mariana* (Mill.) BSP) du nord-ouest du Québec (Canada) avait comme objectifs : (1) de quantifier l'effet de la pente et du temps depuis le dernier feu sur le taux de paludification, (2) de déterminer si l'épaisseur de la couche organique pouvait être estimée à partir de deux variables de surface quantifiables au moyen de la télédétection, et (3) d'établir la relation entre le degré de paludification et la productivité des arbres. Dans cette étude, l'épaisseur de la couche organique du sol a été utilisée pour estimer le degré de paludification. La pente et l'âge des peuplements après feu influencent fortement la dynamique de paludification. La couche organique était plus mince et avait un taux d'accumulation plus faible dans les jeunes peuplements établis sur des pentes fortes que dans les peuplements d'âge similaire établis sur terrain plat. La surface terrière en épinette noire et le recouvrement de sphaignes avaient un fort pouvoir de prédiction de l'épaisseur de la couche organique, ce qui pourrait permettre de cartographier le degré de paludification à l'échelle du paysage. Enfin, la productivité des arbres était négativement reliée à l'épaisseur de la couche organique (R^2 = 0,57). Les équations développées dans ce travail peuvent être utilisées pour quantifier le déclin de productivité forestière dans les peuplements sujets à la paludification, ainsi que le potentiel de récupération de productivité à la suite d'une préparation de terrain appropriée.

Introduction

Forest productivity varies naturally over time and space, and understanding this variability is essential for managing forests in a manner that balances timber production and maintenance of ecological integrity. In boreal ecosystems, the spatial variability of forest productivity is largely driven by fine-scale topography through its control on soil drainage

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(Wang et al. 2003; Bond-Lamberty et al. 2004) and by heterogeneity in disturbance interval and severity (Kimmins 1996). For example, soil burn severity controls postfire recruitment and growth (Lecomte et al. 2006*b*; Greene et al. 2007). Forest productivity has also been shown to decline with age in the absence of large-scale disturbances, and the underlying causal factors of this decline are still debated (Ryan et al. 2004). In northern ecosystems, one probable cause of productivity decline with time is the accumulation of a thick organic layer that cools the soil and reduces nutrient cycling (Van Cleve et al. 1983*a*; Prescott et al. 2000). As a result, soil preparation techniques that disturb soil organic layers to enhance forest productivity are used in many parts of the world (Paavilainen and Päivänen 1995; Lavoie et al. 2005). Prediction of global change and forest management effects in these ecosystems can only be done through a good understanding of how forest productivity varies in time and space (Bond-Lamberty et al. 2004; Grant 2004).

In northwestern Quebec (Canada), on the clay plains of the James Bay Lowlands, boreal forest soils accumulate thick organic layers over time through a phenomenon called paludification (Heinselman 1963; Payette and Rochefort 2001). Paludification is characterized by a gradual colonization of forested sites by *Sphagnum* moss species (Van Cleve et al. 1983*a*; Fenton et al. 2005). After stand establishment following a fire, the gradual accumulation of organic matter lowers soil temperature and creates a perched water table close to the soil surface (Fenton et al. 2006; Simard et al. 2007). Bryophyte and shrub diversity is reduced (Lecomte et al. 2005; Fenton and Bergeron 2006), and as stands open up (Harper et al. 2005; Lecomte et al. 2006*a*), tree productivity declines (Van Cleve et al. 1983*b*; Lecomte et al. 2006*b*). In the extended absence of fire, paludification can reduce forest productivity by up to 50%–80% compared with postfire values (Simard et al. 2007). Forest succession between fire events can therefore be an important driver of paludification, independently of site topography or drainage. Topography also has a determinant effect on paludification rates and productivity (Lavoie et al. 2007). Since it is water retention that ultimately enables the growth of *Sphagnum* and the accumulation of organic matter, sites with greater slopes, and hence more lateral drainage, should show a lower degree of paludification than flatter sites. Generally, paludification is always caused by the same proximate mechanism, i.e., high water table, but is ultimately driven by two different factors (topography and succession) that can independently modulate the rate and magnitude of the paludification process. However, as both drivers operate simultaneously on forest stands, their respective effects are difficult to tease apart.

Fire is an important process that may return paludified sites to their high productivity status by consuming accumulated soil organic layers (Kimmins 1996). Like fire, forest management can modify the successional trajectory of forests and, when used appropriately, could possibly set back the paludification process and restore the productivity of paludified sites (Lavoie et al. 2005). Planning treatments on sites undergoing paludification requires an a priori estimate of their potential for recovery of forest productivity. To do this, we need a method that can be used to quantify the relative importance of succession and topography on paludification, and to evaluate the potential recovery of site productivity at the site and landscape levels.

The goals of this study were therefore (1) to develop empirical models that would allow quantification of both the current state of paludification and the potential degree of paludification following disturbance of the organic layer, (2) to determine whether the degree of paludification could be mapped in forest stands across the James Bay Lowlands, and (3) to relate the degree of paludification to tree productivity. In this study, soil organic layer depth was used as an estimator of the degree of paludification. We hypothesized that initial (postfire) rates of soil organic matter accumulation would decrease with increasing slope and that soil organic layer thickness of sites with different slopes would converge in the long run in the absence of disturbances.

Methods

Study area

The study area (49°00′–50°30′N, 78°30′–79°30′W) is located in the boreal zone of western Quebec, (Canada). This part of the Precambrian Shield is covered with glaciolacustrine clays that have been reworked by glacial surges, resulting in a relatively compact deposit composed of clay and gravel that is called the Cochrane Till (Veillette 1994). The mostly flat region (mean altitude = 250 m a.s.l.) shows three major soil types, Luvisols, Gleysols, and Organic soils (Soil Classification Working Group 1998), which reflect the variable thickness of the organic layer (about 10 to >200 cm). The dominant forest types are black spruce (*Picea mariana* (Mill.) BSP) – feathermoss and black spruce – *Sphagnum*, with an understory dominated by ericaceous shrubs (*Rhododendron groenlandicum*, *Kalmia angustifolia*, *Vaccinium* spp). Jack pine (*Pinus banksiana* Lamb.) and trembling aspen (*Populus tremuloides* Michx.) also occur in pure or mixed stands, and secondary tree species include balsam fir (*Abies balsamea* (L.) Mill.), paper birch (*Betula papyrifera* Marsh.), and tamarack (*Larix laricina* (DuRoi) K. Koch) (Gauthier et al. 2000). The region's mean annual temperature is –0.7 °C (mean temperatures of January and July are –20.0 °C and 16.1 °C, respectively), and annual precipitation is 905 mm, 35% of which falls during the growing season (Matagami weather station (49°46′N, 77°49′W), Environment Canada 2006). Forest harvesting has taken place since the 1970s on the most productive sites.

Site selection

Our intent was to perform field sampling across a broad range of slopes and postfire stand ages. We first selected stands of different postfire ages using a stand initiation map (map of time elapsed since the last stand-replacing fire) developed earlier for the study area (Bergeron et al. 2004) and refined with radiocarbon dating (Lecomte et al. 2006*b*). Postfire stand age was determined from fire-scar dating, tree-ring dating (stump height) of synchronously established cohorts of early-successional tree species (live or dead dominant trees), and radiocarbon dating of soil charcoals (for older fires, when the postfire cohort was missing). Each stand had to be dominated by black spruce, show no sign of anthropogenic disturbance, and be within 2 km of a road. We then systematically distributed sampling plots within

Table 1. Distribution of plots by slope class, stand, and postfire stand age.

		Slope class (%)															
Postfire stand age (years)	No. stands sampled	0	1	2	3	4	5	6	7	8	9	10	11	12	14	16	Total no. of plots
90	2	4	15	22	10	9	6		2	1			1		1	1	72
99	2		9	19	7	1	1										37
173	2	1	15	17	6		1										40
179	2	1	9	18	8	3		1	1			1		1	1		44
229	1		6	9	1		1										17
329	1			4	4	2											10
369	1			1	4	2	1										8
714	1	1	9	14	6	1					1						32
	Total no. of plots	7	63	104	46	18	10	1	3	1	1	1	1	1	2	1	260

each stand on a 100 m grid using a geographic information system with the objective of capturing within-stand topographic variability. In total, we sampled 281 plots (our experimental unit) ranging in slope from 0% to 16%, hierarchically nested in 12 stands ranging in postfire age from 90 to 714 years (Table 1).

Field measurements and sample processing

During the summer of 2004, the sampling plots were located in the field using a GPS unit. From the center of each plot, slope was measured in the four cardinal directions over a 15 m measurement base using a clinometer mounted on a tripod. Tree basal area was measured in three prism points (factor 2, metric): one in the plot center and two more at 15 m on the east and west sides of the plot center. Ground cover (presence, 5%, 10%, 20%, etc.) of major bryophyte taxa (*Sphagnum* spp., feathermosses, lichens) and deadwood was estimated in four 1 m^2 quadrats located 10 m from the plot center in the four cardinal directions. Total depth of soil organic layer was also measured in the four quadrats using a soil auger.

Statistical analyses

Preanalysis of the data revealed a few anomalies with organic layer depth measurements, corresponding to plots where estimation of soil organic layer thickness had been constrained either by frozen ground or by the length of the soil auger in cases of very deep layers. These plots were deleted from the data set. After these modifications, our final data set contained 260 of the original 281 plots (Table 1).

To address our first study objective, we performed a regression analysis to quantify the effect of postfire stand age and topography on the accumulation rate of the organic layer. The effect of postfire stand age (A) and slope (S) and their interaction on soil organic layer depth (D) was tested using a mixed model with stand as a random effect (PROC MIXED, SAS Institute Inc. 2003). The explanatory variable S was defined as the steepest of the four slopes measured at each plot.

To address our second study objective, we related soil organic layer depth (D) to variables that could possibly be detected and mapped through multispectral satellite imagery: plot basal area (G; mean of three prism points) and percent cover of *Sphagnum* mosses (C_{SPH}; mean of four quadrats). The analysis also included the interaction of these two variables, and stand as a random effect. Basal area and *Sphagnum* cover have been shown to vary considerably with the degree of paludification (Fenton et al. 2005, Lecomte et al. 2005), and as surface properties, they can potentially be estimated via remote sensing (Bubier et al. 1997; Hyyppä et al. 2000). The variables A, D, and C_{SPH} were log transformed (base 10 for A and D; $\log(n + 1)$ for C_{SPH}, which had null values) to meet the assumptions of homogeneity and normality of the residuals. For both regressions, model selection was based on the lowest corrected Akaike information criterion value (Burnham and Anderson 2002).

Paludification–productivity relationship

To quantify the relationship between the degree of paludification and tree productivity, we reanalyzed site index and soil organic layer thickness data previously published in Simard et al. (2007). The data were sampled in 22 black spruce stands ranging in postfire age from 52 to 2355 years, all located in the study area. In each stand, we selected three black spruce trees of the dominant cohort and, when present, three additional trees of both the second and third height cohort. We selected the second and third cohorts based on the vertical distribution of trees in the canopy and on the diameter at breast height structure of the stands. The cohorts had to be separated by a vertical distance of at least 5 m, and to avoid sampling suppressed trees, all sampled trees (n = 147) had to be growing in full light and be free of any connection with a living genet.

During the summers of 1999 to 2001, two measurements of soil organic layer depth were taken in opposite directions at 10 cm from the base of each tree. Stem analyses were performed on each selected tree by sampling cross sections at 0 m, 0.4 m, 1 m, and every 1 m thereafter. Cross sections were finely sanded and cross-dated under 40× magnification. For each tree, we calculated site index as the height growth during 50 years of free (i.e., unsuppressed) growth, using stem height increment patterns to define major inflexions in the age–height growth curve indicating growth release (Curtis 1964).

For the current work, we related site index to mean organic layer depth at the tree level using reduced major axis regression on log-transformed variables (Sokal and Rohlf 1995). Only trees belonging to the youngest cohort were kept for the analysis (total n = 64 trees) because site index of young trees is more representative of current growing conditions (current organic layer depth measured in the field) than is site index of older trees. Even then, site index in this data set is slightly overestimated in relation to organic layer depth, because it integrates growing conditions of the past 50 years during which the organic layer was thinner.

Results

Paludification dynamics: effect of postfire stand age and slope

Variability in soil organic layer depth across the 260 plots was best explained by both postfire stand age and slope (Table 2). Rates of organic matter accumulation were highest on flatter sites and diminished with increasing slope (Fig. 1). Soil organic layer depth (D, cm) can be predicted with the following equation:

$$[1] \qquad \log(D) = 0.3728 \log(A) - 0.02089S + 0.8510$$

where S (%) is the maximum of four plot-level slope measurements, and A (years) is postfire stand age.

Predicting organic layer depth

Plot basal area ranged from 10 to 60 m^2/ha, with an average within-plot standard deviation of 4.6 m^2/ha (mean coefficient of variation = 19%). Basal area and *Sphagnum* moss cover together were the best predictors of organic layer depth (Table 3), with deep organic soils associated with low basal area and high *Sphagnum* cover. The depth of the organic layer, our estimator of paludification status, can thus be expressed as a linear combination of *Sphagnum* cover (C_{SPH}, %) and basal area (G, m^2/ha) with the following equation:

$$[2] \qquad \log(D) = 0.09740 \log(C_{SPH} + 1) - 0.00473G + 1.6336$$

Paludification and site productivity

Site index was negatively related to soil organic layer depth, which explained 57% of the variance in site index (Fig. 2). The shape of the relationship suggests that the greatest decline in site index occurs when the first 20 to 40 cm of organic soil accumulate: the regression predicts a 50% drop in site index, from 14 to 7 m, with an increase in organic layer depth from 15 to 30 cm.

Discussion

We have defined two models through which we can estimate soil organic layer depth, used as a proxy for the degree of paludification, and its increase over time in the absence of fire. The dynamic portrait provided by eq. 1 makes possible the estimation of soil organic layer depth as a function of slope and postfire stand age and thus the determination of a postfire stand's possible trajectory from its initial conditions to its various degrees of paludification (Fig. 1). This statistical model supports our hypothesis of slower organic matter accumulation on steeper slopes but does not support the hypothesis that all stands, irrespective of slope, converge to a high degree of paludification. The work nevertheless shows that organic layer accumulation is not confined to flat sites and that successional dynamics in the boreal forest of northwestern Quebec drive all black spruce dominated stands towards greater degrees of paludification.

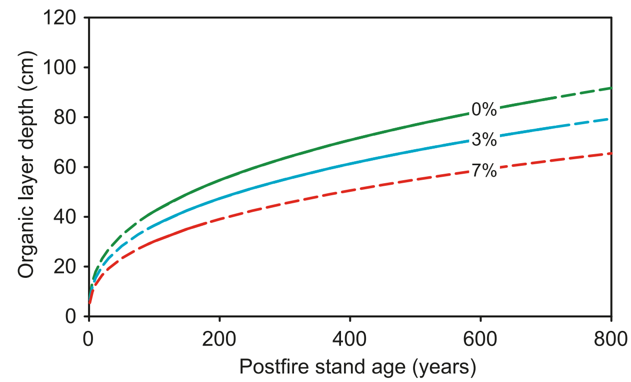
Table 2. Results of the mixed linear model relating soil organic layer depth to postfire stand age (A) and slope (S).

Covariance parameters					
	Ratio	Estimate	SE	Z	P
Stand	1.3268	0.02263	0.01057	2.14	0.0161
Fixed effects					
	ddf*	Estimate	SE	F	P
log(A)	9.89	0.3728	0.1663	5.03	0.0491
S	252	–0.02089	0.004279	23.84	<0.0001
log(A) × S	—	—	—	—	ns

Note: n = 260; SE, standard error; ddf, denominator degrees of freedom; ns, nonsignificant.

*Numerator degrees of freedom are all equal to 1.

Fig. 1. Change in soil organic layer depth with postfire stand age in stands of different slopes (identified above each regression line). Broken lines indicate range of extrapolation.



Equation 2 enables us to quantitatively define the current degree of paludification of a site (i.e., its organic layer depth) based on *Sphagnum* cover and tree basal area. Previous research has shown that the depth of organic layer consumption varies enormously among fires and within a fire (Lecomte et al. 2005, 2006*a*), and including such initial conditions in our analysis would significantly improve the predictive capacity of eq. 1. However, burn severity is not easily obtained in the field, nor is it available spatially. Similarly, the identification of *Sphagnum* species could increase prediction of organic layer depth in the field because different species are associated with different soil moisture levels (Fenton and Bergeron 2006), but again this information cannot be obtained spatially for large areas (10^3–10^4 km^2). By contrast, use of two easily observable variables in eq. 2 offers two advantages. The first is by providing a quick method of evaluating the on-site degree of paludification through easily measurable variables. The second is that, if these two variables can be related to multispectral signatures from satellite imagery, it may then be possible to map the current paludification status of black spruce stands across the James Bay Lowlands.

Figure 1 shows that in this area of low permeability surface deposits and low slopes postfire stand age drives the paludification process, while topography modulates both the degree of initial postfire paludification as well as rates of the

Table 3. Results of the mixed linear model relating soil organic layer depth to basal area (G) and *Sphagnum* percent cover (C_{SPH}).

Covariance parameters					
	Ratio	Estimate	SE	Z	P
Stand	1.1764	0.01624	0.007378	2.20	0.0139
Fixed effects					
	ddf*	Estimate	SE	F	P
G	254	–0.00473	0.000975	23.58	<0.0001
$\log(C_{SPH}+1)$	254	0.09740	0.01475	43.64	<0.0001
$G \times \log(C_{SPH}+1)$	—	—	—	—	ns

Note: n = 260; SE, standard error; ddf, denominator degrees of freedom; ns, nonsignificant.

*Numerator degrees of freedom are all equal to 1.

Fig. 2. Relationship between soil organic layer depth and site index (n = 64; R^2 = 0.57; F = 81.0; P < 0.0001). Shaded area represents 95% confidence limits of the predicted mean.

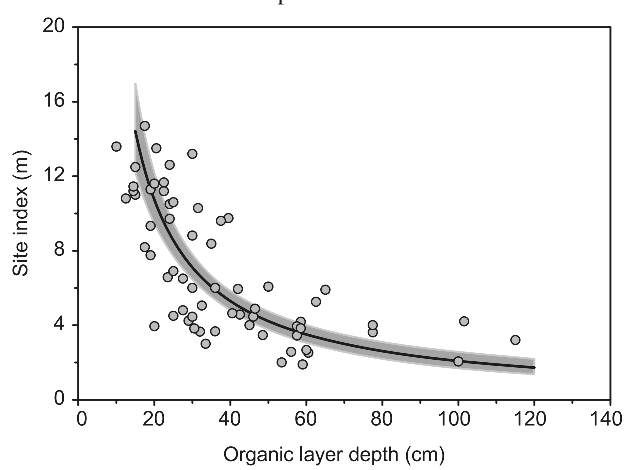
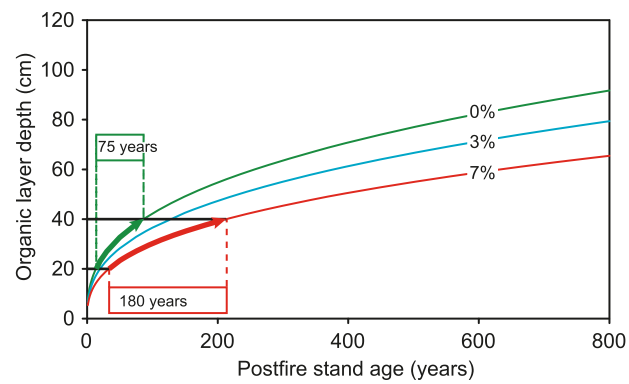


Fig. 3. Example of treatment effect duration (horizontal bars) on a 0% slope site and a 7% slope site. The hypothetical treatment reduces soil organic layer depth to 20 cm, and treatment effect is assumed to end when the subsequent accumulation of organic matter pushes this depth back to 40 cm. Regression lines are the same as in Fig. 1.



paludification process (Table 2, Fig. 1). Young stands growing on flat sites have thick organic layers (about 33 cm at 50 years) and higher initial rates of organic layer accumulation compared with young stands growing on even modestly sloping sites (3% to 7%, which have, respectively, 28 and 23 cm of organic soil at 50 years). This apparently small difference in organic layer depth translates into large differences in productivity because of the nonlinear relationship between soil organic layer depth and site index (Fig. 2). Because black spruce roots are confined to the top 20–30 cm of the soil, the sharp drop in tree productivity associated with the accumulation of the first 20–40 cm of organic matter corresponds to the transition from a state where tree roots are located in the nutrient-rich mineral soil to a state where most roots are located in the organic layer, where nutrient availability is low (Simard et al. 2007).

Predicting potential productivity gains

The difference between the current organic layer depth of an older stand and its initial (at 50–100 years) organic layer depth represents the potential recovery of a site if the effect of succession is reversed through fire or forest management. With the assumption that a reduction of the organic layer would translate to increased forest productivity (Fig. 2), the model suggests that for stands sharing a similar current soil organic layer depth (e.g., current status = 40 cm), stands growing on steeper slopes have a greater recovery potential (e.g., organic layer depth at 50 years on 7% slopes = 23 cm) than stands growing on flat terrain (e.g., organic layer depth at 50 years on 0% slopes = 33 cm). The model also suggests that a soil organic layer depth reduced to 20 cm following fire or scarification would take 180 years to return to a depth of 40 cm for the 7% slope site, but only 75 years for the flat site (Fig. 3). A very small difference in slope, in the order of 3% to 7%, can therefore make a large difference in the maintenance of productivity following treatment.

Forest management through emulation of natural disturbance dynamics is receiving increasing attention in both academia and industry (Attiwill 1994; Perera et al. 2004). The two contrasting trajectories on flat versus sloping sites outlined above provide a basis for managing soil organic layer and forest productivity in the black spruce forests of the Clay Belt of Quebec and Ontario, where forest succession and smoldering fires act antagonistically to move forest stands up or down the productivity gradient. Management strategies for the maintenance or improvement of forest productivity in this area should focus on sloping sites. The lower recovery potential and shorter duration of treatment effects on flat sites provide few ecological or economic motives to manage soils on these sites. The equations developed in this study can be used to estimate potential productivity gains in currently unproductive stands, assuming that the removal or disturbance of the organic layer emulates the effect of fire on the degree of paludification. To quantify the recovery potential of a particular stand, all that is needed is to calculate the difference between its current degree of paludification (soil organic layer depth measured in the field or estimated with *Sphagnum* cover and basal area using eq. 2) and the potential degree of paludification of a young stand (e.g., 50–100 years) on the same slope (using eq. 1). The calculated reduction in organic layer depth can then be expressed in terms of increased potential productivity using the site index – organic layer depth relationship (Fig. 2). Potential productivity gains are greater on steeper slopes and lower on flat sites (Fig. 3).

One important assumption in the methodology to quantify potential recovery following human intervention is that we can indeed emulate site-level effects of natural fires on forest productivity. Disking and trenching are site preparation methodologies with well-documented beneficial effects on soil microenvironment and seedling establishment and growth (Sutton 1993; Lavoie et al. 2005). However, it is not clear at this point how the effectiveness of these methods varies with increased depth of soil organic layer. Prescribed burns may also be used to restore productivity, but more work is required to determine how to best use them for restoring productivity on sites undergoing paludification.

Conclusion

Fire frequency in our study area has decreased over the last centuries (Bergeron et al. 2004) and could potentially continue to decrease in the future (Flannigan et al. 1998, but see Flannigan et al. 2005). Such a trend may gradually bring more forested areas in the region toward a greater degree of paludification and lower productivity. In addition, current forest management practices in the area are designed to minimize soil disturbance, in effect promoting growth of *Sphagnum* moss. Protection of soils through careful logging practices maintains sites on a path leading towards a low-productivity paludified status. Maintenance of forest productivity on these sites may require severe disturbance of organic layers, similar to the effects of high-severity fires (Lavoie et al. 2005). The methodology developed here could be useful in selecting sites where soil management techniques could be applied for maintaining or increasing forest productivity.

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