Editor Decision: Publish subject to minor revisions (review by Editor) (16 Mar 2016) by Dr Nathalie Combourieu Nebout.

Comments to the Author:

Dear authors,

Thank you for sending this new version. I have seen that you have followed most of my requests.

However, regarding my request about the Quercus? I noted that no sentence have been added in the text. Could you please add this sentence and place the scheme proposed in your response in an additional file joined to the paper (see in instruction to authors how doing that).

A clear sentence has now been added to the manuscript, with a figure and its related legend. We hope it is satisfactory now.

In fact, what you present in the response does not exactly respond to my question (see in previous comments). I asked you a question regarding the differences between the Q. ilex and the Q. canariensis. Could it be possible to add the requirements of Q. canariensis on the figure which will be in additional file?

Unfortunately, as you can see it in table 2 we do not have the climate envelope of *Quercus canariensis* among the 34 taxa used for the climate reconstruction. This is the case for other fossil pollen taxa in our records. We would like to mention that this is the case for all climate reconstruction methods, such as the Modern Analogue Technique used in many publications (by Peyron et al. or Guiot et al.). All methods suffer from the same issue, unfortunately.

At the end, reading your last version, I have seen something in the figure 3 with the reconstructed climate parameters. You present temperature curves with errors bars but no error bars have been drawn for the summer and winter precipitation. Why? Could you please add them on the figure 3. Thank you for that.

Thank you for this remark, I have added the error bars to Pw and Ps but not to SI because it is based on Pw and Ps.

I noted also that the present-day winter precipitation is very low comparing to those reconstructed for the present time (O kyrs). Why? If it is due to anthropogenic effect, please mentioned this difference in the text and try to explain it.

Actually, as you can see it in figure 3, the core top does not correspond to the present day and therefore a direct comparison might not be suitable.

As the SI is conditioned by the reconstruction of seasonal precipitation, the present day SI could be near the observed one. Is it the case if the reconstructed winter values are far from the present-day ones? And then what is the influence on the past reconstructions?

Yes definitely. If Pw and/or Ps deviates then SI deviates as well. SI is not reconstructed from pollen data but rather based on Ps and Pw. If I understood your comment correctly, SI does not rely on the method used, its deviation is directly linked to the reconstructed Pw and Ps. Having said this, the obtained modern value (figure 3) is very coherent with those values obtained for the Middle Atlas (figure 7) which are between ca. 5 and 8. I believe that the reader can easily understand these potential “mismatches” when looking at figures 3 and 7. Therefore, I think that no additional explication should be added to the manuscript. However, I am fully ready to add a comment on the manuscript if you decide so.

Thank you for doing these last amendments to your manuscript and figures.

Thank you for these remarks.

Best regards,

Majda Nourelbait

Marked-up manuscript version :

Climate change and ecosystems dynamics over the last 6000 years in the Middle Atlas, Morocco

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Abstract

The present study aims at reconstructing past climate changes and their environmental impacts on plant ecosystems during the last 6000 years in the Middle Atlas, Morocco. Mean January temperature (Tjan), annual precipitation (*P*ann), winter (Pw) and summer (Ps) precipitation and a seasonal index (SI) have all been quantified from a fossil pollen record. Several bio and geo-chemical elements have also been analyzed to evaluate the links between past climate, landscape and ecosystem changes.

Over the last 6000 years, climate has changed within a low temperature and precipitation range with a trend of aridity and warming towards the present. Tjan has varied within a ca. 2°C range and *P*ann within less than 100 $mmyr^{-1}$. The long-term changes reconstructed in our record between 6ka cal BP and today are consistent with the aridity trend observed in the Mediterranean basin. Despite the overall limited range of climate fluctuation, we observe major changes in the ecosystem composition, the carbon isotopic contents of organic matter ($\delta^{13}C$), the total organic carbon and nitrogen amount, and the carbon to nitrogen ratio (C/N) after ca. 3750 cal BP. The main ecosystem changes correspond to a noticeable transition in the conifer forest between the Atlas cedar, which expanded after 3750 cal BP, and the pine forest. These vegetation changes impacted the sedimentation type and its composition in the lake.

Between 5500 and 5000 cal BP, we observe an abrupt change in all proxies which is coherent with a decrease in Tjan without a significant change in the overall amount of precipitation.

1 **Introduction**

The amplitude of climate change during the Holocene (11,700 cal BP to the present) is known to be globally less extreme than during the post-glacial period (Bianchi and McCave, 1999; Bond et al., 2001; Debret et al., 2007). However, several studies have shown that there were climate fluctuations (Alley et al., 1997; Wanner et al., 2008) related to the internal variability of the climate system, solar activity, albedo (Ruddiman, 2003; Eddy, 1982; Stuiver *et al.*, 1991), volcanic eruptions (Kelly ~~&~~ and Sear, 1984; Sear et al., 1987; Bryson, 1989; Mann et al., 2005), ocean circulation (Manabe ~~&~~ and Stouffer, 1988; Dansgaard et al., 1989; Lascaratos et al., 1999; Rohling et al., 2002), etc. which all have a direct impact on the terrestrial ecosystems (Davis, 1963; Emmanuel *et al.*, 1985). Although climate changes were less pronounced during the Holocene (Andersen et al., 2004; Mayewski et al., 2004; Witt and Schumann, 2005; Frigola et al., 2007; Cheddadi ~~&~~ and Bar-Hen, 2009) than during the last post-glacial period, they have still been noticeable enough to be recorded by different proxies (Dorale et al., 1992; Williams et al., 2002; Geiss et al., 2003, 2004). At the global scale, the Holocene climate stability allowed a sustainable vegetation dynamics with long-term ecosystems changes, plant species expansions and migrations, and an increase of species diversity over all latitudes (Rohde, 1992). However, the Holocene period has also recorded some abrupt and cold events such as the one at 8.2 ka cal BP (e.g. Alley and Agustsdottir, 2005) which recorded a depletion of about 4°C in winter temperature in the Eastern Mediterranean (Weninger et al., 2009).

In Morocco, climate changes during the Holocene have also been quantified and they show significant fluctuations (Cheddadi et al., 1998). As a matter of fact, the climate variability of the Holocene is less known than that of the post-glacial (Mayewski et al., 2004) because it has a lower amplitude and is less abrupt. This statement is even more acute in the Mediterranean region where high resolution and chronologically well-constrained Holocene records are much less numerous than in Europe or North America. The Mediterranean area is currently a hotspot of biodiversity (Myers et al., 2000) and it is one of the largest regions in the world that undergo long-lasting and pronounced droughts during the summer season (Roberts et al., 2004; Milano et al., 2013). The southern rim of the Mediterranean region is even more arid than the northern one because of the influence of the Azores high and the Saharan winds which increase the impact of the drought effect during the summer season. Most of the winter precipitation (Pw) originates from the trade winds which carry moisture from the Mediterranean Sea (Martin, 1981). The amount of Pw has a strong impact on the persistence of water bodies and on the lake levels in the Mediterranean area. Strong lake level fluctuations during the Holocene were observed in Lake Van, Turkey (Lemcke and Sturm, 1997), Lago Dell'Accesa and Lago di Mezzano, Italy (Magny et al., 2006), lake Kinneret, (Hazan et al., 2005) and the Dead Sea, Israel (Migowski et al., 2006), lake Siles, Spain (Carrión~~Carrion~~, 2002), and lakes Sidi Ali and Tigalmamine in Morocco (Lamb and Van der kaars, 1995; Märsche-Souli~~e~~é et al., 2008).

The analysis of marine and continental records from the central part of the Mediterranean shows that the lake levels were high between 10,300 and 4500 cal BP due to an enhanced moisture availability during both summer and winter (Magny et al., 2013). After 5000 cal BP, pollen data from southwestern Europe show that drought increased and led to a sustained reduction of the forest cover (Roberts et al., 2001; Jalut et al., 2009; Jiménez-Moreno et al., 2015). These environmental changes show that within the long-term climate trend there were humid-arid episodes that are related to internal forcings of the climate system such as, in the case of these westernmost Mediterranean ecosystems, the centennial changes in the North Atlantic Oscillation modes (Jiménez-Moreno et al., 2015), the enhancement/weakening of the trade winds, or the increase in the coastal upwelling off northwestern Africa (McGregor et al., 2007).

Climate reconstructions from marine pollen records suggest that the Mediterranean environments may react with a reduced time lag to rapid climate changes (Fletcher et al., 2010). The response of the western Mediterranean ecosystems has even been synchronous with the North Atlantic variability during the post-glacial period and the Holocene (Combourieu-Nebout ~~Combourieu Nebout~~ et al., 2009). Changes in the pollen assemblages of a marine record from the Alboran Sea also show very synchronous fluctuations between the surrounding land ecosystems changes and the sea surface temperature fluctuations (Fletcher and Sánchez Goñi, 2008; Combourieu-Nebout ~~Combourieu Nebout~~ et al., 2009). Pollen records from the Middle Atlas (Reille, 1976; Lamb and Van der kaars, 1995; Cheddadi et al., 2009; Rhoujjati et al., 2010; Nour el Bait et al., 2014; Tabel et al., 2016) and the Rif mountains (Cheddadi et al., 2016) show that the Holocene climate change had a major impact on the ecosystems composition with a clear succession of different species sensitive to winter frost, strong rainfall seasonality and/or the total amount of annual rainfall throughout the year.

The aim of the present study is to evaluate the impacts of the climate changes on the ecosystems and the landscape of the Middle Atlas during the last six millennia. Our approach is multidisciplinary and based on the analysis of pollen grains, elemental and isotopic geochemistry and grain size from a fossil record collected in Lake Hachlaf, Middle Atlas.

Temperature and precipitation variables have been quantified. They show a moderate change which is superimposed by an aridity trend that is combined with an increase in winter temperature over the past 6000 years. We also observed some noticeable ecosystem and landscape changes with one rapid and quite abrupt climate fluctuation between 5500 and 5000 detectable in all the proxies used.

2 **Study area**

The Middle Atlas Mountains, lying in northwestern Morocco, consist of two geological sets called Pleated and Tabular Middle Atlas (Fig. 1a). The latter is formed by a Paleozoic basement covered by a Mesozoic thick layer and Cenozoic and Quaternary volcanic flows (Texier et al., 1985; Herbig, 1988; Harmand and Moukadiri, 1986). The Liasic limestone and dolostone are shaped by karstic mechanisms (Martin, 1981; Baali, 1998; Hinaje and Ait Brahim, 2002; Chillasse and Dakki, 2004). In this geomorphological and structural composition, there exist nowadays about twenty permanent or semi-permanent natural lakes (Chillasse and Dakki, 2004) among which we can find the studied site, Dayet (lake) Hachlaf (33°33’20” N; 5°0’0” W; 1700m a.s.l.). This small water body is located about ten kilometers North-East of Ifrane national park (Fig. 1b). Available meteorological data (HCEFLCD, 2004) at Dayet Hachlaf show an average annual rainfall of ca. 600 mm with Pw and Ps ca. 150 and ca. 70 mm, respectively. The mean January temperature is ca 4 °C with ca. 90 rainy days per year, and ca. 70 frosty days among which ca. 17 with snow precipitation. The surface area and depth of the lake change throughout the year reaching up to respectively 14 ha and 4 m during late spring. The lake is fed by rainwater, snow, surface runoff and groundwater and has no river inflow.

The forest cover around the site (Fig. 1c) is composed of holm oak (*Q. ilex* subsp. *rotundifolia)* which is evergreen and zeen oak (*Q. canariensis*) which is deciduous, and Atlas cedar (*Cedrus atlantica*) with occurrences of *Pinus halepensis*. Nowadays, there are some degraded populations of *Cedrus atlantica* with cultivated lands around the lake. At higher altitude (1700 to 2500 m, Fig. 1c) an herbaceous/shrubby vegetation (*Artemisia herba-alba* and Poaceae) dominates the landscape.

3 Materials and methods

In April 2008, a 2.5m core (33°33’2.49” N, 4°59’41.57” W) was collected using a Russian corer. Each section of the core was then sub-sampled for the analysis of pollen content (30 samples), grain size (39 samples), organic matter (43 samples) and its isotopic composition ($\delta^{13}C_{(org)}$; 46 samples), and total nitrogen and carbonates (43 samples).

Pollen grains were extracted using a standard laboratory procedure: HCl (20 %), KOH (10 %), $ZnCl_2$, acetolysis (CH_3CO_2O and H_2SO_4), KOH (10 %), ethanol and glycerine. The identification and counting of pollen grains were performed with an optical microscope (Leica DM750) using a ×40 magnification (×63 for accurate identifications). The pollen percentages were calculated on the total sum of pollen grains originating from vascular terrestrial plants. The total pollen grains counted varies between ca. 200 and 1300. Aquatic plants percentages (including Cyperaceae and Juncaceae) were excluded from the total pollen sum. Cyperaceae were considered as aquatic plants since there are *Juncus* and *Cyperus* genera growing around the lake today.

The particle size analysis was carried out at the "*Laboratoire Marocain d'Agriculture* (LABOMAG)" and was only performed on the sediment fraction < 2 mm. The proportions of five fractions were identified as follows: coarse sand (2000–200 μm), fine sand (200–50 μm), coarse silt (50–20 μm), fine silt (20–2 μm) and clay (below 2 μm).

Organic matter amount (OM) was estimated based on the content of the organic carbon in lacustrine sediments (OC), elaborated by spectrometry (NF ISO 14235). Sediment OC was oxidized in a sulfochromic environment with an excess of potassium dichromate at 135 °C. Subsequently, the determination of chromate ions Cr^{3+} formed was analysed by spectrometry.

For total nitrogen (TN), the method used was based on the Kjeldahl mineralization (ISO 11464: 1994), but the catalyst used was the titanium dioxide (TiO_2). The technique consists in assaying the total nitrogen content in the sediment as ammonium, nitrate, nitrite and organic form.

Carbonates were measured by adding HCl to the bulk sediment to decompose all carbonates (NF ISO 10693: Juin, 1995). The volume of the carbonic gas produced was measured using a Scheibler apparatus.

Stable isotope ratios measurements of carbon were performed on a Thermo Fischer Flash 2000 Elemental Analyzer in line with a VG Isoprime Mass Spectrometer at the University of Bordeaux. All samples were pretreated with 1N HCl to remove inorganic carbon. The analytical precision of 0.15‰ was estimated from several calibrated laboratory standards analyzed along the samples. Stable isotopic ratios were reported as: $\delta^{13}C = [(^{13}C/^{12}C_{sample} / ^{13}C/^{12}C_{std}) - 1] * 1{,}000$, where the standard used is Vienna Pee Dee Belemnita (PDB)

Besides the multi-proxy analysis, four organic samples were dated. All this dates have been done on bulk sediment. We used the BACON software (Blaauw and Christen, 2011) to compute the age/depth model (Fig. 2). The default ^{14}C calibration curve used by BACON for terrestrial northern hemisphere samples is IntCal13. The AMS ^{14}C dates were also calibrated using the "CALIB 7.1" program (Stuiver and Reimer, 1986; table 1). The fossil record continuously encompassed the last 6000 years.

Annual precipitation (Pann), mean January temperature (Tjan) and precipitation seasonal index (SI) assessment (Fig. 3) were based on pollen data as follows:

$$PSI_{(s)} = (\sum P_w - \sum P_s)/\sqrt{P_{ann}}$$

Where PSI(s) is the seasonal index quantified for sample s; Pw is the sum of December, January and February precipitation; Ps is the sum of June, July and August precipitation; Pann is the total annual precipitation.

The monthly mean precipitation and Tjan were obtained using the probability density function of modern plant species (pdf-method). This method is described in Chevalier et al. (2014). In order to apply it to a fossil pollen record collected in the Mediterranean area it required a modern database of Mediterranean plant species distributions and their corresponding modern climate variables. We used a database of plant species that have been georeferenced from *Flora Europaea* (Jalas et al. 1972, 1973, 1976, 1979, 1980, 1983, 1986, 1989, 1991, 1994) and Hulten and Fries (1986). Additional geographical distributions were obtained from GBIF (2012) and personal field observations using GPS in Morocco. In order to use plant species distributions for the pollen-based climate reconstruction we assigned pollen taxa to the most probable plant species in our plant database (table 2). The modern climate variables were extracted from the WORLDCLIM database (Hijmans et al., 2005) and interpolated onto the species occurrences for inferring their pdfs.

4 Results

During the last 6000 years, the main change in the forest cover is marked by a decline of the pine populations, the expansion of Atlas cedars after 3750 cal BP and the persistence of the evergreen oaks. Although the latter dominate today the landscape around Lake Hachlaf, the microscope identification of the fossil pollen grains that originate from deciduous or evergreen plants may often be dubious and therefore, may not be reproducible by another pollen analyst. We have assigned all oak pollen grains to the evergreen *Quercus ilex* in the climate reconstruction since it is the species that dominates the landscape and its climate envelope encompasses that of the other evergreen species (Fig. 4). All other taxa, including trees, shrubs and herbs, also show some changes but within a much lower range than that of the two conifer taxa, Atlas cedar and pine (Fig. ~~4~~5). We have applied a constrained cluster analysis to depict the main changes in the pollen fossil record. There are four main clusters summarizing the main changes in the ecosystem composition around Lake Hachlaf over the last 6000 years (table 3).

The grain size analysis revealed the presence of three fractions (Fig. 3) with the following proportions: clay (22.87%), silt (60.46% with 41.9% of fine silt) and sand (16.67 %). The dominant silty fraction tends to increase from the bottom to the top of the core after a brief decline between ca. 5600 and 5200 cal BP. The sandy fraction follows the same pattern. Clay shows an opposite trend to both the sandy and silty fractions.

Carbonates ($CaCO_3$) content is high throughout the record except around 5200 cal BP (Fig. 3). They are positively correlated with silt and sand. The total organic carbon (TOC) content is also high and varies significantly between 4 and 27.4% (Fig. 3). The total nitrogen (TN) remains low throughout the record. The carbon to nitrogen ratio (C/N) varies between 9 and 17.4, and the δ^{13}Corg between –21 and –27‰ (Fig. 3). Two origins of the organic matter are thus identified, with lake algae characterized by C/N < 11 and very depleted δ^{13}Corg and terrestrial plants characterized by C/N > 11 and less depleted δ^{13}Corg (Fig. ~~5~~6). ~~-~~δ^{13}Corg and C/N are positively correlated (Fig. 3). TOC and TN are highly correlated (0.99, Figs. 3 and 6) as well.

In order to interpret the different bio and geo-chemical proxies within a climatic frame, a pairwise correlation was performed between the three climate variables and δ^{13}C, C/N, TN and TOC (Fig. ~~6~~7). Although there could be no causal relationship, SI and Tjan are well correlated together. They are both correlated negatively with δ^{13}C and C/N and positively with TN and TOC (Fig. ~~6~~7).

5 Discussion

The Holocene climate around the Mediterranean Sea was suitable for the expansion of human populations and their organization towards true civilizations (Kaniewski et al., 2012). The persistence and longevity of many Mediterranean populations may be linked to the relative suitability and also to an overall stability of the Holocene climate. However, climatic events have been recorded within the Holocene (e.g. Rohling and Pälike, 2005) and a causal relationship has been made between some abrupt climatic events and societal changes in the Mediterranean (Berger and Guilaine, 2009; Kaniewski et al., 2008).

In the present study, we have focused on the environmental and climate changes that occurred during the last 6 millennia in the northern part of the Moroccan Middle Atlas Mountains. We have evaluated the vegetation dynamics using the palynological content of a fossil sequence and analyzed its bio- and geo-chemical content to reconstruct the overall landscape changes.

The reconstructed Tjan and Pann show a relatively low amplitude of change over the last 6000 years (Fig. 3). *P*ann decreases progressively by ca. 100mm which is in line with the aridity trend that has been observed in other fossil records (Risacher and Fritz, 1992; Brooks, 2006; Hastenrath, 1991; Anderson and Leng, 2004; Umbanhowar et al., 2006) and particularly in the Mediterranean area (Pons and Reille, 1988; Julià et al., 2001; Burjachs et al., 1997; Yll et al., 1997; Roberts et al., 2001; Valino et al., 2002, Jalut et al., 2009) and northern Africa (Ritchie, 1984; Ballouche~~ et al.~~, 1986; Lamb et al., 1989). At a more regional scale, reconstructed Pann is coherent with that obtained from Lake Tigalmamine (Cheddadi et al., 1998) which shows a decreasing trend over the last ca. 5000 cal BP. The arid trend observed after ca. 5ka cal BP is marked by a spread of Poaceae and a progressive replacement of pines by Atlas cedars which better stand the high seasonal contrast of precipitation at the altitude of Hachlaf Lake. SI increases from 3 to 7 times over the last 6000 years (Fig. 3). A study of drought thresholds influencing the growth and photosynthesis was performed on different cedar stands and species (*C. atlantica*, *C. libani*, *C. brevifolia* and ~~&~~ *C. deodora*) of different origins (Aussenac and ~~&~~ Finkelstein, 1983). This study showed that among many conifers, cedar trees may keep a sustained photosynthesis activity even when drought is very high. Thus, a strong precipitation contrast between Ps and Pw (Fig. 3) may not affect the Atlas cedar overall growth as long as the total amount of rainfall is sufficient (higher than 600 mm/year) and the winter temperature is low enough (below 6°C) for the vegetative cycle (Aussenac et al., 1981). The Mediterranean climate is known for its strong seasonal distribution of precipitation throughout the year. Summers are fairly dry and most of the annual precipitation occurs during the cold months (end of autumn and beginning of winter).

Currently, 75% of the Moroccan territory with a grassy or wooded vegetation (thus excluding the desert) records between 500 and 800mm of annual rainfall with an SI between 5 and 8 (Fig. ~~7~~8). The whole range of SI in Morocco is between –1 in areas where *P*ann is less than 100mm with a random distribution as for instance in the South of Morocco, and 15 in areas where the annual rainfall is quite high (over 800 mm) and occurs mainly in the winter season such as in the Rif mountains today (Fig. ~~7~~8). SI is higher in mountainous areas. Nowadays, in the areas surrounding Hachlaf lake (located at ca. 1600m elevation) SI is around 5. Such SI has changed over the past thousand years as confirmed, at least between 6000 cal BP and today, by the studied fossil archive (Fig. 3). The amplitude between Pw and Ps precipitation has increased 2 to 3 times towards the present (Fig. 3). Since *P*ann has a decreasing trend, the opposite increased seasonality is related to a significant reduction in the amount of rainfall during the months of June, July and August (Fig. 3). This strengthening of the contrast between Pw and Ps had a rather limited impact on the dominating taxa because they can withstand the summer drought and the overall amount of Pw remained sufficient for their persistence. However, a change in the amplitude of SI has probably favoured those species best adapted to the length of the dry season, as for instance evergreen oaks rather than deciduous. Pollen-based climate reconstructions from records collected in the Alboran Sea (Combourieu-Nebout et al., 2009) and Italy (Magny et al., 2013; Peyron et al., 2013) suggest a rather steady and low seasonal contrast between Pw and Ps (about two times) over the past 6000 years cal BP. Such discrepancy between the reconstructed SI from Hachlaf and the marine record may potentially be related to the fact that marine records collect pollen grains from a much wider geographical source area than continental (mountainous) records which probably tends to smooth the local/regional changes. The reconstructed seasonality from the Italian records (Magny et al., 2013; Peyron et al., 2013) is buffered by the less abrupt precipitation seasonal contrast at the European temperate latitude than at the arid Mediterranean one.

SI was lower than 5 before 3750 cal BP despite an amount of precipitation between 600 and 700 mmyr^{-1} (Fig. 3). During that period, water probably persisted in the lake all throughout the year which allowed the presence of aquatic plants (Fig. ~~4~~5) flowering during late spring and summer, and algae identified in the pollen data, through the low values of δ^{13}Corg and the C/N ratio being greater than 11 (Figs. 3 and 5). The proportion of aquatic plants cannot be directly related to a high lake level and may not be used to state the lake level changes but only the presence of water in the site. The δ^{13}Corg and C/N (Fig. ~~5~~6) provide information concerning the origin of the organic matter (*in situ* production versus input from the catchment area) but not on the lake level changes. Thus, high δ^{13}Corg and C/N ratios (Fig. 3) with low presence of aquatic plants (Fig. ~~4~~5) may not be inconsistent in cases where there is a low terrestrial input (low Sand/Silt, Fig. 3) during a period when the lake level is high.

The relationship between δ^{13}Corg and the C/N ratio indicates the occurrence of two main types of organic matter mainly originating from a C3 metabolism. Lacustrine algae can be considered as dominantly autochthonous; in the lower part of the record, the organic matter, with higher C/N ratios and less depleted δ^{13}Corg corresponds to a terrestrial input. Indeed, Fresh organic matter from lake algae is known to be protein-rich and cellulose-poor with molar C/N values commonly between 4 and 10, whereas vascular land plants, are protein-poor and cellulose-rich, creating organic matter usually with C/N ratios of 20 and greater (Meyers, 1994, 2003). However, a C/N ratio > 11 may correspond to a mixture of both local and terrestrial organic matter (Fig. ~~5~~6).

After 3750 cal BP, Atlas cedars noticeably spread around the site while the pine populations strongly regress. A series of fossil pollen records in the Middle Atlas show that Atlas cedar populations expanded after ca. 6 ka cal BP. The sustained expansion of Atlas cedar after ca. 3750 cal BP around Hachlaf Lake expresses its late occurrence at higher altitude. Around lake Tigalmamine (Lamb et al., 1995), the Ras El Ma marsh (Nour El Bait et al., 2014) and the Ait Ichou marsh (Tabel et al., 2016) which are all located at about 100 to 200 meters altitude below Hachlaf lake (ca. 1700m asl), Atlas cedar occurs much earlier. The expansion of Atlas cedar around the lake is probably related to both an upslope spread and a south-north migration.

During this ecosystem transition we observe a major change in both Pann and Tjan. The increase of SI after 3750 cal BP is due to a combined increase of Pw and decrease of Ps (Fig. 3). The expansion of cedar forests in the studied area may be related to their better adaptation to strong SI than pines at higher altitude.

Competition is another parameter that might be worth considering. After 3750 cal BP, the C/N ratio is below 11 and the δ^{13}C remains below –26‰ which suggest the important primary productivity of the lake associated with low input of land plant derived organic matter. Atlas cedar forests have a more important growth in both height and diameter than pines which leads to a higher biomass production. This is linked to the genetic model of growth that is very distinct between the two taxa (Kaushal et al., 1989). Thus, the expansion of Atlas cedar population around the site may explain the high input of OM into the lake.

Over the last six millennia, superimposed to the overall climate trend, we observe one relatively abrupt event between 5500 and 5000 cal BP during which Tjan declined by about 2°C compared to its average over 6000 years. A climatic transition between 6 and 5 ka cal BP at the end of the Holocene thermal maximum has been globally identified (Steig, 1999; Mayewski et al., 2004; Wanner et al., 2008; Brooks, 2012). This transition has been recorded by a wide range of climate proxies (e.g. Kaufman et al., 2004; Jansen et al., 2009; Seppä et al., 2009; Bartlein et al., 2011) and has been related to different biosphere feedbacks and potentially to a decay of the remaining Laurentide ice sheet (Renssen et al., 2009). All proxies from the Hachlaf sequence as well as the reconstructed climate variables have recorded marked changes during that period of time. SI has the lowest value of the record and a succession of abrupt changes are recorded in the C/N ratio, the grain size fractions, the δ^{13}C, TN, TOC and $CaCO_3$ (Fig. 3). Carbonates, considered as a “paleo-thermometer” (Meyers, 1994, 2003), also decrease abruptly around 5200 cal BP (Fig. 3). The latter may be linked to a low evaporation of the lake which may have been favored by low winter temperature around 5200 cal BP. The fine grain size sediment also increased as a consequence of low seasonal precipitation contrast and/or a continuous sediment input to the lake. Such sustained input of clay and decreasing carbonate content suggest a higher lake level between 5500 and 5000 cal BP (Fig. 3). Thus, the Tjan and SI decrease may have contributed to the higher lake level or at least to the presence of water throughout the year (Fig. 3). At the same time, the sand to silt ratio is very low which confirms a low energy during the sedimentation process. The major change in the ecosystem composition around the lake is the rapid collapse of the pine forest which has inevitably released an important amount of terrestrial carbon (biomass) into the lake (positive peaks in $\delta^{13}C$ and C/N, Fig. 3).

6 **Conclusions**

This study marks a new contribution to the knowledge of past climates and environmental history in North Africa mountainous areas. The range of climate change in the Middle Atlas, Morocco, was rather minor between 6000 cal BP and the present. Annual precipitation and January mean temperature have respectively varied within a range of 100 mm and 2 to 3°C. However, they both show a trend towards a more arid and warmer climate as well as a higher rainfall seasonality. Pann became as contrasted as today after 3750 cal BP. The aridity trend observed in Hachlaf over the last 6000 years is consistent with other climate reconstructions available from other Mediterranean fossil records. Besides these overall climatic trends, we also observe an abrupt cold event between 5500 and 5000 cal BP which is well marked in all environmental proxies from our studied fossil record. The $\delta^{13}C$ and C/N ratios, which are well correlated together, suggest an increase in the organic matter input from the catchment area. Concomitantly, the pollen record indicates a decline of the pine forest which may have contributed to the organic matter input into the lake too. The marked change in both the carbonates content and clay composition of the record were probably related to a perennial presence of water throughout the year. Synchronously, seasonality index and January mean temperature were the lowest of the record which has contributed to a reduction of the evaporation.

The increase in rainfall seasonality has probably favored the expansion of Atlas cedars around the studied site at the expense of the pine forest.

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Depth (cm)	Material dated	^{14}C age yr BP	95,4 % (2δ) cal age ranges (BP)	Relative area under probability distribution	Median probability cal BP
60	Bulk	2535 ± 30	2494 – 2746	0,447	2624
120	Bulk	3220 ± 35	3371 – 3509	0,936	3436
170	Bulk	4390 ± 35	4859 – 5047	0,991	4949
240	Bulk	5200 ± 40	5897 – 6021	0,943	5958

Pollen taxa	**Plant species**
Alisma	*Alisma plantago-aquatica*
Alnus	*Alnus glutinosa*
Berberis	*Berberis hispanica*
Brassica	*Brassica*
Campanula	*Campanula afra*
Caryophyllaceae	Caryophyllaceae
Centaurea	*Centaurea cyanus*
Chenopodiaceae	Chenopodiaceae
Asteroideae	Compositae Subfam. Asteroideae
Cichorioideae	Compositae Subfam. Cichorioideae
Corylus	*Corylus avellana*
Cupressaceae	Cupressaceae
Ephedra	*Ephedra fragilis*
Euphorbia	*Euphorbia characias*
Geranium	*Geranium macrorrhizum*
Helianthemum	*Helianthemum canariense*
Ilex	*Ilex aquifolium*
Juglans	*Juglans regia*
Myriophyllum	*Myriophyllum aquaticum*
Plantago	*Plantago lanceolata*
Polygonaceae	Polygonaceae
Ranunculaceae	Ranunculaceae
Salix	*Salix pedicellata*
Saxifraga	*Saxifraga*
Taxus	*Taxus baccata*
Urtica	*Urtica dioica*
Papaveraceae	Papaveraceae
Pinus	*Pinus halepensis*
Olea	*Olea europaea*
Paronychia	*Paronychia argentea*
Erica	*Erica arborea*
Quercus	*Quercus ilex*
Cedrus	*Cedrus atlantica*
Artemisia	*Artemisia herba-alba*

Zones	Depth (cm)	Age (cal BP)	Pollen data description		
Zone I	250 – 190	6227 – 5171	AP	27 – 60%	- Mainly *Quercus* and *Olea*. - Peak of *Pinus* (47%) at 6100 cal BP then decreasing. - Low percentages of *Cedrus atlantica* with initial spread around 5800 cal BP.
			NAP	39 – 72 %	- Herbs dominated by Poaceae (11 – 48 %), *Illecebrum* (3 – 19 %), Apiaceae (2 – 5 %), Brassicaceae (1 – 5 %), Asteraceae (0 – 5 %), Cichorioideae (1 – 6 %), Chenopodiaceae (0.5 – 2 %) and Cereals (0 – 1 %).
			DT	18 – 26	- Rapid fluctuations
Zone II	190 – 111	5171 – 3651	AP	28 – 56 %	- *Pinus* dominates the pollen record but regresses at 5500 cal BP (from 44 to less than 2 %). - *Cedrus atlantica* continues to expand (0 – 5 %). - We observe a peak of Rosaceae (6 %).
			NAP	43 – 72 %	- Herbs are dominated by Poaceae, *Illecebrum* and Asteraceae which reach their maximum (53, 20 and 10 %, respectively). - Cereals disappear.
			DT	19 – 29	- Moderate to high with two peaks.
Zone III	111 – 60	3651 – 2351	AP	23 – 58 %	- Strong expansion of *Cedrus atlantica* and *Quercus*. - An abrupt decline of *Cedrus atlantica* around 2653 cal BP is recorded. - *Pinus* regresses as well but shows a peak of 20% at 3300 cal BP.
			NAP	41 – 76 %	- Herbs dominate the pollen record. - Sharp decline in Poaceae, Asteraceae, Chenopodiaceae and Caryophyllaceae at 5600 cal BP. - Appearance of Cereals around 2653 cal BP.
			DT	20 – 31	- High.
Zone IV	60 – 5	2351 – 173	AP	23 – 43 %	- Abundance of *Cedrus atlantica*, *Quercus*, *Olea* and Rosaceae. - Sharp decline and disappearance of *Pinus*.
			NAP	56 – 76 %	- Herbs continue to dominate the pollen record with Poaceae, Cereals, Brassicaceae, Chenopodiaceae and Caryophyllaceae which are most abundant. - Asteraceae, *Illecebrum* and Apiaceae decline. - Centaurea and Cichorioideae disappear.
			DT	21 – 32	- High.

Table 1. Radiocarbon ages for the Hach-I core. Calibrations were performed using Calib 7.1 (Stuiver and Reimer, 1986).

Table 2. Pollen taxa assigned to the most probable plant species in our plant database.

Table 3. Pollen zones identified in the fossil record using a constrained cluster analysis. AP: arboreal pollen taxa, NAP: non-aroboreal pollen taxa, DT: taxa diversity.

Figure 1. The study area. **(a)** Geographical location of the tabular and pleated Middle Atlas (MA); **(b)** sketch of the geological and geomorphological characteristics of the Hachlaf area (from Martin, 1973); **(c)** phytoecological map showing the main ecosystems and the location of the Hachlaf Lake (Dayet Hachlaf) within an oak forest (from Lecompte, 1969).

Figure 2. **(a)** Lithology of the core Hach-I and radiocarbon ^{14}C dates; **(b)** age/depth model from BACON software (Blaauw and Christen, 2011).

Figure 3. Diagram showing the sediment fractions (clay, silt and Sand/Silt ratio), the pollen percentages of *Cedrus atlantica* and *Pinus*, geochemical elements (delta 13 C [δ^{13}C‰], nitrogen to carbon ratio [C/N], total organic carbon [TOC], Total Nitrogen [NT]) and carbonates concentrations ($CaCO_3$), January mean temperature (Tjan), Annual precipitation (*P*ann), winter and summer precipitations (Pw and Ps) and precipitation seasonality index (SI). The red rectangles are pointing the values of present-day Tjan, Pann, Pw and Ps (HCEFLCD, 2004), t~~. T~~he red line shows the limit 3.7 ka cal BP and the blue rectangle shows the time interval of the cold phase 5.2 cal PB~~ and therefore the response of the main proxies studied~~.

Figure 4. Density plots of Tjan for the three dominating *Quercus* species in Morocco (*Q. ilex*, *Q. coccifera* and *Q. suber*). The median values are the following for *Q. ilex*: 6.5°C, *Q. coccifera* = 7.4°C and *Q. suber* = 7°C.

Figure 5. Diagram showing the percentages of the main pollen taxa identified in the Hach-I core. Cyperaceae and Juncaceae are included within aquatic taxa. The dashed black curves shows an exaggeration (×7) of the percentages of some taxa. On the right, pollen zones with their boundaries are set up using a constrained hierarchical clustering (R Development Core Team, 2013). The taxonomic diversity is computed using a rarefaction analysis. The red line shows the limit 3.7 ka cal BP.

Figure 6. ~~**Figure 5.**~~ δ^{13}C and C/N bi-plot (from Meyers, 1994).

Figure 7. ~~**Figure 6.**~~ Pairwise correlation between the three climatic variables (Tjan, *P*ann and SI) and the chemical elements.

Figure 8. ~~**Figure 7.**~~ Modern SI (upper panel) and *P*ann (middle panel) from the gridded WorldClim dataset (Hijmans et al., 2005) over Morocco. The lower panel shows the distribution of *P*ann vs. SI: the lowest index occurs in southern Morocco where *P*ann is lower than 200 mm.y^{-1} and the highest index occurs in the high altitudinal areas (Middle Atlas and Rif mountains).