Comments on “Late Holocene vegetation changes in relation with climate fluctuations and human activities in Languedoc (Southern France)” by J. Azuara et al.

Reviewer 1: J. Carrión (Referee)

This is an excellent paper, and I have no hesitation to suggest acceptance in its current form, and congratulate the authors.

Thank you very much we are glad you appreciate the paper.

Reviewer 2: Anonymous

The manuscript presents a new pollen record from a coastal lagoon located in southern France (Palavas) spanning the past 4500 years. Sediments from the same core had already been studied to reconstruct the frequency of storm events and the link between variations of past storm frequency and mechanisms causing climate changes. The lagoon is located in a region that has been settled several millennia ago, and has archeological and environmental-archaeology records that are sufficiently vast to get an, at least, qualitative picture of settlement history and past land-use changes. The authors use pollen percentages, pollen-percentage ratios of selected taxa, and storm frequency as inferred from sedimentology to investigate the links between storminess in Palavas and changes in vegetation composition in the surroundings of the lagoon.

They also compare the records from the sediment core to glacier advances in central Italy and to ice-rafted debris records from the N-Atlantic (Bond events). A substantial part of the manuscript deals with vegetation history in relation to land-use changes during the Antiquity and Historical times.

The data presented in this manuscript seem interesting but the manuscript itself could be substantially improved. At some points it is sloppy under several aspects (interpretation, structure, figure quality, captions). I therefore invite the authors to revise the manuscript profoundly and invite them to consider the few suggestions here below:

Thank you very much for your comments and advices. We answer below each of your comments.

General comments:

1. Writing style should be revised. I found it particularly disturbing to read at times that Fagus decreased", or "increases in Quercus:". The authors should take care of making a clear distinction between the evidence (pollen percentages) and the interpretation (population-size changes, vegetation composition).
Corrected

2. The hypotheses that are going to be addressed should be clearly declared in the Introduction. The aim of the study, as declared in the Intro, is to "deciphering climatic and human causes of environmental changes". However, when I arrived at the end of the manuscript I could neither figure out if this was actually achieved nor could I understand how it had been done.
Corrected. We modified the introduction in order to make our aims clearer.

The authors first discuss (5.1) the effects of the “long-term aridity trend” on vegetation, which caused the disappearance of Fagus and Abies stands in the warmer lowlands near the lagoon. However, surprisingly they state that variations of Fagus pollen % after 1084 cal BP (AD 866) are independent of climate changes “they cannot be interpreted in term of climate fluctuations because of the strong human influence”. Later (6.1) they discuss the effects of the long-term aridity in relation to evergreen-oak-forest development: they arrive at the conclusion that the evergreen oak were favoured by anthropogenic activities already starting from at 4000 cal BP.

The reader is therefore confronted with an interpretation envisaging that some trees (Abies and Fagus) migrated northwards because climate became drier, while other species (Quercus ilex) established and expanded because of human activities.

I wonder two things here: first, how was the date 1084 cal BP found? There is a dating precision in this age estimate that suggests it has not been determined based on the pollen record;
Corrected. This very precise age is in reality the estimated age (cal BP) of the last sample before the important deforestation recorded during the 10th century. So we replaced it by an approximate age which is much more appropriate (around 1100 cal BP).

second, how can the authors reject a theoretically possible alternative hypothesis, which envisages that changes in vegetation composition were favoured by the combined effects of both climatic changes and anthropogenic activities? Regardless, I found that the discussion could be improved, particularly concerning the palaeoecological records of evergreen Quercus. There's some recent literature that could be useful. One paper to start with: Henne et al. (2015).
We are not rejecting the hypothesis that the variations described in the article could be the result of both climatic and human influences. We just pointed out that variations in Fagus proportions (and Abies to a lower extend) are highly correlated with climate fluctuations and not with human activities. At the same time, the variations in arboreal taxa and evergreen Quercus proportions don't match with climatic records while they are in good agreement with the archeological and historical record. Therefore, even if the environments are influenced by both climatic and human factors, some pollen taxa are good proxies of climate changes while others are better to evidence anthropogenic impact.

Also, concerning the expansion of evergreen oaks, the authors conclude that (last sentence of Conclusion) that "evergreen Quercus expansion is related to coppicing and the increase in fire frequency". However, the authors have no data for fire frequency at Palavas and base their conclusion on studies focusing on fire disturbances in eastern Spain (Pinol 1998) and in Europe (Schelhaas et al 2003). The Schelhaas reference does, however, not support the authors' statement because Schelhaas et al. (2003,page 1629) wrote that "Figure 3 shows a fast increase in the number of forest fires over time. This apparent trend is most likely also influenced by the aforementioned increase in forest fire detection and alertness. However, it is impossible to separate this trend into a real increase and an apparent increase due to better detection methods." Hence the conclusion that "evergreen Quercus expansion is related to fire frequency" seems unsopported by data.
Corrected, we moderate our conclusions.

In this paper there are also other hypotheses that have been addressed: (i) the potential effect of climatic changes that occurred in correspondence with Bond events on vegetation in Palavas (and thus on the S-French coast); (ii) the vegetation history of the surroundings of Palavas in relation to land-use changes during the Antiquity and Historical times. The latter part reads differently than the former one because the text follows a different narrative style, it is more focussed on describing historical facts and their link with vegetation history. I found this part interesting but could not figure out what research question the authors wanted to address. Again, the Introduction failed to introduce the goals and aims of the paper. In summary, the authors should declare in the Intro the aims of the study, thus also including hypothesis (i) and the more descriptive part (ii). What where the expectations (hypotheses) of the authors? Which hypotheses were rejected? Also, it would be useful to summarize the land-use changes that are discussed in the text in a table, giving age limits for each period.
Corrected, we completed the introduction according to you suggestions and ages have been added to the table describing the main vegetation changes.

3. The link between changes in vegetation composition and storminess is unclear. The authors should better declare their hypothesis in the Introduction.
Corrected we modified the introduction to clarify the aims of the paper.

Which effects do they expect from storminess on vegetation composition?

No direct effects of storminess on the vegetation were expected and actually no such effects were observed. We compared our data with the storminess record because it is an interesting and complementary climate proxy available in the same core which make the comparison more reliable, especially for correlation with Bond events.

In section 5.2. one can see that the storminess record was compared to the Fagus/Quercus ratio. The authors explain that Fagus is at the southern distribution limit in this region and that it therefore may be sensitive to variations in moisture availability (besides, the authors could support this basic assumption with references to studies showing this). Hence decreases of the F/Q ratio are interpreted as indicating "arid events" related to Fagus pollen decreases. What is unclear is: why did they use the F/Q ratio rather than just the Fagus % record?
Arid events are highlighted by Fagus proportions minima coinciding with deciduous Quercus proportions maxima. Doing the ratio of these two variables was the easiest way to represent their variations with just one curve.

Also, in which season of the year do storms occur at present? Does the season of occurrence of storms coincide with the drier season for Fagus (a deciduous tree)? Further, what is most striking is that the duration of low F/Q-ratio values is rather short compared to the duration of low storminess. One may thus wonder why Fagus population would recover after few centuries although the climatic conditions remain dry?
The storms occur in winter while the dry season is summer. The link between storminess and aridity/humidity is not straightforward. Fagus proportions and storminess are two different proxies linked with the atmospheric circulation in the north-Atlantic. We compared them in order to find common patterns. The closeness in time of arid events and high storm activity periods suggest that this variability is linked with changes the atmospheric circulation. However these two proxies are probably also influenced by other factors and that's why their fluctuations are not completely consistent. In the future, a detailed statistical analysis need to be done when the palynological data will be available for the last 7500 years to better understand the link between aridity and storminess.

4. The Fagus pollen decreases are interpreted as "northward migration of Fagus at higher altitudes". I'm rather surprised and puzzled by this interpretation and invite the authors to think better at what "migration of plants" means. For example, this interpretation implies high dispersal rates and dispersal distances, and low ages to reach reproductive maturity for Fagus trees. Have the authors done such calculations? Are the figures obtained realistic? There are possibly other, more realistic alternatives to this interpretation, and I would invite the authors to explore other interpretations.
Corrected. We modified this conclusion. We choose to interpret decreases in Fagus pollen proportions in term of "contraction range" that may also have been amplified by drops in pollen productivity due to environmental stress.

2. The authors discuss the changes in storminess and vegetation composition in terms of "NAO-like" climatic patterns. However, to do this consistently they might also discuss, in my humble opinion, the following aspects in order to give the reader a complete picture: the NAO index describes weather patterns in winter (Nov-Mar), and thus a link between Fagus and NAO would imply that Fagus needs precipitations in winter. Do the authors have any evidence to support this hypothesis? Wouldn't Fagus need moisture during the dry summer months (say July-August)? What is the link between NAO and July-August precipitation?
In the Mediterranean region Fagus forests can grow outside their optimum area and support the lack of precipitation in summer getting water from localized fogs. Because Fagus is able to get water without precipitations it is difficult to link Fagus repartition with summer precipitations. Spring precipitation are probably more crucial.
We are aware that the relation between the arid events and the NAO-like climatic pattern remain unclear. We choose to present this mechanism as an hypothesis because it is an explanation often found in the literature which is consistent with some aspects of our study. More data are needed to fully understand the mechanism that explain the observations made in Palavas. The aim of this paper was just to separate climatic and human influence. In the future, we want to dedicate an entire survey to the climate variability in the southern France including a longer record, a more extensive comparison with other data and a careful mathematical analysis.

3. The link between Bond events, 14C production, storminess, and changes in vegetation composition is explored in Chapter 5.2. Concerning this chapter it is a pity that the reader hardly gets to know that the comparison between Bond events, 14C production, and storminess had already been discussed and published in a previous paper (Sabatier et al. 2012). This should have been mentioned in the Introduction.
Corrected. We added a sentence in the introduction

Also, the last paragraph of this chapter (dealing with wavelet analyses and solar forcing) seems out of place, or has not been sufficiently introduced.
We just wanted to put into perspective our results with the forcing factors of Holocene climate variability. We modified the paragraph to make it clear.

4. The authors conclude that the variations of the "deciduous Quercus/evergreen Quercus" pollen % ratio might be the evidence of anthropogenic activities", which therefore caused evergreen oaks to replace deciduous oaks. Here again, as in the case of the F/Q ratio, I wonder if the Q/Q-ratio has been validated and/or calibrated to show that it can be used to infer ’aridification’ or ’anthropogenic activities’. Following questions arise: is the ratio not influenced by variations of other pollen taxa as well? Is the ratio representative of which anthropogenic activities? If so, it would make the interpretation stronger. If not, I would suggest to omit the Q/Q-ratio curve. But regardless, it would be useful to plot the simple pollen percentages of Fagus, deciduous Quercus, evergreen Quercus in Figure 3.
The Q/Q-ratio is use by Jalut (in Jalut et al 2009) on a wide range of palynological data from the Mediterranean area as an indicator of the late Holocene aridification. We wanted to compare our data with these results to show that in Palavas region, this ratio is unlikely related with climate. Archeobotanical and ecological studies suggest that in our case, evergreen Quecus forest dynamic seems much more related to human activites. Even if this ratio don’t represent a specific type of activities, we think that this comparison is important to assess that the interpretation of a same indicator (in this case Q/Q-ratio) can be different from an area to another.

Methods are not sufficiently explained:
- There are several issues with the chronology (see detailed comments for Page 4128);
Corrected
- The use of ratios of pollen percentages is not justified;
Corrected. We added a sentence to justify into the article the use of ratios.
- which pollen keys were used to identify pollen grains?
Corrected

- On what data is the vegetation map based? Please cite the source or explain the method used to draw the Figure 1c (see further comments below)
Corrected

Figures are sloppy (see detailed comments for Figures below). A Table with 14C datings and other control points (storm events) used to establish the age-depth model should be added.
We added a table with all the dates and control points as an annex of the article.

Detailed comments:

Abstract:
- 2nd sentence: separating the effects is not needed to "reconstruct paleoenvironments". Please rephrase sentence

Corrected

- L10: why are arid events also periods of "climatic instability"? Did all other periods have a stable climate?
Corrected. "Climatic instabilities" was not appropriate so we replaced it by "periods of high frequency climate variability" in reference to the two phases pattern observed in these very short time periods.

- L13-14: few lines above you said that there was a "long-term aridification". Now you say that spread of evergreen taxa and loss of forest cover result from anthropogenic impact. The two statements are not consistent with each other because a shift to drier climate conditions might also have caused loss of forest cover and a spread of evergreen angiosperms.
It is true that anthropogenic impact also could have led to deforestation and spread of evergreen Quercus. This is why it is so difficult to separate human activities consequences from climatic impact on the vegetation. However in Palavas region, the comparison of our palynological data with climate proxies and archeological and historical archives demonstrate that evergreen Quercus forest dynamic is probably more related with anthropogenic impact.

Please note here (and elsewhere in the text) that the term "evergreen taxa" also includes many conifers, such as Abies...which in your interpretation decreased due to aridification. Hence, please change the term 'evergreen taxa' unless you want to include most conifers.
Corrected

- L4-5: Why is this relevant? If Capestang had a well-dated pollen record, why is it necessary to be mentioned here? Is it because you plan to compare your results with the Capestang record? Or are there other reasons?
It is relevant to introduce Capestang because we compared our results with these sequence (part 5.1).

- L6: I'm not really sure that a sampling resolution of 2-10 cm can be truly termed "high resolution". But I know that many use the term in a generous way.
The time-interval between each sample is around 50 years or even smaller for most of the samples, which can be termed "high resolution" dealing with pollen analyses and vegetation history.

- L22: in the previous paragraph you mentioned the "lagoons", in this sentence there's only one lagoon, hence the question: which one?
Corrected

Page 4127
- Lines 1-19: the description of the distribution of the dominant taxa is very useful. However, the source of the information given in this paragraph and in Figure 1b is unknown to the reader. Is it a result of the current study? If so please explain in the Method section what has been done. If not, please cite the source.
Corrected. We used the vegetation maps of the national forestry inventory.

Also, Ericaceae are also abundant in some environments. Given that Ericaceae pollen % show an interesting pattern, could the authors also introduce the distributions of species belonging to that family in this paragraph and in Figure 1b?
Corrected. The national forestry inventory maps we used in order to draw the map presented in Figure 1 are mostly interested in trees. Thus, they contain few information about Ericaceae distribution. We know by by field experience from other works that many Ericaceae are present in all the region such as Erica arborea, E. multiflora, E. cinerea, E. scoparia, Calluna vulgaris, Arbutus unedo. We completed the vegetation description.

Further, for Figure 1b following questions seem relevant to me: - what do the circles indicate? Vegetation surveys in a plot? A tree? A minimum abundance/density of the species? - sometimes the circles are so well connected to each other that a line appears. What do the lines indicate? Surveys along a track?

Each spot represent a forest patch according to the maps of the National Forestry Inventory.

-L13-14: distinguished in routine pollen analysis, “which limits the interpretation of Pinus pollen variations in terms of…” ?
Corrected. We added “in terms of vegetation changes and climate variations”

Page 4128
L5: here you mention "the last 5 millennia" but at the end of the paragraph you mention "the last 7000 years". Please correct one of the them.
Corrected

L13: eight, not height in PB06
Corrected

L22: Cerastoderma glaucum
Corrected

L23 and following: it is unclear to what extent the present chronology of PB06 coincides with the chronology of the same core as published in previous papers. The authors refer to Sabatier & Dezileau (2010) and Sabatier et al (2012). I looked at those two papers and noted some inconsistencies that would be worth to address in the current manuscript: The authors mention that 14C ages were calibrated with Calib 5.2 as in Sabatier & Dezileau (2010). However, in Sabatier & Dezileau (2010) only the top 300 cm of the core where published, the chronology was shorter than in the present manuscript, and Calib 5.0.2 was used, not Calib 5.2. On the other hand, in Sabatier et al. (2012) one can read that the chronology was obtained using an age-depth model software (Clam) but nothing is said concerning the calibration software or calibration dataset. Please clarify which software, which calibration dataset, which reservoir age, and which storm events were used to build the age-depth model. Please add that as a table as supplementary material because otherwise it will be very difficult to understand in the future what has been done in this study.
Corrected

Page 4129:
L 7: "average time resolution is around 50 years". 50 years is not a resolution, 50 years tells the duration in time of something (as number of years). Resolution can be defined as years/sample (i.e. years between samples), or as "deposition time" (i.e. years within sample). Please clarify.
Corrected

L9-10: could you better explain what is meant with "insufficient" pollen concentration? Insufficient is a rather vague term.
Corrected. According to the taphonomical study done previously on storm layers we define the minimum pollen concentration as 5000 grains/g.

L14: to dissolve Lycopodium spores one generally uses HCl first, then HF later. Please bring correct order.
Corrected

L15: please cite Stockmarr (1971).
Corrected

L17: "minimum sum of 300 grains excluding Pteridpohyta,and dominant taxa". Which dominant taxa were excluded? And why?
Corrected
Sorry this was not clear. We just wanted to explain that we followed the rules of Berglund and Ralska-Jaciewiczowa (1986) for pollen counting but actually there is no dominant taxa in the sequence and thus no taxa was excluded. We corrected to make this sentence clearer.

L19: "Proportions were calculated using the total sum of identified pollen grains". Where also the obligate acquatics such as for example Sparganium/Typha included? Also Pteridphytes? If so, please clarify why the pollen sum was not limited to terrestrial plants.

The pollen sum include aquatic taxa but not Pteridophytes. The cumulated proportions of Typha/Sparganium, Cyperaceae and other marsh taxa are very low (few percents at maximum). There was no point to exclude them.

L21: please explain the rationale for using ratios of pollen percentages. Has such a ratio been used previously by other scientists? For the same pollen taxa? What are the modern evidences that validate the use of such ratios as climate proxies?

Arid events are highlighted by Fagus proportions minima coinciding with deciduous Quercus proportions maxima. Doing the ratio of these two variables was the easiest way to represent their variations with just one curve.

The Q/Q-ratio is use by Jalut (in Jalut et al 2009) on a wide range of palynological data from the Mediterranean area as an indicator of the late Holocene aridification. We wanted to compare our data with these results to show that in Palavas region, this ratio is unlikely related with climate. Archeobotanical and ecological studies suggest that in our case, evergreen Quecus forest dynamic seems much more related to human activites. Even if this ratio don't represent a specific type of activities, we think that this comparison is important to assess that the interpretation of a same indicator (in this case Q/Q-ratio) can be different from an area to another.

L24: delete "with distorted pollen proportions".

A careful taphonomic study allow to demonstrate that pollen proportions in storm events layers are really distorted. It is mentioned in the part "Results"

Page 4130:

L1-12: this paragraph is rather difficult to understand and raises a number of questions:

- the authors say that "pollen analyses from the overwash layers and the samples from immediately underlying sediments with conc. < 5000 grains/g have been discarded from the record to avoid taphonomic perturbations". However, it is unclear if the discarded pollen samples (not pollen analyses!) were deleted before plotting Figures 2 and 3 or if they were discarded only in Figure 3 or if they are plotted in both Figures (probably not, I assume).

The pollen spectra of the samples with a very low pollen concentration (less than 5000 grains per grams) were discarded in Figure 2 and 3. They were not considered at all.

- Also, I wonder why storm layers were actually sampled for pollen analysis in the first place: the pollen grains in those layers are almost certainly coming from reworked material;

Some samples from the storm layers were analyzed in order to characterize the influence of such perturbations on pollen spectra. It allows us to figure out that some samples above the storm layers were also affected by taphonomic biases.

- Further, it would be important to know how thick (in cm) these storm layers are in the cores. In theory, because the storm layers were deposited in few hours, their thickness should be deleted from the core to obtain a new "corrected depth scale" without the storm layers. The final age-depth model should be based on the new corrected depth scale, not on the original depth scale.

This point is already discussed in Sabatier et al 2012.

- L15: Eleven pollen zones in Figure 2. Please correct.

Corrected

- L15:"pollen zones based on pollen assemblages describe" Please change to "pollen assemblage zones were visually determined."

Corrected

Page 4131:
L3: "Abies disappears". Please find another term for ’disappears’. Also, it is the Abies pollen, not the Abies that disappears. Here and in the following sentences the authors should distinguish the subject of the sentences: the pollen (the evidence), the plants and vegetation (the interpretation).
Corrected

L5: tree pollen abundance decreases (tree pollen cannot decrease)
Corrected

L9: What is meant with "Forest taxa"? In figure 3 I see a curve showing Arboreal taxa (pollen %), not Forest taxa? Are Olea, Castanea, Juglans thought to occur as trees in the forests?
Corrected. We replaced the expression “forest taxa by a”arboreal taxa”. Olea, Castanea and Juglans are not included in arboreal pollen proportions. We clarified in the material and methods part the definition of all the groups of taxa.

L12: Cerealia-type pollen reach
Corrected

L14: why ’relatively low’? Relatively compared to which other records? Please clarify.
Corrected. We clarified it in the text. We meant relatively low compared to the rest of the sequence.

L16: "while cultivated trees decrease" please rephrase
Corrected

Page 4132
L4: Abies and Fagus pollen...
Corrected

L5: late occurrence compared to which other records? Please clarify
Corrected. We deleted the word “late”.

L12: expansion towards the south or simply to lower elevation?
Corrected

L19: where might have the shady slopes and valleys have been? From the map in Figure 1a one can see that the topography is rather flat (0-200 m asl) for more than 10 km around the coring site. Please clarify.
The present pollen spectra and the size of the lagoon suggest that an important part of the pollen rain is regional. Fagus pollen grains are found in the present pollen spectra while the nearest Fagus forest are around 100km away. Thus our data suggest that Fagus forest were present at lower altitudes but not necessary on the coast.

L20: but in Mat & Methods we were told that Pinus pollen could not be determined at species level. Hence, the hypothesis that the decrease of Pinus pollen here occurs because Pinus sylvestris shifted northwards is a statement that is skating on thin ice.
This is why we just mentioned it as an hypothesis.

L20: also, a shift northwards implies that the species was not present in the north.
Have you any evidence for this?
Corrected. “shift” was not the appropriate term. We modified the text and replaced it by “contraction range”

Page 4133
L16: see previous comment concerning the interpretation of a "northward shift".
Corrected

L22: Pollen % decreases of Fagus (e.g. the short-term decrease 4600-4300 cal BP) may be linked to "repetitive northward migrations". This interpretation implies that (1) Fagus trees were absent in the hills/mountains north of the Etang before 4600 cal BP, and (2) that they migrated to the north at 4600, stayed there between 4600 and 4300, and migrated back to the south at 4300 cal BP? However, there is no evidence to support hypothesis (1); moreover, hypothesis (2) seems rather striking (and unrealistic) and would imply extremely high dispersal distances and small ages to reach maturity for such trees. Please consider other, potentially more realistic, alternatives.
Corrected

Page 4134
L1: "Such arid events" what is meant with "such events"?
Corrected. We deleted the word "such".

L5-6: "Discrepancies in chronologies are probably due to model uncertainties". Why should arid events in Albania/Montenegro and in southwestern Spain occur simultaneously? Is there any evidence to support this hypothesis? Is this hypothesis actually relevant in the context of this paper?
Arid events in those records don't have to be strictly contemporaneous. However they are close in time and considering the uncertainties of age models it is impossible to address time lags between them.

L1-17: please move this paragraph further below and describe first the relationships between the proxies of your sediment core.
We choose to discuss first the short arid events in our data and other records or proxies, and then their link with the probable variations in atmospheric circulation patterns.

Page 4135
L7-8: "two Bond events might be divided in two phases". I think the authors want to say that the effect of climate changes during Bond events changed over time, with an intial phase at the onset of the event leading to more humid climate in Palavas, and a second rather final phase leading to drier climate with less frequent storms.
Yes

L27-28..: I cannot truly understand the meaning of this last sentence. Please clarify (1) what evidences, and (2) how & why a better understanding of mechanisms involved in these which climatic oscillations have been brought by your study.
Corrected. We changed this paragraph to make it clearer. Our data show that arid events and high storms activity periods are linked in southern France and that Bond events may display a two phases pattern. These observation should be taken into account in future attempts to understand the mechanisms involved in late Holocene climate variability in the Mediterranean.

Page 4136
L6-9: The first sentences of this paragraph are not consistent with what had been written at the beginning of Chapter 5.1. In the latter the interpretation given, albeit without much discussion, was that vegetation changed due to the long-term aridification. Here instead the authors set out that the interpretation given previously in Chapter 5.1 is actually debated. It is rather striking to read that now.
This paragraph is consistent with the previous ones. The long term aridification was clearly evidenced in Palavas region by the long term decrease in Fagus and Abies pollen proportions. Here we are pointing out that in this region the situation is more complicated for evergreen Quercus fluctuations.

Please restructure text. And please update the references including also more recent studies.
Corrected

L13: "increases in evergreen Quercus pollen and arid events do not correlate". Which increases in evergreen Quercus pollen? No increases were described in the previous sentence. And I can't see a correlation anywhere? What is the correlation coefficient? Please clarify and show the correlation statistics.

Corrected
We just meant that there were no increases in evergreen Quercus proportions corresponding to the arid events.

L14: delete "classic" from ’classic picture’ simply because it is not classic. There are different hypotheses (as described in the first few lines of section 6.1), that’s all.
Corrected

L19: "arid climate, which is usually expressed by the replacement of deciduous Quercus by evergreen Quercus". Why usually? This is surely not valid for Australia, just to give one example. Also, the argument given by the authors here is not consistent with what had been written on lines 1-5 and with what comes later (lines 24-25 and following); (1: "arid climate is usually expressed by the replacement of deciduous oaks by evergreen oaks"; 2: the deciduous/evergreen oak ratio decreases (thus evergreen oak increases); 3: conclusion: the deciduous/evergreen oak ratio is evidence for anthropogenic activity). please rephrase.
Corrected

L20-23: "therefore climate variability alone cannot explain". Sorry, climate variability from which proxy records? Please specify the subject and objects of the sentences.
Corrected

Page 4142 This whole paragraph is interesting but needs a more balanced discussion. See for example other palaeoecological and vegetation-modelling studies such as Henne et al. (2015).
Corrected. We updated the bibliography and modify this paragraph to make it clearer and more balanced as suggested.

Figure 1a: add names of rivers.
Corrected

Figure 1b:
- what do the circles indicate? Vegetation surveys in a plot? A tree? A minimum abundance/density of the species? sometimes the circles are so well connected to each other that a line appears. What do the lines indicate? Surveys along a track?
Corrected. The national forestry inventory maps we used in order to draw the map presented in Figure 1 are mostly interested in trees. Each spot represent a forest patch according to the maps of the National Forestry Inventory.

Figure 2:
- Why is there a gap in the pollen diagram between 200 and 600 cal BP (i.e. AD1750 to AD1350)?
This gap correspond to a period of high sedimentation rates where the few samples available are below an important storm layer and are affected by taphonical process.

- Y-axis label: Age yr BP cal BP or not cal BP? Please correct
Corrected

- Archeo periods: why are there no horizontal lines marking the limits between the cultural periods? Does the ’Modern period" go back to 800 cal BP (i.e. about AD1200)?
Corrected. We added limits to the archeo periods. The modern period go back to the 15th century.

- What is meant with "Antiquity"? I can’t find it in an english dictionary (e.g. http://dictionary.cambridge.org/dictionary/english/antiquity). Or do you mean "Classical Antiquity"?
Corrected

- x-axis label: "Deciduous trees" all deciduous trees? Only some deciduous trees? Please clarify

Corrected. We changed other deciduous trees, that is to say al the deciduous trees except the ones already plotted (Fagus, deciduous Quercus and the riparian). We added a paragraph in order to clarify the definition of all the groups used in the diagram.

- Other Riparian trees not Ripparian. Besides, what does this category include? Please clarify all categories in the Mat & Methods
Corrected

- What is "Sclerophyllous Quercus"? They are never mentioned in the text. Do you mean "Evergreen Quercus"? Please homogenize terminology.
Corrected

- Pollen concentration: correct dimension. should be grains per gram
Corrected

Figure 3:

- what do the green and red histograms indicate?
Corrected

- what do the different vertical shadings indicate?
Corrected

Reviewer 3 : W.Fletcher

This paper presents the findings of original palynological research on a composite core sequence from the Palavasian lagoon system in southern France. The methods are sound and the new pollen diagram is well supported by a robust chronology and cross-proxy comparisons with previous research on the same cores. The interpretation of the findings is well grounded in regional ecological perspectives and supported by reference to a wide range of relevant literature. The paper is well-written, concise and clear, and the figures clear and useful. In my view, the particular value of the study is evident in (i) the decadal to centennial temporal scale of the pollen record, (ii) the extension of the record up to present day in good detail through the composite sequence approach, (iii) the good level of integration with anthracological, archaeological and historical data. The paper represents a valuable contribution to the palaeoecological and palaeoclimatological literature for the southern France region, with implications for wider western Mediterranean. The paper is suitable for publication in Climate of Past,with minor recommendations and corrections:

Thank you very much for your comments and advices. We answer below each of your comments

4124 (abstract and throughout) -the term "The Antiquity" is not used in English, and should be replaced by "Classical Antiquity" (without "the")

Corrected

4124 Line 25 - change "especially, concerning" to "especially concerning"

Corrected

4125 Line 3 - change to "is a crucial issue"

Corrected

4125 Line 12 - change to "remains a challenging"

Corrected

4127 Line 13 - discrimination of pine pollen is indeed possible (e.g. Desprat et al., 2015) but is not possible using routine techniques - this point should be corrected

Corrected

4128 Line 7 - "repetitive marine influence" - this word choice is ambiguous in meaning- please change, e.g. to "recurrent marine influence" (i.e. fluctuating, repeated) or "constant/continuous marine influence"(i.e. throughout the whole interval)

Corrected

4129 Line 17 - please specify what is meant by "dominant taxa" here and why they are excluded - is this referring to local marsh vegetation?

Sorry this was not clear. We just wanted to explain that we followed the rules of Berglund and Ralska-Jaciewiczowa (1986) for pollen counting but actually there is no dominant taxa in the sequence and thus no taxa was excluded. We corrected to make this sentence clearer.

4129 Line 19 - were the proportions calculated on the "total sum of identified grains" as reported, or on the basis of the "main sum" as defined in Line 17? Please clarify

The proportions were calculated on the total sum of identified pollen grains, thus excluding spores and NPP. We clarified the text.

4131 Lines 19-25 (and elsewhere) - here the aridification trend is reported as beginning at 3000 cal BP, but elsewhere in the text, e.g Conclusions, is reported as beginning at 4600 cal BP. In my experience working particularly in the Iberian Peninsula, my understanding is that enhanced moisture and precipitation of the mid-Holocene does not extend to 3000 cal BP, but that aridification trends are evident from 5000 cal BP or even earlier (e.g. Fletcher et al, 2007; Carrion et al., 2010, and other papers already cited by the authors here, e.g. Perez-Obiol et al., 2011, Jimenez-Moreno et al., 2015,etc...). The authors should clarify their views and make the text internally consistent.

Corrected. We modified this paragraph as suggested to make our text internally consistent and with an aridification beginning around 5000 cal BP, as shown by our data and the articles cited.

4132 Line 25 - the mechanistic link between decreasing summer insolation and reduced winter precipitation should be briefly specified in this sentence

Corrected. We added more information about the mechanism of this climate change :

"This aridification trend has been linked to a decrease in summer insolation which could have resulted in reduced lower sea-surface temperatures, reduced land-sea contrast and thus lower precipitation during the fall-winter season (Marchal et al., 2002; Jimenez Moreno et al., 2015)."

4133 Lines 1-5 - the inferred link between basin size and pollen catchment area would depend on a main vector being atmospheric deposition over the basins. Can the authors discuss briefly, or are there any previous studies relating to, pollen transport vectors into the Palavasian lagoon, and whether waterborne pollen via fluvial and tidal sources is likely to be important? Does this have any bearing on the interpretation of the record?

Corrected- We add a short discussion about this issue. We were not able to detect any fluvial or marine influences (aside the storm events discussed). Thus we assume that the main pollen transport vector is wind.

Section 5.2 - regarding timing and interpretation of arid episodes, the paper should cite Fletcher et al., 2013 - within chronological uncertainties, there are parallels between the records, and the NAO interpretation is developed in detail in that paper.

Corrected. We compared the results of the paper Fletcher et al 2013 to our data and added it to the citations of this paragraph.

Section 5.2 - regarding similarities and differences between the clay mineralogy and pollen records, it may be interesting to consider the proxy-specific response times to the different aspects of climate change (storminess, aridity) inferred as part of a prevailing NAO-lie oscillation

We tried to explain our results considering possible differences in response times and also threshold effects, however it was difficult to explain all the observation consistently in this way. We planned to write a more detail article when the entire sequence of 7500 will be available. It will be possible to address more rigorously this issues using appropriates mathematical tools.

4141 Line 17, 18 - change "(T)/the reforestation" to "reforestation"

Corrected

Section 7 Conclusions - regarding the arid events, I would recommend that the authors summarize here also the phasing with previously reported storm events and their interpretation regarding NAO dynamics

Corrected. We completed the conclusion as suggested.

4143 Line 24 - correct spelling of "Michelle Farrell" in acknowledgements!

Corrected

Table 1 - the authors should consider adding an additional column with ages in BC/AD - this will be helpful for the reader (especially if working in historical/archaeological contexts).

Corrected

Figure 2 - correct spelling of "riparian"

Corrected

Figure 3 - the caption should directly state the significance of the shaded bars (1,2a,2b,3); perhaps I missed something but I am confused by the labelling of "a","b",..."g" inside the diagram - these should be clarified in the caption, and an alternate system "i","ii" / "A" "B" etc should be used to avoid confusion with the labellingof the different records/proxies in the axis labels - or perhaps these can be deleted altogether? As the main interpretive diagram of the paper, it could be furthermore useful to add a second (BC/AD) timescale, and label the archaeological/historical periods discussed throughout the text.

Corrected

Reviewer 4 : G. Jiménez Moreno (Referee)

In this interesting study, Azuara et al. carried out a high-resolution pollen study of two mid- to late Holocene cores from S France. The data was interpreted in terms of vegetation changes due to climate and human impact. I don't have problems with the science of the paper and the data seem sound. However, in my opinion there are some issues that should be addressed before publication– see below:

Thank you very much for your comments and advices. We answer below each of your comments.

-My mayor concern is the interpretation of the vegetation changes. One of the main goals of this study would be to separate the climate signal from the human impact. Sometimes this is not an easy task but the way this was done here is kind of confusing as many of the changes observed are explained as caused by both climate and human impact in two different sections (5 and 6). A better way of doing this would be dealing with a change at a time (from past to Present) and discussing about both factors in the same section.
We first tried to organize the paper in a chronological way as you suggest to do. However, it was very difficult because the vegetation changes highlighted in the study (driven by climatic or anthropogenic factors) have very heterogeneous durations (several millennia, around one thousand years, few hundred years, hundred years,…). Therefore the chronological outline was very confusing and the clarity of the paper would have suffer from this. That is why we finally choose to follow a thematic outline.

-I was trying to find information about the lithology and age control of the studied cores but they were nowhere to be found. It seems that this information has been previously published but for many people this would be the first time they see these two records and so I strongly recommend showing this.

We added a table with al the ages and control points of the sequence and r we draw in the palynological diagram the position of the storms layers (arrows) and the high storm activity periods that also appear in the figure 3.

In this respect, the sand intervals that are mentioned in the text are very interesting as they could somehow explain some of the changes observed in the pollen due to local vegetation changes in the marshy area.

The pollen abundance of the local marshy vegetation is very low. Because the lagoon is very large, the pollen spectra mainly represent the regional vegetation. Moreover, no change in this local vegetation is recorded in relation with the storminess. However the changes in the lagoonal sedimentation due to the storms could have led in the case of Palavas lagoon to taphonomical issues. This is why we chose to discard the samples with a low pollen concentration according to a previous taphonomical study we carried out. While some major vegetation changes affecting hinterland taxa such as Fagus are correlated with the storminess they are not exactly contemporaneous. This confirms that these changes are effective and not due to a biases linked to the sedimentation changes.

-It is not clear in the paper why the expansion of evergreen Quercus is related with human impact. Please explain. Could that be due to climate? Maybe more seasonality in the precipitation in the late Holocene?

The paragraph explaining this point of the demonstration was not clear so we modified it.

To sum up, the hypothesis of climate driven evergreen Quercus spread in southern France is not consistent with all the observations. Of course, it is not possible to completely discard a climatic influence on evergreen Quercus forest but the anthropogenic causes are much more supported by the data.

-In many different parts of the paper the authors talk about “migration” of plant species (Fagus, Abies, etc) towards the North during arid periods. This should be changed as plants do not migrate – they cannot “walk”. Those plants rather disappeared from the South due to tough conditions and remained in the North were they probably already occurred during mild conditions.

Corrected. Talking about migration was not appropriate so we replaced this term by “range contraction” as you suggested.

-It took me a while to get that a composite record is shown. That should be clearly stated in the material and methods section.

Corrected

-The graphical information in the paper is quite poor – only three figures are shown. Why aren’t the red shade-lines going to the top of figure 3, towards the AP proportions? In the same figure it is not clear why there are two colors in the graph with macrofloral remains. The use of letters in the different plots is kind of confusing as well.

We modified Fig 3 to clarify that point, adding more captions into and below the figure. The shaded area are not reaching the top because it was clearer to keep in two different parts of the figure the climatic and the anthropogenic data. Otherwise too many information would have been superimposed.

I hope my comments help improving the manuscript.

Cheers, Gonzalo Jiménez-Moreno

Editor:

Dear authors,
you can see in the reviewers comments that you paper has been received positively. I think that it is not too complicated to provide a response for each of them.

I have a personal comment on Figure 3. I have some difficulties to accept the idea that anthropisition is inverse to humidity in 3d and related to the ratio Dec Q/ Ev Q, while Fagus/Dec Q is proportional to Humidity. This is really a subjective interpretation and maybe a circular argument. This needs a more quantitative approach or at least a better explanation.

Best regards
Joel Guiot

Both text and figures were not clear on this point so we modified both to clarify our conclusions.

In short, during the late Holocene increasing anthropisation and decreasing humidity (both highlighted in many previous studies) are difficult to separate because they can have similar effects on the vegetation. To do this we compared our record with both climatic proxies and archeological archives. We found that while changes in Fagus abundances well coincide in time with climate changes they poorly correlates with human activities. This is why we interpreted variations in Fagus proportions in term of climate changes. On the contrary evergreen Quercus and arboreal pollen proportions poorly correlate with climate changes while they fit well with historical and archeological archives. This is why we interpreted them in term of anthropisation indicators.

Using our pollen data to demonstrate climate changes and afterward compared these climate changes with the same data to highlight the anthopogenic impact would have been circular. On the contrary we compared our pollen data with known climate changes and known changes in human land use (both from previous studies). This comparison with independent data prevent us against a circular argument.

Text with modifications:

Late Holocene vegetation changes in relation with climate fluctuations and human activities in Languedoc (Southern France).

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Abstract

Holocene climate fluctuations and human activities since the Neolithic have shaped present-day Mediterranean environments. Separating anthropogenic effects from climatic impacts to better understand Mediterranean paleoenvironmental changes over the last millennia remains a challenging issue. High resolution pollen analyses were undertaken on two cores from the Palavasian lagoon system (Hérault, southern France). These records allow reconstruction of vegetation dynamics over the last 4500 years. Results are compared with climatic, historical and archeological archives. A long-term aridification trend is highlighted during the Late Holocene and three superimposed arid events are recorded at 4600-4300, 2800-2400 and 1300-1100 cal BP. These periods of high frequency climate variability coincide in time with the rapid climatic events depicted in the Atlantic Ocean (Bond et al., 2001). From the Bronze Age (4000 cal BP) to the end of the Iron Age (around 2000 cal BP), the spread of sclerophyllous taxa and loss of forest cover result from anthropogenic impact. Classical Antiquity is characterized by a major reforestation event related to the concentration of rural activities and populations in coastal plains leading to forest recovery in the mountains. A major regional deforestation occurred at the beginning of the High Middle Ages. Around 1000 cal BP, forest cover is minimal while cover of olive, chestnut and walnut expands in relation to increasing human influence. The present day vegetation dominated by Mediterranean shrubland and pines has been in existence since the beginning of the 20th century.

1. Introduction

Global climate projections (IPCC, 2014) show that the Mediterranean will be significantly impacted by 21st century temperature increases associated with a major drop in precipitation. The Mediterranean area is now included as one of the most sensitive regions to future climate change especially concerning moisture availability. Consequences for Mediterranean environments will be particularly important since they have been largely modified by humans during the last millennia and are therefore very vulnerable even to weak influences. In this context, deciphering climatic and human causes of environmental changes is a crucial issue for understanding vegetation response to both forthcoming climate change and present land management policies.

Various Holocene climate archives are available from the Mediterranean and the Atlantic, such as marine Ice Rafted Debris in the North Atlantic (Bond et al., 2001), lake-level fluctuations in the Alps and the Mediterranean (Magny et al., 2002, 2013; Magny, 2004, 2013), glacier oscillations in the Apennines (Giraudi et al., 2004, 2005, 2011), lake isotope records from the whole Mediterranean basin (Roberts et al., 2008) and changes in storminess (Sorrel et al., 2009; Sabatier et al., 2012). They highlight important climatic variations during the latter half of the Holocene which are correlated with vegetation changes. Nevertheless, in the Mediterranean region, separating the impact of human activities from climate remains a challenging task (Roberts et al., 2011). During the mid-Holocene climate optimum, deciduous trees dominated the Mediterranean forest but after 5 000 cal BP, evergreen sclerophyllous taxa expanded and replaced the deciduous vegetation in many places (Reille and Pons, 1992; Jalut et al., 2000; Carrion et al., 2003; Sadori et al., 2014). This major vegetation change could be attributed either to climate change or human impact because during the same period farming spread across the northwestern Mediterranean region (Vaquer, 2010). Over the last millennia, environmental changes have resulted from interactions between climate and human activities, and there is no clear understanding of their respective influence (De Beaulieu et al., 2005).

The Languedoc is located in southern France under both Mediterranean and Atlantic climatic influences. Numerous archeological and historical records are available in this region, including archeobotanical studies valuable for assessing human impact on the environment (Durand, 2003; Chabal, 2007; Jorda et al., 2008; Caveiro et al., 2010; Figueiral et al., 2010). Various studies focus on the rural world in the Languedoc from the Neolithic to Modern periods (Durand, 2003; Schneider et al., 2007; Gascò, 2010; Jallot, 2010; Janin, 2010; Ouzoulias, 2013). The variety of these archives may provide an extensive dataset to compare climatic, archeological and historical records with vegetation history in the Languedoc. Nonetheless, despite the existence of various Holocene pollen sequences in Languedoc such as those from Marsillargues (Planchais, 1982), Lez estuary (Planchais, 1987), Palavas (Aloisi et al., 1978) and Embouchac (Puertas, 1998), Capestang is the only record which provides chronologically well-constrained high-resolution pollen data (Jalut et al., 2009).

This paper presents a new high-resolution composite pollen record from a sedimentary sequence recovered from the Palavasian wetland complex. The chronologically well-constrained pollen sequence documents the last 4500 years cal BP, from the final Neolithic to the present. This detailed study enables identification of both climatic and anthropogenic impacts on vegetation dynamics. First, the comparison between this new vegetation record and climatic archives helps to identify the consequences of both long term and multi-decadal climate variability on Mediterranean environments. Second, the detailed correlation with archeological and historical archives from the Languedoc region allows understanding the link between vegetation history and land-use changes at historical and pre-historical times.

2. Physical settings

The Palavasian wetland complex is located on the southeastern French coast in the northwestern part of the Mediterranean Sea (Fig. 1). The complex consists of narrow lagoons, of 2 km width and between 4 to 8 kilometers long, which run parallel to the shoreline and have shallow water depths (less than 1 m). The lagoons are isolated from the sea by a continuous 150 m wide wave-produced sandy barrier.

The hydrographic network is composed of the Lez and Mosson rivers. The Lez flows directly into the sea while the Mosson splits into two branches near the coast, one flowing into the lagoons and the other joining the Lez before its mouth. Their respective watershed is quite small (653 km^2), extending over 50 km inland.

The climate is Mediterranean with a four-month summer drought and mild and rainy winters. Mean temperature and rainfall are respectively 23°C and 26.2 mm in summer and 3.3°C and 58 mm in winter (Méteo France data, Montpellier Fréjorgues station).

The distribution of the main forest types classified by dominant taxa is drawn using vegetation maps from the IFN (Inventaire National Forestier, BD Forêt 1 (Fig.1). The regional vegetation forms altitudinal belts from the sea-shore to the southern part of the Massif Central (Cevennes range): the Meso-Mediterranean belt is dominated by *Quercus ilex* and *Pinus halepensis*; the Supra-Mediterranean belt is dominated by *Quercus pubescens* on limestone and by the introduced *Castanea sativa* on siliceous substrates; finally, the

Mountain belt is dominated by mixed forests of *Abies alba* and *Fagus sylvatica*. Pine woods are present at all altitudes, and constituted by three main different species in the study area: *P. halepensis* forms extensive, mostly fire-induced pinewoods at low altitudes close to the coast, the endemic *P. nigra* subsp *salzmannii* occupied restricted areas on dolomitic limestones in the Causse region, and *P. sylvestris* developed as a pioneer in the Cevennes range. Each *Pinus* species has its own ecological requirements, and should respond differently to climatic changes. Unfortunately, these different species cannot be discriminated in routine pollen analysis, which complicates the interpretation of *Pinus* variations in terms of vegetation changes and climate changes. Halophytic vegetation is dominant in the vicinity of the coastal lagoons, mainly with Amaranthaceae such as *Arthrocnemum macrostachyum*, *Sarcocornia fruticosa*, *Salicornia europaea*, and *Halimione portulacoides*. The rivers supplying lagoons in freshwater are bordered by riparian forests composed of *Alnus glutinosa*, *Fraxinus angustifolia*, *Populus alba*, *Populus nigra*, and *Ulmus minor*. Finally, in the region, the Ericaceae are represented by an important diversity of species throughout the different altitudinal belt. The most frequent ones are *Erica arborea, E. scoparia, E. multiflora, E. cinerea, Calluna vulgaris* and *Arbutus unedo.*

3. Materials and methods

Pollen analyses were undertaken on two cores, EG08 (1.31 m long) and PB06 (7.71 m long), recovered from the adjacent lagoons of Prevost and Pierre Blanche (Fig. 1). Eighty eight pollen samples were analyzed from these two cores with a sampling resolution varying from 2 to 10 cm.

3.1. Lithology and sedimentation

Previous sedimentological and geochemical analyses of both PB06 and EG08 cores highlight a clayey-silty sedimentation with shell fragments and intercalated fine layers of sandy material (Sabatier and Dezileau, 2010; Sabatier et al., 2012; Dezileau et al., 2011). The complete studied record covers the last 5 millennia from the Mid-Holocene to the present day. During that time, the Palavasian complex was characterized by a lagoonal depositional environment with a recurrent marine influence through permanent connections with the sea. A major change in faunal content chronologically constrains the final closure between the lagoon and the sea at around 1000 cal BP (190-170 cm in PB06). From that time, the lagoon became more and more isolated.

Variations in marine mollusk abundance, granulometry and Zr/Al and smectite/(illite+chlorite) ratios highlight three paleostorm events in EG08 core and eight in PB06. (Dezileau et al., 2011; Sabatier et al., 2012). The three more recent overwash layers recorded in both cores can be correlated between EG08 and PB06. They are identified as single storm events matching with historical storms documented and dated in historical archives to 1742, 1848 and 1893 (Dezileau et al., 2011). The fourth overwash layer recorded in PB06 is interpreted as another single storm event and the four older ones are interpreted as high storm activity periods (Fig. 2).

3.2. Chronology and age model

The PB06 age model has been built using ^{137}Cs, ^{210}Pb and AMS ^{14}C dates on monospecific samples of *Cerastoderma glaucum* shells (Sabatier and Dezileau, 2010; Sabatier et al., 2012). ^{14}C ages were corrected according to reservoir age as defined by Sabatier et al. (2010) and then calibrated using the R-code package “clam” (Blaauw, 2010) and the Intcal09 calibration curve (Reimer et al., 2009) at 2 standard deviations (Sabatier et al, 2012). The whole core provides a high resolution record over the last 7000 years, however this particular study focus only on the late Holocene period.

The EG08 age model has been developed by stratigraphic correlation with core PB06 (Dezileau et al., 2011). Core EG08 records the last 300 years and allows reconstruction of a very high resolution vegetation history during the modern period.

3.3. Pollen analysis

Pollen analyses performed on PB06 and EG08 are combined in a composite record: 13 samples in EG08 for the last 200 years cal BP and 75 samples in PB06 from 200 to 4600 cal BP. The resulting average time between each samples is around 50 years for the whole sequence with variations from 10 to 100 years. There are two small gaps in the pollen sequence between 1555 and 1316 cal BP and between 622 and 202 cal BP (Fig. 2) because of insufficient pollen concentration in and below the storm sediments (<5000 grains.g^{-1}).

Pollen extraction followed a standard method modified from Faegri and Iversen (1989). For each sample, 1 g of sediment was sieved on 250 µm and 5 µm mesh, then processed with HCl and HF for mineral digestion and sodium polytungstate for density separation. One tablet with a known amount of Lycopodium spores was added to estimate pollen concentration (Stockmarr, 1971). Pollen counts were performed at x400 magnification though pollen grains were identified at x1000 magnification with pollen keys (Punt, 1976; Beug, 2004) and atlases (Reille, 1992). A minimum pollen sum of 300 grains excluding Pteridophyta and non-pollen palynomorphs (NPP) was reached for each sample (Berglund and Ralska-Jaciewiczowa, 1986). Proportions of each taxon were calculated using the total sum of identified pollen grains without considering NPP and spores. The simplified pollen diagram (Fig. 2) was drawn using PSIMPOL (Bennet, 1992). The category “arboreal pollen” includes all the tree taxa except the cultivated ones (*Olea*, *Castanea* and *Juglans*), the category “other deciduous trees” includes *Acer*, *Ulmus*, *Betula*, *Carpinus* and *Corylus*, the category “evergreen shrubs” includes *Pistacia*, *Cistus* and *Buxus* and finally the category “other riparian trees” includes *Fraxinus*, *Salix* and *Tilia*. The ratio deciduous/evergreen *Quercus* was computed in order to be compared with results of previous studies (Jalut et al., 2009) and the ratio *Fagus*/deciduous *Quercus* in order to highlight covariation of these two taxa.

4. Results

4.1. Pollen taphonomy

Pollen concentration in the composite sequence is generally high, ranging from 1 000 to 100 000 grains.g^{-1}. Major drops in pollen concentration with distorted pollen proportions are recorded in the three sandy overwash layers in EG08 and in the four layers corresponding to single storm events in PB06. Surprisingly the clayey layers just below these storm events also contain low pollen concentrations. It is assumed that during a storm event, the clayey surface sediments at the bottom of the lagoon were disturbed before the deposition of the sandy layer. This resulted in partial to total removal of the polleniferous material, with huge declines in pollen concentration through the sequence. Samples from the recent overwash layers in EG08 and PB06, identified as single storm events, represent sediments deposited within a few hours and naturally record no environmental information. Consequently, pollen analyses from these overwash layers and the samples from immediately underlying sediments with pollen concentrations lower than 5000 grains.g^{-1} have been discarded from the pollen record to avoid taphonomic perturbations. On the contrary, no taphonomical issues are detected in the four older high storm activity periods in the lower part of PB06.

4.2. Pollen transport vectors

Alnus is the only riparian taxa which is well represented in the sequence, reaching almost 10% between 2000 and 1000 cal BP (Fig. 2). However studies interested in quantifying the relative contribution of different taxa to the pollen rain show that *Alnus* is a high pollen producer (Broström et al., 2008). Therefore, it is unlikely that this taxa could represent the rivers contribution to Palavas pollen assemblages. The other riparian taxa display very low pollen proportions in present as in past pollen assemblages in agreement with the small size of the Lez and the Mosson rivers (Fig. 2) and the position of the cores located far away from their mouths. This suggests that fluvial sources represent only a minor contribution to pollen assemblages. Moreover, despite that the lagoons were in permanent connection with the sea before 1000 cal BP, no vegetation change is contemporaneous from the sandy barrier closure. Thus, even if a marine influence existed it probably not influences the pollen spectra with the exception of storm events already discussed. Finally, the main pollen transport vector into the Palavasian lagoon system is assumed to be associated with wind.

4.3. Vegetation history in Palavas area

The pollen record from the EG08 and PB06 cores illustrates vegetation dynamics over the last 5 millennia. Eleven pollen assemblage zones were visually determined, describing the sequence of vegetation changes (Table 1, Fig. 2).

Tree pollen (50 – 90 %) dominates the pollen spectra for almost the entire sequence, mainly comprising deciduous *Quercus* (10 - 40 %) associated with *Pinus* (1 - 20 %), evergreen *Quercus* (3 - 20 %) and *Fagus* in the lower part of the sequence (up to 20 %) (Fig. 2). *Alnus* is present in significant proportions (up to 10 %) as well as *Abies* (up to 3 %) at the base of the sequence.

Between 4700 and 4000 cal BP, *Pinus* proportions decrease and the first occurrence of *Cerealia*-type pollen is recorded (Pal-I and first part of Pal-II, Fig. 2). *Vitis* is recorded sporadically throughout the sequence. After 4000 cal BP, *Fagus*, *Abies* and the deciduous/evergreen *Quercus* ratio show a long term downward trend (Fig.s 2 and 3). *Fagus* displays several fluctuations superimposed on this overall decline. *Fagus* minima coinciding with deciduous *Quercus* maxima occur at 4600-4300 cal BP (Pal-I), 2800-2400 cal BP (Pal-III and Pal-IV) and 1300-1100 cal BP (Pal-VII) (Table 1, Fig. 2). Such oscillations are particularly highlighted by changes in the *Fagus*/deciduous *Quercus* ratio (events 3, 2 and 1 in Fig. 3). At 3300 cal BP, arboreal pollen proportions start to decline (85 to 70 %) (Pal-II, Fig. 3). *Abies* pollen disappears almost completely from the record around 2500 cal BP. Just before 2000 cal BP, arboreal pollen proportions rise sharply to their maximum (up to ca. 85 %). However after 300 years, tree pollen abundance decreases again to 55 % (Pal-III and IV, Fig. 3). Around 1300 cal BP, a short-lived peak in deciduous *Quercus* interrupts this general decline (Pal-VII, Table 1, Fig. 2). After this brief reforestation event, forest decline begins again and appears more intense (Pal-VI, Fig. 3). Arboreal taxa reach their minimum (45% of arboreal pollen) around 1000 cal BP. While cultivated tree pollen such as *Olea*, *Castanea* and *Juglans* start to increase (Pal-VII, Fig. 3), *Fagus* disappears (Pal-VIII). At the same time, Ericaceae and herbaceous taxa including Poaceae (up to 15 %) and *Cerealia*-type pollen (up to 3 %) reach their highest values (Pal-VIII and Pal-IX, Table 1, Fig. 2). During the 19th century arboreal pollen proportions remain relatively low (~50%) compared to the rest of the sequence and *Castanea* pollen percentages sharply increase (Pal-X, Table 1, Fig. 2). In the last hundred years *Pinus* and evergreen *Quercus* pollen become the dominant trees of the Mediterranean forest while cultivated trees abundance (*Olea*, *Castanea* and *Juglans*) decrease.

5. Climate interpretation

5.3. The long term aridity trend

In the Mediterranean basin, the Early and Mid-Holocene are characterized by enhanced moisture and precipitation increases until ~5000 cal BP (Carrion et al., 2002; Fletcher et al., 2007; Magny et al., 2012), then followed by long term aridification throughout the region, recorded by many proxies such as palynology, geochemistry, lake-levels, semi-mobile dune systems and Saharan eolian dust (Zazo et al., 2005; Jalut et al., 2009; Perez-Obiol et al., 2011; Roberts et al., 2011; Jimenez-Espejo et al., 2014; Jimenez-Moreno et al., 2015). This aridification trend has been linked to a decrease in summer insolation which could have resulted in reduced lower sea-surface temperatures, reduced land-sea contrast and thus lower precipitation during the fall-winter season (Marchal et al., 2002; Jimenez Moreno et al., 2015).

Between 4500 and 2000 cal BP, the noteworthy occurrence and/or high abundance of *Abies* and *Fagus* pollen at the base of the Palavas pollen record suggests their presence close to the Palavasian Lagoon (Fig. 2). The occurrence of *Fagus* at low altitude in southern France is also recorded in Lez delta pollen sequence and in the Rhône valley anthracological record (Planchais, 1987; Delhon et al., 2005). It matches well with the mid Holocene enhanced moisture recorded in the western part of the Mediterranean basin. In fact, *Abies* and *Fagus* are now found only on the mountainous hinterland, more than 70 km north of the lagoon (Fig. 1). Therefore, in the Palavasian pollen record, high percentages of *Abies* and *Fagus* before 2 800 cal BP may be linked to their broader expansion towards the south at lower elevations. Such a conclusion is corroborated by charcoal data recovered from coastal archeological contexts, indicating that 1) *Fagus* was present at ca. 3000 cal BP (Etang de l'Or Tonnerre I) and 2000 cal BP (Port Ariane), and 2) *Abies* was present at ca. 2000 cal BP (Lattara and Port Ariane) (Chabal, 2007; Jorda et al., 2008; Caveiro et al., 2010). These two species do not tolerate summer dryness and their expansion to lower altitudes in southern France implies that more humid conditions prevailed in the Languedoc at least locally (Quezel, 1979 ; Delhon et al., 2005).

From 4500 to 3000 cal BP, *Pinus* declined steadily. This might express a range contraction toward the north in *Pinus sylvestris* associated with the onset of Late Holocene aridification (Fig. 2). The parallel long-term downward trend expressed in the *Abies* and *Fagus* abundance curves from 3000 to 1000 cal BP surely follows the Holocene long-term aridification (Figs. 2 and 3). At the same time, deciduous *Quercus* proportions remain very high around Palavas (Fig. 2). No clear decrease in *Quercus* is evidenced which is inconsistent with results from other sites in the Languedoc. For instance, in the Capestang sequence, less than 100 km from Palavas, deciduous *Quercus* begins to decline at 4 000 BP cal in correlation with an increase in evergreen *Quercus* (Jalut et al., 2009). Such a replacement of deciduous forest by sclerophyllous evergreen forest is lacking in Palavas at the same period, occurring only during the last century. The Capestang core was sampled in a wetland area with small ponds (Jalut, 1995). Considering the size of these ponds (around 100m wide), the pollen record at this site probably documents a more local scale vegetation history compared to Palavas sequence with its much larger basin (around 2km wide) (Sugita, 1993). Actually, in the Palavas region, the mountainous hinterland massifs might have favored the continuation of relatively humid conditions and hence the persistence of deciduous *Quercus* forests until the historical period. The same deciduous *Quercus* forests were disadvantaged in the plains surrounding Capestang, resulting in the absence of a deciduous *Quercus* pollen signal. A similar situation is recorded at lake Skodra (Albania/Montenegro) where a strong altitudinal gradient, combined with sufficient moisture availability, favored the development of deciduous forest throughout the Late Holocene (Sadori et al., 2014).

Around 2000 cal BP, *Abies* almost disappears from the palynological record and definitively from the Languedoc lowlands, and *Fagus* persists up to 1000 cal BP. Late Holocene climate changes have hence caused the northward range contraction in *Abies*, *Fagus* and probably also *Pinus sylvestris* towards their present-day mountainous location. These same changes favored the development of deciduous *Quercus* forests and Mediterranean Pines at the studied location.

5.4. Short-term climatic fluctuations

Sharp decreases in *Fagus* pollen proportions coinciding with deciduous *Quercus* maxima occurred at 4600-4300 cal BP, 2800-2400 cal BP and 1300-1100 cal BP (Fig. 2), and are highlighted through sharp decreases in the *Fagus*/deciduous *Quercus* ratio (Fig. 3). Oscillations might be linked to repetitive *Fagus* retreats toward higher altitudes coinciding with repeated expansions of deciduous *Quercus* close to Palavas at lower altitudes (Figs. 2 and 3). These decreases might also correspond to major drops in *Fagus* pollen productivity caused by enhanced environmental stresses. In the French mountainous area of the Mediterranean, *Fagus* is at the limit of its geographical range (Quezel, 1979) and it's therefore very sensitive to climatic variations, especially regarding moisture availability (ref). Since *Fagus* is less tolerant to dryness than deciduous *Quercus*, each fluctuation may be related to repeated arid episodes.

Arid events have been already reported in the central and western Mediterranean from lake Skodra (Albania/Montenegro) soon before 4000 cal BP, around 2900 cal BP and around 1450 cal BP (Sadori et al., 2014) and in southwestern Spain at 4 000 cal BP, 3000-2500 cal BP and 1000 cal BP (Jimenez-Moreno et al., 2015). Discrepancies in the chronology of these events between sites are probably due to age model uncertainties. Furthermore, these arid events correspond in time to Calderone glacier extension phases in the Appenines around 4200 cal BP, between 2855-2725 cal BP and 1410-1290 cal BP (Fig. 3) (Giraudi, 2004, 2005; Giraudi et al., 2011). They are also concurrent with the rapid vegetation and marine environment changes recorded in Mediterranean (e.g. Cacho et al., 2001; Fletcher et al., 2007; Frigola et al., 2007; e.g. Kotthoff et al, 2008 ; Schmiedl et al., 2010; Combourieu-Nebout et al, 2009, 2013; Desprat et al., 2013; Fletcher et al, 2013). These climatic events fit with the general picture of climate change depicted by lake level fluctuations in central Europe and the northern Mediterranean (Magny, 2013; Magny et al, 2013). Moreover they are contemporaneous with North Atlantic Bond events around 4200, 2800 and 1400 cal BP, underlining the efficient climatic coupling between the North Atlantic and the Mediterranean during the Late Holocene (Fig. 3).

Variations in clay mineralogy in the core PB06 provide a proxy of past storm frequency in Palavas region complementary to pollen data which may give useful information to investigate mechanisms of these climatic oscillations (Sabatier et al., 2012). Arid events depicted by vegetation are contemporaneous with sharp variations in storminess. They occur during transition periods, before (event 3) or after (event 1 and 2) high storm activity periods

(Fig. 3). Increases in storm frequency have been interpreted as periods during which westerlies, and thus storm tracks, were shifted to the south, bringing more precipitations in the Mediterranean. These situations are similar to persistent negative NAO-like periods (North Atlantic Oscillations) and may be caused by the southward displacement of the polar front linked to a weakening of the Atlantic Meridional Overturning Circulation (AMOC) during colder periods (Dezileau et al., 2011; Trouet et al., 2012). Such an interpretation is consistent with the humidity recorded in PB06 during high storm activity periods and with the Calderone glacier expansion phases (Giraudi et al., 2004, 2005, 2011). Conversely arid events 2 and 1 might correspond to persistent positive NAO-like periods. According to this mechanism, these events might correspond to warmer periods with a decreasing storm frequency when westerlies and storm tracks are shifted to the north. The closeness in time of arid events 2 and 1 with respectively high storm activity periods 2a and 1 within the Bond event 2a and 1 time windows, suggests that these two Bond events might be divided in two phases, a humid one followed by an arid one. A similar schema is reported during older arid episodes, Heinrich events 4, 2 and 1 (Naughton et al., 2009). A two-phase pattern occurs within these three Heinrich events with a change from wet and cold to dry and cool conditions. The proposed mechanism involving the succession of opposite persistent NAO-like periods is very similar to the one developed for the Late Holocene rapid climatic events (Trouet et al., 2012), despite Heinrich events are recorded in a glacial period. The arid event 3 remains more difficult to interpret because it seems contemporaneous with a storminess increase. However; it is difficult to define its lower boundary because it is located at the bottom of the sequence. Further analyses are needed to determine properly its chronological extension and link to high storm activity periods.

Bond events have been correlated with fluctuations in 14C production rate, suggesting a solar forcing (Bond et al., 2001) (Fig. 3). However, no exceptional residual 14 C excursions are depicted around 4200 and 1400 cal BP and the variability in solar activity cannot explain all the observed changes (Debret et al., 2007; Sabatier et al., 2012). Wavelets analysis performed on Bond et al (2001) IRD time series and other marine paleoclimatic proxies highlight three major climate cyclicities: 1000, 1500 and 2500-year. The two cyclicities of 1000 and 2500 years are solar related, while the 1500-years climate cycles, dominant during the second part of the Holocene, appear to be clearly linked with the oceanic circulation (Debret et al., 2007). In the Mediterranean, the succession of stormy/humid periods and arid events close in time within some Bond events time windows bring new elements to characterize Late Holocene climatic oscillations that should be taken into account in the future attempts of understanding the mechanisms involved in climate variability.

6. Anthropogenic impact on vegetation

6.1. Ecological significance of evergreen *Quercus* development during the Late Holocene in southern France

During the Late Holocene, in the north-western Mediterranean, sclerophyllous evergreen forest development has been controversially interpreted either as an effect of Late Holocene aridification (Jalut et al., 2000, 2009) or as a consequence of increasing anthropogenic impact (Triat-Laval, 1978; Planchais, 1982; Reille et al., 1992; Tinner et al., 2009; Henne et al., 2015).

In the Palavas record the deciduous/evergreen *Quercus* ratio displays a regular decrease through the sequence which could result from the Late Holocene aridification trend (Fig 3). However, after 2000 cal BP, deciduous and evergreen *Quercus* forests both decline at the same time. This simultaneous decline of evergreen and deciduous *Quercus* is not consistent with variations driven by the increasing aridity. Moreover, no correlation can be found between increases in evergreen *Quercus* proportions and the short arid events discussed before (Figs. 2 and 3) which conversely correspond to deciduous *Quercus* increases. The transition from deciduous to evergreen forest is not clearly recorded in Palavas before the last century. Therefore climate variability cannot explain alone the evergreen *Quercus* dynamic around the Palavasian wetland complex, and other factors have to be considered.

6.2. Influence of human societies on forest composition before Classical Antiquity

At the end of the Neolithic, between 4500 and 4000 cal BP, the decrease in the deciduous/evergreen *Quercus* ratio might be the first evidence of anthropogenic impact on Mediterranean forest composition (Pal-I in Fig 2 and event a in Fig. 3). In fact, more than a hundred small villages were present during this period in the Palavas region (Jallot, 2011). Farming societies were very wealthy and dynamic with a higher influence and control of the environment than during previous periods (Jallot, 2010). The increase in agricultural activities may thus have favored the evergreen *Quercus*, a tree taxon which is especially resilient to high frequency disturbances (Barbero et al., 1990).

After 3300 cal BP, at Port Ariane (Chabal, 2007) and Tonnerre I (Cavero et al., 2010), the anthracological records display higher abundances of evergreen *Quercus* in comparison to the Palavas pollen data (Figs. 2 and 3). These results illustrate the over-representation of evergreen *Quercus* in the areas surrounding human settlements during Bronze Age and confirm that evergreen *Quercus* forests were already favored by humans.

Between 2800 cal BP and 2000 cal BP, the deciduous/evergreen *Quercus* ratio decreases again (event b in Fig. 3). At that time, evergreen *Quercus* dominates the Port Ariane and Lattara anthracological assemblages (event b in Fig. 3) (Chabal, 2007; Jorda et al., 2008). Evergreen *Quercus* abundance around archeological sites reinforces the link between increases in evergreen *Quercus* pollen and the enhanced anthropogenic influence since 2800 cal BP. These changes correspond to the Bronze Age/Iron Age transition, a crucial period in Languedoc prehistory. During the Iron Age, the coastal area around the Palavasian lagoons became an important trading area with Mediterranean civilizations. The development of Lattara city near the lagoon shores attests to the significant increase in human activities between 2500 and 2000 cal BP (Cavero et al., 2010). Nevertheless, the second arid event recorded between 2800 and 2400 cal BP in the Palavas sequence may have triggered forest changes or exacerbated human impact on vegetation. As well as changes in forest composition, human activities also began to affect forest cover through deforestation.

6.3. Classical Antiquity

During Classical Antiquity, the maximum expansion of forest recorded at Palavas (event c in Fig. 3) does not seem to fit with widespread economic development in the Languedoc. However, settlements migration from the hinterland to the coast, beginning during the Iron Age, allowed forest expansion in the hinterland. Archeologists observed a decrease in the number of small settlements in mountainous areas while the coastal cities such as Lattara expanded (Janin, 2010). Thus, during Classical Antiquity, most of the *villae* in this part of the Languedoc were located in coastal plains (Ouzoulias, 2013; *carte archéologique nationale BD patriarche* http://www.villa.culture.fr/#/fr/annexe/ressources/t=Ressources). Therefore the forest expansion possibly corresponds to forest recovery in the mountains which were less densely populated at this time. Reforestation was probably also favored by enhanced humidity attested by the relative importance of *Fagus* in the deciduous forest (Fig. 2).

6.4. Transition between Classical Antiquity and Early Middle Ages

The collapse of the Roman Empire is generally considered to have been a major crisis of the rural world, leading to widespread land abandonment and reforestation (Kaplan et al., 1994). However, the Palavas pollen record clearly shows a major deforestation (event d in Fig. 3), which is consistent with the most recent historical and archeological studies carried out in the Languedoc, but does not support the theory of a major crisis. Historians now interpret the decrease in *villae* (roman farms) numbers at the end of Classical Antiquity as the result of an agrarian system transformation in the Gallia Narbonensis province. Numerous small *villae* were replaced gradually by larger ones, fewer in number but less vulnerable to economic hazards. At the beginning of the 5th century (1550 cal BP), while the number of *villae* sharply decreased in the Languedoc, important extensions of the Loupian *villae* (Fig. 1) are recorded on the lagoon shore (Schneider et al., 2007). Moreover recent archeological excavations in this area have discovered a new type of rural housing which developed during the Early Middle Ages on, and alongside, the former Roman territorial network. Two new settlements of this type were founded near abandoned *villae* in Lune-Viel and Verdier between the 4th to the 5th centuries (Fig. 1) (Schneider et al., 2007). During the same period, the Roc de Pampelune village started to develop in the mountains where territories were free of human occupation during Classical Antiquity (Fig. 1) (Schneider et al., 2007). Finally a new diocese was established in the 6th century in La Maguelone isle (Fig. 1) (Schneider, 2008). In such a context of human occupation, the major deforestation event recorded at Palavas (Figs. 2 and 3) is consistent with the archeology, which provides evidence of a very dynamic rural world despite the collapse of the Roman Empire.

6.5. Crisis of the rural world ?

Following the major forest decline associated with Classical Antiquity-Early Middle Ages transition, significant reforestation occurred between 1300 and 1200 cal BP (650 and 750 cal AD) (Pal VII in Fig. 2 and event e in Fig. 3). This event timely coincides with a gap in the archeological record between the 7th and the 8th centuries. In fact, during this period, many archeological settlements are abandoned in the Languedoc. For instance, Roc de Pampelune village and Dassargue farm, near Palavas, were abandoned between 1350 and 1300 cal BP (600 and 650 cal AD) while new settlements were founded in their vicinity approximately one hundred years later (Schneider et al., 2007) (Fig. 1). For now, this settlement abandonment alone does not demonstrate a rural decline at this time (Schneider et al., 2007). On the other hand, the reforestation recorded in the Palavas pollen sequence attests to a major crisis during this period and confirms that human activities caused forest loss before the 7th century (Fig. 3). This reforestation is characterized by an important increase in most of deciduous trees pollen proportions including deciduous *Quercus*, but excepting *Fagus* which display very low abundances related with the arid event 1 discuss previously (Fig. 2). In spite of the Late Holocene aridification and the arid event 1, the increase in deciduous *Quercus* indicate that climatic conditions in the hinterland were still favorable to deciduous forest development except *Fagus*.

6.6. The High Middle Ages

During the High Middle Ages (11th, 12th and 13th centuries), new types of human settlements are identified in the Languedoc (Durand, 2003; Schneider et al., 2007). Historical studies have identified 128 new fortified villages (*castra*) in the region with at least eight of them within the watershed of the Palavasian lagoon. Thirty three new (or innovative) rural settlements called "*Mansus*", specifically located in or close to recently deforested areas, were located near Palavas. Two major abbeys were established at Aniane and St-Gilhem and developed intensive land use practices. Feudal lords deforested river banks to extend their lands in order to grow cereals. At least 27 of these cereal fields were present along the Mosson and Lez rivers. Finally the city of Montpellier was also established during this period and became an important city in France in the 13th century (Britton et al., 2007). These settlement expansions explain the major forest loss (event f in Fig. 3) and the evergreen shrubland extension (Fig. 2) recorded in the Palavas pollen record from 1150 to 850 cal BP (from ca. 800 to 1100 AD). Historical and palynological studies both highlight the strong human influence on the environment during the High Middle Ages.

Just like during the reforestation of the 7th and 8th centuries, *Fagus* abundance changes around 1100 cal BP are not consistent with variations in proportions of other forest taxa. *Fagus* is the only pollen taxa which display a significant increase at this time (Fig. 2). Though *Fagus* may be affected at that time by human activities, the decorrelation between *Fagus* signal and the anthropogenic vegetation changes reinforce the interpretation of *Fagus* as a good climate indicator until this approximate date. However, after 1100 cal BP *Fagus* proportions increasingly drop. Human impact on forest taxa should be too strong and *Fagus* can no longer be used as an aridity proxy.

6.7. Cultivated plants record

The first evidence of *Cerealia*-type pollen recorded in the Palavas pollen sequence at 4400 cal BP (Fig. 2) is congruent with the Embouchac pollen record, attesting to cereal cultivation in the vicinity of the lagoon shores by Neolithic populations (Puertas, 1999) (Fig 1). Later, during the Middle Ages (Fig. 2), the maximum of *Cerealia*-type pollen correlates with the strong anthropogenic impact associated with the cereal fields planted along the Mosson and Lez rivers flowing into the lagoon (Fig. 1) (Durand, 2003).

In the archeologial record, evidence for grape cultivation occurs from the Iron Age and accounts for the presence of *Vitis* pollen after 2500 cal BP (Alonso et al., 2007, 2008). Earlier, *Vitis* pollen grains may originate from wild grapes naturally growing in this area (Ali et al., 2008). Moreover archeobotanical studies demonstrate that Neolithic and Bronze Age populations were gathering wild grapes and thus may have favored this taxon near the lagoon (Alonso et al., 2007, 2008; Chabal and Terral, 2007).

Before Classical Antiquity, it is assumed that the few *Olea* pollen grains found at Palavas (Fig. 2) refer to wild olive trees probably present in narrow thermomediterranean coastal areas. The later continuous record of *Olea* since Classical Antiquity (Fig. 2) is probably related to its introduction and cultivation by the Romans in southern France (Leveau, 2003). However at Palavas, low proportions of *Olea* are recorded throughout the first millennium AD. Indeed, various archeological archives attest to limited cultivation of olives in this area during the Roman period (Alonso et al 2008, Leveau 2003). Historical studies demonstrate that olive cultivation developed later in Languedoc, during the High Middle Ages (Leveau 2003) in agreement with our pollen data (Fig. 2).

During the medieval period, simultaneous increases in *Juglans* and *Castanea* with *Olea* (Fig. 2) suggests an expansion of tree cultivation and corroborates the major influence of human activities on the environment in the Palavas region around 1000 AD.

6.8. Reforestation during the last century

At the beginning of the 20th century , the major reforestation with evergreen *Quercus* and *Pinus* recorded at Palavas is consistent with land registry data which indicate that forest cover increased from 80 000 to 190 000 ha between 1900 and 2000 AD in the French department of Hérault (Koerner et al., 2000). This change corresponds to the well-known industrial revolution, which resulted in migration of rural populations towards cities, and to widespread land abandonment. The mechanization of farming at the beginning of the 20th century amplified the abandonment of land unsuitable for modern agriculture, which was consequently recolonized by the forest.

6.9. The deciduous forest replacement

During the 20th century reforestation, *Pinus* and evergreen *Quercus* proportions rise while deciduous *Quercus* proportions remain stable (Pal-VIII in Fig 2 and Fig 3). The expansion of evergreen *Quercus* and *Pinus* forest has no equivalent in the past. Indeed at the end of the 9th century, after one hundred years of reforestation the dominant taxon was still deciduous *Quercus*.

Differences between the reforestation dynamic of the 20th century compared to that of the 9th century might be related to the Late Holocene aridification. During the last one thousand years, the enhanced dryness could have favored *Pinus* and evergreen *Quercus*. However, ecological studies in southern France demonstrate that in the near future *Quercus pubescens*, the present deciduous species in this area, could replace *Quercus* ilex and *Pinus halepensis* in many places (Bacilieri et al., 1993). Indeed, *Pinus halepensis* is a pioneer species of Mediterranean ecological successions that will typically be replaced by *Q. ilex*. Furthermore, it is known that *Q. ilex* inhibits the germination of its own seeds and not those of *Q. pubescens* (Barbero et al., 1990; Bran et al., 1990; Bacilieri et al., 1993; Li and Romane, 1997). Such processes of auto-allelopathy enable the replacement of *Q. ilex* by Q. pubescens. Vegetation surveys over several decades show that without any human disturbances the proportions of *Quercus pubescens* in the vegetation increase (Barbero et al., 1990).

Therefore the *Pinus* and evergreen *Quercus* expansion is more likely related with enhanced anthropogenic impact on forests. Indeed *P. halepensis* was widely planted (Barbero et al., 1988) and coppicing was widespread in southern France during the first half of the 20th century (Ducrey, 1988; Barbero et al., 1990; Koerner et al., 2000). As a consequence of coppicing, *Quercus pubescens* has been supplanted by *Q. ilex* as the deciduous oak is less efficient for resprouting and thus less resilient to high frequency disturbances such as forest harvesting compared to the evergreen oak (Barbero et al., 1990). Similar situations where the present Mediterranean vegetation is strongly shaped by recent human activities more than climatic factors are also recorded in Italy (Henne et al., 2015).

7. Conclusion

Based on the Palavas pollen record, vegetation changes highlighted during the last 4600 cal BP are interpreted in terms of climate and/or human influence and indicate:

A clear aridification trend from 4600 cal BP to the present-day expressed through the range contraction toward the north in *Fagus* and *Abies*.

Three short arid events which interrupt the general trend at 4600-4300 cal BP, 2800-2400 cal BP and 1300-1100 cal BP. These events coincide in time with rapid climatic events that occurred during the late Holocene. The closeness in time of arid events with high storm activity periods within the Bond windows, suggests a two phases pattern with a humid phase followed by an arid one.

Oscillations of evergreen *Quercus* representation and arboreal pollen proportions mainly correlated with human history. Firstly farming activities favored evergreen *Quercus* since the Neolithic, gradually changing the forest composition. Secondly three deforestation episodes are depicted 1) from the Bronze Age to the end of the Iron Age, 2) at the transition between Classical Antiquity and Middle-Ages and 3) during the 9th century. Between the two first episodes, Classical Antiquity is characterized by a major reforestation related to the concentration of rural activities and populations in plains leading to forest recovery in the mountains. At the beginning of the 20th century, a new reforestation occurred due to farming mechanization. Evergreen *Quercus* and *Pinus* expansion is related to coppicing and the increase in fire frequency.

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Table caption

Table 1. Short description of the PB06/EG08 pollen diagram zonation

Figure caption

Figure 1. Geographical settings: (a) Studied cores, main cities and rivers, topography and archeological sites mentioned in the articles. (b) Vegetation map showing the distribution of forest types by dominant taxa (data from the National forestry inventory, IFN BD forêt 1).

Figure 2. Pollen diagram of the cores PB06 and EG08. Pollen curves are presented in calendar year BP (correspondence between age and depth is presented on the left). On the right of the diagram are represented the pollen zones.

Figure 3. Comparison of the pollen data from the core PB06 and EG08 with anthracological and climatic data. Orange shaded bars represent arid events and grey shaded bars represent high storm activity periods. i) Arboreal pollen proportions; ii) Proportion of cultivated taxa; iii) proportions of both *Quercus* type charcoals in Lattara and Port Ariane archeological sites; iv) logarithm of deciduous/evergreen *Quercus* (orange) and *Fagus*/deciduous *Quercus* (blue) ratios, after ~1100 cal BP (10th century) the *Fagus*/deciduous *Quercus* ratio (in dotted light blue) cannot be interpreted in term of climate fluctuations because of the strong human influence; v) Smectite/Illite+Chlorite ratio in the core PB06 (Sabatier et al., 2012); vi) Calderone glacier expansion periods in the Apennines : the width of each blue box represent the estimated time during which the glacier expand (Giraudi et al., 2011); vii) Proportion of hematite stained grains in the cores MC-52/VM29-191 in the north Atlantic (Bond et al., 2001); viii) ^{14}C production rate (Bond et al., 2001).