Journal of Arid Environments 124 (2016) 102–110

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Dendroclimatology and wheat production in Algeria

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ARTICLE INFO

Article history:
Received 18 September 2014
Received in revised form
21 February 2015
Accepted 29 July 2015
Available online 14 August 2015

Keywords:
Tree ring
Drought
Seascorr
Agriculture
Reconstruction

ABSTRACT

Drought is one of the main natural factors in declining tree-ring growth and the production of agricultural crops in Algeria. This paper addresses the variability of growing conditions for wheat in Algeria with climatic data and a tree-ring reconstruction of January–June precipitation from ten *Pinus halepensis* tree-ring chronologies. A regression-based reconstruction equation explains up to 74% of the variance of precipitation in the 1970–2011 calibration period and cross validates well. Classification of dry years by the 30% percentile of observed precipitation (131 mm) yields a maximum length of drought of five years (1877–1881) and increasing frequency of dry years in the late 20th and early 21st centuries. A correlation-based sensitivity analysis shows a similar pattern of dependence of tree-growth and wheat production on monthly and seasonal precipitation, but contrasting patterns of dependence on temperature. The patterns are interpreted by reference to phenology, growth phases, and – for wheat – agricultural practices.

1. Introduction

The relationship between agriculture and climate in North Africa, specifically in Algeria, is complex and complicated by economic factors. Drought is a main natural factor in declining production of wheat and barley, the major crops in Algeria. These crops represented 63% of all cultivated areas in 1987 (Metz, 1994). Benbelkacem and Kellou (2000) reported that *Wheat durum* represents 46% of grain crops in Algeria. Algeria, with a population of 35 million, is one of the world's biggest importers of grain. On average, 5 million tons of grain was imported over the past five years; peak imports reached 7.4 million tons in 2011 and 6.9 million tons in 2012. Grain self-sufficiency dropped from 91% at independence, in 1962, to 18% in 1990 (Chikihi, 2013). Smadhi and Zella (2009) reported that rain self-sufficiency was 25% from 1970 to 2007. Several other factors, including population and demand increase, agriculture mismanagement, and rural migration to urban centers, have contributed to the drop in crop production. Grain production dropped 25 percent between 1986 and 1990, but returned to a record level in 1991. Regardless of the rebound in production, Algeria continues to import 75 percent of its grain needs. The European Community is the major supplier of barley. Corn imports also doubled between 1985 and 1990, with the United States providing 75 percent of the total.

Nachit et al. (1998) reported that drought can cause yield losses at any stage of wheat development. The effect of water deficit on crop performance depends on the stage of growth at which the deficit occurs. For durum wheat (*Triticum durum* Desf.) in the Mediterranean region, yield losses due mainly to drought have been reported to vary from 10% to 80% depending on the year.

The effects of severe drought in Algeria are difficult to manage without careful planning. This requires the ability to anticipate climatic variability, especially drought. Skilled management of water and other natural resources requires sufficient information about the probable duration, distribution and intensity of future drought. To understand drought we need to characterize the variability of climate on time scales of decades to centuries. Most of the high-quality instrumental climate records are short, and so contain little information on variability over decades and longer periods. Indirect evidence of climatic variability, such as long time series of tree-ring growth measurements spanning several centuries, may serve as proxy records of past conditions. These series provide us

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http://dx.doi.org/10.1016/j.jaridenv.2015.07.016
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with knowledge of the past frequency and severity of droughts, wet periods, and other climate events, and that knowledge can be applied to anticipate the probability of such events in the future.

The objectives of this research paper are to 1) develop a dendroclimatic reconstruction of precipitation (P) for northeastern Algeria from Aleppo pine (*Pinus halepensis*); 2) characterize the historical occurrence of drought events through the last three centuries; and 3) summarize the statistical relationship between drought events and wheat production.

2. Methods

2.1. Tree-ring data

Ten tree-ring chronologies were developed from field collections in 2006 and 2012. Samples were collected from *P. halepensis*, a tree species with a known high degree of common variation (among trees) strongly driven by climate (Fig. 1 and Table 1). Increment cores were taken at all sites. Samples were fine-sanded and crossdated and ring widths were measured to the nearest 0.01 mm using standard dendrochronological techniques (Stokes and Smiley, 1968).

Each series of measured ring width was fit with a cubic smoothing spline with a frequency response of 0.50 at 67% of the series length to remove trend possibly due to age, size, and the effects of stand dynamics (Cook and Briffa, 1990). The detrended series were then prewhitened with low-order autoregressive models to remove persistence, which was observed to be appreciably higher in the tree-ring series than in seasonal and annual precipitation. The resulting series is called a "residual" index. The individual indices were combined into single averaged chronologies for each combination of site and species using a bi-weight robust estimate of the mean (Cook, 1985). The expressed population statistic (EPS) (Wigley et al., 1984; Cook and Briffa, 1990) was used to identify the period over which chronologies are well-enough replicated to capture the unknown common population tree-ring signal at a site.

2.2. Climate data

Monthly climatic data for six stations distributed over an elevation range 1040–1200 m were obtained from the National Office of Meteorology and the National Agency of Water Resources of Algeria (Fig. 1). The only one of these stations with a reasonably long temperature (T) series is Batna, whose record begins in 1950. A regional monthly P series, 1970–2012, was computed from the six stations by the method of averaged standardized anomalies (Jones and Hulme, 1996) for use in calibration of tree-ring reconstruction models. A climogram of monthly precipitation from the regional series emphasizes the Mediterranean precipitation regime of north–central to northeastern Algeria (Fig. 2).

2.3. Precipitation reconstruction

The relationships between the tree-ring chronologies and climate (regional P and Batna T) were investigated using Seascorr, which computes correlations and partial correlations between tree-ring data and monthly P and T data integrated over seasons of variable length (Meko et al., 2011). The procedure was repeated for the relationship between annual wheat production and climate.

The reconstruction model was developed by linear regression, calibrated and verified on the period 1970–2011. A nested reconstruction was developed to accommodate the varying chronology lengths while exploiting the potential to accurately capture the long-term extreme events history of the region (Touchan et al., 2011, 2014). This procedure also allows for a maximum length reconstruction, although the earliest part of a record may be reduced in robustness because of small sample size. Stepwise regression was used to select predictors for the models. Predictors for the final nested reconstruction models were selected from the full pool of available PCs by stepwise regression with *p*-to-enter and *p*-to-remove set at 0.15. The adjusted R^2 and Mallows's C_p statistic (Mallows, 1973) were used as guides to guard against overfitting. The predictors for the regression models are principal components (PCs) of chronologies when two or more chronologies are available; otherwise the predictor is the single available chronology. The period for detailed analysis of the reconstruction was truncated in accordance with EPS evidence of the reliable portions of component tree-ring chronologies. The strength of the reconstruction model was summarized by regression R^2, and the prediction sum of squares (PRESS) procedure was used for cross-validation (Touchan et al., 2014). The PRESS method is equivalent to leave-one-out cross-validation, in which a model is validated iteratively by repeated calibration and validation, each time leaving one observation out of the calibration set and applying the model to predict the omitted observation. The P data for Batna, which starts in 1930,

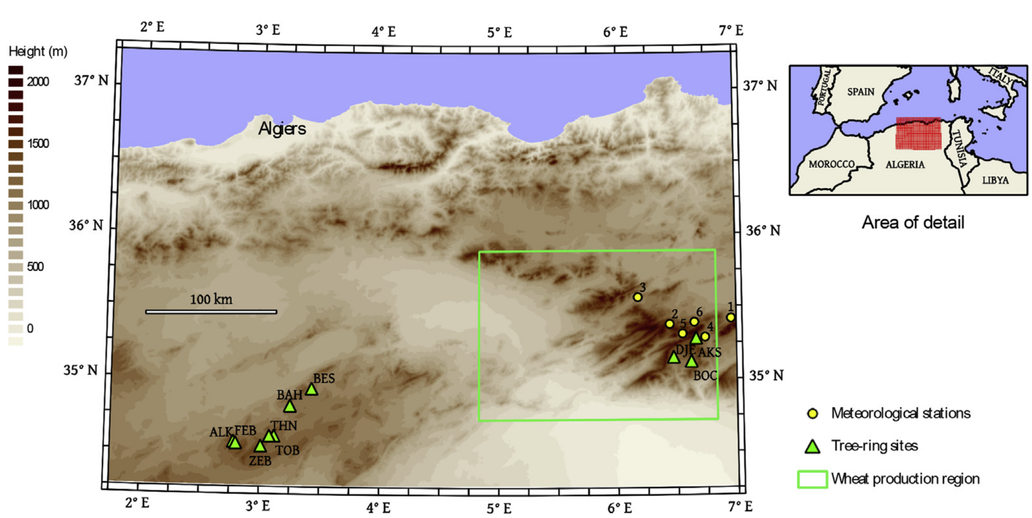

Fig. 1. Map of the area.

Table 1
Pinus halepensis tree-ring chronology sites, listed from north to south.

Site name	Site code	Elevation (m)	Latitude	Longitude	Time Span	Total no. of years	No. of trees	No. of cores
Aksra	AKS	1413	35.28	6.66	1851–2011	161	21	41
Djeniene	DJE	1180	35.15	6.47	1834–2011	178	40	80
Bout-Chaout	BOC	1273	35.12	6.62	1695–2011	317	43	77
Besbassa	BES	1216	34.93	3.43	1887–2011	125	22	43
Bahrara	BAH	1136	34.81	3.25	1875–2011	137	21	44
Tobji	TOB	1390	34.60	3.12	1851–2011	161	40	78
Thniet	THN	1393	34.60	3.08	1830–2011	182	42	83
Faijat El Bagra	FEB	1334	34.56	2.78	1794–2011	218	31	60
Al-Khadra	ALK	1360	34.55	2.80	1853–2011	159	21	44
Zebash	ZEB	1418	34.53	3.01	1835–2011	177	21	41

was used for an additional check on consistency of reconstructed P with observed P prior to the start of the calibration/validation of the reconstruction models.

2.4. Identification of extreme dry and wet events

The short-term drought properties in the January to June P reconstruction were summarized by runs analysis (Sadeghipour and Dracup, 1985), with thresholds for extreme dry and wet years arbitrarily set at the 30th and 70th percentiles of observed P, 1970–2011. The 30th percentile corresponds to 131 mm, or 75% of the mean; and the 70th percentile to 198 mm, or 114% of the mean.

3. Results and discussion

3.1. Tree-ring data

Ten ring-width chronologies (Fig. 1) were developed for use in the reconstructions. Statistics of chronologies are listed in Table 2.The length of the ten chronologies ranges from 125 to 317 years. The mean correlation among individual radii at each site represents the strength of their common signal and ranges from 0.68 to 0.79. The mean sample segment length (MSSL) of the chronologies ranges from 75 to 160 years, and nine have MSSL greater than 100 years. Principal component analysis (PCA) applied to the ten chronologies showed a strong common statistical growth signal for their overlapping years. The first principal component (PC1) of the ten chronologies accounts for 70% of the tree-ring variance.

3.2. Precipitation reconstruction

Seascorr identified January to June total P as the most appropriate seasonal predictand for reconstruction. T influence, summarized by partial correlations in Seascorr, is significant for the single months of May, June, and July. The negative sign of partial correlations for those months indicates that high T exacerbates the negative tree-growth anomaly associated with a given P deficit.

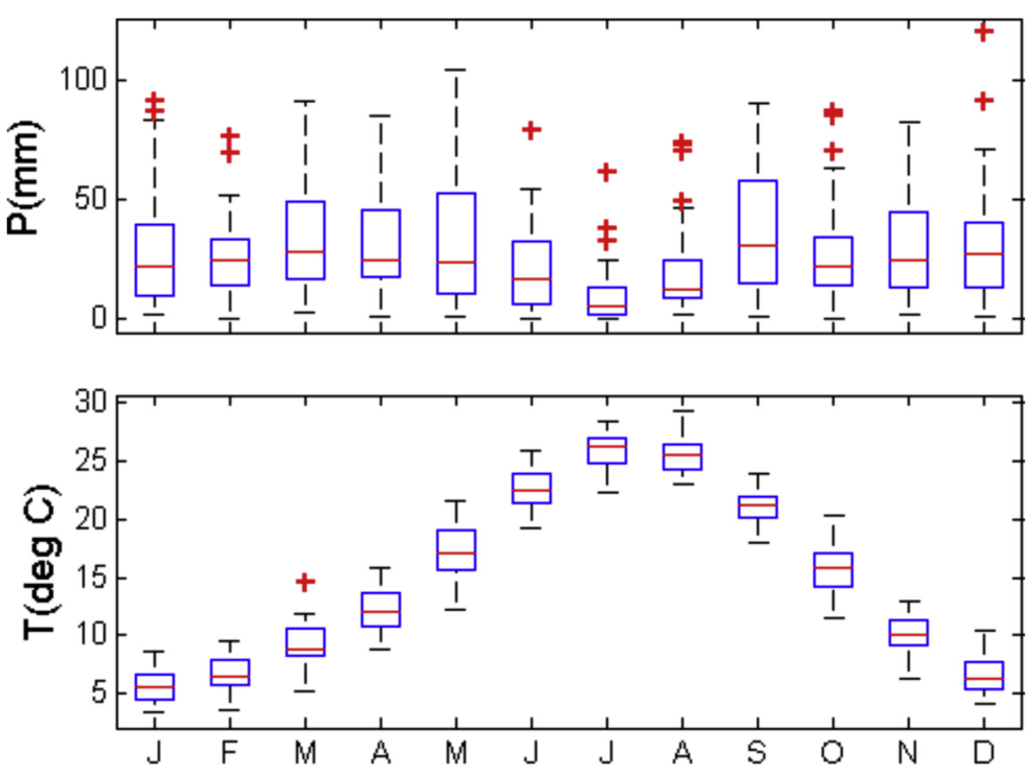

Fig. 2. Climogram of monthly mean precipitation and temperature in Algeria, 1972–2011. Precipitation series developed by standardized anomaly method of six stations. Temperature is based the Batna's climate station.

Table 2
Summary statistics for the ten chronologies from program ARSTAN (Cook and Holmes, 1999; Cook and Krusic, 2005).

Country	Site code	Total chronology					Common interval		
		MSSL[a]	Std[b]	SK[c]	KU[d]	1st year EPS[e] > 0.85	Time Span	MCAR[f]	Ev[g] PC1 (%)
	AKS	113	0.42	0.06	0.31	1856	1906–2010	0.75	76
	DJE	124	0.42	0.36	0.58	1850	1911–2006	0.74	75
	BOC	160	0.49	0.73	2.16	1756	1901–2006	0.76	76
	BES	75	0.39	1.40	5.30	1893	1964–2011	0.79	79
	BAH	102	0.43	0.98	2.11	1883	1915–2011	0.78	79
	TOB	142	0.39	0.53	2.20	1854	1889–2006	0.68	69
	THN	121	0.34	0.78	3.24	1844	1897–2006	0.68	69
	FEB	122	0.42	0.92	2.57	1796	1909–2011	0.76	77
	ALK	115	0.36	0.72	2.74	1866	1924–2011	0.74	75
	ZEB	144	0.38	0.75	2.79	1842	1881–2011	0.75	76

[a] MSSL is Mean Sample Segment Length.
[b] Std is Standard Deviation.
[c] SK is Skewness.
[d] KU is Kurtosis.
[e] EPS is Expressed Population Statistic (Wigley et al., 1984).
[f] MCAR is Mean Correlation Among Radii.
[g] EV is Explained Variance.

January to June total P was adopted as the variable for reconstruction. This P variable has no significant (0.05 level) autocorrelation at lags 1–20 years.

Precipitation was applied in three different reconstruction models with varying time coverage and chronology makeup. The first reconstruction model covers the common period 1887–2011 and the earliest model, based on a single chronology, extends back to 1756. The EPS (Wigley et al., 1984) was used to identify the earliest year for possible reconstruction by the single-chronology model. Stepwise regression with adjusted R^2 and Mallow's Cp (Mallows, 1973) as selection cutoff criteria indicated that PC1 and PC2 should be used as predictors for the models with data beginning in 1888 and 1830. Selection of predictors did not apply to the earliest model (1756 start year) as only one predictor was available. Nested models calibrated on 1970–2011 explain 60–74 percent of the calibration-period variance, according to the regression adjusted R^2 (Table 3). Time plots of reconstructed and observed P for the calibration periods of the three models are included in Fig. 3. The start years of the nested reconstructions are 1756, 1830, and 1888; the number of chronologies contributing to those models is 1, 3 and 10, respectively. For brevity, we refer to the models by start year: M1756, M1830 and M1888. Cross-validation using the PRESS procedure (Weisberg, 1985) indicated that the three models can adequately estimate P data not used to fit the model (Table 3).

Our P reconstruction is significantly correlated with a previous reconstruction of regional October–June P (1771–2002) (Touchan et al., 2008a); May–August PDSI (1756–2002) (Touchan et al., 2008b); and regional May–August PDSI (1756–2002) (Touchan et al., 2011). The correlations respectively are: $r = 0.43$, $n = 232$, $p \leq 0.0001$; $r = 0.80$, $n = 247$, $p \leq 0.0001$; $r = 0.58$, $n = 248$, $p \leq 0.0001$. Our reconstruction includes four updated chronologies that were used in Touchan et al. (2008b) (BOC, DJE, TOB, and THN).

Our reconstruction is also significantly correlated ($r = 0.44$, $n = 30$, $p < 0.013$) with the part of the Batna observed P record prior to the start of the 1930–1969 calibration/validation period of the reconstruction models.

3.3. *Identification of extreme dry and wet events*

The reconstructed January-to-June P time series is plotted in Fig. 4. The reconstruction contains 47 dry years, comprising 37 distinct drought events with a mean recurrence interval of 5.1 years. The number of events classified by durations is as follows: durations of 1, 2, 4, and 5 years have 32, 3, 1, and 1 events, respectively.

The maximum interval between events is 24 years (1881–1905). The two longest droughts are a four-year event in 1999–2002 and a five-year event in 1877–1881. The driest year (62 mm) in the reconstruction is 2002, while the driest year (52 mm) in the observed January–June P data is 1983. The frequency of single dry years increases markedly in the 20th century, and all three of the two-year events occurred in the 20th century.

A five year moving average of the reconstruction demonstrates multi-annual to decadal variation in January–June P and suggests several prolonged wet and dry events (Fig. 4). The driest five-year reconstructed period is 1999–2003 (108 mm). The wettest five-year reconstructed period is 1883–1887 (222 mm), a period of exceptionally high tree-growth. Some parts of the record vary only slightly on multi-decadal scales (e.g., 1965–1995).

A 41-year moving average of the reconstructed drought frequency, restricted to the more robust 1756–2011 part of the reconstruction, shows that the frequency of dry years is highest in the second part of the 20th century (Fig. 5).

Several major historical events coincide with extreme dry periods in reconstruction (De Lartigue, 1904; Boudy, 1952, 1955; Abdessemed, 1981; Turin, 1983). De Lartigue (1904) and Boudy (1952, 1955) reported that drought in 1872–1882 caused the dieback of cedar in the Aures and Belezma forest, and that the effect extended to other parts of Algeria, such as Bou-Thaleb (part of Hodna district, west of Aures and Belezma region). This drought caused the death of 1/3 of the cedar forests. De Lartigue (1904) also mentions that in 1877 an insurrection almost erupted because of the decline in crop production and the spreading famine. This notable period of disturbance is coincident with the longest period of extended extreme drought in the reconstruction (1877–1881). Other authors identified single year short-term events, such as a 1867 drought causing famine, the spread of cholera and the death of 2324 people in the city of Batna (Turin, 1983). Abdessemed (1981) reported that drought and famine in 1871 and 1916 caused a large uprising by the local people.

3.4. *Tree growth and wheat production in response to climate*

3.4.1. *Tree growth response to climate*

3.4.1.1. Precipitation and temperature. Our reconstruction can furnish a better understanding of the potential effect of droughts

Table 3
Calibration and validation statistics for reconstruction models calibrated on period 1970–2011.

Reconstructions model[a]	Variable	Coefficient	Adjusted-R^2 calibration	PRESS	No. of chronologies
M1888	Constant	174	0.74	0.72	10
	PC1(69%)[b]	17.1			
	PC2(17%)	17.2			
M1830	Constant	171	0.70	0.67	3
	PC1(72%)	29.0			
	PC2(21%)	24.6			
M1756	Constant	79.2	0.60	0.57	1
		92.8			

[a] Model coded by start year of segment of reconstruction period. All models.
[b] Proportion of tree-ring variance accounted for.

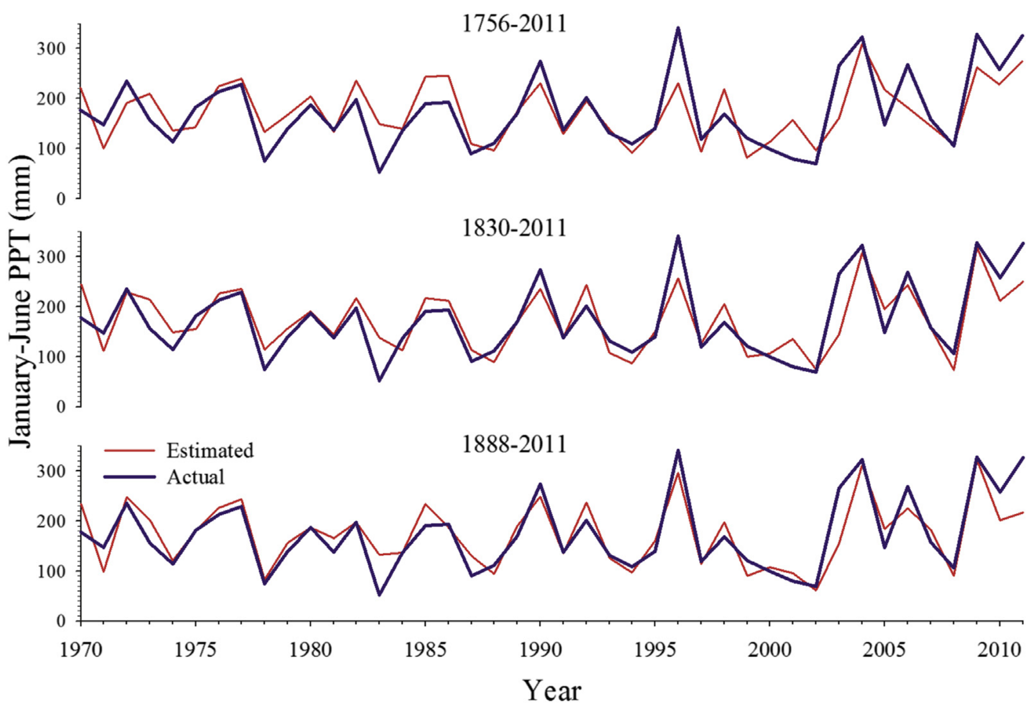

Fig. 3. Time plots of reconstructed and observed precipitation for the calibration periods of the three models. The start years of the nested reconstructions are 1756, 1830, and 1888; the number of chronologies contributing to those models is 1, 3 and 10.

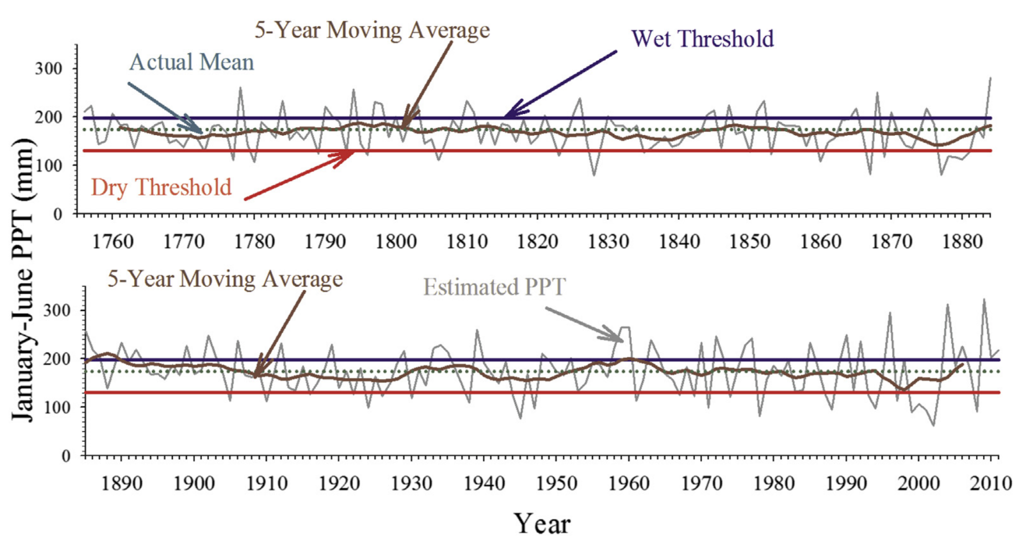

Fig. 4. Time series plot of reconstructed January–June precipitation, AD 1756–2011.

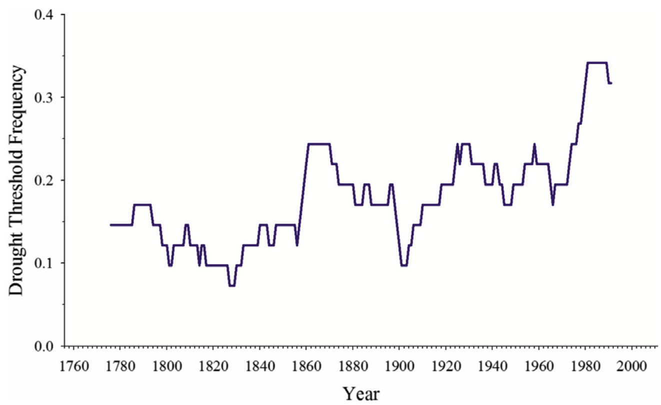

Fig. 5. Time plot of sum of dry years in a moving 41-year window. Sum plotted at center of 41-year period.

and the natural variability of climate on agricultural production. The extreme reconstructed events, in particular, give a temporal perspective on growing-season conditions that have affected wheat production (WP) in the instrumental period. For this assessment, it is also necessary to investigate how tree-ring growth (TRG) and WP differ in seasonal response to climate. Seascorr shows that TRG and WP have roughly the same seasonal response to P (Figs. 6 and 7). However, the seasonal responses of TRG and WP to T differ considerably. The discussion in the following paragraphs elaborates on these relationships.

P. halepensis TRG responds positively to monthly P in the period from August of the previous year to September of the current year (Fig. 6). The significant correlation is moderate in the fall of the previous year and high in current winter and spring. The highest monthly correlation is reached in January, but remains strong in March, April and May. The correlations of TRG with P are not significant in summer.

The positive correlation of TRG with previous October P is likely explained by polycyclism, the ability of a plant to produce several flushes in the same growing season. Polycyclism is characteristic of *P. halepensis* (Girard et al., 2011), and may be associated with a flush of new needles in October in response to P. These needles contribute to photosynthesis and the building of carbohydrate reserves needed to support the spring-season flushes and promote photosynthesis in the growing season. The high correlation of TRG with January P, when the cambium is in the dormant phase, could also be related to photosynthesis or a preconditioning of the photosynthesis in February. Snowpack could also be important to the January and February correlation, as precipitation in January can be stored for later release and watering of the trees by snowmelt at the start of the growing season.

The non-significant effect of February P on TRG may be spurious, but may indicate that trees use more stored carbohydrate than immediate photosynthate at the start of growing season. It may also indicate that stored soil moisture is already sufficient to allow a break of dormancy and release of stored carbohydrate (Henderson and Grissino-Mayer, 2009). The rainfall of late winter and spring exerts a strong positive effect on TRG through the formation of new needles starting in March or earlier because cambial activity early in the growing season relies more on current photosynthate than on stored carbohydrates. In contrast, cambial activity later, during the dry and hot summer, relies largely on stored carbohydrates. Henderson and Grissino-Mayer (2009) reported that earlywood formation in *Pinus palustris* is strongly correlated with spring P and that latewood formation depends heavily on current summer P.

The correlation between summer P and TRG is weak, probably because storms in summer are infrequent and high in intensity. High intensity of rain favors surface runoff over infiltration of water into the soil; a large proportion of the water is lost to runoff rather than supplied to the root zone of the tree.

Partial correlation between TRG and T is significant only in May–June, and then it is negative (Fig. 1). Even when not significant, T correlation is predominantly negative throughout the growing season. Low T (cool temperatures) helps offset water deficiency in this period by decreasing the evapotranspiration. The negative correlation is strongest in May, June and July, the period of full cambial activity. T affects photosynthesis in trees by regulation of respiration, transpiration and gas exchange, and high T tends to favor respiration over net carbon assimilation (Foster and Brooks, 2001; Kozlowski, 1971).

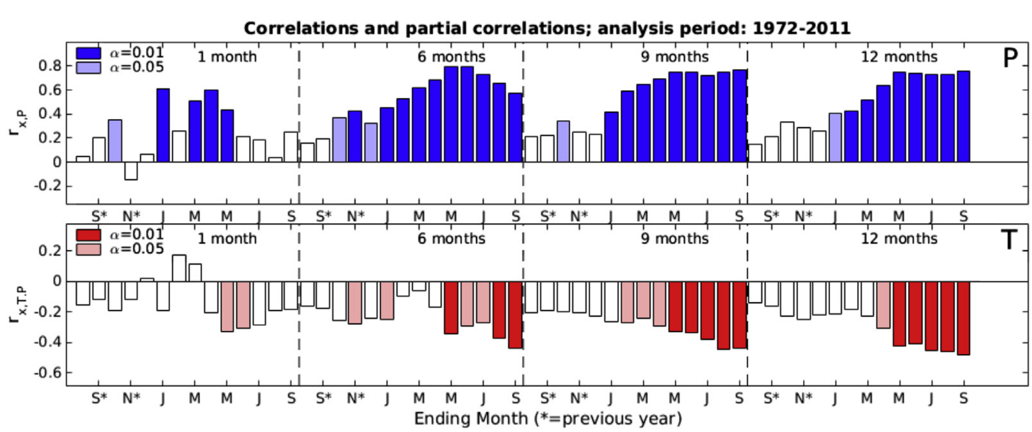

Fig. 6. Program Seascorr summary of seasonal climatic signal in TRG data. The tree-ring variable is the score time series of the first principal component (PC1) of ten residual tree-ring chronologies (PC analysis described in text). Climatic variables are regional-average monthly precipitation and T. (Top) Correlation of tree-ring variable with monthly, 6-month total, 9-month total and 12-month total precipitation for ending months from August preceding the growth year through September of the growth year. (Bottom) Partial correlations (controlling for precipitation) of tree-ring variable with monthly average T. The y-axis, $r_{x,P}$ for the top plot is the Pearson, or product-moment, correlation between the tree-ring index (×) and monthly or seasonal-total precipitation (P). The y-axis, $r_{x,T.P}$ for the bottom plot is the partial correlation of x with monthly temperature or seasonal-average temperature (T) after both x and T have been adjusted for removal of linear dependence on P. Colors indicate Monte-Carlo-derived significance of correlation or partial correlation (Meko et al., 2011) for α-levels 0.01 and 0.05. Analysis period is tree-ring years 1972–2011. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

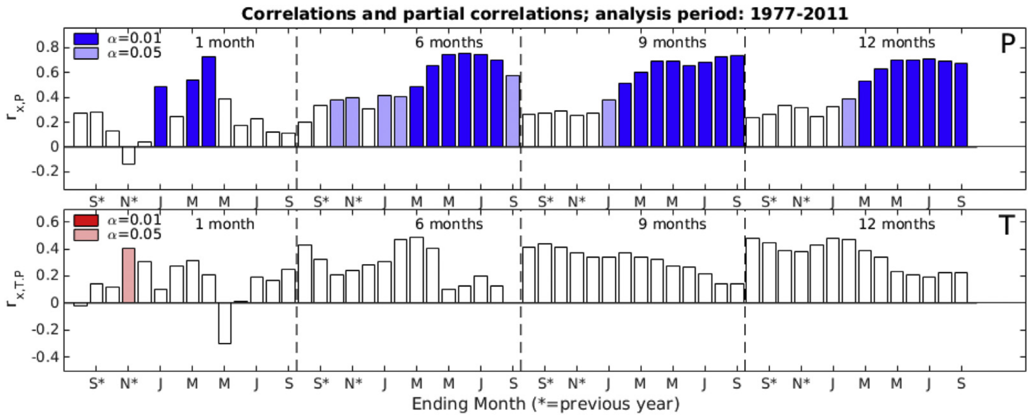

Fig. 7. Program Seascorr summary of seasonal climatic signal in WP data. Climatic variables are regional-average monthly precipitation and T. (Top) Correlation of WP variable with monthly, 6-month total, 9-month total and 12-month total precipitation for ending months from August preceding the growth year through September of the growth year. (Bottom) Partial correlations (controlling for precipitation) of tree-ring variable with monthly average T. Labels of y axes defined as in Fig. 6. Colors indicate Monte-Carlo-derived significance of correlation or partial correlation (Meko et al., 2011) for α-levels 0.01 and 0.05. Analysis period is tree-ring years 1977–2011. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4.2. *Wheat production in response to climate*

3.4.2.1. Precipitation and temperature. While the seasonal responses of WP and TRG to P are similar, the corresponding responses to T differ considerably (Figs. 6 and 7). Except for November and May, WP responds positively to both P and T over the 14-month Seascorr window. WP is determined by the amount of P during the main season (December–February), which affects the available soil moisture during the reproductive period, and is modified by rainfall in April and May (Kayam et al., 2009). The positive relationship between WP, P, and T is related to metabolic processes (chemical and physiological) (Macha and Paulsen, 2001). The growth stages of flowering and fruiting require high soil water content and benefit from high water use efficiency accompanied by suitable T. Water is crucial for this process and it is the only carrier to the outputs of photosynthesis.

The WP response to T and P in November (+T and −P) and May (−T and +P) is different from the response in other months (Fig. 7). In November, the partial correlation of WP with T is significantly positive, and correlation with P is negative, but non-significant. The November correlation signature is explained by the needs of seed germination. While warm temperatures and adequate moisture level favour seed germination and seedling emergence, rainfall at the beginning of November, before plowing and sowing, can delay the sowing date (Baldy, 1974). Delayed sowing (after November), coinciding with cold and frost risks, extends the interval between the sowing and seedling emergence. Moreover, the early physiological processes take longer in cold weather than in warm weather. Gate (1995) reported that the usual interval between the sowing and emergence (under adequate T with early sowing) is about 8–10 days, but can be extended to 30–40 days by low T. Delayed sowing can affect all the yield components by limiting germination and growth process, seedling and leaf emergence, tillering, and likely grain filling, through poor growth of the root system.

The correlation between the WP and P is high from January to April, and especially high in April. Low T and high P in March promote tillering and improved soil moisture, vital for stem elongation and booting/stem-storage. Low rainfall in April can affect ear emergence and cause pollen sterility, reduce the principal yield component (grain number per spike) and the grain yield (Debaeke et al., 1996). Consequently at this time of the year, high T and adequate P are required for high yield.

In May, when grain is filling, the relationship between the WP and T becomes negative because hot weather reduces grain weight by shortening the period of grain growth. The hot weather could be related to the sirocco. This weather feature is characterized by very dry and hot wind from the south (Sahara) that can cause grain scalding and lead to a low yield (Gate et al., 1993; Wardlaw, 2002). Low T prolongs grain filling, and in combination with adequate moisture will increase grain weight (weight of 1000 grains) and give a high yield.

3.5. *Relevance of dendroclimatology to agriculture*

During the Roman Empire (BC 27-AD 467), parts of North Africa were among the richest and most prosperous places in the western world. North Africa was the “granary of Rome” (Reale and Dirmeyer, 2000) North Africa now imports grains, and Algeria is one of the world's biggest importers –an average of 5 million tons in the past five years. Such radical historical changes in grain production depend on many factors, including societal changes, technology, economics and also climate variation. Dendroclimatology in concert with other disciplines can be applied to unravel questions about historical agricultural variations and also about future vulnerability of crop production to climate variation and change.

The reconstruction and climate sensitivity analysis presented here contribute to the understanding of the relationship of wheat production in Algeria to extreme climate events, such as drought. The correlation of annual wheat production with our January-to-June precipitation reconstruction is highly significant ($r = 0.62$, $n = 35$, $p \leq 0.0001$), attesting to a common influence of climate on tree-growth and wheat production (Fig. 8). The seasonal climate analysis, conducted with the aid of Seascorr, also demonstrates that there are important differences in the way wheat production and tree-growth respond to climate, especially to temperature anomalies at seasonal or monthly resolution.

4. Conclusion

Precipitation reconstructed from tree rings provides a baseline for studying past climate variability in Algeria. Calibration and validation statistical analyses indicate high accuracy for reconstruction of precipitation for the six-month interval January–June. In the 255-year tree-ring record, the longest reconstructed drought, defined as consecutive years below the 30th percentile, is five years. A 41-year moving average of the reconstructed drought frequency shows that the frequency of dry years is highest in the second part

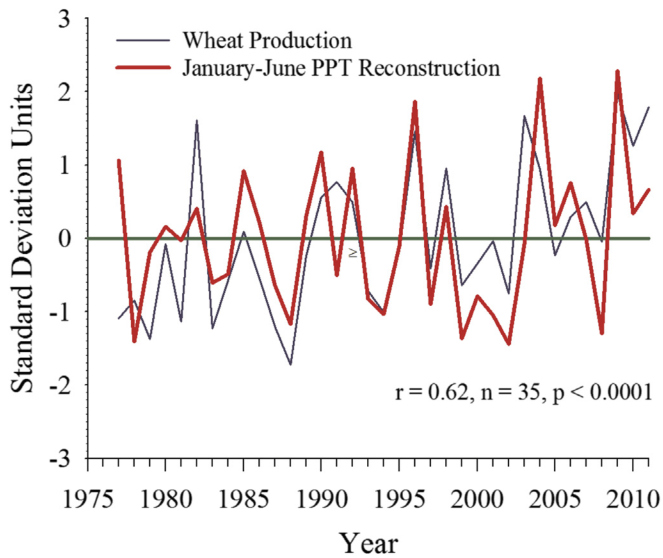

Fig. 8. Annual changes in wheat production and January–June precipitation for the period 1977–2011.

of the 20th century.

This is the first study investigating the relationship between tree-ring-reconstructed precipitation and wheat production in North Africa. Correlation analysis shows that tree-growth and wheat production depend similarly on monthly and seasonal precipitation, but have contrasting patterns of dependence on temperature. The contrasts can be linked to agricultural practices and the phenology of wheat. In applying dendroclimatology to agriculture, it is important to understand differences in the responses of tree growth and crops to climate. The assessment should specifically consider crop phenology and the climate constraints on the particular crop of interest. Our work adds a new dimension to the relationship between dendroclimatology and agriculture.

Acknowledgements

The authors wish to thank our colleagues and various institutions from Algeria: Abdallatif Guasmi (Director of Forest, Batna) and Athmane Briki (Batna Forest Department) for making this study possible, the Directory of Agricultural Services for providing us with the wheat crop data, and the National Office of Meteorology and the National Agency of Water Resources, Algeria, for providing the climate data. We thank Alexis H. Arizpe and Christopher Baisan for their valuable assistance in the field. We thank Jim Burns for his help in dating the tree-ring sites. We thank the numerous student workers who have assisted in sample preparation. We thank Martin Munro for helping with the graphics. Funding was provided by the US National Science Foundation, Earth System History (Award No. 0317288) and Paleo Perspectives on Climate Change (Award No. 1103314).

References

Abdessemed, K., 1981. Le cèdre de l'Atlas (Cedrus atlantica Man.) dans les massifs de l'Aurès et du Belezma. Etude phytosociologique. Problèmes de conservation et d'aménagement. Thèse de docteur ingénieur. Université de Droit d'Economie et des Sciences d'Aix-Marseille, France, p. 201.

Baldy, C.H., 1974. Contribution à l'étude fréquentielle des conditions climatiques : l'influence sur la production des principales zones céréalières d'Algérie. MARA, Projet Céréales, Alger, p. 152.

Benbelkacem, A., Kellou, K., 2000. Evaluation du progrès génétique chez quelques varietés de lé dur (*Triticum Turgidum* L. Var durum) cultivées en Algérie. In: Royo, C., Nachit, M., Di Fonzo, N., Araus, J.L. (Eds.), Durum Wheat Improvement in the Mediterranean Region: New Challenges. CEHEAM, Zaragoza, pp. 105–110 (Options méditerranéennes: Série A. Séminaires méditerranéens; n. 40).

Boudy, P., 1952. Guide du forestier en Afrique du Nord. La Maison Rustique, Paris, p. 505.

Boudy, P., 1955. Economie Forestière Nord-Africaine. Tome 4– Description Forestière de l'Algérie et de la Tunisie. Larose, Paris, p. 483.

Chikihi, L., 2013. Algeria grain Crop Hit by Poor Rainfall, Recovery Seen Possible. http://www.reuters.com/article/2013/04/07/algeria-grain-harvest-idUSL5N0CU09V20130407.

Cook, E.R., 1985. A Time-series Analysis Approach to Tree-ring Standardization. Ph.D. Dissertation. Dept Geosciences, The University of Arizona, Tucson.

Cook, E.R., Briffa, K.R., 1990. A comparison of some tree-ring standardization methods. In: Cook, E.R., Kairiukstis, L.A. (Eds.), Methods of Dendrochronology. Kluwer, Dordrecht, pp. 104–123.

Cook, E.R., Holmes, R.L., 1999. Program ARSTAN – Chronology Development with Statistical Analysis (Users Manual for Program ARSTAN). Laboratory of Tree-Ring Research, University of Arizona, 18 pp.

Cook, E.R., Krusic, P.J., 2005. Program ARSTAN- A Tree-Ring Standardization Program Based on Detrending and Autoregressive Time Series Modeling, with Interactive Graphics. Tree-Ring Laboratory, Lamont Doherty Earth Observatory of Columbia University, Palisades, NY. http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software.

De Lartigue, R.J.F., 1904. Monographie de l'Aurès. Marle Audrino, Paris, p. 493.

Debaeke, P., Puech, J., et Casais, M.L., 1996. Elaboration du rendement du blé d'hiver en condition de déficit hydrique. I. Etude Lysimètres Agron. 16, 3–23.

Foster, T.E., Brooks, J.R., 2001. Lomg-term trends in growth of *Pinus plolustris* and *Pinus elliottii* along a hydrological gradient in central Florida. Can. J. For. Reaerch 31, 1661–1670.

Gate, P., Bouthier, A., Casabianca, H., Deleens, E., 1993. Caractères physiologiques décrivant la tolerance à la sécheresse des blés cultivés en France : Interprétation des correlations entre le rendement et la Composition Isotopique du carbone des grains. Colloque diversité génétique et amelioration variétale, Montpellier (France), 15–17 décembre 1992. Les Colloques, n°64. INRA éditions, Paris.

Gate, P., 1995. Ecophysiologie du blé : de la plante à la culture. Tec et Doc Lavoisier, p. 429.

Girard, F., Vennetier, M., Ouarmim, S., Caraglio, Y., Misson, L., 2011. Polycyclism, a fundamental tree growth process, decline with recent climate change: the example of *Pinus halepensis* mill. in mediterranean France. Trees - Struct. Funct. 25 (2), 311–322.

Henderson, J.P., Grissino-Mayer, H.D., 2009. Climate-tree growth relationships of longleaf pine (*Pinus palustris* mill.) in the southeastern coastal plain, USA. Dendrochronologia 27 (1), 31–43.

Jones, P.D., Hulme, M., 1996. Calculating regional climatic time series for temperature and precipitation: methods and illustrations. Int. J. Climatol. 16, 361–377.

Kayam, Y., Ozsoy, U., Lomas, J., Oden, O., Mandel, M., Gurbuz, M., 2009. The Impact of Climatic Change on Wheat Production of Agean Region in Turkey: the Effect of a Reduction of Rainfall and the Increase of Temperature on Wheat Yields. www.fao.org/sd/climagrimed/pdf/ws01_26.

Kozlowski, T.T., 1971. Growth and Development of Trees: Cambial Growth, Roots Growth, and Reproductive Growth, Vol. II. Academic Press, New York, p. 514.

Macha, S., Paulsen, G.M., 2001. Combined effects of drought and high temperature on water relations of wheat and sorghum. Plant Soil 233 (2), 179–187.

Mallows, C.L., 1973. Some comments on cp. Technometrics 15, 661–675.

Meko, D.M., Touchan, R., Anchukaitis, K.J., 2011. Seascorr: a MATLAB program for identifying the seasonal climate signal in an annual tree-ring time series. Comput. Geosciences 37 (9), 1234–1241.

Metz, H.C., 1994. Algeria: a Country Study. GPO for the Library of Congress, Washington. http://countrystudies.us/algeria.

Nachit, M.M., Picard, E., Monneveux, P., Labhilili, M., Baum, M., Rivoal, R., 1998. Présentation d'un programme international d'amélioration du blé dur pour le bassin méditerranéen. Cah. Agric. 7 (6), 510–515.

Reale, O., Dirmeyer, P., 2000. Modeling the effects of vegetation on mediterranean climate during the Roman classical period Part I: climate history and model sensitivity. Glob. Planet. Change 25, 163–184.

Sadeghipour, J., Dracup, J.A., 1985. Regional frequency analysis of hydrologic multiyear droughts. Water Resour. Bull. 21 (3), 481–487.

Smadhi, D., Zella, L., 2009. Céréaliculture en sec et precipitations annuelles: le cas de l'Algérie du Nord. SECHERESSE 20 (2), 199–203.

Stokes, M.A., Smiley, M., 1968. An Introduction to Tree-ring Dating. University of Chicago Press, Chicago.

Touchan, R., Meko, D.M., Aloui, A., 2008a. Precipitation reconstruction for northwestern Tunisia from tree ring. J. Arid Environ. 72, 1887–1896. http://dx.doi.org/10.1016/j.jaridenv.2008.05.010.

Touchan, R., Anchukaitis, K.J., Meko, D.M., Attalah, S., Baisan, C., Aloui, A., 2008b. The long term context for recent drought in northwestern Africa. Geophys. Res. Lett. 35, L13705. http://dx.doi.org/10.1029/2008GL034264.

Touchan, R., Woodhouse, C., Meko, D., Allen, C., 2011. Millennial precipitation reconstruction for the Jemez mountains, New Mexico, reveals changing drought signal. Int. J. Climatol. 31, 896–906. http://dx.doi.org/10.1002/joc.2117.

Touchan, R., Anchukaitis, K.J., Shishov, V., Sivrikaya, F., Attieh, J., Ketmen, M., Stephan, J., Mitsopoulos, I., Christou, A., Meko, D.M., 2014. Spatial patterns of eastern mediterranean climate influence on tree growth. Holocene 24 (4), 381–392. http://dx.doi.org/10.1177/0959683613518594.

Turin, Y., 1983. Affrontements Culturels Dans L'Algérie Coloniale. Ecoles, Médecines, Religion, 1830–1880. ENAL, Réghaïa, p. 434.
Wardlaw, J.F., 2002. Interaction beween drought and chronic high temperature during kernel filling in wheat in a controlled environment. Ann. Bot. 90, 469–476.
Weisberg, S., 1985. Applied Linear Regression. Wiley, New York.
Wigley, T., Briffa, K., Jones, P., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J. Clim. Appl. Meteorology 23, 201–213.