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Water and Photosynthetic Rate Flows Under Drought Conditions in a Cork Oak (*Quercus suber* L.) Forest of Tunisia

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Abstract

Relationships between drought, carbon and water fluxes have been rarely studied in south Mediterranean forests. The present research focused on the determination of seasonal and annual water and carbon fluxes of *Quercus suber* L. forests in northern Tunisia. The methodology was based on the calculation of the standard precipitation index, measurements of trees sap flow and net photosynthesis. Estimations of photosynthesis and transpiration during the 1965-2003 period were used on crop coefficients and water use efficiency terms.

Results indicate a wide evapotranspiration rates fluctuating from 354 mm y^{-1} to 784 mm y^{-1} with an average value of 553 mm y^{-1}. Extreme values of the standard precipitation index were -2.4 and +2.7. The carbon flux ranged from 0.255 to 0.586 kg y^{-1} m^{-2} with a mean value of 0.448 kg y^{-1} m^{-2} while average water efficiency reached 0.8 gr C kg^{-1} H_2O. Despite the fact, that there is a significant difference between the four studied sites and important annual variability of carbon fluxes, the correlations between water and carbon fluxes and drought index were very low. The results clearly indicate that deep transformations are occurring in the *Quercus suber* L. forests, as a result of carbon dioxide fertilization being cancelled by the drought effect.

Keywords: *Quercus suber* L., draught, net photosynthesis, evapotranspiration, mediterranean forests

1. Introduction

Global climatic models predict a change in rainfall pattern in Tunisia, characterized mainly by a decrease in summer rainfall coupled with greater inter-seasonal and inter-annual variability (IPCC, 2007; Hulme et al., 2001). These previsions for the near future reveal an accentuation of the drought, which means that increasingly longer and more intense dry periods to be expected (Giannkopoulos et al., 2005). The dry period of the year and the succession of two or more dry years would be greater when compared to the reference period (Nasr et al., 2008).

The study of the climate during the last century showed that drought remains a recurring and cyclical phenomenon in Tunisia (Benzarti, 1994). In fact, 50% of dry years were located in North of Tunisia where the climate is mostly humid. Severity of draught is dominated in and it is dispersed within the same region. Hajri (1996) showed that driest years occurred in the 1940s. However, in the 1960s it was more likely of the local type. The phenomenon of the isolated dry year is the most common in Northern Tunisia; it occurred 48% to 66% of the observed period. During the period 1985-1997, the succession of three consecutive dry years was recorded only in Beja province (1987-1990), but no succession of four consecutive dry years has been ever recorded. It is good to notice that the North-West Tunisia area is an important reserve of water and biodiversity. The *Quercus Suber* L. Forest is one of the most fragile ecosystems in this region. This forest has been an alarming deterioration, it now occupies an area of 90 000 hectares against 140,000 hectares 100 years ago (Boudy, 1952). However, it still offers several goods and services to society mainly the photosynthesis carbon capture insured by these forming trees which are threaten by the expected drought and the alteration of water and carbon flows.

The determination and modeling of water and carbon flows have shown the complexity of the exchanges between both forest and atmosphere (Le Dantec et al., 2000; Davi, 2000). These predictive models usually require a lot of data and observations (Dewar, 1992; Granier et al., 2000) of daily weather, soil and vegetation which are often unavailable. In this study, a simple approach based on accurate measurements of evapotranspiration and photosynthesis for a full year and a historical simulation that assumes the consistency of water efficiency and crop coefficient were proposed. The main objectives are both the seasonal determination of flows and their simulation during the period 1965-2003.

2. Material and Methods

2.1 Study Site

The Tunisian cork oak (*Quercus suber* L.) forest is located on the northwest border of the country. It belongs to the humid and sub-humid bioclimatic stage (Figure 1). It is characterized by Mediterranean climate with four seasons where rainfall is mainly concentrated in autumn and winter and dry spring and summer. The maximum precipitations were 1550 mm and the isohyets indicated a strong NE-SW gradient. The landscape of the Kroumerie-Mogods region is typically that of a mountain forest with persevering hardwoods (43%), conifers (8%), maquis and scrubland (49%).

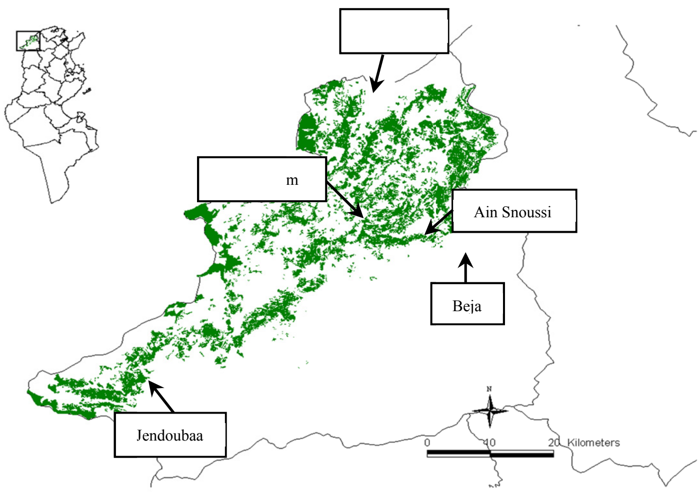

Figure 1. Geographical location of the Tunisian Suberie: experimental site and meteorological stations

The experimental site for the present study was located in Ain Snoussi forest (Lat N: 36°52′, Long E: 8°57′ and Alt: 640 m). This site belongs to the moisture cool winter bioclimatic stage. The average rainfall and temperature were, respectively, 1120 mm and 15.2 °C. The reference evapotranspiration estimated by the FAO-Penman formula is ETo = 1100 mm. The density of this forest varied greatly from 150 to 400 trees ha^{-1}. The soil is loam and rather deep with limited water reserves, Pf (0.3) = 15%; Pf (4.2) = 28%; Bulk density, ds = 1.35. A plot of 30mx30m oriented south-east was chosen. The perimeters of trees measured at 1.30 m from the ground vary from 70 to 130 cm. The average height of the trees was 10.3±1.2 m. The undergrowth is dominated by annuals and some shrubs. Vegetation cover was estimated at 78% during the wet season and 42% in the dry season. Eight trees, two per diameter class were chosen to measure sap flow and photosynthesis during the 2008 and 2009 season.

2.2 Measurements and Treatment of Climate Data

In Ain Snoussi, a HOBO weather station provides continuous measurements of air and soil temperatures (°C), solar radiation (µmol m^{-2} s^{-1}), wind speed and direction (ms $^{-1}$ and degree), relative humidity (%). An appropriate computer program allows calculation of sap flow as well as reference evapotranspiration (ETo, mm j^{-1}) using the FAO formula (Allen et al., 1996).

Historical temperature and precipitation data for representative forest stations (Table 1); Beja (BJA), Jendouba (JND), Ain Drahem (ADH) and Tabarka (TAB) were collected from the database of the National Institute of Meteorology of Tunis for the period 1965-2003. The temperature data (min and max) were used to calculate the reference evapotranspiration (Allen et al., 1996). The monthly precipitation was used to estimate the drought Index, SPI (Standard Precipitation Index) defined by McKee et al. (1993).

Table 1. Geographical Characteristics, temperature (°C) and mean precipitations (mm) of stations during the period 1961-1990

Stations	Lat N	Long E	Alt (m)	Tn (°C)	Tx (°C)	Rainfall (mm)
ADH	36°47'	8°43'	715	10.6	17.9	1488
BEJ	36°44'	9°11'	360	10.5	23.9	557
TAB	36°57'	8°45'	166	13.1	22.9	961
JND	36°29'	8°48'	143	11.1	25.2	460

2.3 Measurement of Sap Flow, Photosynthesis and Soil Moisture Content

Four trees were equipped with thermal sensors to continuously heating Granier. Tree diameters were between 20 and 40 cm. 2 cm deep is too shallow even after bark removal. Needles 5 and 10 cm long are available. The sensors were protected against radiation by an aluminum film. An acquisition unit type ΔT ($DL2^{-e}$) continuously (every 30 sec) measures signals that are averaged over 1 hour and stored in memory. The calibration equation established by Granier (1987) was used to calculate flow density;

$$SFd = 136.828K^{1.2997} \quad (1)$$

The index K of flux calculated by the formula;

$$K = \frac{dT_o - dT}{dT_o} \quad (2)$$

Where, SF_d: flow density (10^{-6} m/s); dT_o: temperature different (°C) when flow is zero, late night in wet period; dT: temperature difference for a positive flow density (°C).

An empirical relationship established in the study area connecting the tree diameter (DBh) to the sapwood section Sa (r = 0.65) by core sampling was used to calculate the daily flow;

$$Sa = 1.058DBh^{1.2889} \quad (3)$$

The average transpiration of the trees (Tr, mm j^{-1}) was calculated by weighting the DBhi of the tree i. The total daily flow was found by integrating the hourly flows and weighting by the diameters of the trees.

$$\frac{\sum_{i=1}^{i=4} SFDi \times DBHi}{\sum_{i=1}^{i=4} DBHi} \quad (4)$$

Soil water content was measured monthly by a TDR30 at depths of 10 and 30 cm at eight points, thus integrating the undergrowth cover. A simplified water balance was calculated on the 0-40 cm layer based on the soil field capacity value and precipitation recorded at the same site.

$$\Delta S = Es + P - D \pm R \quad (5)$$

Soil water content was measured monthly by a TDR30 at two depths (10 and 30 cm) at eight points, thus integrating the undergrowth cover. A simplified water balance was determined on the 0-40 cm layer based on the soil field capacity value and precipitation recorded at the same site.

The measurements of net photosynthesis were carried out on the eight trees chosen, for a full year by choosing to make these measurements in 5 typical days of each season of the year.. Net photosynthesis was measured by a Li-COR6400 device (Nebraska, USA) on the 4th leaf of young twigs, one from each orientation (North and South) (Nasr et al., 2012). The measurements included sun lit leaves (Pns), leaves in the shade (Pno) and dark respiration measurements (Rn). The total resulting was then calculated assuming equal leaf surfaces in the sun and leaves in the shade, such as:

$$Pn = \frac{Pns + Pno}{2} + Rn \quad (6)$$

2.4 Estimates of Seasonal Photosynthesis During the Climatic Period 1965-2003

Seasonal values of water efficiency, EUE = Pn/Tr and evapotranspiration coefficients, KT = Tr/ETo and KTo = (Tr + Es)/ETo were determined from the measurements made in the station of Ain Snoussi during the year 2008-2009. These values of EUE, KT and K To have been adapted after adjustment for the BJA, ADH, TAB and JND stations by a ratio of the vapor pressure deficits between that of Ain Snoussi and those of the other stations for the 2008-2009 periods. This assumes that the CO_2 and H_2O gas exchanges are essentially controlled by the stomatal conductance via the vapor air pressure deficit. These seasonal ratios ranged from 0.31 to 1.19. Thus, from the monthly temperature and precipitation data for the 1965-2008 periods, the terms SPI, ETo, ET and Pn have been calculated for each season and each station.

$$
\begin{aligned}
&P \succ K_{To}.ET_o \Rightarrow ET = K_{To}.ET_o \\
&P \leq K_{To}.ET_o \Rightarrow ET = P \\
&P_n = EUE.K_T.ET_o
\end{aligned} \tag{7}
$$

2.5 Statistic Analysis

SAS GLM procedure was performed for all collected data using the. The comparison of averages was performed by The Newman-Keuls test at the 5% risk threshold.

3. Results

3.1 Seasonal Photosynthesis and Evapotranspiration Values

Seasonal mean values of tree transpiration (Tr) and evapotranspiration of the undergrowth (Es) showed that maximum values were reached in spring being 1.4 mm/d and 1.3 mm/d, respectively (Figure 2). There was also a significant decrease in term of evapotranspiration and a slight decrease in tranpiration amounts during the summer season. It was recorded that annual water consumption of trees was 342 mm and evapotranspiration of undergrowth was 192 mm. For the growing season March-October, the tree transpiration (from trees sap flow) and the evapotranspiration (from soil water content variation) of the undergrowth were about 308 mm and 80 mm, respectively.

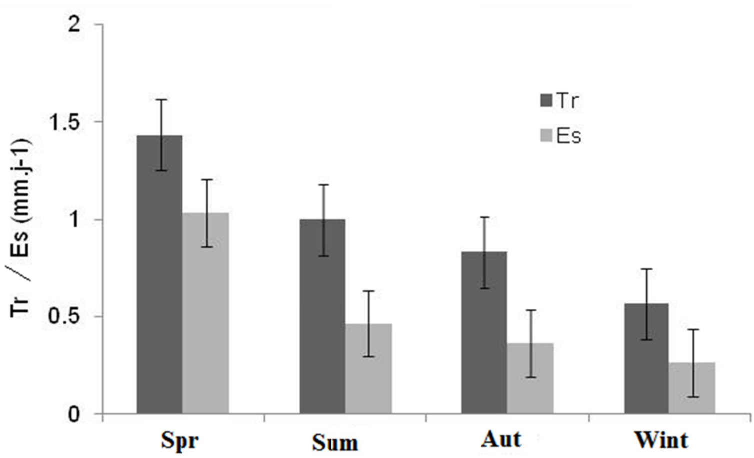

Figure 2. Seasonal evolution of tree transpiration and evapotranspiration of the undergrowth measured in a cork oak forest in northern Tunisia (2008-2009)

The highest values of the net photosynthesis were recorded in spring, with a mean value of 9 µmol m^{-2} s^{-1} for leaves in the sun in comparison with 4.3 µmol m^{-2} s^{-1} for those in the shade (Figure 3). During the dry season, there was a significant decline in net photosynthesis. Hereafter, net photosynthesis has increased significantly following probably the autumn rains to fall in winter as a consequence of lower temperature. Furthermore, nighttime breathing was maximal in summer, lowest in winter and average in autumn. The recorded values did not exceed (-2) µmol m^{-2} s^{-1}.

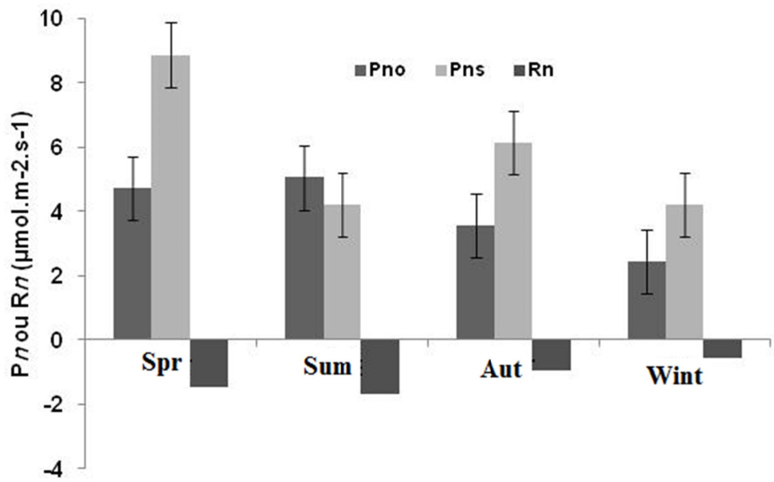

Figure 3. Seasonal values of Pno, Pns and Rn in a cork oak forest in northern Tunisia (2008-2009)

3.2 Historical Analysis of Drought and Seasonal Flows in 1965-2003

The estimation of drought by SPI showed very few wet years, 2 years at ADH. Normal years were dominant in 65% of cases (Table 2). However, we can note that a number of very dry years are more than very wet ones. Then, we showed an asymmetry between the numbers of dry and wet years which the percentages varied from 9 to 20%.

Table 2. Percentage of dry and wet years according to the SPI drought index for the 4 stations (TH: very wet year, H: wet year, N: normal year, S: dry year)

Stations	TH (Spi > 2)	H (1 < Spi < 2)	N (-1 < Spi < 1)	S (Spi < -1)	TS (Spi < -2)
TAB	0	20%	65%	12%	3%
ADH	2%	9%	67%	14%	5%
JDB	0	14%	67%	19%	0
BJA	0	18%	64%	18%	0

The analysis of simulated Fc fluxes showed to be greater in autumn and spring comparing to winter with the summer flows being the lowest (Figure 4). Summer fluxes are also the least variable from year flow to another. The most variable flows are those of the winter season where we note an increase in the carbon flux during mild winters such as 1987 or 2001. Furthermore, there was a slight upward trend in spring and autumn flows that started especially since the warming period of 1975.

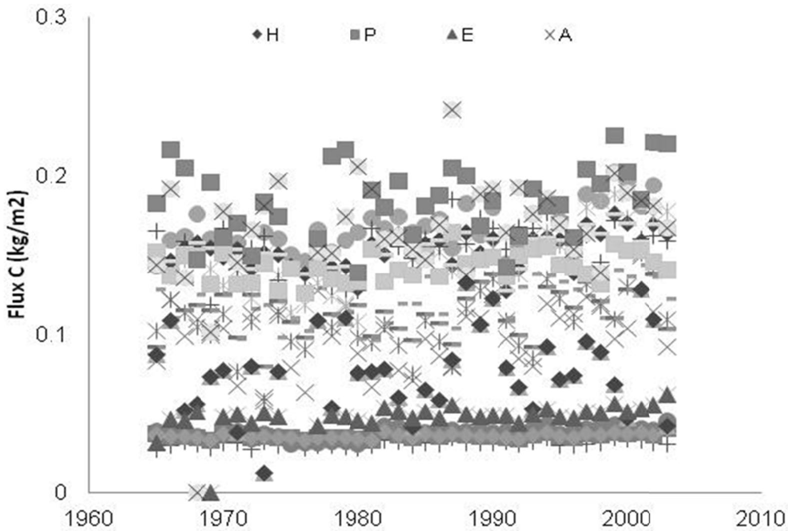

Figure 4. Simulated values of seasonal carbon fluxes (A: autumn, E: summer, H: winter, P: spring) for ADH, BEJ, TAB and JEN during the 1965-2003 simulation period. Ilm faut faire chaque station à part

3.3 Statistical Analysis of Tr, Fc and SPI Parameters in 1965-2003

For the different stations evaluated, Initial evapotranspiration (ET_0) varied from 354 mm year^{-1} to 784 mm year^{-1} with an average value of 553mm year^{-1}. The SPI values ranged from -2.4 to +2.7 and a variation of Fc from 0.255 to 0.586 kg an^{-1} m^{-2} was recorded with an average 0.448 kg an^{-1} m^{-2}. The water use efficiency reached 0.8 gr C kg^{-1} H_2O, which was slightly higher during a dry year (Table 3).

Table 3. Analysis of Fc, ET and SPI averages for DHA, BEJ, TEB and JEN stations during the period 1965-2003

Variable	Mean	SD	Sum	Min	Max
Fc	0.45	0.047	69	0.25	0.59
ET	1.5	0.35	233.4	0.95	2.15
SPI	-0.005	1	-0.8	-2.41	2.7

The GLM and SNK analysis indicated for Fc that the ADH station showed the highest mean comparing to the stations from BJA, TAB and JEN, but no significant differences between the other stations was recorded (Table 4). For Tr value, two groups can be distinguished, one with BEJ and ADH stations, the other with TAB and JEN stations (Table 5).Whereas, for the SPI index, no significant effect was recorded between the stations.

Table 4. Analysis of Fc, ET and SPI averages for DHA, BEJ, TEB and JEN stations during the period 1965-2003

Variable	DDL	Sum of Square Mean	Square Mean	Value F	Pr >F
Fc	3	0.04611361	0.0153712	7.92	<0.0001
ET	3	12.2891453	4.09638178	104.1	<0.0001
SPI	3	0.0359695	0.01198565	0.01	0.9983

Table 5. SNK analysis of the Fc, SPI and ET parameters for the ADH, TAB, BEJ and JEN stations during the period 1965 and 2003

Variable	SNK group	Mean	Station
Fc	A	0.47573	ADH
	BB	0.44859	JEN
	BB	0.44082	TAB
	B	0.42797	BEJ
ET	AA	1.80641	BEJ
	A	1.79514	ADH
	BB	1.26179	TAB
	B	1.21231	JEN
SPI	AA	0.01128	ADH
	AA	0.00256	TAB
	AA	-0.00474	BEJ
	A	-0.02949	JEN

Positive correlations between ET and Fc and low negative correlations with SPI were observed. It is evident that a significant station effect was present for the Fc and ET variables but no significant station effect at the 5% threshold for the SPI variable was found (Table 6).

Table 6. Correlations between the Fc, SPI and ET parameters for the ADH, TAB, BEJ and JEN stations during the period 1965 and 2003

	Fc	SPI	ET
Fc	1.000	-0.0876	0.456
SPI	-0.0876	1.000	-0.01023
ET	0.456	-0.01023	1.000

3.4 Evolutions of Fc and SPI in 1965-2003

From the results presented in Figure 5, it can be observed that there is certain cyclist of photosynthesis as well as for drought. On an annual scale, the synchronization between SPI and Fc is not established; in some cases it is even reversed. There is a clear downward trend in photosynthesis during major dry periods, such as that of 1987-1993. The lowest variation of Fc was recorded in JND, the highest one in ADH, while TAB and BJA were overall similar.

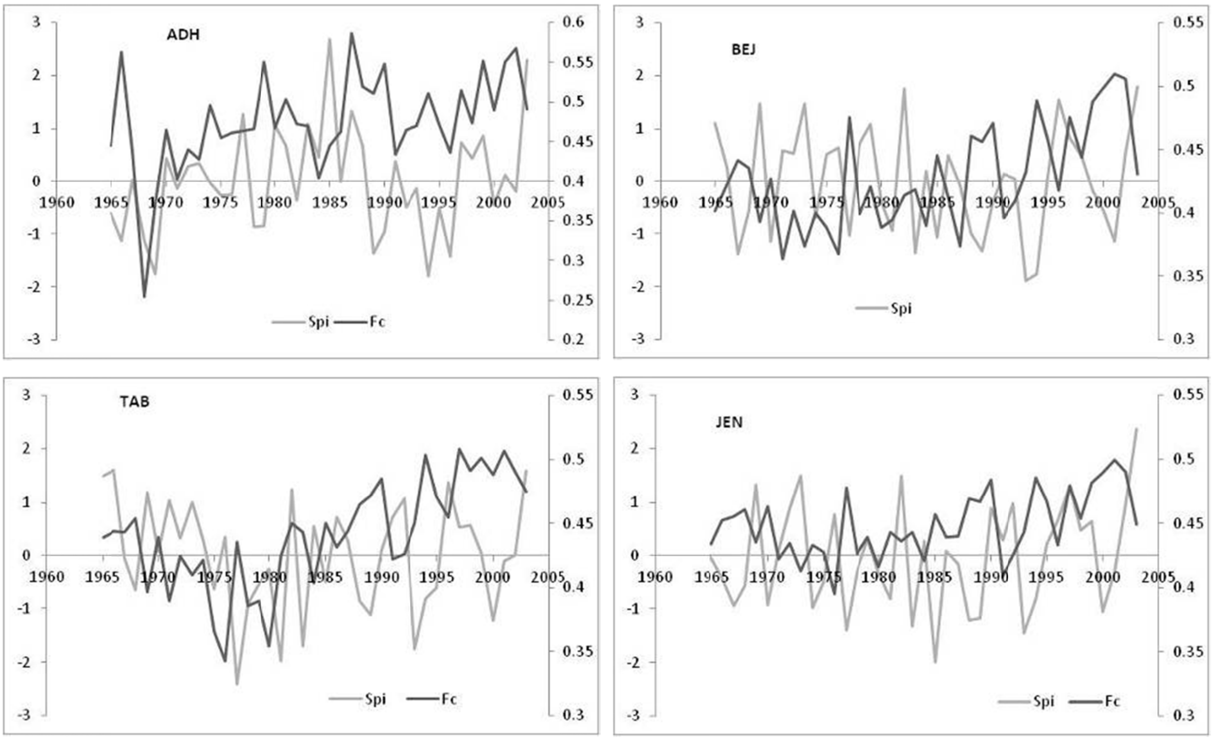

Figure 5. Variations in annual SPI and Fc values for BJA, ADH, TAB and JND stations during the period 1965-2003

4. Discussion

The physical errors in the estimation of sap flow by the Granier sensor have been widely discussed in the literature. They can be caused by the representation of the measurement according to the orientation and depth of the probes (Nasr et al., 2012). Our measurements were made at a depth of 2 cm assuming that most of the water flow passes through this slice. Thus, the South-East orientation chosen cannot represent the average of the flows. Poyatos et al. (2007) showed that 85% of the fluxes pass close to the cambium and a lower contribution of the heartwood. On *Quercus ilex*, Infante et al. (2007) used the Granier technique and showed a fairly large flux variation of 2 to 3.5 L dm^{-2} h^{-1} depending on the orientation.

Repetitive measurements of the net photosynthesis at the foliar scale on eight trees may not represent the average carbon fluxes of the forest. Indeed, the variability of measurements between trees, orientations and leaves was very important. The coefficient of variation has in some cases exceeded 50%.

Despite these sources of multiple errors, the average values of tree transpiration, soil evapotranspiration and net photosynthesis are quite comparable to the values observed in the Mediterranean forests. According to Tognetti et al. (1998), *Quercus ilex* sap fluxes were in the order of 50 L j^{-1} with a maximum hourly flux of 3 L hr^{-1}. Furthermore, Vincke et al. (2005) from sap flow measurements showed that declining trees responded to fluctuations in climate demand but their transpiration remained low and less than 1 mm/d. Under these conditions, the herbaceous layer can consume more water than the trees, up to 2.9 mm/day.

Using the flux method (Eddy covariance) on a 38% mixed forest (*Q. robur*/*Q. petraea*) and 31% Scots pine, Gerricle et al. (2005) estimated a primary productivity of 630 g C m^{-2} an^{-1}. In the same context, Periera et al. (2007) estimated by the eddy covariance in oak forest in Portugal that a primary productivity varied between 500 and 1000 g C m^{-2} an^{-1}. While, Wilkinson et al. (2012) obtained higher flows in the order of 1500 g m^{-2} year^{-1} during the period 1999-2010 in a forest of Fraxinus and *Quercus robur*. The annual phytomass of Ain Snoussi Forest was evaluated at 5.98 T ha^{-1} year^{-1} (Sebei et al., 2004), which equates to 0.29 kg of C m^{-2} year^{-1}.

Several authors have also highlighted the effects of drought on the carbon balance of forests. In fact, Breda et al. (2006) was able to show the consequences of an extreme event (drought in 2003) on typical Mediterranean stands. The low water availability of the soil in summer resulted in a very low carbon balance associated with low carbohydrate accumulations in the trunks.

For the simulations made, it was assumed that the ET/ETo and Pn/Tr ratios are constant from one year to another, as well as a constant value of the leaf area index (Lai) was assumed. This hypothesis remains valid for the leaf surface unit, but it did not allow the spatial integration of the simulated values. According to Davi et al. (2008), although the Lai varied slightly, it remained the main variable controlling both water and carbon flows and also the relationship between this parameter and the density for a Mediterranean forest of *Quercus ilex* and *Pinus halepensis*. Additionally, the control mechanisms for canopy transpiration are mainly stomatal regulation, hydraulic conductance and leaf area adjustment. The decrease in leaf area appears as the main mechanism for adjusting transpiration to new water conditions (Limosin, 2009) in *Quercus ilex* species.

During the period 1965-2003, the rate of atmospheric CO_2 had to increase approximately from 260 ppm to 380 ppm. This enrichment did not cause a net increase in calculated carbon fluxes. As if drought have counterbalanced the fertilizing effect of atmospheric carbon. However, in a controlled environment, it was previously highlighted that the effect of carbon enrichment on oak by an increase in the net photosynthesis capacity (Vivin & Gehl, 1997).

5. Conclusions

The simulations carried out showed evapotranspiration flux ranging from 0.95 to 2.15 kg m^{-2} d^{-1} wile photosynthesis flux ranged from 0.255 to 0.586 kg m^{-2} $year^{-1}$, SPI were -2.41 and 2.69 for a dry and wet year, respectively.

These simulations showed some inter annual variability of flows with a special site effect. However, synchronization with the climatic drought by the SPI index has not been established. In addition to this variability, it was not possible to observe clearly a trend upward or downward flows, but rather certain cyclicality was clearly noticed.

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