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Research Article

Ecophysiology of Four Mediterranean Forest Species

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Abstract

Forest degradation has become increasingly pronounced in recent times due to shifts in climate patterns and prolonged drought periods. This investigation aims to cultivate high-quality vegetation and gain insights into their ecophysiological responses under conditions of water stress. Specifically, we conducted experiments on 6-month-old individuals from two deciduous species (*Quercus suber* and *Ceratonia siliqua*) and two conifers (*Tetraclinis articulata* and *Cedrus at-lantica*), subjecting them to water stress conditions. We measured and analyzed both the basic (Ψb) and minimum (Ψm) leaf water potentials, factoring in climatic variables for all four forest species. Our findings reveal that *Quercus suber* exhibits more negative values, with a basic leaf water potential of -0. 42 MPa and a minimum leaf water potential of -1. 43 MPa, compared to the other studied forest species. On the contrary, *Cedrus atlantica* displays less negative values for the minimum leaf water potential, recording -0. 89 MPa. These outcomes enable us to identify the species displaying greater resilience against water stress and climate fluctuations. Nevertheless, they also prompt broader inquiries into the underlying mechanisms governing water utilization in forest flora.

More Information

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Introduction

Forest Ecosystems are terrestrial environments containing many forms of life, where forests play an essential role in the major biogeochemical cycles [1] the natural cycles of carbon, nitrogen, phosphorus, and water. Thanks to the phenomena of absorption and evapotranspiration, forests help to purify the air and water. They also help to build, enrich, and protect the soil through the many exchanges between species of plants and animals, bacteria and fungi, and even human beings who draw their livelihood needs from them [2].

Morocco's forest ecosystems are located in semi-arid, sub-humid, and humid climates, covering an area of 5,719,000 ha. They are made up of 66% hardwood species, 18% softwood species, 9% artificial plantations, and 7% low-lying formations [3,4]. Situated at the confluence of two seas, Morocco's unique geographical position engenders a Mediterranean climate influenced by the Atlantic Ocean to the west and the Mediterranean to the north. Its diverse topography results in a wide range of bioclimatic zones, fostering rich biodiversity characterized by both pristine forest ecosystems (forests) and pre-forest ecosystems (such as matorrals and steppes). To ensure the long-term survival of the forest, the National Water and Forestry Agency carries out annual regeneration campaigns using natural species and reforestation using introduced species [5]. To support these efforts, the Forest Research Center conducts research to identify deciduous and coniferous species that are more resistant to drought stress [6,7]. With this in mind, we have studied the physiological behavior of certain forest species, namely *Quercus suber, Ceratonia siliqua, Tetraclinis articulata, and Cedrus atlantica*, as a function of climatic parameters. The primary objective of this research is to scrutinize the ecophysiological adaptations of these four forest species by evaluating basic and minimum leaf water potentials following induced drought conditions through cessation of watering. Examination of leaf water potential changes during drying highlights diverse responses among forest species. Under water stress, daily leaf water potential swings widely, impacting plant health significantly. A robust correlation exists between leaf water potential, climate factors like VPD, and sunlight. Conifers demonstrate superior drought tolerance compared to hardwoods, as evidenced by the findings.

Materials and methods

Desiccation test

In this study, we utilized six-month-old seedlings from four forest species, comprising two hardwood species (Quercus suber and Ceratonia siliqua) and two conifer species (Tetraclinis articulata and Cedrus atlantica). These seedlings were deliberately exposed to a severe water stress condition by discontinuing irrigation for a duration of 30 days within a controlled greenhouse environment. Physiological measurements were taken at four-day intervals from three independent replicates for each treatment and species.

Physiological and climatic parameters

For the assessment of physiological parameters, we determined both the basic (Ψb) and minimum (Ψm) leaf water potentials. The water potential is a measure of the energy of water within a biological system or environment, indicating the force driving water movement. It depends on factors such as pressure, solute concentration, and physical interactions. It is crucial for understanding water movement in plants and soils, as well as for assessing water availability for living organisms. The basic leaf water potential (Ψb) signifies the leaf water potential of the plant measured before sunrise when the plant is considered to be in equilibrium with the soil. Conversely, the minimum leaf water potential (Ψm) represents the leaf water potential of the plant measured in the middle of the day, this potential corresponds to the minimum water content of the plant resulting from the balance between transpiration and water absorption. The maximum amplitude of daily variation in leaf water potential is determined as the absolute difference between the minimum potential and the base potential. This value characterizes the extent of fluctuation in a plant's leaf water potential throughout the day and provides insight into the volume of water transpired through the stomata.

To monitor the changes in leaf water potential within our first plants, we employed the Scholander pressure chamber (Figure 1). This method involves the application of pressure to a sample (stem or branch) placed inside the chamber, utilizing nitrogen gas from the container, until the sap within the sample emerges through a section. The resulting pres-sure, as read on a manometer, corresponds to the water potential of the leaves within the sampled portion.

Figure 1: Scholander Pressure Chamber (Source: Pmsinstrumen)

Climatic parameters, including temperature, humidity, vapor pressure deficit (VPD), and solar radiation, were recorded hourly throughout the measurement period. The obtained results underwent statistical analysis through the calculation of correlation coefficients to establish the relationship between the two variables. All of these statistical analyses were conducted using Microsoft Excel software, specifically version 2208.

Results

Leaf water potential

Figure 2 and Tables 1,2 show the average change in daily leaf water potential for the 4 species as a function of climatic parameters. It can be seen that the basic daily leaf water potential curves have negative values close to zero, but as soon as the climatic parameters start to change throughout the day these values start to become increasingly negative until midday (12 noon) when the leaf water potential reaches its minimum. At around 2 pm in the early afternoon, all the plants recovered (returned to their initial state) by increasing their water potential.

For an average temperature of 12.67 °C, average humidity of 82.83%, VPD of 0.27 KPa, and zero solar radiation, the average basic leaf water potential (5h) was -0.42 MPa for *Quercus suber*. Whereas for the other species *Ceratonia siliqua*,

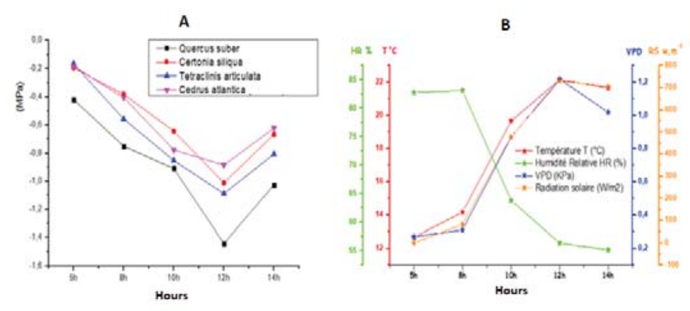

Figure 2: Daily Changes in Leaf Water Potential (A) as a Function of Climatic Parameters (B).

Table 1: Mean values of Leaf Water Potential (Ψ_L).

Hours	Leaf Water Potential (Ψ_L) *Cedrus atlantica*	*Tetraclinis articulata*	*Quercus suber*	*Ceratonia siliqua*
5h	-0,19	-0,17	-0,42	-0,20
8h	-0,40	-0,56	-0,75	-0,38
10h	-0,78	-0,85	-0,91	-0,64
12h	-0,89	-1,09	-1,44	-1,01
14h	-0,62	-0,81	-1,03	-0,67

Table 2: Mean values of climatological parameters.

Hours	Temperature (°C)	VPD (kPa)	Relative Humidity (%)	Solar Radiation (w/m²)
5h	12,67	0,27	82,83	0
8h	14,17	0,31	83,17	83,33
10h	19,67	0,87	63,83	479,33
12h	22,17	1,22	56,33	732,33
14h	21,67	1,02	55,17	706,33

Tetraclinis articulata, and *Cedrus Atlantica* is -0.2; -0.17, and -0.19 MPa respectively.

This difference in Ψb between *Quercus suber* and the other species shows that cork oak is slightly stressed compared with the others. On the other hand, we note that the basic leaf water potential of the two softwood species is higher than that of the hardwoods, which can be explained by the larger leaf area of the hardwoods compared with the softwoods.

At midday, where the average climatic parameters are a temperature of 22. 17 °C, humidity of 56. 33%, VPD of 1. 22 KPa, and solar radiation of 732. 33 w/m^2, we recorded an average minimum leaf water potential Ψm of -1. 44 MPa for *Quercus suber*, -1. 01 MPa for *Ceratonia siliqua*, -1. 09 MPa for *Tetraclinis articulata* and -0. 89 MPa for *Cedrus atlantica*. These measurements show that the most stressed species is *Quercus suber*, followed by *Tetraclinis articulata*, then *Ceratonia siliqua,* and, lastly, *Cedrus atlantica*, whose value (-0.89 MPa) is lower than that of the other species.

Maximum daily variation amplitude of leaf water potential

During the desiccation test period, the plants of different species exhibited highly variable maximum daily variation amplitudes of leaf water potential. Figure 3 illustrates that at the beginning of the cycle, *Quercus suber* displayed the least negative value (0. 4 MPa) compared to the other plants. In the middle of the cycle, *Cedrus atlantica* exhibited the highest value (1. 2 MPa). Towards the end of the desiccation cycle, the highest value was recorded for *Quercus suber* (1. 88 MPa), followed by *Ceratonia siliqua* (1. 75 MPa), *Tetraclinis articulata* (1. 33 MPa), and *Cedrus atlantica* with the lowest value (0. 76 MPa) (Table 3).

These values provide insight into the amount of water transpired through the stomata. It can be observed that under similar water stress conditions, *Quercus suber* tends to have less effective stomatal closure compared to other species, which reduce their transpiration rates, especially *Cedrus Atlantica* [8].

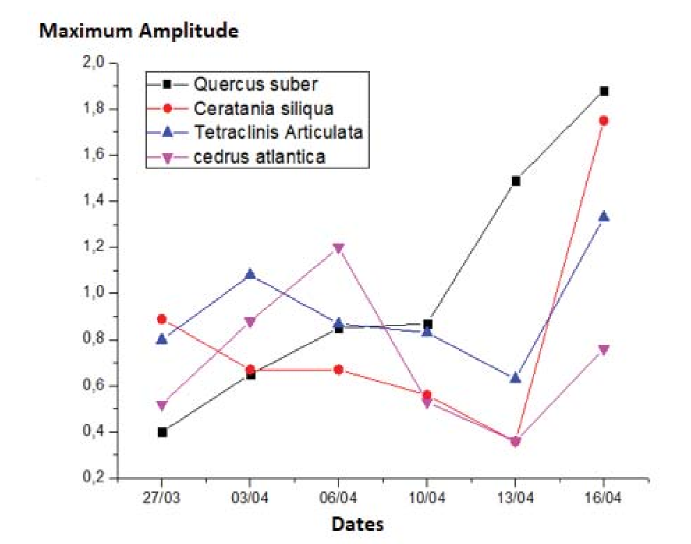

Figure 3: Graphs depicting the Maximum Amplitude of Leaf Water Potential (Ψ_L).

Relationship between leaf water potential and climatic data

Figure 4 illustrates the correlation between absolute leaf water potential and climatic parameters (VPD, and solar radiation). During the morning, it is noticeable that leaf water potential decreases as solar radiation increases, reaching its minimum value around noon (12 PM). In the early afternoon, we observe a recovery in leaf water po-tential even though solar radiation has remained relatively constant. This recovery can be explained by a decrease in VPD.

According to the correlation curves, it can be concluded that stomatal opening at dawn is influenced by solar radiation, while closure is regulated by VPD. To better understand and determine the relationship between leaf water potential and climatic parameters, we calculated and plotted a correlation curve of leaf water potential with these two parameters (VPD and solar radiation) for all the species (Figure 4, Table 4).

Table 4 illustrates the correlation coefficients of leaf water potential for each species with VPD and solar radiation. For *Quercus suber*, the correlation with VPD is approximately 0. 83 and 0. 79 with solar radiation, while for *Ceratonia siliqua*, the correlation with VPD is around 0. 91 and 0. 84 with solar radiation. Regarding the conifers, *Cedrus atlantica* leaf water potential has a correlation coefficient of 0. 84 with VPD and 0. 78 with solar radiation, whereas *Tetraclinis articulata* has a correlation coefficient of 0. 83 with VPD and 0. 81 with solar radiation.

Discussion

The study of the daily evolution of leaf water potential during the water desiccation cycle revealed differences among the studied species. At the end of the cycle, the

Table 3: Measurements of the Maximum Amplitude.

	Leaf Water Potential (Ψ_L)			
Dates	*Cedrus atlantica*	*Tetraclinis articulata*	*Quercus suber*	*Ceratonia siliqua*
27/03	0,52	0,8	0,4	0,89
03/04	0,88	1,08	0,65	0,67
06/04	1,2	0,87	0,85	0,67
10/04	0,53	0,83	0,87	0,56
13/04	0,36	0,63	1,49	0,36
16/04	0,76	1,33	1,88	1,75

Table 4: Correlation Coefficient Measurements of Leaf Water Potential (Ψ_L) with VPD and Solar Radiation.

Correlation coefficient (r)		
Species	VPD	Solar Radiation
Cedrus atlantica	0,84	0,78
Tetraclinis articulata	0,83	0,81
Quercus suber	0,83	0,79
Ceratonia siliqua	0,90	0,84

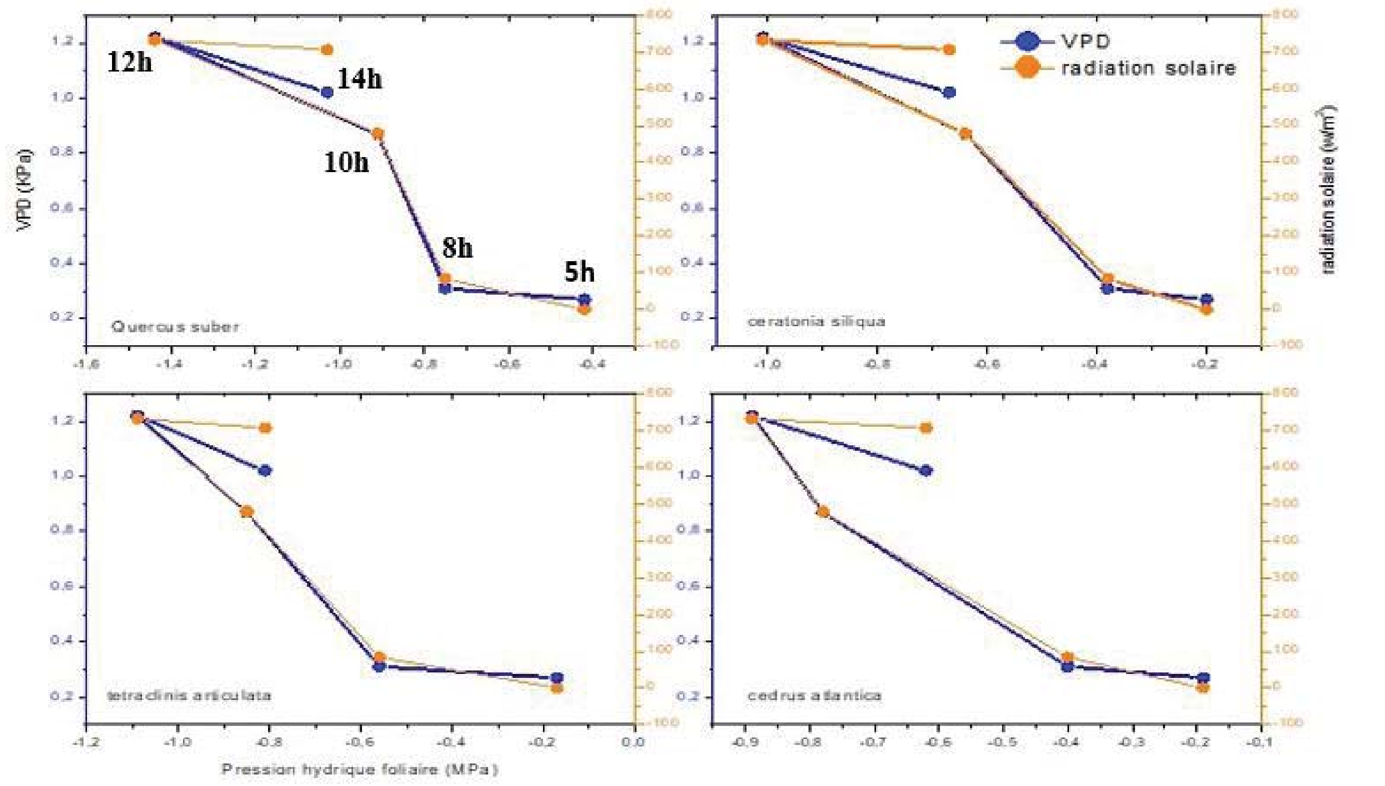

Figure 4: Correlation curves of Leaf Water Potential (Ψ_L) for the Four Species with VPD and Solar Radiation.

average daily leaf water potential for *Quercus suber* reached the most negative values, with -0. 42 MPa for the basic leaf water potential. In contrast, the other species exhibited nearly equal values for the basic leaf water potential (-0.2 MPa, -0.19 MPa and -0.17 MPa, respectively, for *Ceratonia siliqua*, *Cedrus atlantica*, and *Tetraclinis articulata*).

The values of minimum leaf water potential are influenced by plant evapotranspiration, which is linked to temperature, VPD (Vapor Pressure Deficit), and solar radiation. When the maximum temperature is reached, both VPD and solar radiation peak, resulting in the lowest minimum leaf water potential. We recorded the most negative value for *Quercus suber*, which reached approximately -1.44 MPa, while *Cedrus atlantica* exhibited the least negative value of -0.89 MPa. *Tetraclinis articulata* (-1.09 MPa) and *Ceratonia siliqua* (-1.01 MPa) displayed nearly equivalent values. As the water stress intensifies, stomatal closure in response to increasing VPD has been widely documented [8-10]. This physiological response to water deficit signifies an adaptation mechanism [6,7]. Based on these results, we can conclude that *Quercus suber* experiences the highest level of stress, while *Cedrus atlantica* experiences the least amount of stress.

The maximum amplitude of variation in leaf water potential reflects the intensity of stomatal opening. At the end of the desiccation cycle, *Quercus suber* plants displayed very high values (1. 88 MPa), followed by *Ceratonia siliqua* (1.75 MPa), then *Tetraclinis articulata* (1.33 MPa), and finally *Cedrus atlantica* (0.76 MPa). These values provide insight into the amount of water transpired through the stomata. It can be observed that, under similar water stress conditions, broad-leaved species (*Quercus suber* and *Ceratonia siliqua*) exhibit less effective stomatal closure compared to conifers (*Tetraclinis articulata* and *Cedrus atlantica*), which reduce their transpiration rates. This helps explain the strong correlation between VPD, solar radiation, and minimum leaf water potential.

Based on the representative curves of leaf water potential and climatic parameters, it is evident that the leaf water potential of forest species negatively correlates with VPD (Vapor Pressure Deficit) and solar radiation. We can observe that *Quercus suber* experiences stress around noon due to a relatively low temperature of 22 °C, which leads to a decrease in humidity and an increase in VPD. This increase in VPD results in the movement of water from the plant into the atmosphere (in the soil-plant-atmosphere system, water flows from areas of higher potential to lower potential). When the atmosphere becomes dry, with a high VPD value, water exits the plant through stomatal cells into the atmosphere. As water stress intensifies, a physiological response to water deficit often observed is the closure of stomata in response to an elevation in VPD (Vapor Pressure Deficit) [11,12].

In light of the leaf water potential results obtained for *Quercus suber*, we find that Ψb is -0. 42 MPa, and Ψm is -6. 50 MPa. Similar results were reported by Acherar, et al. 1991

[13], where Ψb was -0. 73 MPa at the beginning of desiccation and -3. 70 MPa at the end, averaging -2. 25 MPa. For *Ceratonia siliqua*, the leaf water potential does not exceed -1 MPa. According to Rajeb, et al. 1991 [14], the midday leaf water potential varies between -2 and -4 MPa. Regarding *Tetraclinis articulata*, the leaf water potential does not exceed -1.09 MPa. Similar results were found by Aussenac and Oleffe, 1984 [15], who reported values ranging from -0. 1 MPa to -2. 1 MPa. As for cedar (*Cedrus atlantica*), its basic leaf water potential fluctuates between -0. 1 and -0. 2 MPa, and its midday leaf water potential ranges from -0. 5 to -1. 7 MPa, according to Zine El Abidine, et al. 2013 [16]. These values are quite similar to our findings (Ψb of -0. 19 MPa and Ψm of -0. 89 MPa). Furthermore, the results obtained indicate that softwoods tolerate drought stress better than hardwoods [7].

Conclusion

Our experimentation aims to study the behavior and adaptation of four Mediterranean forest species (*Quercus suber, Ceratonia siliqua, Tetraclinis articulata*, and *Cedrus atlantica*) in response to drought. The analysis of the evolution of leaf water potential during the desiccation phase reveals the following: Daily leaf water potential varies among different forest species. The daily amplitude of leaf water potential variation reaches high values under water stress conditions, explaining the critical level of the plants. A strong correlation is observed between leaf water potential and climatic parameters (VPD and solar radiation). Stomatal closure occurs at more negative leaf water potentials but requires. Although the results obtained indicate that conifers tolerate drought better than hardwoods, a comprehensive understanding of the physiological behavior of forest species under water stress requires consideration of other parameters such as stomatal conductance, leaf surface area, photosynthesis, soil water potential, and vulnerability to xylem cavitation in stems and roots. These parameters help determine and better understand the adaptation and behavior of plants under water stress conditions.

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Author contributions

All authors contributed to the study conception and design. Data collection and analysis were performed by MM, ON and MO. All authors contributed to interpret the data. MM wrote the manuscript with the help of the other authors, and all read and approved the final version of the manuscript.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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