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Water balance and pattern of root water uptake by a *Quercus coccifera* L. evergreen scrub

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Summary. The water balance of a *Quercus coccifera* evergreen scrub was studied over 7 consecutive years. This scrub grows on hard limestone. Soil water content was measured with a neutron meter. Calibration curves were calculated from (1) the thermal neutron macroscopic cross-sections of soil (<2-mm fraction) and rock samples, and (2) the profile of wet bulk density measured with a subsurface gamma-ray gauge. The annual and seasonal patterns of actual evapotranspiration and of deep drainage were calculated using field-measured drainage characteristics. The soil water content data were used to compute water uptake rates and pattern for the root zone over a 4-month drying period. The 906 mm of mean annual precipitation yielded 603 mm of actual evapotranspiration (AET) and 296 mm of drainage. No drainage occured with precipitation less than 578 mm. The average AET values for the months from April to September were 57, 74, 89, 96, 70, and 42 mm respectively. It was found that *Quercus coccifera* consumed considerable quantities of water from the soil-rock complex. Roots could extract 270 mm of water in the first 470 cm of soil. The results showed a gradual downward shift of the zone of maximum root water uptake as the soil dried.

Introduction

The *Quercus coccifera* evergreen scrub (garrigue) still covers more than 100,000 ha in the south of France. The main studies on this plant community have been devoted to carbon and nutrient cycling (Lossaint 1973; Rapp and Lossaint 1981), and the effects of fire and grazing on the vegetation dynamics (Trabaud 1980, 1981; Trabaud and Lepart 1981; Poissonet et al. 1981). Although water plays a key role in mediterranean-type climates, the lack of studies concerning the transfer of water can be explained by the technical difficulties of the measurement of water balance components in vegetation-soil-rock complexes. The research on water relations in other mediterranean-type ecosystems has focused on plant water relations (Poole and Miller 1975, 1978; Miller and Poole 1979; Giliberto and Estay 1978; Miller et al. 1983) and soil water balance (Shachori et al. 1967; Specht and Jones 1971; Scholl 1976; Ng and Miller 1980). No studies have been conducted to show the dynamics of water extraction by root systems.

Our specific objectives are to describe: (1) the seasonal pattern of soil moisture in the *Quercus coccifera* evergreen scrub; (2) the annual and seasonal progression of actual evapotranspiration; and (3) the pattern of root water uptake during a drying cycle.

Site description

The study site is located 10 km north of Montpellier (43°41′N, 3°49′E), at the top of a west-facing 15% slope. This karst formation is characteristic of the Lutetian formation. It is heterogenous and composed of soft to hard limestone covered with a very shallow soil mantle. Clay loam soil fills up the cracks and fractures and this provides a source of water throughout the long dry summers for some penetrating deep-rooted species.

The vegetation is a dense continuous canopy of shrubs. Unburned since 1951, it is about 80 cm high with a total cover varying within the range 80%–100%. Average spring cover, expressed in percent of ground shaded, is 95% for shrubs and 15% for grasses and herbs. The shrub cover consists of 95% *Quercus coccifera* L., an evergreen sclerophyllous species, 5% of *Dorycnium pentaphyllum* Scop. subsp. *pent.*, and *Genista scorpius* (L.) D.C. The herbaceous understory is principally *Brachypodium retusum (Pers.) Beauv.*, and *Rubia peregrina* L. (Trabaud 1980). The leaf area index of *Quercus coccifera* is about 2.5.

The area has a mediterranean-type climate. Table 1 summarizes the climate characteristics at the research site. Rainfall occurs during autumn and winter, and 78% is between September and April. Mean annual precipitation is 957 mm with a range of 500–1803 mm, recorded over the previous 33 years. Mean monthly temperatures range from 5.8° C in January to 22.0° C in July with a mean annual value of 13.3° C.

Methods

Meteorological data

Precipitation was measured with both a standard and a recording rain gauge. Air temperature and relative humidity were obtained from a hygrothermograph inside a ventilated shelter at a height of 2 m. Measurements of wind run and incoming shortwave solar radiation started in September 1978 and August 1979 respectively. The Penman potential evapotranspiration (PET) estimates, computed using these solar radiation, wind run, temperature and humidity data, were within 5% of the PET recorded at Montpellier, so the Montpellier data were used to give a continuous record of PET over the 1975–1981 period.

Table 1. Climate characteristics at the research site. Air temperatures were averaged over 1964–1982, precipitation over 1980–1982

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Maximum air temperature (°C)	9.1	10.8	13.0	15.8	19.5	24.2	27.2	26.5	22.8	18.2	12.8	9.8
Minimum air temperature (°C)	2.4	3.4	4.8	7.4	10.7	14.3	16.7	16.5	13.8	10.2	5.8	3.0
Monthly total precipitation (mm month^{-1})	104	74	99	64	63	53	35	47	94	159	78	87

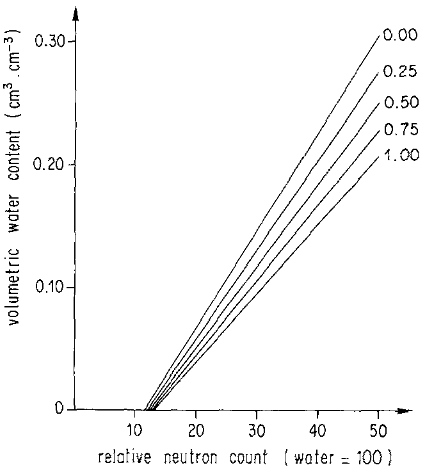

Fig. 1. Calibration curves for neutron moisture gauge for soils with different volume ratios of rocks (figures on right-hand side of diagram)

Soil water content measurement

In the autumn of 1974, eight holes were drilled to 5 m, below the rooting range of *Quercus coccifera,* for installation of access tubes for the neutron moisture gauge. At this depth the bedrock prevents further extensive root penetration, as Gouisset (1981) found by endoscopy of boreholes. The holes were drilled on a square grid pattern at 2-m intervals, with a self-propelled wagon-drill. A whole winter was allowed for the settling of loose materials around the access tubes. Readings were made at 10 cm intervals, from 10 to 470 cm in depth. Measurements were made each week from 15 March to 15 October, and once a month during the other months. Each time, a cat-walk was placed above the canopy to prevent damage to the vegetation. Because of the great spatial variability of the percentage of stone an individual calibration curve was required for each depth of measurement in each access tube. It was calculated, following a method proposed by Rambal (1979), from the direct measurement of the thermal neutron cross-sections of fine fraction (particle size <2 mm) and rock samples, and the determination of the wet bulk density with a subsurface gamma-ray gauge. The cross-sections, measured at the Nuclear Center of Cadarache (France), made it possible to obtain the calibration curves for the fine fraction and the rocks (Couchat et al. 1975) and thus to calculate a set of calibration curves, as shown in Fig. 1, with the volume ratio of rocks as a variable. If the volume ratio of rocks is k, the wet bulk density ρ_t of a volume of soil can be represented by the expression:

$$\rho_t = (1-k)\,\rho_b + k\rho_s + \theta\rho_w \qquad (1)$$

ρ_b is the bulk density of the <2 mm fraction, ρ_s and ρ_w are the rock and water densities respectively, and θ is the volumetric water content, expressed on the basis of the total volume of soil. At a given depth of measurement, k and θ are unknown. Assuming that ρ_b and ρ_s are constant over the soil profile, the k parameter was adjusted with a numerical procedure detailed in Rambal (1979) so as to find the same estimation of θ with Eq. 1 and with the calibration curves.

After the first year of measurement, we analysed the intertube correlations between the time series of the changes in stored water measured at each access tube. The time interval between the observations was sufficiently large to assume that the terms in the series were stochastically independent. We selected the two tubes which showed the highest correlations with all the others. This is a standard method used in the optimization of hydrometeorological networks. From 1976, tubes 2 and 4 only were used.

Surface runoff measurement

Surface runoff generated from a 7.5 × 20 m area with 15% slope was collected and then conducted into a tipping bucket flowmeter by plastic tubing. This flowmeter consists of two balanced water-receiving units, which tip to and fro as they are alternately filled with water. The daily runoff was computed from the number of tips recorded by a mechanical count-meter. Based on the work of Chow (1976), the capacity of each receiving unit was calibrated to 750 cm^3.

Water balance equation

$$\Delta S = P - R - \mathrm{AET} - D \qquad (2)$$

where ΔS is the daily change in stored water, P is the precipitation, R is the surface runoff, AET is the actual evapotranspiration and D is the flow of water at the bottom of the root zone measured in mm day^{-1}. The precipitation, runoff and change in storage are readily measurable, but AET and D are both difficult either to measure or to calculate. The flow of water at the bottom of the root zone may be described by Darcy's equation for unsaturated soil:

$$D = -K(\theta)\frac{\delta H}{\delta z} = -K(\theta)\left(\frac{\delta h}{\delta z} - 1\right) \qquad (3)$$

where K is the hydraulic conductivity (mm day^{-1}), expressed as a function of the volumetric water content θ (cm^3 cm^{-3}), and the hydraulic head H (cm) is the sum of the soil water pressure head and of the gravitational head. This latter is equal to the soil depth measured positively downward z (cm). Because of the rockiness of the soil and the deep root system of *Quercus coccifera*, tensiometric measurement of the soil water pressure head below the root range is a physical impossibility. A simplified method is justified for obtaining a less accurate, but useful description of soil-water movement.

The work of Black et al. (1969), Davidson et al. (1969) and Black et al. (1970) shows that drainage at depth z may often be related directly to the water content averaged over z, $\bar{\theta}$ (cm^3 cm^{-3}).

Hence, Eq. (1) becomes

$$\Delta S = z\,\Delta\bar{\theta} = P - R - \mathrm{AET} - \mathrm{f}(\bar{\theta}) \tag{4}$$

The function relating the drainage at depth z to the average water content is called the drainage characteristic.

Drainage characteristic determination

A 10 × 10 m area, around the access tubes, was irrigated sufficiently to wet the soil to a depth of at least 5 m. During the subsequent drainage period, the plot was covered with a thin film of plastic to prevent infiltration and evapotranspiration. Measurements were made 0.01, 0.04, 0.07, 1, 2, 3, 4, 7, 14, and 21 days after irrigation. At each access tube, average water content was related to time following the mathematical equation suggested by Richards et al. (1956) and Wilcox (1959). This relationship can be expressed in the form:

$$\bar{\theta} = a\,t^{-b} \tag{5}$$

The a and b parameters were estimated by the least-square method. The derivative of Eq. 5 with respect to time gives the rate of drainage per unit of depth:

$$\frac{\mathrm{d}\bar{\theta}}{\mathrm{d}t} = \frac{D}{z} = -a\,b\,t^{-(b+1)} \tag{6}$$

Substituting for t from Eq. 5 into Eq. 6 yields the drainage characteristic:

$$D = e^{c + d \log\theta} = f(\bar{\theta})$$

$$\text{with } c = -\log a^{1/b}\,b\,z \quad \text{and} \quad d = b + 1/b \tag{7}$$

The mean characteristic was calculated in the same way from the mean measurements of the two representative tubes.

Water balance computation

The average periodic field measurements of the water content were included in Eq. 2, which was written in a finite difference form, using as an estimation of $\bar{\theta}_i$.

$$z\,(\bar{\theta}_{i+1} - \bar{\theta}_i) = P - R - \mathrm{AET} - \mathrm{f}(\bar{\theta}_i) \tag{8}$$

The weekly analysis was solved repeatedly with a time increment of 1 day, starting on any measurement $\bar{\theta}_0$ and ending on the next $\bar{\theta}_n$, adjusting AET at each loop until measured and computed $\bar{\theta}_n$ agreed. Actual evapotranspiration therefore represented all changes in moisture content not accounted for by other terms in the water balance equation.

Results and Discussion

Annual water balance

The 7 years of measurement are divided into three classes. The first corresponded to the "dry years", and included 1976, 1978, and 1979. For each of these years, similar drying curves were observed (Fig. 2). They show an asymptote at 0.032 cm^3 cm^{-3} water content, corresponding to 150 mm of water storage in the first 470 cm of soil. With an estimated field capacity of 0.090 cm^3 cm^{-3}, which gave a water storage of 420 mm, the *Quercus coccifera* evergreen scrub was thus able to use 420 − 150 = 270 mm of the soil water reserve. "Wet years" were 1975 and 1977, when the water content did not fall below 0.050 cm^3 cm^{-3}. The "average years" class includes 1980 and 1981. The analysis of the cumulated rainfalls of the May-August period confirmed this classification. The precipitation observed at the research site during this 4-month period was 272, 110, 352, 155, 80, 217, and 190 mm respectively for the 7 years, with a mean value, calculated over the 1950–1982 period, of 199 mm.

Annual water balances for the 7 year period are presented in Table 2. Mean annual rainfall was 906 mm (coefficient of variation CV = 0.31). Surface runoff occured when rainfall intensity exceeded about 40 mm h^{-1}. On 14 September 1976, rainfall of 220 mm falling in 3 h produced a surface runoff of 90 mm. In other years surface runoff was negligible. Mean annual drainage loss was 296 mm (CV = 0.81). Average actual evapotranspiration was 603 mm (CV = 0.07), which gave 240 mm per unit of leaf area, for a leaf area index of 2.5 m^2 leaf m^{-2} ground. The function relating drainage loss D and precipitation P minus surface runoff R was calculated as:

$$D = 0.907\,(P - R) - 515$$

$$\text{(least-squares regression: } r = 0.970,\ n = 7,\ p < 0.001) \tag{9}$$

These results showed that when annual precipitation was less than 578 mm, deep drainage loss is negligible and almost all precipitation infiltrating the soil is lost by evapotranspiration.

Monthly water balance

When soil moisture was near the field capacity, the actual evapotranspiration rate AET was high and tended to its potential value PET. Thus, the AET/PET ratios for June 1977 and July 1981 were 0.81 and 0.75 respectively, and these corresponded to a monthly AET values of 113 mm and 118 mm. This means that the daily rate was equal to 3.8 mm, or 1.5 mm per unit of leaf area. These high values indicate high water consumption.

The AET/PET ratio decreases as soil moisture decreases through the year. It was 0.28 in September 1978, only 0.24 in August 1979, and 0.23 in September 1979. Daily evapotranspiration rates during this period were between 0.7 and 1.2 mm. The average monthly AET values for the April-September period were 57, 74, 89, 96, 70, and 42 mm. The corresponding PET values were 93, 117, 154, 168, 140, and 87 (Fig. 3). In addition to these intensively measured periods, we estimated AETs of 37 and 28 mm for March and October respectively. The corresponding PET values were 51 and 50 mm.

Pattern of root water uptake

For analysis, the soil was divided into layers of 50 cm thickness. Root water uptake was estimated from the change of water storage, taking into account for he top layer the amount of precipitation. In clayey soils, the hydraulic con-

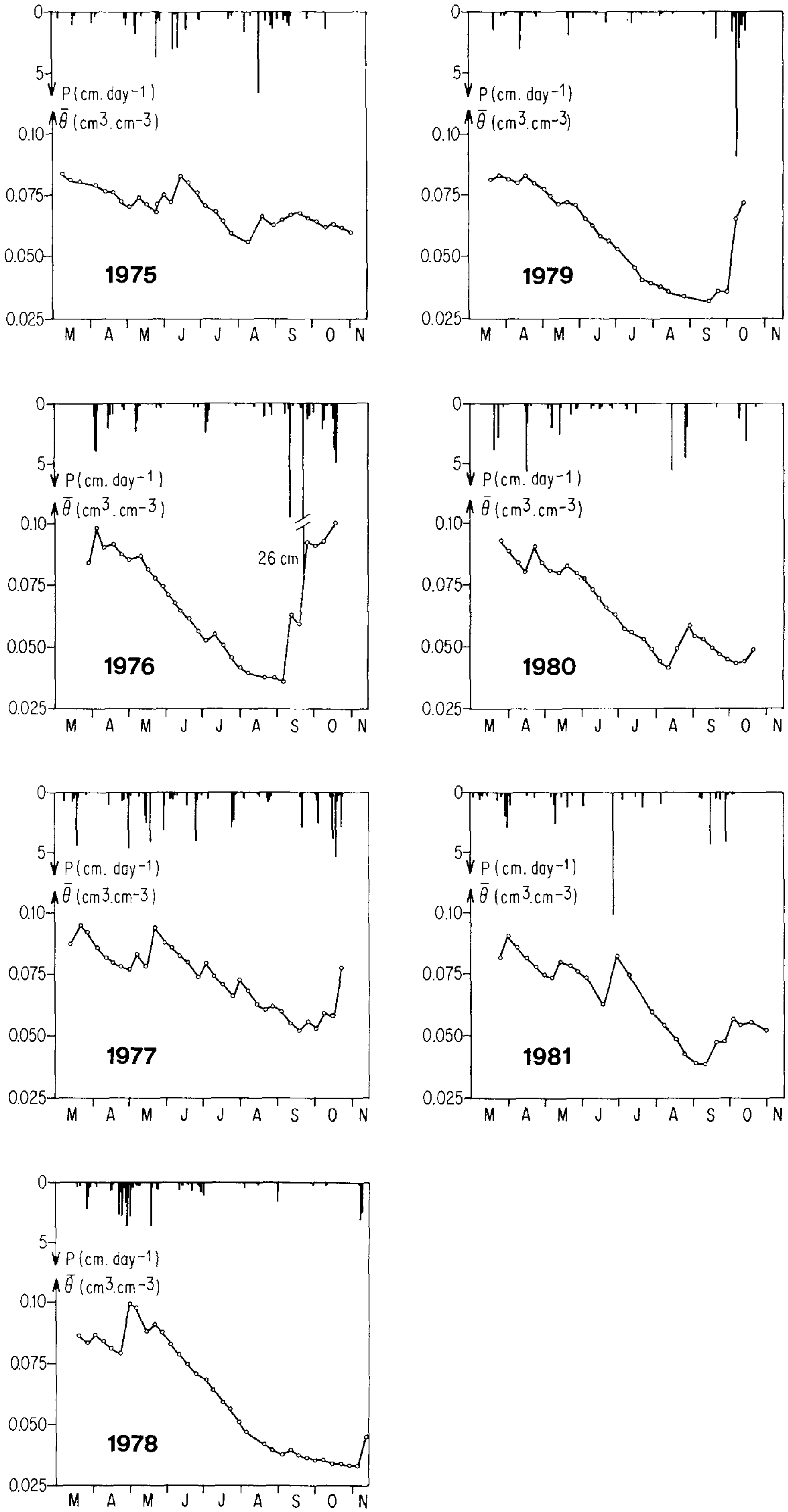

Fig. 2. Daily precipitation and average soil water content for the years 1975–1981

Table 2. Annual water balance for 1975–1981

	1975	1976	1977	1978	1979	1980	1981
Precipitation *P* (mm)	713	1437	1013	812	1050	632	686
Potential evapotranspiration PET (mm)	923	953	892	979	1023	992	921
Actual evapotranspiration AET (mm)	614	597	665	573	529	640	602
Drainage *D* (mm)	120	676	391	277	496	105	6
Surface runoff *R* (mm)	–	90	–	–	–	–	–

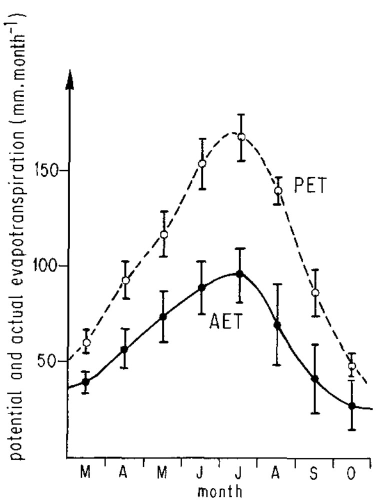

Fig. 3. Mean monthly values of actual evapotranspiration AET and potential evapotranspiration PET. Vertical bars represent 68% confidence intervals (±standard deviation)

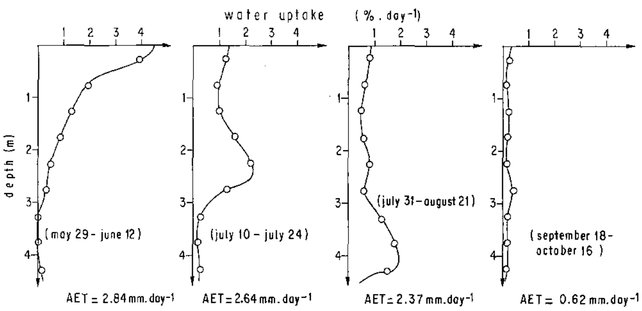

Fig. 4. Water uptake from different soil layers for four periods of a drying cycle. For each layer, the daily water uptake is expressed as a percentage of its total reserve

ductivity quicky drops by several orders of magnitude as volumetric water content decreases. At water contents below field capacity, the conductivity may be so low that very steep hydraulic head gradients are required for any appreciable flow to occur. Hence, the redistribution of water from one layer to another was negligible. In our case, we have expressed the daily contribution of a layer to the root water uptake as a percentage of the total reserve of this layer. The reserve was the difference between the field capacity and the minimum storage ever observed (16 October 1978). This reserve reached 44 mm in the upper layer and decreased regularly to 10 mm in the 300–350 cm layer. Between 350 cm and 450 cm, the weathered joint plane, located at the soil-bedrock interface, was able to yield 58 mm of water. Deeper than this, the reserve was near zero.

We distinguished four stages in water loss processes throughout the drying cycle (Fig. 4). Water loss at the beginning of the cycle (May + June) occured exclusively from the top 0–50 cm layer, which lost 4% of its storage per day. The upper meter supplied 72% of the total water evapotranspired. In the second stage of the summer period, root water uptake decreased in the upper layer, which then lost only 1.2% of its reserve per day. High root water uptake occured at 2.50 m depth. This layer supplied 0.62 mm day^{-1} of 2.64 mm day^{-1} of evapotranspired water. The third stage (end July and August) was characterized by unevenness of water loss. All the upper layers were depleted and only the lower layers were able to supply water. During these two late periods, the deepest soil layers were contributing as much water as the top. At the end of the dry period, between 18 September and 16 October, all the layers were depleted. The flat profile did not allow the uptake of water at a rate greater than 0.62 mm day^{-1}. During the first three stages, the daily rates of actual evapotranspiration were 2.84, 2.64, and 2.35 mm respectively.

Discussion

On an annual basis, our results are consistent with some but not all other studies. Ng and Miller (1980) suggest that measurable drainage loss occurs in the chaparral of southern California only if annual precipitation is about 550–600 mm. In a chaparral of central Arizona, drainage is negligible with an annual precipitation of 544 mm (Scholl 1976). Shachori et al. (1967) observed a deep drainage of 230 mm with an annual precipitation of 700 mm in a *Quercus coccifera* maquis in Israel. On the other hand, our results do not fit well with the equation proposed by Shachori and Michaeli (1965). They show that evapotranspiration uses all the precipitation up to 400 mm $year^{-1}$ in woodlands (scrub and forests). Based on their equation, drainage from our area should be 188–836 mm, depending on the annual precipitation. The observed values are less than our calculated ones by about 120 mm.

On a monthly basis, if we characterize the variability of AET by its coefficient of variation, this latter is near 20% during the October-March period, then it decreases to 16% in June, and reaches its minimum of 14% in July (Fig. 5). The soil water reserve functions as a shock absorber for rainfall fluctuations and tends to damp oscillations in actual evapotranspiration. After July, the soil moisture is no longer sufficient to act as a damping mechanism for pluviometric hazards and the vegetation is exposed to the variability of the climate. The coefficient of variation of actual evapotranspiration rises to over 40%, and that of the precipitation increases irregularly from 31% in March to 162% in September. It is interesting to observe that AET variability is lowest during the period of young leaf develop-

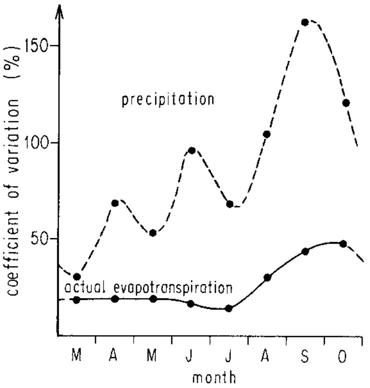

Fig. 5. Monthly values of the coefficient of variation of precipitation and actual evapotranspiration

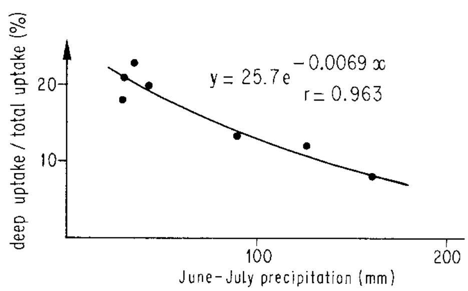

Fig. 6. Relationship of the deep uptake/total uptake ratio to precipitation in June-July

ment, which begins in April, with leaf growth ending in July (Le Floc'h 1981; Sobhani-Nejad 1982).

We could distinguish two stages of the dry summer season: one when the water consumption remained at high rates, and the other when the water consumption was reduced to very low rates. During the first stage our results were similar to those obtained by Amireh (1961), if we assume that the evaporation rate from bare soil is low in our study. For the same species of oak, he observed daily transpiration rates of 4.3 mm (with a leaf area index of 2.0) and instantaneous rates of 2.8 µg H_2O cm^{-2} leaf s^{-1}, using Huber's cut-leaf weighing technique. Similarly, this rate for *Quercus coccifera* reached 3.5 µg H_2O cm^{-2} leaf s^{-1}, measured with a porometer (Tenhunen et al. 1981).

Specht (1972) suggested that there would be moderate water use in the evergreen species of the Australian mediterranean scrub. This suggestion is consistent with the pattern of water use observed by Miller and Poole (1979) in the chaparrals of southern California which are dominated by a single species. However, the previous data contradict Specht's hypothesis. The non-conservative water use pattern of *Quercus coccifera* may be a relict from the past, when it lived as an understory shrub in the original climax mixed evergreen woodlands, or was confined to screes or dry rocky habitats (Barry 1960 quoted in Trabaud 1980). Now, its rôle is different due to land use practices which have degraded the original woodlands into garrigue shrublands. In the present situation, it is a low shrub growing essentially in a monoculture with very few other overstory or understory species.

Duhme (1974) found that during the dry part of the summer stomata of *Quercus coccifera* were essentially closed, with possibly a short period of opening in the morning. He suggested daily transpiration rates near 1.5 mm, comparable with those observed. Braun-Blanquet and Walter (1931) and Wraber (1952) found no appreciable change of osmotic potential in mature leaves during this dry period. These results, as well as those of Poole and Miller (1978) and Hinckley et al. (1980), suggest that osmotic adjustment is not a drought avoidance mechanism in *Quercus coccifera*. The significant change in the threshold of potential for stomatal closure, found by Duhme (1974), may therefore be associated with the stage of leaf development.

The observed pattern of water uptake clearly illustrates the phenomenon of the zone of maximum root water uptake moving progressively from shallower to deeper depths as the soil dries. During the first stage, the maximum of water uptake was located in the top 0–50 cm layer; it reached 2.50 m in mid-July, and passed beyond 4 m in mid-August. This corresponded to a rate of displacement of 0.056 m day^{-1}. When the soil was at field capacity to a depth of 5 m *Quercus coccifera* gradually drained the water reserves, satisfying its requirements as fully as possible. Then, when the water reserve was exhausted, it settled down to consume small quantities of water. The duration of this period of high soil moisture availability was about 3 months and corresponded to the growth period.

The amount of water taken up from any soil layers depends on both the water content and the rooting density. Thus, when the soil profile is uniformly wet from top to bottom, most of the water uptake occurs in the surface layers which also have the highest rooting density. As the soil dries, the deeper soil layers, which are then wetter than the surface layers, contribute an increasing fraction of the total water uptake despite their lower rooting density. The contribution of the deeper layers to the total evapotranspiration varied as a function of precipitation. For the 7 years of measurements, the layers below 2 m supplied respectively 13%, 20%, 8%, 23%, 21%, 18%, and 12% of the total evapotranspiration (Fig. 6). These values were related to the June-July precipitation (Eq. 10), showing that the early summer precipitation played an important role in the summer water balance.

$$y = 25.7\, e^{-0.0069x}$$

(least-squares regression: $r = 0.963$, $n = 7$, $p < 0.001$) (10)

x is the June-July precipitation (mm) and y the ratio deep uptake/total uptake (%).

The pathway of water movement in soil and plant can be considered as comprising two main resistances in series, the soil-to-root surface resistance or rhizospheric resistance, and the plant resistance. At high water content, the rhizospheric resistance is negligible. The major resistance to water uptake appears to be inside the root. Consequently, there is a good correlation between water uptake and rooting density (Taylor and Klepper 1975; Nnyamah and Black 1977). Hence, the late spring profile of water uptake can be considered as an estimate of the root density profile. The greatest accumulation of root mass was in the top meter. Below 1 m root mass decreased gradually with depth. This profile is similar to that of shrub live oak (*Quercus turbinella* Greene) observed in Arizona by Davis and Pase (1977). We made a gross estimate of the root/top ratio in the following manner. The total weight of oven-dry burls and roots was 5 ± 1.5 (SD) kg m^{-2} in the top 0.3 m (Poissonet and Thiault 1981). This value did not include the major part of the fine root fraction, those roots with a diameter less than 2.5 mm. We assumed that fine roots represent 10% of the total roots (Kummerow et al. 1977) and that the root/burl ratio varies within the range 0.40–0.60. The total weight of roots, excluding the burls, therefore lies between 8 and 12 kg m^{-2}. With an oven-dry weight of the clipped top of 1.8 ± 0.6 (SD) kg m^{-2}, the estimated range of the root/top ratio was 4.4–6.7. If the burls are included in the weight of the root, then the root system's estimated weight varies within the range 11–14 kg m^{-2}, and the root/top ratio was 6.3–7.9. This ratio is 2.5 for California scrub oak (*Quercus dumosa* Nutt.) in Southern California (Hellmers et al. 1955), and 3.2 for shrub live oak (Davis and Pase 1977). Only *Lithrea caustica* (Mol.) H. et Am., in the Chilean Matorral, has a high ratio of 4.9 (Hoffman and Kummerow 1978).

Conclusions

Quercus coccifera is well adapted to its environment. Its vigorous capacity for sprouting allows it to thrive under a natural or artifical regimen of periodic wildfire (Trabaud 1980). This prodigious regenerative capacity is supported by stored energy reserves in the burls and roots and by supplies of water and nutrients made available by an extensive root system. Its extensive, deeply penetrating root system allows it to extract water reserves that are inaccessible to other species during the summer. It can thus maintain a high transpiration level for the period of time necessary to develop its young leaves. *Quercus coccifera* also has a highly developed surface root system to use surface soil moisture. This gives it a competitive advantage over grasses and may explain the difficulties of establishing and maintaining perennial grasses after a brush-to-grass conversion (Poissonet et al. 1981).

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