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Original article

Water and bioelement fluxes in four *Quercus pyrenaica* forests along a pluviometric gradient

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Summary — Water and several bioelement balances were established for four *Quercus pyrenaica* forests along a pronounced pluviometric gradient, located in the Sierra de Gata mountains (central Spain), to obtain information on the effect of rainfall on annual and summer evapotranspiration, on nutrient leaching from the soils and on the evolution of fertility. There was a positive correlation between the annual evapotranspiration and the precipitation in the May–August period, but not with annual precipitation. From all water fluxes within the ecosystems, deep drainage represented the most important difference between plots. An excess of water in the soil is produced in winter, resulting in nutrient leaching of the soil and a consequent loss of fertility, which becomes greater as the pluviometry gradient increases. This was confirmed by the net balance of several bioelements, the Cation Denudation Rate, the Ca/Al ratio and pH of the soil solution and canopy leaching values.

water balance / nutrient balance / water consumption / soil fertility / *Quercus pyrenaica*

Resumé — Flux d'eau et de bioéléments dans quatre forêts de *Quercus pyrenaica* le long d'un gradient de précipitation. *Les bilans d'eau et de plusieurs nutriments ont été établis pour quatre écosystèmes de* Quercus pyrenaica *le long d'un gradient pluviométrique important situé dans la Sierra de Gata (centre de l'Espagne) afin d'obtenir des informations sur l'effet de la quantité de pluie sur l'évapotranspiration annuelle et estivale, le lessivage des nutriments, et l'évolution de la fertilité des sols. Une corrélation positive entre l'évapotranspiration annuelle et la pluviométrie de la période de mai–août a été observée. Elle ne se retrouve pas avec la précipitations annuelle. Parmi les flux d'eau dans les écosystèmes, le drainage profond présente les variations les plus marquées entre parcelles. Il existe un excès d'eau dans le sol qui provoque un lessivage de nutriments et une diminution importante de la fertilité qui s'accentue avec le gradient pluviométrique. Ceci est confirmé par le bilan net de plusieurs bioéléments, le taux de perte de cations, la relation Ca/Al, le pH de la solution du sol et les valeurs de lessivage de la canopée.*

***bilan hydrique / bilan des nutriments / fertilité du sol /* Quercus pyrenaica**

INTRODUCTION

Actual evapotranspiration is an essential parameter in the functioning of Mediterranean terrestrial ecosystems, where water availability is scarce during the summer periods (Piñol et al, 1991). The soil behaves as a buffering system which receives water intermittently and releases it continually by evapotranspiration (Garnier et al, 1986). Thus, in climates with a Mediterranean influence, greater winter rainfall may positively affect soil moisture during the active period. Any possible variation in water availability may cause differences in both the photosynthetic efficiency and the light interception (Tenhunen et al, 1990), due to limitations in transpiration.

However, the differences in the volume of rainfall also affect the formation and properties of the soil profile, with low base saturation and deeper weathering of the original material usually associated with humid regions (Birkeland, 1984). This is due to differences in the amount of excess water in the soil produced by the different rainfall, favouring leaching processes of nutrients in the soil, accordingly resulting in a loss of fertility in the area where rainfall is higher.

This influence of rainfall on both water and nutritional availability appears to have positive and negative effects, respectively, on forest productivity. Results from four *Quercus pyrenaica* forests, situated across a rainfall gradient, indicate that neither productivity nor leaf area index responded positively to that gradient (Gallardo et al, 1992).

This study was part of a research project on the ecology of the *Q pyrenaica* forests. Water fluxes have been considered as a major aspect of vegetation growth as well as a vector for nutrient transport within the ecosystem. The simultaneous establishment of water and nutrient balances, comparing imports with exports, is an approach frequently used during the last two decades for forest system studies (Likens et al, 1977; Jordan, 1982; Miller et al, 1990; Belillas and Rodá, 1991); these studies are based on the fact that the only important inputs are associated with the meteorological vector and the only important losses are associated with the hydrological vector (Avila, 1988).

In this study, we have tried to establish water and several bioelement balances in four *Q pyrenaica* forests along a marked pluviometric gradient, in order to obtain information on the effect of rainfall amounts on annual and summer evapotranspiration, and on nutrient leaching from the soils, and their fertility.

METHODS

The study area

This study was carried out in *Q pyrenaica* natural forests, classified as *Quercus robori-pyrenaicae* communities, located on the northern face of the Sierra de Gata (40°2'40"N; 3°0'50"W, Salamanca Province, central Spain). *Q pyrenaica* is a deciduous Mediterranean species, whose distribution area corresponds to the southwestern region of Europe.

Four experimental plots, situated close to one another (maximum 15 km), were selected along a pluviometric gradient. The major characteristics of the plots are summarized in table I. The S1 (Navasfrías site), S2 (El Payo site), S3 (Villasrubias site) and S4 (Fuenteguinaldo site) notation in table I follows the decreasing order of precipitation and will be used hereafter in the text. The climate is humid Mediterranean, according to the Emberger's climogram, most of the rainfall being concentrated in the cold part of the year, and dryness coinciding with the warmer season and the growing period. The soils are generally humic Cambisols (Gallardo et al, 1980), over Paleozoic granites and slates.

Field sampling procedure

The devices used, in each plot, for collecting water for chemical analysis are the following:

Table I. Specific characteristics of the four plots.

	Navasfrías (S1)	*El Payo (S2)*	*Villasrubias (S3)*	*Fuenteguinaldo (S4)*
Slope (%)	5–15	5	10–15	2–5
Altitude (m asl)	1 000	940	900	870
P (mm)	1 580	1 245	872	720
Temp (°C)	11.4	nd	nd	13.3
Substrate	Slates and greywackes	Calc-alkaline granite	Slates and greywackes	Calc-alkaline granite
Dominant vegetation	*Q pyrenaica* + *Pteridium* + grasses	*Q pyrenaica* + grasses	*Q pyrenaica* + scrubs + grasses	*Q pyrenaica* + abundant scrubs
Td (no ha^{-1})	820	406	1 043	738
Mth (m)	13	17	8.5	12
DBH (cm)	15.2	25.4	11.0	16.5
LAI ($m^2\ m^{-2}$)	1.8	1.9	2.0	2.6

P: mean annual precipitation; Temp: mean annual temperature (means calculated from 20–30 recorded years); Td: tree density; Mth: mean tree height; DBH: mean tree diameter at a height of 1.3 m; LAI: leaf area index; nd: no data available.

Above the canopy or in a large forest gap close to the plot

– Three aerodynamically shielded rain gauges ('open gauge') for collecting bulk precipitation (Bp).

– Three funnels surmounted by an inert wind filtering of polyethylene-coated wire mesh ('filter gauges'), collecting bulk precipitation plus certain additional amounts of dry and mist deposition (Fg).

The 'filter gauge' enhances the aerosol impaction, and the 'open gauge' minimizes this component in bulk precipitation (Miller and Miller, 1980).

Beneath the trees

– Twelve standard rain gauges, randomly located, for collecting throughfall (Tf).

– Twelve helicoidal gutters, around trunks, for collecting stemflow (Sf). Three trees from each diameter class were selected, covering the basal area range. Sf amounts were calculated in terms of mm of precipitation from the mean volume collected and the number of trees per hectare in each diametric class (Cape et al, 1991).

On and in the soil

– Six nonbounded Gerlach-type collector troughs in each plot (Sala, 1988) for measuring surface runoff (Sr).

– Six free-tension lysimeters installed 20 cm below the soil surface, to collect soil solution draining from humic horizon (Wh); other six installed at 60–100 cm, to collect deep drainage soil solution (D).

The lysimeters were made with PVC material, and the different type of rain gauges used polyethylene funnels. Stemflow samplers were connected to 60 L storage bins and the rest of them were connected to 5 L collecting bottles. Filters of nylon tissue and washed glass fiber were used to prevent contamination of water.

Water precipitation was also recorded hourly with two tipping-bucket rain gauges located above the crown in S1 and S4. Global shortwave radiation, air temperature, relative humidity and wind velocity were recorded as hourly means, using a data logger (Starlog 7000B Unidata).

The soil water content was measured with a neutron moisture gauge (Troxler 3321 A 110 mC of Americium/Berylium) in 12 access tubes in each stand. Soil moisture was measured every 20 cm from 20 to a maximum of 100 cm, according to the depth of the soil. On the surface, the moisture was determined by gravimetric method. Measurements were taken approximately once a month (occasionally every 2 weeks) from March 1990 until September 1993. The calibration curves were determined from gravimetric samples and dry bulk densities, according to Vachaud et al (1977).

The physical and chemical soil characteristics were studied in three selected profiles of each plot. The results have been discussed in previous papers (Quilchano, 1993; Moreno et al, 1996).

Calculation of water balance

The daily distribution of rainfall on S2 and S3 was estimated using the hourly records from S1 and S4, once the high correlation existing between the distribution of rainfall on the four sites was verified. These data were also used to estimate the daily distribution of throughfall, taking into account the crown capacity for water retention (Zinke, 1967). The Penman potential evapotranspiration (PET) was estimated from the hourly data of global shortwave radiation, air temperature, relative humidity and wind velocity.

The following water balance equation was used as a basis:

$$dS/dt = Bp - AET - Sr - D \qquad [1]$$

where S is the soil water storage, Bp the precipitation, AET the actual evapotranspiration, Sr the surface runoff and D the deep drainage, ie, the flow of water below the root zone. These notations will be used hereafter. The precipitation, runoff and changes in soil water storage are readily measurable, but both AET and D are difficult to measure or to calculate. Hence, a water balance model was used which employed a simplified relationship between the drainage component and soil water content, characterizing the downflow of water across a certain level according to the water content existing above that level. This function is called the *drainage characteristic*; more detailed information can be found in Rambal (1984), Joffre and Rambal (1993) and Moreno et al (1996).

The equation [1] is solved iteratively, for each period between two readings of soil moisture, with increases in time of 1 day (during periods of heavy precipitation, increases of 1 hour), ie, starting at S_n and ending at S_{n+1} (two consecutive measurements of S), fitting the term AET, the only unknown. The iterations continue until the measured and calculated value of S_{n+1} coincide. It is always considered that AET $\leq$ PET + INT (potential evapotranspiration plus intercepted precipitation).

During rainy days, AET normally is higher than Penman-PET because of the strong coupling between the forest canopy and the atmosphere, resulting in a high evaporation rate from the wet canopy (Lankreijer et al, 1993), generally an order of magnitude greater than water transpiration rate (Dolman, 1987); however, AET is lower than PET + INT due to the fact that part of the available energy is consumpted in the evaporation of the intercepted water. Thus, PET $\leq$ maximum AET $\leq$ PET + INT. Therefore, AET values are overestimated, but probably minimal due to the moderate volume of INT that is obtained in these forests (see fig 1).

When it is not possible to obtain the equality (equation [1]), a term known as *others* is introduced. This may be because deep drainage can occur before complete water saturation of the soil, following paths of rapid circulation, such as through macropores (Beven and German, 1981), which is not taken into account by the calculation model used. Therefore, this flow is assumed to be drainage.

Calculation of nutrient fluxes

Above-ground, water volumes were measured on an event basis (64 cases), immediately after each rainfall event, from 21 September 1990 to 20 September 1993. In 23 cases, water was collected for chemical analysis.

The fluxes on a mass basis (kg ha^{-1}), for each parameter, are calculated by multiplying the average weight concentration (mg l^{-1}) by the amount of water (mm), either measured (above-ground parameters and surface runoff, Sr) or calculated (deep drainage, D).

The net deposition in the canopy (ie, deposition in throughfall + stemflow, minus bulk deposition) is regressed against the gain in the deposition resulting from the aerosol deposition on the 'filter gauge' (Fg – Bp). This regression results in an intercept term representing the mean value of canopy exchange (CE: leaching or uptake) for equal time periods (Lakhani and Miller, 1980). Dry deposition (Dd) is calculated thus: Dd = Tf + Sf – Bp – CE, where Tf, Ef, Bp and CE are known. More detailed information can be found in Lakhani and Miller (1980) and Moreno et al (1994).

Then, the following calculations are made:

$$\text{Nutrient balance} = \text{Input} - \text{Output}$$

where Input = total deposition of nutrient from the atmosphere (Tdep) = Bp + Dd; and Output = total losses of nutrient from the soil (Tloss) = Sr + D.

Laboratory analytical procedure

pH was measured on a pHmeter (Beckman 3500), and dissolved organic carbon (DOC) was measured on a TOCA (315A Beckman). These analyses were performed as soon as possible after collection (within the first day). Na and K were analysed by flame emission (Varian 1475); Ca and Mg by atomic absorption spectrometry (Varian 1475); Fe, Mn, Cu, Zn and Al by ICP Perkin Elmer Plasma-2; $H_2PO_4^-$ was determined spectroscopically by the molybdenum-blue method (Varian DMS90); Cl^-, NO_3^-, SO_4^{2-} and NH_4^+ were analysed by ion-chromatography (Dionex 350). Complete analyses were generally done within about 1 week after samples collection.

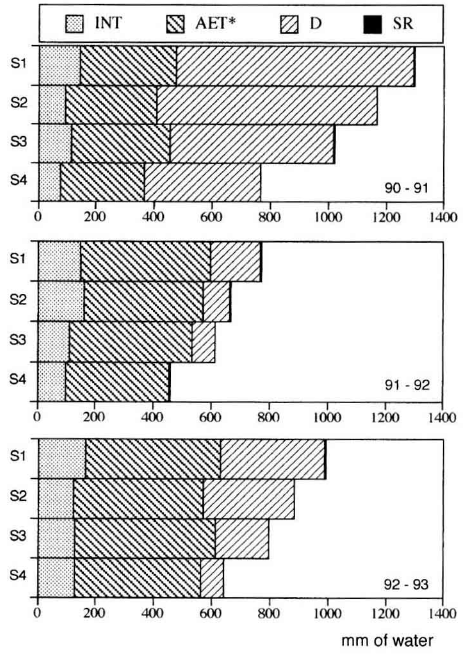

Fig 1. Annual water fluxes of the four plots (S1 to S4) in three different years. INT: intercepted water; AET*: actual evapotranspiration minus INT volume; D: deep drainage; SR: surface runoff. All are expressed in mm $year^{-1}$.

The following soil analyses were carried out: soil pH in water with a soil/solution ratio of 1:2.5; organic C, total N, cation exchange capacity and exchangeable cations by percolation with 1N ammonium acetate at pH 7 (Soil Survey Staff, 1981); plant available nutrients were extracted with DPTA and total elements by acid digestion, both followed by analysis by atomic absorption spectrometry (Varian 1475).

RESULTS

Water balance

Figure 1 represents the value of all water fluxes which originate within the forest ecosystem: intercepted water of the forest canopy, surface runoff, drainage and evapotranspiration. The sum of all corresponds to rainfall volume.

Precipitation

Figure 1 shows the annual rainfall values for the 3 years, which, from the point of view of rainfall and on comparing them with the mean values (see table I), can be defined as normal (1990–1991), very dry (1991–1992) and moderately dry (1992–1993). During the 3 studied years, the pluviometric gradient from which we started a priori was maintained; the differences between plots remained fairly constant during the 3 years, in relative terms (88, 78 and 59% for S2, S3 and S4, respectively, relative to rainfall in S1). Precipitation differed significantly, between all plots and across all years ($P < 0.001$ in both cases). Nevertheless, rainfall distribution was similar in all the plots, with correlation indices around 90%. The seasonality of the rainfall and its acute irregularity are outstanding features; for example, in the 1990–1991 period, rainfall was very abundant during autumn–winter but no major precipitations were recorded after 17 March 1991. On the other hand, over the following 2 years, the rainfall, although less abundant, was distributed more regularly with precipitation recorded up to the beginning of June.

Interception

The percentage of intercepted water was low (16% of the annual rainfall; fig 1) in relation to that mentioned in the literature (eg, Aussenac, 1980; Parker, 1983; Cape et al, 1991). It amounts to only between 22 and 27% (in S4 and S1, respectively) of total evapotranspirated water. This is due to the majority of the rainfall in winter during the period when trees are leafless, coinciding at the same time with low available energy for evapotranspiration. The percentage of intercepted water did not vary along the pluviometric gradient, although a lower percentage of intercepted water might have been expected with higher precipitation (Nizinsky and Saugier, 1988).

Surface runoff

The volume of water lost through surface runoff was also very low (< 0.5% of rainfall; figs 1 and 2), as is frequently found in forest ecosystems (Rambal, 1984; Francis and Thornes, 1990; Soler and Sala, 1992). This result may be explained by low rain intensity, slight slopes, high infiltration and absence of impermeable layers near the soil surface.

Drainage

Drainage (D) increased with rainfall (figs 1 and 2), and significant differences were established both on the level of years ($P < 0.001$) and of plots ($P < 0.05$). Thus, a highly significant relationship between precipitation amount and drainage is found:

$$D = 0.98^{*}Bp - 521$$

$r = 0.93$

Thus, above 532 mm of annual rainfall, there would be a soil water excess and loss to drainage. Annual values for drainage represent, on average, 43, 42, 33 and 26% of rainfall in S1, S2, S3 and S4, respectively, which means a mean of 450, 356, 276 and 162 mm of drainage (respectively) in these forests, clearly following the pluviometric gradient during the 3 years. In the driest year, there was no drainage at all in S4.

Evapotranspiration

On the other hand, the AET (monthly as well as annual values) only differs significantly among S4-S1 plots ($P < 0.05$; fig 1); S4 generally gives lower values, due to the lower precipitation and reduced soil water storage (Moreno et al, 1996). However, these differences are mitigated even more if we subtract the intercepted water, of little value for the vegetation (Rutter, 1975), from AET. The dynamics in the four plots is very similar, with correlation indices above 0.85.

Significant differences of AET values between years are found ($P < 0.001$), which are lower during the year of higher precipitation. If Bp versus AET are compared, a complete lack of direct relationship is observed (fig 2); nevertheless, there is a

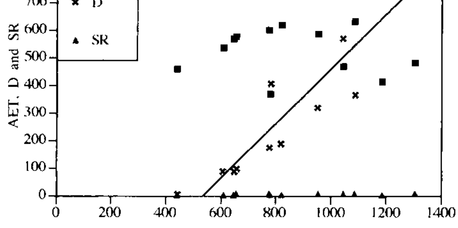

Fig 2. Relationship between annual precipitation and surface runoff (SR), deep drainage (D) and actual evapotranspiration (AET). Significant regression only between rainfall (x) and deep drainage (D). R^2: regression coefficient.

positive correlation between precipitation in the May–August period and the annual AET values (r = 0.85, P < 0.001, data not showed). On average, annual values of AET represent 54, 56, 65 and 74% of rainfall of S1, S2, S3 and S4, respectively, which means a mean of 567, 520, 536 and 460 mm of AET (respectively).

The maximum values of actual evapotranspiration in absolute terms were generally reached in June (sometimes May or July) and the minimum in August. The daily mean values of AET for these periods are shown in table II.

Nutrient balances

Table III shows the values of the atmospheric inputs, differentiating between dry (Dd) and bulk deposition (Bp), and the losses by runoff (Sr, generally negligible) and deep drainage; the net balance (gain or loss) for each element within the forest system can also be seen. Values are expressed in kg ha^{-1} yr^{-1}.

Atmospheric deposition

The standard errors of the the regressions for estimating Dd, using the Lakhani and Miller model (1980), were generally high. However, the results obtained (table III) are in good agreement with the deposition ratios – amount of nutrients in Tf + Sf, divided by those in Bp – and the literature (Moreno et al, 1994); therefore, these results are considered acceptable, at least as an indicator of the origin of the different elements and their orders of magnitude.

In most of the cases, dry depositions are lower than the inputs in rain (paired t-test, P = 0.01). Regarding the differences along the rainfall gradient, bulk deposition is greater in plots with higher precipitation (ANOVA, P = 0.077) and dry deposition is higher in plots with lower pluviometry (ANOVA, P = 0.106), so when the total deposition is considered (bulk and dry), the inputs were similar among plots (ANOVA, P = 0.383).

Canopy exchange of nutrients

Another aspect of interest for the nutrient flow is the process of ionic exchange within the forest canopy (table IV). Some elements are moderately or slightly leached; others are taken up by the leaves. Generally, the higher leaching values (DOC, P, K) and the lower uptake values (H^+, SO_4^{2-}, NO_3^-) are found in the less rainy plots. Therefore, nutrient loss from leaves through leaching (outstanding P, K and Mg) is less in plots with soils of lower fertility (table V; see later).

Table II. Mean daily values of actual evapotranspiration (AET) in two different periods, maximum (May-June-July: M-J-J) and minimum AET (August: A). Values expressed in mm day^{-1}.

Years	*S1 M-J-J*	*S1 A*	*S2 M-J-J*	*S2 A*	*S3 M-J-J*	*S3 A*	*S4 M-J-J*	*S4 A*
1990	1.84	0.92	1.82	0.80	1.83	0.89	1.40	0.63
1991	1.80	0.40	1.47	0.74	1.75	0.90	1.33	0.41
1992	2.47	1.02	2.29	0.86	2.18	0.80	1.67	0.42
1993	2.78	0.91	2.83	0.91	2.86	0.79	3.44	0.84
Means	2.22	0.81	2.10	0.83	2.16	0.88	1.96	0.57

Table III. Annual balance of dissolved elements in the four plots (S1 to S4), calculated as the difference (Gain) between input (Bp + Dd) minus output (Sr + D). Values expressed in kg ha^{-1} yr^{-1}.

Plots		*H^+*	*DOC*	*Cl^-*	*NO_3^-*	*SO_4^{2-}*	*$H_2PO_4^-$*	*Na*	*NH_4^+*	*K*	*Mg*	*Ca*	*Fe*	*Mn*	*Al*
	Bp	0.038	67.5	11.0	4.7	17.2	0.44	5.1	2.8	2.2	1.5	6.8	0.10	0.09	0.41
S	Dd	0.047	1.6	2.1	11.3	0.8	0.99	1.4	2.7	1.7	0.7	4.3	0.14	0.09	0.02
1	Sr	0.000	2.0	0.1	0.1	0.1	0.02	0.0	0.0	0.2	0.1	0.1	0.00	0.01	0.01
	D	0.015	37.9	12.7	3.0	13.4	0.17	4.8	1.1	2.4	2.9	5.5	0.36	0.39	2.09
	Gain	0.070	29.2	0.2	12.9	4.4	1.25	1.7	4.4	1.2	–0.8	5.4	–0.12	–0.21	–1.68
	Bp	0.042	55.0	12.4	5.4	15.2	0.53	4.9	2.4	2.2	1.7	10.2	0.15	0.06	0.40
S	Dd	0.024	13.0	2.1	12.7	0.5	1.84	1.8	4.7	3.5	1.8	1.8	0.02	0.31	0.04
2	Sr	0.000	1.5	0.1	0.1	0.0	0.02	0.0	0.0	0.2	0.0	0.0	0.00	0.00	0.01
	D	0.006	19.8	15.1	6.7	10.1	0.29	4.6	1.6	3.5	2.8	7.4	0.28	0.31	1.06
	Gain	0.060	46.6	–0.7	11.3	5.6	2.06	2.0	5.4	2.0	0.7	4.6	–0.12	0.06	–0.63
	Bp	0.022	51.7	10.6	4.6	13.7	0.63	4.5	5.3	2.8	1.7	7.8	0.17	0.12	0.22
S	Dd	0.017	11.7	3.6	10.2	1.4	2.01	2.5	7.0	3.0	1.2	2.1	0.02	0.31	0.31
3	Sr	0.000	1.4	0.1	0.1	0.1	0.04	0.0	0.0	0.3	0.1	0.1	0.00	0.01	0.01
	D	0.005	48.2	12.5	9.2	11.8	1.29	3.9	1.4	3.2	2.6	5.2	0.43	0.32	1.57
	Gain	0.034	13.9	1.6	5.6	3.2	1.31	3.0	10.8	2.3	0.2	4.6	–0.24	0.10	–1.05
	Bp	0.020	44.0	8.6	3.7	11.1	0.41	3.4	3.2	1.5	1.4	5.8	0.10	0.07	0.15
S	Dd	0.040	17.1	5.6	7.3	2.0	2.71	1.0	4.5	6.8	2.8	4.3	0.13	0.23	0.07
4	Sr	0.000	0.0	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00
	D	0.001	20.7	13.5	4.6	10.3	0.12	2.0	0.8	2.8	1.7	6.2	0.02	0.14	0.29
	Gain	0.059	40.4	0.7	6.3	2.8	3.00	2.3	6.9	5.4	2.5	3.9	0.22	0.16	–0.07

Bp: bulk deposition; Dd: dry deposition; Sr: surface runoff; D: deep drainage.

Gallego et al (1994) found that the leaf bioelement content varies the long of the year; a decrease of N, K and P (very strong in S1) and an increase of Ca were observed in the oak leaves. In contrast, Mg maintained their leaf concentration. Nevertheless, in general, the content of N, Ca, K and P is higher in S4 than in S1, but the leaf Mg content is higher in S1 probably because of an antagonistic effect (low soil Ca content in this plot).

Net losses or gains of nutrients

The losses of the majority of the nutrients from the studied forests are lower than the atmospheric inputs, resulting therefore in a net gain (table III). The order of these gains (% with respect to the total deposition, averaging out the four sites) is: $H^+ > NH_4^+ > H_2PO_4^{2-} > NO_3^- >$ DOC > K ≈ Ca ≈ Na > $SO_4^{2-} >$ Mg > $Cl^- >$ Mn > Fe > Al (the latter two with net losses).

The sum of the net losses (outputs – inputs), on equivalent basis, of the four major cations is known as the Cation Denudation Rate (CDR), and provides one of the best ecosystems-level estimates of the acid neutralizing capacity of the terrestrial ecosystems (Belillas and Rodá, 1991). Negative figures mean, obviously, gains of cations.

In our case, the results are: –0.24 (S1), –0.35 (S2), –0.24 (S3) and –0.57 (S4) keq ha^{-1} yr^{-1}, ie, net gains occur. These results

Table IV. Annual values of canopy exchange of different dissolved elements: positive values = leaching, and negative values = uptake. Values expressed in kg ha^{-1} yr^{-1}.

Plots	H^+	*DOC*	Cl^-	NO_3^-	SO_4^{2-}	$H_2PO_4^-$	*Na*	NH_4^+
S1	−0.045	28	4.1	−11.1	−2.6	0.10	−1.6	−3.1
S2	−0.029	48	4.2	−11.4	−0.1	1.30	−1.2	−4.6
S3	−0.011	55	3.8	−8.9	−1.0	0.45	−1.9	−10.0
S4	−0.01	71	4.5	−7.1	−0.6	3.15	−0.8	−4.5
Plots	*K*	*Mg*	*Ca*	*Cu*	*Fe*	*Mn*	*Zn*	*Al*
S1	4.6	2.6	1.7	0.19	0.02	0.26	−0.21	0.04
S2	10.0	2.4	0.2	0.18	0.07	0.36	0.18	0.02
S3	7.8	4.4	1.9	0.08	0.08	0.54	0.32	0.17
S4	9.4	2.0	0.9	0.08	0.04	0.25	0.24	0.32

Table V. Chemical characteristics of the soil of the four plots.

Site/soil type		*C org*	*N*	*C/N*	*CE C*	*1/2* Ca^{2+}	*1/2* Mg^{2+}	K^+	Na^+	*V*	*pH*
Horizon	*cm*	*(g* kg^{-1}*)*	*(g* kg^{-1}*)*		*(*$cmol_c$ kg^{-1}*)*	*(*$cmol_c$ kg^{-1}*)*	*(*$cmol_c$ kg^{-1}*)*	*(*$cmol_c$ kg^{-1}*)*	*(*$cmol_c$ kg^{-1}*)*	*(%)*	*(*H_2O*)*
S1	hC										
Ah1	0–20	84.0	4.31	19.5	30.5	0.8	0.4	0.3	0.2	5.6	5.1
Ah2	20–40	42.0	2.60	16.2	20.4	0.3	0.1	0.3	0.1	3.9	5.2
C	40–55	6.0	0.49	12.2	12.1	0.3	0.1	0.2	< 0.1	5.0	5.1
CR	55–80	4.1	0.32	12.5	11.7	0.3	0.1	< 0.1	< 0.1	3.4	4.9
S2	hC										
Ah	0–25	69.4	4.20	16.4	26.5	0.6	0.3	0.2	< 0.1	4.2	4.8
Abw	25–40	35.8	2.61	13.8	22.1	0.3	0.3	0.2	< 0.1	2.3	5.0
Bw	40–60	13.6	1.39	10.1	9.5	0.4	< 0.1	0.4	< 0.1	9.5	5.1
BC	60–150	3.8	0.51	7.8	9.7	0.4	< 0.1	0.2	< 0.1	6.2	5.0
S3	hC										
Ah	0–20	67.3	3.99	16.8	19.8	0.4	0.6	0.3	0.1	7.0	4.6
Bw	20–40	12.0	1.25	9.6	5.4	< 0.1	0.1	0.1	0.0	4.8	5.1
C	> 40	6.1	0.91	6.6	3.9	< 0.1	< 0.1	0.1	0.1	4.3	5.2
S4	gC										
Ah	0–20	42.2	2.62	16.1	15.2	5.6	2.6	0.5	0.1	57.6	5.8
ABw	20–30	15.0	0.94	16.0	6.9	0.3	0.5	0.3	< 0.1	15.7	5.5
Bw	30–45	4.7	0.36	13.1	4.7	0.1	0.3	0.2	< 0.1	11.0	5.2
BC	45–70	3.4	0.28	12.1	5.5	0.1	0.2	0.2	< 0.1	8.4	5.0
Cg	70–120	2.8	0.27	10.3	5.9	< 0.1	0.1	0.2	< 0.1	6.7	5.0

hC: humic Cambisol; gC: gleic Cambisol; V: base saturation; CEC: cation exchange capacity.

also indicate a lower ability to supply cations to percolating water in the drier plot. If we consider Bp instead of Tdep, in order to compare it with the results in the literature, the results are: 0.14 (S1), 0.06 (S2), 0.07 (S3) and 0.10 (S4) keq ha^{-1} yr^{-1}. In addition to the four basic cations, the net gains for H^+ and Fe increase, and the net losses of Mn or Al decrease, when precipitation is reduced.

In summary, the losses from the soil are lower than the atmospheric inputs, resulting in a net gain, more evident in S1 for NO_3^- and SO_4^{2-} (depending mainly on the rainfall volume), and in S4 for $H_2PO_4^-$, K, Mg, Fe and Mn (depending mainly on the ion solubility).

Soil fertility

Table V shows the values of some characteristic soil variables. All soils show a very low base saturation level and there is an inverse relation between the base saturation and the amount of precipitation; the content of the exchangeable bases Ca, Mg and K, and pH show the same pattern. All these differences are more pronounced in the humic horizons (Quilchano, 1993) and generally the differences between S4 site and the other three plots are more evident (table V). In contrast, Na seems to be independent from rainfall.

Martín et al (1993) pointed out that the accumulation of litter being higher in the more rainy plots, in spite of there being a higher above-ground production in the drier plot (S4), because the litter decomposition rate is higher in the last site. Thus, a lineal relation can be observed between soil organic carbon content and annual rainfall. These authors found the following equation:

$$C\ (\%) = 4.65 + 0.065{*}P\ (\mathrm{mm\ yr^{-1}})$$

$r = 0.93$ ($P = 0.02$)

where C is soil organic carbon and P annual rainfall.

The larger accumulation of soil organic matter in the wetter plots is associated with a high level of soil nitrogen in these plots (table V).

Another parameter indicating the soil fertility conditions are the pH and Ca/Al quotient (molar quotient) of the soil solution. Abrahamsen (1983) points out that a value of Ca/Al quotient of 1 or less indicates a degraded state of the forest soils or even phytotoxicity by Al. Table VI represents the obtained values for this ratio. Ca/Al values do not indicate a very unfavourable situation; nevertheless, the results do show the effect of the abundant precipitation on the soil fertility, with values for S1 indicating a lower level of fertility, and with high levels of Al in the soil water. The situation improves (lower relative importance of Al) as the pluviometric gradient decreases.

DISCUSSION

Although this study dealt with situations where the precipitation was markedly different, both between year and across plots (range from 442–1 306 mm yr^{-1}), the soils had a similar water content for each year at the beginning of the active growth period of the vegetation (about 250 mm of soil water hold capacity; Moreno et al, 1996). This water content mainly depended on the soil characteristics and less on the precipitation received during the wet season. Therefore, the amount of evapotranspirated water does not vary with the increase of rainfall volume, but the deep drainage water increases with the rainfall. In other words, AET does not vary significantly between plots (when intercepted water, the little values for the vegetation, is subtracted) but, on the contrary, deep drainage does. Moreover, the vegetation shows great dependence on the rains of the dry season, but

Table VI. pH and Ca/Al molar quotient of water draining from humic horizon (Wh) and deep drainage water (D).

	pH				*Ca/Al*			
	S1	S2	S3	S4	S1	S2	S3	S4
Wh	5.73	5.81	6.22	6.62	0.95	1.52	2.07	4.04
D	5.49	5.79	5.72	6.12	1.79	4.73	2.23	14.7

not on the annual rainfall. The water gradient does not seem to highlight differences in the water consumption patterns for the vegetation in this area. Therefore, from all water fluxes within the ecosystem, deep drainage represents the most important differences between plots.

The results indicate how easily an excess of water, and therefore deep drainage, can occur in these soils; a precipitation above 532 mm yr^{-1} causes an excess of water in the soil, and practically anything exceeding that figure will be drained. This number is lower than the average annual precipitation of even the driest plot (720 mm yr^{-1}), but as stated previously, S4 has no drainage in dry years. In other papers, this limit was 360 (Avila, 1988), 400 (Piñol et al, 1991), 470–500 (Lewis, 1968) and 578 (Rambal, 1984) mm yr^{-1}, all them in Mediterranean regions with evergreen wood vegetation. In wetter areas, the limit was, for instance, 450 (Likens et al, 1977) and 420 (Hudson, 1988) mm yr^{-1}. Additionally, the rapid wetting of the deep horizons (Moreno et al, 1996) could indicate the existence of water loss by drainage, due to rapid circulation via macropores (Beven and German, 1981), although the soil would still be below field capacity, a fact that is not included in the model used.

Taking as a basis the soil water balance, decreasing transpiration rates are observed over the active period, reaching acutely low levels. Consumption begins to decrease generally in July, reaching very low values as early as August (table II), when the soil water content is practically depleted (Moreno et al, 1996), remaining almost constant for approximately 1 month, depending on when the first autumn rains occur. Paz and Díaz-Fierros (1985) found in *Q robur* that the soil remained dry for 2 months in a year with 1 368 mm of rainfall in the northwest of Spain. Joffre and Rambal (1988, 1993) obtained similar results in southern Spain. Unless the oaks have an efficient deep radicular system for extracting water from the weathered bedrock, they could be subjected to an important restriction of water during part of the summer season. The moderate amount of water stored in the soil (Moreno et al, 1996) does not prevent the existence of a pronounced water deficit during the active period.

On the other hand, amounts of atmospheric deposition (bulk and dry) can be described as moderate to low, in almost all the elements, when compared with those obtained in the east of Spain (Avila, 1988; Bellot, 1989; Belillas and Rodá, 1991), central and northern Europe (Mayer and Ulrich, 1980; Miller et al, 1987; van Breemen et al, 1989; Tietema and Verstraten, 1991), the United States (Likens et al, 1977; Lindberg et al, 1986) and with mean values obtained by Parker (1983). The atmospheric depositions are especially low for ions such as H^+, SO_4^{2-}, NH_4^+ and NO_3^-, which are mainly from anthropogenic origin (Belillas and Rodá, 1991), and because of this, the more industrialized regions show higher values. There is no evidence of acid or polluted depositions of anthropogenic origin in this Spanish region.

On the contrary, an appreciable amount of atmospheric input of P and K was obtained. High inputs of P in the Mediterranean region have been attributed to soil particles of Saharian origin, rich in P (Bergametti et al, 1992). Nevertheless, as Lindberg et al (1986) pointed out, the source of some element in dry deposition, even in bulk precipitation, may be suspended soil or biological material of local origin and may not represent 'new' inputs. This overestimation of inputs is more probable for K (Lindberg et al, 1986) and P (Gielt and Rall, 1986) in forest ecosystems.

The leaching of elements from the soil is a process controlled mainly by the concentration of anions and hydrogen, while maintaining electrochemical equilibrium in the solution draining from the soil (Johnson et al, 1986). Cl^- and SO_4^{2-} passed through the soil subsystem without significant gains or losses. These ions represent an important flow as regards the leaching of cations, but their concentrations reflected the low atmospheric deposition rates, especially concerning SO_4^{2-} (considered to be largely responsible for the leaching of bases; David et al, 1991). Other anions, NO_3^- and $H_2PO_4^-$, are retained in the soil subsystem, the latter anion as a consequence of the high adsorption capacity of the soil minerals for P (Yanai, 1991); NO_3^- is exchanged within the canopy (table IV). Therefore, these anions do not seem to be an important cause for the leaching of bases in the soils studied. The low acidity of the precipitation also leads to the reduced leaching of the bases of these soils. As a consequence, the study forests have a very low ability to supply cations to percolating water or to neutralize acidity, therefore resulting in, in general, a positive balance of ions in the ecosystems (table III), with the cations being retained in the system either by root absorption or by soil exchange.

The values of Cation Denudation Rate (CDR) are well below the mean of 1.03 keq ha^{-1} yr^{-1}, described by Avila (1988). Of the 22 cases given by this author (the values ranging from –0.12 to 4.4), 19 show net loss values higher than those obtained in our plots (see earlier), two of them show similar values, and only one shows net losses lower than our case. In the Mediterranean region, the values obtained are 1.3 in Montseny (Avila, 1988) and 1.8 in Prades (Escarré et al, 1984). Our low values of CDR are in accordance with the restricted leaching found, in general, for the ions (table III).

Nevertheless, as a result of the excess of water in the soil, a natural process of leaching (not modified by slight-acid atmospheric inputs) and a loss of fertility occur, which become greater as the pluviometric gradient increases. This is clearly reflected in the figures of the net balance of the several elements (table III), CDR, pH and Ca/Al rate of the soil solution (table VI); also it is reflected in the soil base content, the degree of saturation of the exchange complex and the soil pH, especially in the humic horizons (table V). All these parameters have more favourable values for the S4 plot, because it works as a close system in the drier years.

Martín et al (1994) discussed the relation between soil fertility and turnover of the bioelements in these four forests, concluding that the S4 plot is the less dystrophic system because of a more efficient cycle. Quilchano (1993) also found that this bioelement turnover affects mainly the first 10 cm of the soil profile (table V).

Finally, canopy leaching is more important in sites of low precipitation. Jordan (1982) and Parker (1983) pointed out the effect of the trophic conditions on canopy exchange processes, leaching and uptake; the latter author considered that the level of leaching could constitute a quite good index of the trophic state of forest ecosystems. Thus, a low soil nutrient availability results in a lower index of canopy leaching, because of a lower root absorption and translocation to the above-ground organs, resulting generally in a lower bioelement content of the leaves.

CONCLUSION

It can be concluded that most of the exposed results are in agreement with the oligotrophic conditions of the study area and more pronounced with the increase of the precipitation. The greater amounts of rainfall in the wet season does not increase water consumption by the vegetation or, at least, not substantially. On the other hand, it does entail a greater leaching of the soil and, as a consequece, a progessive loss of fertility, which is especially demonstrated in a decrease of exchangeable bases, degree of saturation and pH.

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