Int J Biometeorol (1989) 33:124–130

International Journal of Biometeorology IJB

Atmospheric deposition of nutrients in a coastal maquis ecosystem of northeastern Greece

M. Arianoutsou

Division of Ecology, Department of Biology, University of Thessaloniki, U.P. Box 119, GR-54006 Thessaloniki, Greece

Abstract. The deposition of nutrients N, P, Ca, Mg, Na and K from the atmosphere on a coastal maquis ecosystem was studied over a 12-month period (1981–1982). The annual precipitation during that period was 1065 mm. Nutrient input was estimated as 5.72, 0.24, 30.31, 3.40, 23.99 and 1616 kg ha^{-1} year^{-1} for N, P, Ca, Mg, Na and K, respectively. Chemical analysis of throughfall showed enrichment for all the nutrients studied. It was concluded that nutrient input from bulk precipitation is an important contribution to nutrient cycling of the Greek maquis ecosystem.

Key words: Nutrients – Precipitation – Throughfall – Maquis – Greece

Introduction

Although the atmosphere has long been recognized as a source of chemicals (Tamm 1958), only recently have biologists stressed its role in the biogeochemical cycles of terrestrial ecosystems (Bormann and Likens 1967; Guthrie et al. 1978; Schlesinger and Hasey 1980; Feller 1981; Schlesinger et al. 1982; Brown et al. 1984). Mediterranean-type ecosystems usually occur on nutrient-poor soils. The low plant productivity, the steep or dissected topography and the relatively high erosion rates in most of the areas with mediterranean-type ecosystems (southern California, central Chile, Mediterranean Basin) limit soil development and fertility. In general, soil nutrient deficiencies have been noted in most mediterranean-climate areas (Rundel 1979, among others). Although the deposition of nutrients from the atmosphere is small compared to the annual uptake by the plant community, it is of equal importance if the low soil fertility is considered.

This study deals with nutrient input from precipitation to an area of coastal maquis (evergreen sclerophyllous tall shrub communities) of northeastern Greece. It is part of a broader study on nutrient cycling in this mediterranean-type ecosystem (Arianoutsou 1989; Arianoutsou and Paraskevopoulos, unpublished data), and aims to give some estimation of the geochemical cycle of nutrient imports to the ecosystem.

Study area

Bulk precipitation (rainfall plus dry fallout) was collected at Stavros, the experimental site (40°39′ N, 23°43′ E, ca. 20 m above sea-level, 60 km northeast of Thessaloniki, Greece). The vegetation is maquis and the soil is alluvial on biotitic-gneiss amphibolitic metamorphic rocks, up to 1 m deep with pH of 5.5–6.0 and an organic matter content of 7.5% (0–2 cm depth). The vegetation is 20–25 years old and is dominated by *Quercus coccifera* L. (32% in biomass) and *Arbutus unedo* L. (15% in biomass). Other woody species occurring in the area are *Phillyrea media* L., *Erica arborea* L., *Quercus ilex* L. and *Cistus* sp. The average canopy height is 2.0–2.5 m and the area has a mediterranean climate.

Materials and methods

Rainfall was collected at regular 20- to 30-day intervals from two rain-gauges which were maintained at fixed openings throughout the experimental period. Rainwater as throughfall underneath the canopy was also collected from six rain-gauges placed in groups of three under the dominant shrubs *A. unedo* and *Q. coccifera* chosen at random.

The rain-gauges (200 cm^2 in surface area) were set 0.5 m above ground-level. They were covered with fibreglass mesh (1 mm^2) to prevent contamination from birds, insects and fallen leaves. Each rain-gauge funnel was attached to a stainless steel collecting bottle. A preservative (0.5 cm^3 0.05% $HgCl_2$/1 N

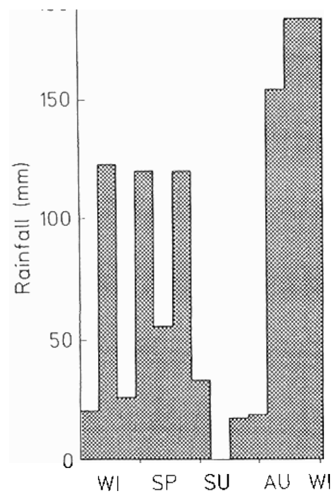

Fig. 1. Total annual precipitation, by season, at Stavros during 1981–1982. WI, winter; SP, spring; SU, summer; AU autumn

HCl) was added to each collecting vessel. The funnels and the bottles were washed with chloroform and double deionized water after each collection.

The water samples were stored below 4° C until analysis. They were analysed for cation (K, Na, Mg and Ca) concentrations by atomic absorption spectrophotometry. Total dissolved phosphorus was determined by predigesting all solutions with HNO_3 and then determining the resulting orthophosphate in a Technicon Autoanalyser according to the method of Varley (1966). Total nitrogen was considered to be the sum of nitrate, nitrite and ammonium nitrogen. After Kjeldahl digestion, total nitrogen was determined automatically using a Technicon Autoanalyser (Varley 1966).

Results

During 1981–1982, total annual precipitation was 1065 mm and was unevenly distributed in time (Fig. 1). There were two peaks in spring and autumn and two lows in winter and summer. Nutrient inputs during this period ranged from 0.24 kg ha^{-1} year^{-1} for phosphorus to 30.31 kg ha^{-1} year^{-1} for calcium (Table 1).

There was variation with time in nutrient deposition (Table 1) and concentration (Table 2) which did not show any clear seasonal pattern. Monthly nutrient inputs from rainfall were correlated with monthly precipitation volumes in the case of nitrogen, magnesium, sodium and potassium but not in the case of phosphorus and calcium (Table 3).

The comparison of concentrations of nutrients in rainfall (Table 2) with those in throughfall (Table 5) shows that the rainwater was enriched by its passage through the stand canopy. This enrichment is shown better when using the ratio of throughfall to bulk precipitation inputs based on the concentrations of the nutrients (Table 7). On the other hand, when comparing the deposition of nutrients from rainfall (Table 1) with those from throughfall (Table 4) no such evidence can be seen (see also Table 8). The reason for this difference is that the final volume of rainwater reaching the ground after passing through the canopy is usually less than that in the open. Therefore, even if the concentration of an element in throughfall is higher than that in rainfall, the overall amount of the

Table 1. Monthly deposition of nutrients from precipitation at Stavros, northeastern Greece. The annual deposition of each element is given at the bottom of each respective column

Collection date	Precipitation (mm)	Nutrient deposition (kg ha^{-1})					
		N	P	Ca	Mg	Na	K
1981:							
December 16	20.55	0.042	0.0006	0.234	0.028	0.148	0.120
1982:							
January 19	123.30	0.295	0.1100	1.530	0.339	3.436	0.368
February 11	26.71	0.204	0.0010	0.412	0.065	0.286	SC
March 3	80.70	0.617	0.0056	2.794	0.199	0.930	0.424
March 17	40.54	0.310	0.0020	0.719	0.276	0.428	0.214
April 6	55.98	0.264	0.0006	1.762	0.177	1.104	0.157
May 18	120.80	0.930	0.0902	3.820	0.678	2.219	2.527
June 23	34.21	0.370	0.0034	1.504	0.129	0.683	0.446
August 23	18.75	0.555	0.0104	0.619	0.074	0.298	0.262
September 23	19.41	0.336	0.0110	1.138	0.079	0.243	0.249
October 23	155.08	0.744	ND	0.140	SC	SC	SC
November 1	184.12	0.898	0.0038	5.258	0.753	5.000	10.525
December 20	185.00	0.152	0.0018	10.383	0.605	9.220	1.316
Dec. 16, 1981–Dec. 20, 1982	1065.15	5.72	0.24	30.31	3.40	23.99	16.16

ND, not detectable; SC, sample not collected

Table 2. Monthly nutrient concentration in the precipitation at Stavros, northeastern Greece. The mean annual concentration of each element and the relative SE are given at the bottom of each respective column

Collection date	Precipitation (mm)	Nutrient concentration (mg l^{-1})					
		N	P	Ca	Mg	Na	K
1981:							
December 16	20.55	0.209	0.003	1.14	0.43	0.72	0.58
1982:							
January 19	123.30	0.240	0.092	1.24	0.27	2.80	0.30
February 11	26.71	0.768	0.004	1.53	0.24	1.07	SC
March 3	80.70	0.768	0.007	3.58	0.25	1.17	0.53
March 17	40.54	0.768	0.005	1.78	0.68	1.06	0.53
April 6	55.98	0.475	0.001	3.15	0.31	1.98	0.28
May 18	120.80	0.770	0.075	3.20	0.56	1.82	2.06
June 23	34.21	1.080	0.010	4.43	0.92	2.01	1.32
August 23	18.75	2.970	0.056	3.38	1.16	1.58	1.40
September 23	19.41	1.650	0.054	5.60	0.39	1.19	1.22
October 20	155.08	0.490	ND	1.88	1.18	SC	SC
November 1	184.12	0.490	0.002	2.99	0.43	2.75	5.17
December 20	185.00	0.823	0.010	4.97	0.33	5.49	0.63
Dec. 16, 1981–Dec. 20, 1982	1065.15	0.88 ± 0.20 ($n=13$)	0.024 ± 0.009 ($n=13$)	2.99 ± 0.40 ($n=13$)	0.47 ± 0.09 ($n=13$)	1.97 ± 0.37 ($n=12$)	1.27 ± 0.40 ($n=11$)

Table 3. Correlation between monthly precipitation nutrient inputs and monthly precipitation volumes. The model of regression applied is shown in parenthesis

Correlation	Correlation coefficient (r)					
	N	P	Ca	Mg	Na	K
Input-precipitation volume	0.76 (Linear)	0.38 (Linear)	0.15 (Multiplicative)	0.71 (Linear)	0.62 (Exponential)	0.76 (Linear)

Table 4. Monthly deposition of nutrients in throughfall of *Arbutus unedo* (AU) and *Quercus coccifera* (QC) at Stavros, northeastern Greece

Collection date	Throughfall (mm)		Nutrient deposition (kg ha^{-1})											
			N		P		Ca		Mg		Na		K	
	AU	QC	AU	QC	AU	QC	AU	QC	AU	QC	AU	QC	AU	QC
1981:														
December 16	8.72	7.18	0.058	0.027	0.0022	0.0004	0.316	0.211	0.042	0.108	0.134	0.178	0.248	0.451
1982:														
January 19	60.02	43.81	0.581	0.239	0.0816	0.0250	2.352	0.658	0.865	0.142	2.228	1.524	2.909	0.861
February 11	10.15	5.88	0.087	0.063	0.0063	0.0013	0.630	0.110	0.115	0.115	0.356	0.310	0.661	0.134
March 3	34.48	22.50	0.038	0.099	0.0051	0.0007	2.152	2.510	0.152	0.354	0.787	0.969	0.736	0.664
March 17	23.10	17.93	0.124	0.072	0.0037	0.0030	0.942	0.797	0.183	0.115	0.876	0.427	0.394	0.547
April 6	25.68	16.87	0.102	0.082	0.0008	0.0148	1.734	1.078	0.223	0.149	1.186	0.948	0.377	0.558
May 18	73.75	52.95	0.356	0.158	0.0442	0.0111	2.883	1.554	0.434	0.259	1.575	1.084	1.342	1.404
June 23	12.57	10.39	0.204	0.190	0.0006	0.0054	0.500	1.488	0.046	0.195	0.175	0.137	0.300	0.142
August 23	9.55	6.07	0.202	0.183	0.0071	0.0078	0.796	0.868	0.143	0.205	0.365	0.199	0.462	0.460
September 23	7.85	9.87	0.137	ND	0.0103	0.0317	1.019	1.710	0.063	0.132	0.141	0.187	0.273	0.370
October 20	71.47	62.20	0.319	0.449	0.0714	0.0882	4.306	3.645	0.379	0.641	1.591	1.082	2.626	2.415
November 1	113.33	97.50	0.520	0.721	0.0102	0.1268	4.487	1.822	1.163	2.017	3.733	2.466	1.917	3.686
December 20	6.36	3.68	0.080	0.093	0.0004	0.0086	2.100	SC	1.397	SC	6.763	SC	8.393	SC
Dec. 16, 1981– Dec. 20, 1982	457.03	356.83	2.81	2.38	0.140	0.325	43.12	16.45	5.21	4.43	19.91	9.51	47.65	11.69

Table 5. Monthly nutrient concentration in throughfall underneath *A. unedo* (AU) and *Q. coccifera* (QC) at Stavros, northeastern Greece

Collection date	Throughfall (mm)		Nutrient deposition (mg l^{-1})											
			N		P		Ca		Mg		Na		K	
	AU	QC	AU	QC	AU	QC	AU	QC	AU	QC	AU	QC	AU	QC
1981:														
December 16	8.72	7.18	0.661	0.380	0.025	0.006	4.11	2.79	0.51	1.18	1.72	3.28	2.90	6.78
1982:														
January 19	60.02	43.81	0.969	0.546	0.136	0.057	4.16	1.49	1.55	0.33	3.79	3.68	4.87	2.01
February 11	10.15	5.88	0.855	1.073	0.062	0.022	1.58	3.22	1.10	1.62	3.39	5.56	6.30	2.96
March 3	34.48	22.50	0.112	0.441	0.016	0.003	6.28	10.87	0.58	1.39	2.25	4.91	1.99	3.41
March 17	23.10	17.93	0.537	0.399	0.016	0.017	4.20	4.76	0.78	0.91	3.70	1.94	1.79	3.89
April 6	25.68	16.87	0.398	0.487	0.003	0.088	7.23	6.51	0.91	0.92	4.73	5.69	1.38	3.15
May 18	73.75	52.95	0.483	0.299	0.006	0.021	4.00	2.84	0.58	0.49	2.07	2.21	1.80	2.71
June 23	12.57	10.39	1.621	1.823	0.005	0.052	8.12	15.72	0.75	2.06	2.85	3.06	4.87	1.50
August 23	9.55	6.07	2.113	3.008	0.074	0.128	8.08	12.87	1.53	0.37	4.03	2.97	4.98	5.05
September 23	7.85	9.87	1.749	ND	0.132	0.481	10.57	17.29	0.98	1.34	1.49	1.89	3.00	3.74
October 20	71.47	62.20	0.447	0.739	0.010	0.145	5.78	6.40	0.53	1.18	2.19	2.23	2.77	4.53
November 1	113.33	97.50	0.459	0.739	0.009	0.130	6.54	2.28	1.06	1.82	3.31	4.12	1.94	3.47
December 20	6.36	3.68	1.258	2.530	0.006	0.233	16.24	4.97	1.08	0.33	5.23	SC	6.49	0.63
Dec. 16, 1981– Dec. 20, 1982	457.03	356.83	0.897 ± 0.17	0.958 ± 0.25	0.038 ± 0.01	0.106 ± 0.04	6.68 ± 1.02	7.25 ± 1.60	0.92 ± 0.10	1.13 ± 0.16	3.13 ± 0.32	3.46 ± 0.39	3.47 ± 0.50	3.60 ± 0.40
								($n=13$)						

Table 6. Correlation between monthly throughfall nutrient inputs and monthly throughfall volumes for *A. unedo* (AU) and *Q. coccifera* (QC)

Correlation	Correlation coefficient (r)					
	N	P	Ca	Mg	Na	K
Input-throughfall volume	(AU) 0.80 (Linear)	0.48 (Exponential)	−0.57 (Reciprocal)	0.63 (Exponential)	0.44 (Exponential)	−0.65 (Reciprocal)
	(QC) 0.83 (Linear)	0.79 (Linear)	0.57 (Linear)	0.82 (Exponential)	−0.75 (Reciprocal)	0.90 (Linear)

Table 7. Ratios of throughfall to bulk precipitation inputs based on the mean monthly values of the relative nutrients

Species	Throughfall/precipitation ratio (based on mg l^{-1})					
	N	P	Ca	Mg	Na	K
Arbutus unedo	1.02	1.58	2.23	1.96	1.59	2.73
Quercus coccifera	1.09	4.42	2.42	2.40	1.76	2.83
Mean	1.05	3.00	2.32	2.18	1.67	2.78

Table 8. Ratios of throughfall to bulk precipitation inputs based on annual values of the relative nutrients

Species	Throughfall/precipitation ratio (based on kg ha^{-1} $year^{-1}$)					
	N	P	Ca	Mg	Na	K
Arbutus unedo	0.49	0.58	1.42	1.53	0.83	2.95
Quercus coccifera	0.42	1.35	0.54	1.30	0.40	0.72
Mean	0.45	0.96	0.98	0.41	0.61	1.83

element finally deposited on the ground underneath the canopy will be lower. There was a tight correlation between monthly nutrient inputs in throughfall with monthly throughfall volumes for most of the nutrients (Table 6).

Discussion

The location of mediterranean-type ecosystems near the coast of the continents means that these systems are subject to relatively high deposition

Table 9. Annual atmospheric nutrient deposition in bulk precipitation in several ecosystems

Locale and reference	Annual precipitation (mm)	Distance from the sea (ka)	Nutrient deposition (kg ha^{-1} year^{-1})					
			N	P	Ca	Mg	Na	K
Mediterranean-type ecosystems:								
California chaparral (Schlesinger and Hasey 1980)	450–770	5–10	1.00	–	1.40	0.80	6.10	0.40
California chaparral (Schlesinger et al. 1982)	756	10	1.50	–	1.90	1.00	–	0.60
California coastal scrub (Clayton 1972)	635	2	–	–	7.60	3.80	68.60	14.90
France garrigue (Lossaint and Rapp 1971; Lossaint 1973)	770	20	14.60	1.00	10.50	1.50	22.60	2.00
South Australia eucalyptus open forest (Guthrie et al. 1978)	1295	?	–	–	1.27	1.40	17.93	4.20
South Africa coastal fynbos (Brown et al. 1984)	381	?	–	0.19	–	–	–	–
Northeast Greece maquis (Present study)	1065	<1	5.72	0.24	30.31	3.40	23.99	16.60
Other forests:								
Oregon coniferous forest (Tarrant et al. 1968)	2286	10	1.50	–	–	–	–	–
New Hampshire temperate forest (Likens et al. 1977)	1250	116	20.70	0.04	2.20	0.60	1.60	0.90

of ions such as sodium, which are plentiful in seawater (Junge 1963; Art et al. 1974). In the present study, approximately 24 kg ha^{-1} of sodium were deposited annually, indicating the relative importance of the sea as a source of this element. There is considerable evidence that magnesium is also derived from marine sources (Schlesinger and Hasey 1980). Our data show that 3.4 kg ha^{-1} were deposited annually on the site. The values given in the bibliography for several mediterranean-type ecosystems vary from 0.80 kg ha^{-1} for a Californian chaparral (Schlesinger and Hasey 1980) to 3.80 kg ha^{-1} for a coastal scrub community (Clayton 1972) (Table 9). The value observed for our site is closer to that for the coastal shrub community than to that for the chaparral and the reason probably is that both sites are typically "coastal".

Although calcium and potassium may also be derived from maritime sources, their amount in the precipitation comes mainly from clay minerals in soil dust and increases with continental influence (Gorham 1961). A high amount of these two nutrients was deposited at the Stavros site (30.31 and 16.60 kg ha^{-1} for calcium and potassium, respectively). Whether or not these amounts were of maritime origin cannot be directly answered by using the data on hand. However, we can postulate that during the year of this study there was no dry period long enough to be considered a period of drought (Fig. 1) that could be sufficient to cause complete drying of the surface soil so as to render it erodible by wind. Furthermore most of the ground is covered by litter, so that it is not directly subjected to wind erosion. Therefore it is reasonable to hypothesize that most of these elements derive from seawater.

Published data for other mediterranean-type ecosystems of the world give various values of nutrient deposition (Table 9). Although the amount of potassium deposited in the 1-year study at Stavros is quite similar to that deposited at the coastal scrub community of California (16.60 and 14.90 kg ha^{-1}, respectively), calcium deposition is much higher (30.31 versus 7.60 kg ha^{-1}). The value for annual nitrogen deposition may be considered high (5.72 kg ha^{-1}, and is much higher than the amount reported for Californian chaparral (cited in Table 9: Schlesinger and Hasey 1980; Schlesinger et al. 1982) but lower than that of the French maquis (also cited in Table 9: Lossaint and Rapp 1971; Lossaint 1973). Although there is some evidence that much of the nitrate nitrogen in bulk precipitation in southern California may also be derived from soil dust (Schlesinger and Hasey 1980), no such evidence is available for the French garrigue or for the Greek maquis mostly because of lack of data on dry deposition. Considering that the available soil phosphorus at the Stavros site is very low (0.0011% for the top 2 cm and 0.00033% for the lower 2–20 cm (Arianoutsou and Paraskevopoulos, unpublished data), the deposition of 0.24 kg ha^{-1} of phosphorus by rainfall is rather important. Brown et al. (1984) estimated that 4.5% of the soluble soil phosphorus of a coastal fynbos ecosystem originates from precipitation, by which 0.19 kg ha^{-1} of phosphorus are annually deposited on the ecosystem (Table 9).

Chemical analysis of throughfall showed enrichment for all the nutrients studied, as water passes through the canopy (Tables 5, 7). It has been shown (Attiwill 1966; Nihlgard and Lindgren 1977) that the major source of enrichment is foliar leaching. Quantities of all the nutrients reaching the soil surface will not be increased because of the lower water volume containing an otherwise increased nutrient concentration. Other investigators have observed similar chemical changes in throughfall compared to precipitation (Guthrie et al. 1978; Rolfe et al. 1978; Carlisle et al. 1966). Some of these chemical fluxes can be attributed to leaching from plant tissue. For example, the presence of sodium and potassium in the cell sap accounts for their being leached readily by rainwater. Guthrie et al. (1978) found that foliar leaching accounts for 66% of the total return of sodium from biomass to soil and for 56% of the total return of potassium. Additions of nutrients by foliar leaching should not be considered as being directly of atmospheric origin, but only indirectly, since leaching would not happen without rain.

The nutrient cycling processes in any ecosystem, namely (i) the geochemical cycles of import to and export from the ecosystem (precipitation, dry deposition, stream flow), (ii) the biogeochemical cycles between plant and soil within the ecosystem (decomposition, leaching) and (iii) the biochemical cycles of internal transfer within the biomass (Switzer and Nelson 1972) define the vigour and the stability of the ecosystem. The balance between the inputs of nutrients to any ecosystem in rainwater and the output of nutrients from the ecosystem will define its productivity, and furthermore will be the basis for any management plan for that ecosystem. The evergreen sclerophyllous ecosystems of Greece, known as maquis, are threatened from fire and overgrazing. The result of both fire and overgrazing are one of the causes of considerable nutrient losses (Arianoutsou-Faraggitaki and Margaris 1981, 1982; Arianoutsou-Faraggitaki 1985). The understanding of the phenomena mentioned above as a source of nutrients in the mediterranean-type ecosystems (not only in Greece) is therefore of major importance and needs further investigation.

Acknowledgements. I am grateful to Dr. S. Tselas and Mr. L. Loukas for their help in the analytical work. I would like also to express my thanks to Mr. Th.A. Mardiris and Dr. D. Alifrangis for their help in the atomic absorption spectroscopy. Editorial assistance was generously provided by Prof. P.A. Gerakis; Ms. A. Karamanli-Vlahopoulou prepared the manuscript. The work would not have been possible without the encouragement and understanding of my companion.

References

Arianoutsou M (1989) Timing of litter production in a maquis ecosystem of North-Eastern Greece. Acta Oecol (in press)

Arianoutsou-Faraggitaki M (1985) Desertification in Greece: the case of Lesvos island. J Arid Environ 9:237–242

Arianoutsou-Faraggitaki M, Margaris NS (1981) Fire-induced nutrient losses in a phryganic ecosystem. Int J Biometeorol 25:341–347

Arianoutsou-Faraggitaki M, Margaris NS (1982) Phryganic (East Mediterranean) ecosystems and fire. Ecol Medit 8:473–480

Art HW, Bormann FH, Voigt GK, Woodwell GM (1974) Barrier island forest ecosystem: Role of meteorologic nutrient inputs. Science 184:60–62

Attiwill PM (1966) The chemical composition of rain-water in relation to cycling of nutrients in mature *Eucalyptus* forest. Plant Soil 24:390–406

Bormann FH, Likens GE (1967) Nutrient cycling. Science 155:424–429

Brown G, Mitchell DT, Stock WD (1984) Atmospheric deposition of phosphorus in a coastal ecosystem of the South-Western Cape, South Africa. J Ecol 72:547–551

Carlisle A, Brown AHF, White EJ (1966) The organic matter and nutrient elements in the precipitation beneath a sessile oak (*Quercus petraea*) canopy. J Ecol 54:87–98

Clayton JL (1972) Salt spray and mineral cycling in two Californian coastal ecosystems. Ecology 53:74–81

Feller MC (1981) Catchment nutrient budgets and geological weathering in *Eucalyptus regnans* ecosystems in Victoria. Austr J Ecol 6:65–77

Gorham E (1961) Factors influencing supply of major ions to inland waters, with special reference to the atmosphere. Bull Geol Soc Amer 72:795–840

Guthrie HB, Attiwill PM, Leuning R (1978) Nutrient cycling in a *Eucalyptus obliqua* (L'Hérit.) Forest. II. A study in a small catchment. Austr J Bot 26:189–201

Junge CE (1963) Air chemistry and radioactivity. Academic Press, New York

Likens GE, Bormann FH, Pierce RS, Eaton JS, Johnson NN (1977) Biogeochemistry of a forest ecosystem. Springer, New York

Lossaint P (1973) Soil-vegetation relationships in mediterranean ecosystems of southern France. In: di Castri F, Mooney HA (eds), Mediterranean-type ecosystems: Origin and structure. Springer, New York, pp 199–210

Lossaint P, Rapp M (1971) Repartition de la matière organique, productivité et cycles des elements mineraux dans des écosystèmes de climat méditerranéen. In: Duvigneaud P (ed), Productivity of forest ecosystems. UNESCO, Paris, pp 597–617

Nihlgard and Lindgren (1977) Plant biomass, primary production and bioelements of three mature beech forests in south Sweden. Oilos 28:95–104

Rolfe GL, Akhtar MA, Arnold LE (1978) Nutrient fluxes in precipitation throughfall and stemflow in an oak-hickory forest of southern Illionis. Agric Experim Stn For Res Rep, 78. Univ of Illinois, Urbana, Illinois

Rundel PW (1979) Ecological impact of fires on mineral and sediments pools and fluxes. In: Agee JK (ed) Fire and fuel management in mediterranean-climate ecosystems: Research priorities and Programmes. MAB Tech Note 11, UNESCO, Paris, pp 17–21

Schlesinger WH, Hasey MM (1980) The nutrient content of precipitation, dry fallout, and intercepted aerosols in the chaparral of southern California. Am Midl Nat 103: 114–122

Schlesinger WH, Gray JT, Gilliam FS (1982) Atmospheric deposition processes and their importance as sources of nutrients in a chaparral ecosystem of Southern California. Water Resour Res 18:623–629

Switzer GL, Nelson LE (1972) Nutrient accumulation and cycling in Loblolly pine (*Pinus taeda* L.) plantation ecosystems: the first twenty years. Soil Sci Soc Am Proc 36:143–147

Tamm CO (1958) The atmosphere. Handb Pflanzenphysiol 6:233–242

Tarrant RF, Lu KC, Chen CS, Bollen WB (1968) Nitrogen content of precipitation in a coastal Oregon forest opening. Tellus 20:554–556

Varley JA (1966) Automatic method for the determination of nitrogen, phosphorus and potassium in plant material. Analyst 91:119–126

Received July 6, 1988; revised February 6, 1989
Accepted February 17, 1989