Intensive Monitoring of Forest Ecosystems

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Summary

Pollution inputs and their impact on Irish forests are intensively monitored at four forest ecosystems. The sites, in Cork (Ballyhooly), Mayo (Brackloon), Galway (Cloosh) and Wicklow (Roundwood), supply stand and other environmental data to assist in interpretation of forest health surveys. They also contribute to research on the effects of plantations on freshwater stream ecosystems. The chemical composition of water, from the incoming rain, through the forest ecosystem and out through the soil is monitored. Results here are for three years for Ballyhooly and one year for the others.

There is significant pollution at Roundwood. At Ballyhooly, ammonium, apparently much of it from local dairy farms, has a potentially damaging long-term impact. Rain at the western sites is relatively clean, although there is evidence of a small but significant pollution influence in the region. The marine influence is strong at all sites, with very high inputs of the main marine ions, sodium and chloride, at Brackloon and Cloosh. The forest intercepts substances in the atmosphere and by this and other processes, deposition of ions on the forest floor (and consequently to forest soils and adjoining ecosystems) is generally greater than on open, non-forested land. This process is clearly seen at Roundwood where nitrogen inputs are augmented to the point where degradation of the ecosystem is likely to occur. Nitrogen inputs at the western sites are very low, but high salt inputs here may acidifiy adjoining freshwater ecosystems.

Long-term support for intensive monitoring is needed. There is a real risk of damage to forest ecosystems, and via forests to other ecosystems. Deposition and its impacts vary greatly with weather conditions, and, as with climatological monitoring, good evidence for effects which take many years must be based on several years' continuous monitoring.

Introduction

Leaching and acidification are the dominant processes in mineral soils of humid temperate climates. Leaching occurs since rainfall greatly exceeds evapotranspiration (Rohan, 1986). This removes basic cations released from minerals, which are replaced by the constant net acid inputs of rain (always acid, whether 'clean' or not) and acid excreta from plant nutrient uptake and microbial metabolism. Soil solution acidification is buffered under increasingly acidic conditions by carbonate minerals, weathering of silicate minerals and exchangeable base-generating cations; cycling of ions from deeper soil layers via plant uptake, and mixing by soil fauna also offset acidification effects. The natural acidification process can be accelerated by increased rainfall and increased or concentrated acid inputs in polluted rain.

Polluted rain has been responsible for accelerated soil acidification in continental Europe and has been implicated in a variety of growth disorders in forests. Forest decline, which has been a cause of concern in Europe since the late 1970s, takes many forms (Roberts *et al.,* 1989). Premature needle loss of conifers, premature leaf abscission of broadleaved species and yellowing arising from deficiencies of magnesium and potassium are commonly reported symptoms. Experts disagree on the underlying cause of these problems, but it is generally agreed that pollution is a factor.

The European Community Forest Health Survey was established by the Directorate-General for Agriculture in 1987 (Council Regulation (EEC) no. 3528/86). By 1990 a network had been established throughout the Community comprising 2,005 plots with a further 878 plots in non-EC European countries (Anon., 1991). The network of observation points used in the inventory is on a 16x16 km grid and covers the entire forest area of the Community. In Ireland, Coillte Teoranta is responsible for this network (McCarthy 1993).

Four intensive monitoring sites have been established in forest ecosystems by the Forest Ecosystem Research Group (FERG) in the Department of Environmental Resource Management, University College Dublin. They are designed to supply detailed information on stand, site and other environmental parameters in order to assist in the interpretation of forest health survey data. They also contribute to other studies, including research on the interaction of plantation forests and freshwater stream ecosystems (Giller *et al.,* 1993). Water, as it passes through the ecosystem is sampled continuously and analysed regularly, giving information on the effect of atmospheric deposition on the forest ecosystem, the potential impact of the forest on adjoining ecosystems, such as streams, and on elemental turnover within the ecosystem. Resources for the collection and analysis of samples are maximised through collaboration with a number of other agencies in Ireland, principally Coillte Teoranta, and in Germany (University of Munich). Joint research projects involve collaboration with several European research institutes.

Elemental turnover studies have been used extensively to advance the understanding of ion translocation, nutrient conservation and soil acidification processes within forest ecosystems (Miller *et al.,* 1979; Evans, 1984; Horn *et al.,* 1989; Heij *et al.,* 1991). They are also valuable in assessing the impact of pollutants on forests, thus contributing to the study of forest decline and understanding its causes (Ulrich, 1984). The ionic composition of precipitation is obviously relevant in this regard, but more important to the question of pollutant loads is deposition beneath the forest canopy. Although a significant proportion of the incoming precipitation is intercepted by the forest canopy, deposition of ions is often greater than on an open, non-forested site. Ionic deposition occurs, not only with rain (wet deposition), but also as aerosol and dust particles (dry deposition) and associated with fog or mist (referred to as *occult deposition*, but often included, loosely, with dry deposition). Forests, particularly coniferous forests, intercept dust and aerosol particles from the atmosphere, the so-called *scavenging effect*. Aerosols and particles, whether sea salts or pollutants, once trapped in forest canopies are washed down in subsequent rain events. In consequence, throughfall, rain which has passed through the forest canopy, usually has both higher concentrations and larger loads of most ions than the rain itself. The product of the concentration of an ion in throughfall and the volume of the throughfall gives an estimate of the deposition or load on the forest floor. The difference between throughfall and precipitation loads, therefore, is the net result of processes which include absorption through the foliage and bark (Eilers *et al.*, 1992; Klemn *et al.*, 1989), enrichment by dry and occult deposition, and leaching from the foliage.

Elemental turnover studies are important not only in the context of forest decline, but also in relation to the human influence on the landscape. The landscape of Ireland has, over the past three hundred years, been seriously disturbed by human activity. The native broadleaved forests were exploited almost to the point of extinction (Neeson, 1991) with consequences for soil fertility which are difficult, in retrospect, to quantify. Deforestation has led to the slow degradation of our soil resource and possibly to an extension of peatland development in upland regions. By 1900 little more than 1% of the land surface was under forest. As a consequence of the policy of afforestation followed throughout this century, the proportion of the land under forest is now close to 7%. Natural and semi-natural ecosystems have been disrupted by this afforestation. This has resulted in the interruption of nutrient cycles and the alteration of the ecology of ecosystems. Peatland forestry, in particular, has been the subject of debate and controversy (Hickie, 1990; Farrell, 1990a; Farrell, 1991; Farrell and Boyle, 1990). The interaction of these peatland plantations with the environment and in particular, with freshwater stream ecosystems is of importance to the economic development of regions where tourism and salmonid fisheries are major industries. Under polluted conditions in the United Kingdom, for instance, plantation forests have had a negative impact on stream water quality and on macroinvertebrate and fish populations (Gee and Stoner, 1989; Stoner and Gee, 1985; Harriman and Morrison, 1982; Hornung and Newson, 1986). Studies in sensitive fishery regions in Ireland have shown negative effects of forests on water quality (Allott *et al.*, 1990; Giller *et al.*, 1993). In this paper, the intensive monitoring of forest ecosystems in Ireland is described and preliminary results are reported.

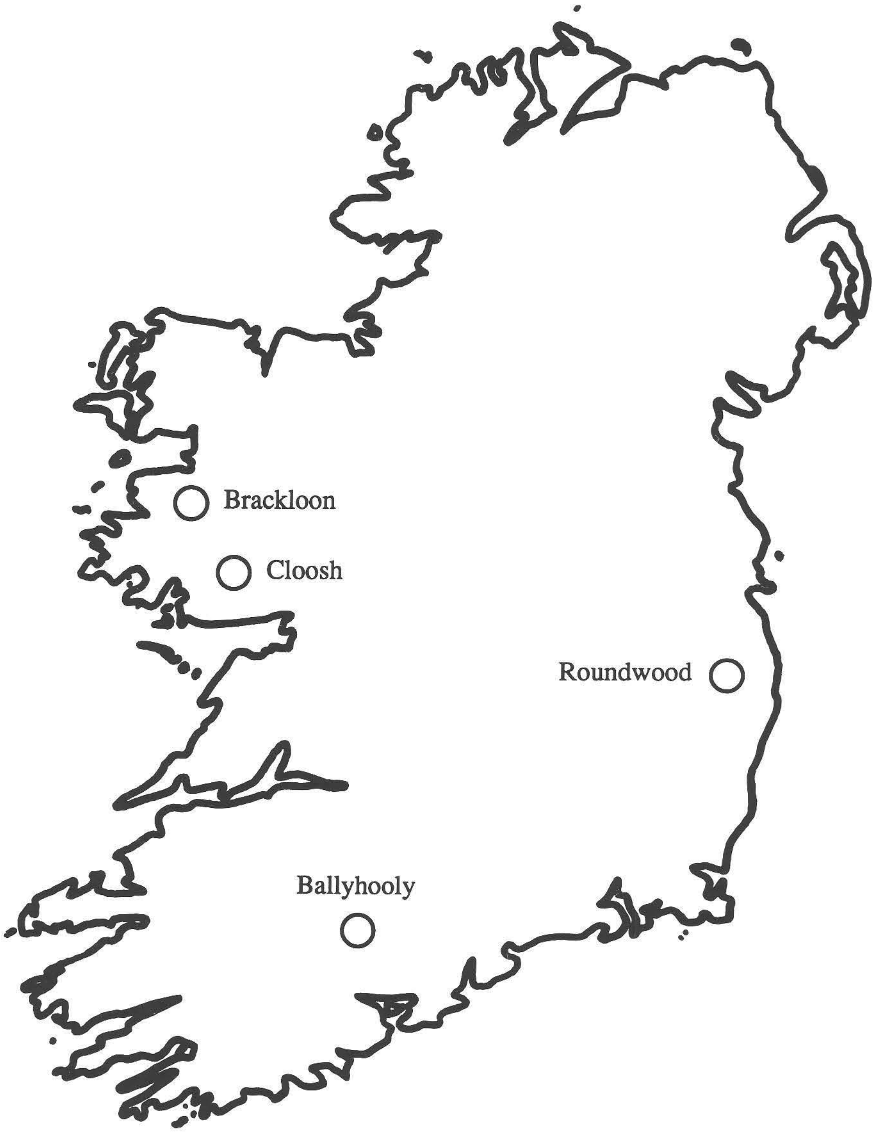

Figure 1: Location of monitoring sites.

Monitoring Sites

Details of the four monitoring sites operated by FERG in UCD are presented in Table 1 and their locations are shown in Figure 1. Each site was selected subjectively as representative of an important forest ecosystem. The first plot was established at Ballyhooly in Co. Cork in late 1988. The tree crop is a mature stand of Norway spruce (*Picea abies* (L.) Karst.) and the soil is acid and free-draining.

The other sites were established in 1991. Two are Sitka spruce (*Picea sitchensis* (Bong.) Carr.) plantations, at Cloosh in Co. Galway, on blanket peat and at Roundwood Co. Wicklow, on an acid mineral soil. The third, at Brackloon near Westport, Co. Mayo is a semi-natural oak-wood (*Quercus petraea* (Matt.) Lieb.). The soils at both Roundwood and Brackloon have podzol characteristics.

Sample Collection and Measurement

The details of sample collectors below apply to the Ballyhooly site unless otherwise stated. Installations at the other sites are broadly similar in design and distribution on site. In general, samples from individual collectors are bulked to give a single sample of each ecosystem component for each sampling event. At intervals of a few months, samples from each collector are analysed individually in order to give a measure of variance.

Precipitation: On an open site, approximately 300 m from the plot, there are three bulk precipitation collectors, each consisting of a permanently

Table 1: Details of intensive monitoring sites.

Site	Location	Stand / planting year or age	Soil / Geology	Monitoring start
Ballyhooly, Co. Cork	W 724 981 52°8'N 8°25'W	Norway spruce, 1939	Podzol / Old red sandstone colluvium	January 1989
Brackloon, Co. Mayo	L 973 799 53°46'N 9°33'W	Semi-natural oak, over 150 years old	Peaty podzol / Schist	January 1991
Cloosh, Co. Galway	M 104 346 53°21'N 9°20'W	Sitka spruce, 1958	Blanket peat / Granite	January 1991
Roundwood, Co. Wicklow	O 180 073 53°6'N 6°14'W	Sitka spruce, 1955	Peaty podzol / Schist	January 1991

open collector of radius 5 cm (collection area is 0.0079 m^2), connected via a coarse filter to a polyethylene bottle. Bulk precipitation (so called because, as the collectors are permanently open, the sample includes, in addition to wet deposition, some dry deposition) is collected weekly (or twice weekly in periods of heavy rainfall) and dispatched to the laboratory. Volumes are recorded and the samples bulked and analysed for pH, NH_4^+, P, Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, HPO_4^{2-} and SO_4^{2-}. pH is measured on arrival at the laboratory, by low-conductivity combination electrode. $NH4^+$-N and P are measured colorimetrically using a visible-ultra-violet spectrophotometer. Cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) are measured by inductively coupled plasma spectrophotometry (ICP). Anions ($C1^-$, NO_3^-, HPO_4^{2-}, SO_4^{2-}) are measured by ion chromatography (IC) using an anion exchange column and conductivity detection.

Throughfall: Throughfall is collected weekly in nine collectors, of a similar design to the bulk precipitation collector, located below the tree canopy but above the herb layer. The samples are bulked and throughfall water is analysed in a similar manner to the bulk precipitation. Throughfall collectors are systematically located at equidistant intervals on a plot diagonal at Ballyhooly. At the other sites they are more numerous and are randomly distributed throughout the plot.

Stemflow: Stemflow collection equipment consists of helical silicon rubber gutters, with the water diverted into 80 l PVC containers. The samples are bulked and analysed as for bulk precipitation with, additionally, dissolved organic carbon (DOC) being measured.

Soil water: Soil water is collected weekly at the forest floor-soil interface, and is extracted under suction, fortnightly, from two depths, 25 and 75 cm approximately, in the soil. There are four soil water measuring stations within the plot. Installed at each, are one zero-tension humus lysimeter, located at the forest floor-mineral soil junction and four P/80 ceramic-cup soil water samplers (two at 25 cm and two at 75 cm). In addition, a further three humus lysimeters are randomly located around the plot. Soil water is extracted using a suction of 600 hPa, which is applied four days prior to sample collection. The eight samples from each of the two depths are pooled for analysis. The analysis is similar to that for the bulk precipitation and throughfall, except that in addition, Al^{3+} is measured either by graphite furnace atomic absorption spectrometry (GFAA) or by ICP-OES. Ten tensiometers, installed at each of the two depths (25 cm and 75 cm) are read on a weekly basis.

Litter: Plant litter is collected monthly in ten collectors. Nitrogen is determined by Kjeldahl digestion and distillation. Sulphur is determined by x-ray fluorescence spectrometry (XRF). All other elements (P, K, Ca, Mg, Na and Mn) are analysed by ICP on a nitric-perchloric digest.

Table 2: Ionic fluxes ($mol_c\ ha^{-1}\ year^{-1}$) at Roundwood, 1991. Percipitation and throughfall fluxes are calculated from the product of sample concentration and water flux; humus and soil water fluxes are estimated from sample concentration, with chloride concentration used as an indicator of water flux. Chloride flux is assumed constant from throughfall to deep soil water, and on the open site, from precipitation to shallow soil water.

	H_2O	pH	H^+	NH_4^+	NO_3^-	Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	SO_4^{2-}
	mm		$mol_c\ ha^{-1}\ year^{-1}$								
Precipitation	1204	4.36	522	414	337	151	238	32	1511	1618	632
Throughfall	789	3.91	946	784	883	455	719	382	2945	3430	1633
Humus water	605	3.62	1449	1585	1295	853	879	423	2872	3430	1937
Soil water shallow	471	3.77	806	12	556	82	400	38	2584	3430	970
Soil water deep	681	4.04	618	48	1534	133	624	63	3120	3430	1514
Soil water shallow, open site	784	3.45	2750	6	116	145	311	69	1638	1618	881

Table 3: Ionic fluxes ($mol_c\ ha^{-1}\ year^{-1}$) at Cloosh, 1991. Calculations as in Table 2.

	H_2O	pH	H^+	NH_4^+	NO_3^-	Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	SO_4^{2-}
	mm		$mol_c\ ha^{-1}\ year^{-1}$								
Precipitation	1463	4.88	195	126	133	300	1072	109	5653	6134	890
Throughfall	790	4.60	199	67	110	746	1728	463	8172	9475	1428
Humus water	1092	3.67	2337	216	129	574	1733	307	8369	9475	1749
Soil water shallow	368	3.57	988	388	0	298	1903	16	6360	9475	1226
Soil water deep	513	3.99	528	1062	1	238	2021	38	6547	9475	1033

Table 4: Ionic fluxes (mol_c ha^{-1} $year^{-1}$) Brackloon, 1991. Calculations as in Table 2.

	H_2O	pH	H^+	NH_4^+	NO_3^-	Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	SO_4^{2-}
	mm		mol_c ha^{-1} $year^{-1}$								
Precipitation	1302	4.84	187	158	107	314	953	103	6803	6759	954
Throughfall	1143	5.17	78	90	79	907	2070	710	11236	14732	1885
Humus water	1317	4.04	1189	229	63	1458	2925	1547	14350	14732	1970
Soil water shallow	908	3.84	1300	28	0	879	2456	818	11446	14732	2004
Soil water deep	701	4.39	283	9	0	334	2537	256	9024	14732	1618

Table 5: Ionic fluxes (mol_c ha^{-1} $year^{-1}$) at Ballyhooly, 1989-'91. Calculations as in Table 2.

	H_2O	pH	H^+	NH_4^+	NO_3^-	Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	SO_4^{2-}	Al^{3+}
	mm		mol_c ha^{-1} year									
Precipitation	1027	5.18	67	311	126	188	352	60	2405	2232	443	
Throughfall	578	5.23	34	582	222	404	738	552	3353	4179	886	
Humus water	490	3.79	791	994	484	599	915	541	3449	4179	929	
Soil water shallow	417	4.09	332	32	413	271	584	59	3234	4179	730	610
Soil water deep	457	4.43	157	47	490	340	747	108	3508	4179	666	506

Atmospheric gases: Atmospheric gases are collected with a High Efficiency Annular Denuder (HEAD), located on an open site, and run occasionally for periods of about one week. Quantitative collection of gases, and their separation from particulate matter is achieved with appropriate sorbents as denuder coatings. These are leached off and the leachate analysed by IC (DIONEX).

Results and Discussion

Data presented are, for Ballyhooly, the mean of the three years 1989-91 and for the other three sites, for one year only (1991). Experience has shown that due to variability in weather conditions from year to year, data for a single year should be treated with caution. For precipitation and throughfall, ionic concentrations, measured in the laboratory are presented as fluxes, which are the product of concentration and the volume of water in precipitation or throughfall. Quantitative collection of humus and soil water is not possible, however. In these cases, ionic concentrations are converted to fluxes by reference to changes in chloride concentration from throughfall to the stratum in question. This assumes conservation of chloride, ie. that uptake or sorption of chloride is negligible, and that soil water movement is vertical. The second assumption is not entirely valid at all sites, thus flux data must be considered to be preliminary in nature, pending application of a more sophisticated soil-water-flux model to these sites.

There is a significant pollution influence at one of the four monitoring sites, Roundwood (Table 2; Figure 2). This forest stand has an easterly aspect within sight of the Irish Sea. It receives a cocktail of pollutants on easterly airstreams. These mostly occur under fairly dry conditions. This dry deposition is held in the canopy and appears in the throughfall following rain sometime later. As a result, deposition of sulphate, ammonium and nitrate is relatively high and throughfall pH at 3.92, is extremely low (volume-weighted mean). By comparison, the other three sites are relatively unpolluted. Deposition of the major pollutant ions at the two western sites, Cloosh and Brackloon is very low (Tables 3, 4; Figures 3, 4). In the latter two sites, the throughfall fluxes of ammonium and nitrate are both lower than the precipitation fluxes (in contrast to most ions). Ballyhooly is in an intermediate position, but even here, only ammonium deposition approaches significant levels (Table 5; Figure 5).

About 90% of ammonia emissions to the atmosphere, which give rise to ammonium in rain, are attributable to human activity, of which 90% is directly or indirectly due to livestock production (Isermann, 1991). The main source of nitrogen oxides, NOx, on the other hand, which gives rise to nitrate, has been considered to be high-temperature combustion of fossil fuels by motor traffic. However, recent evidence suggests that other terrestrial sources for nitrogen gases particularly nitrous oxide

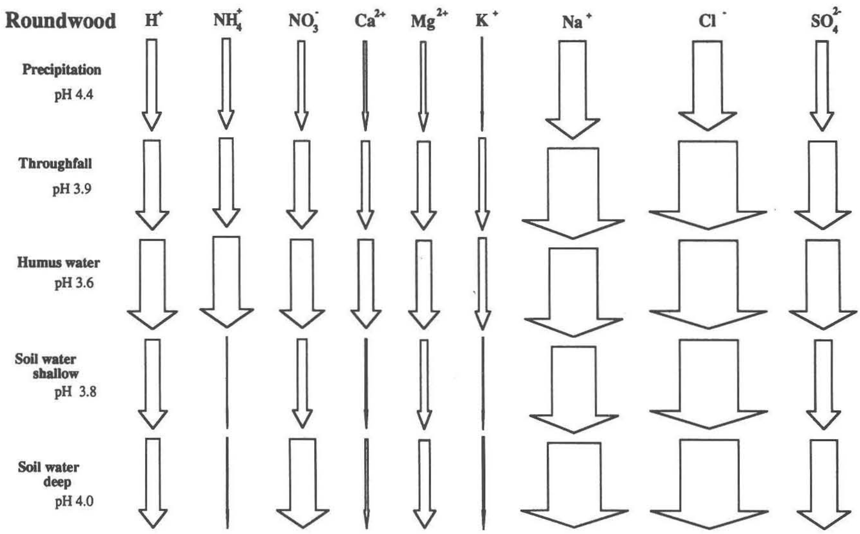

Figure 2: Ionic fluxes, Roundwood ($mol_c\ ha^{-1}\ year^{-1}$). Values are as in Table 2.

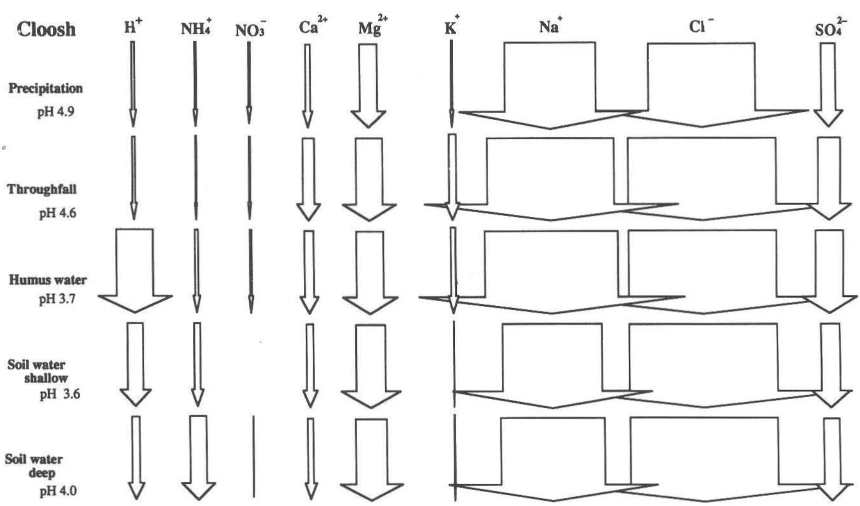

Figure 3: Ionic fluxes, Cloosh ($mol_c\ ha^{-1}\ year^{-1}$). Values are as in Table 3.

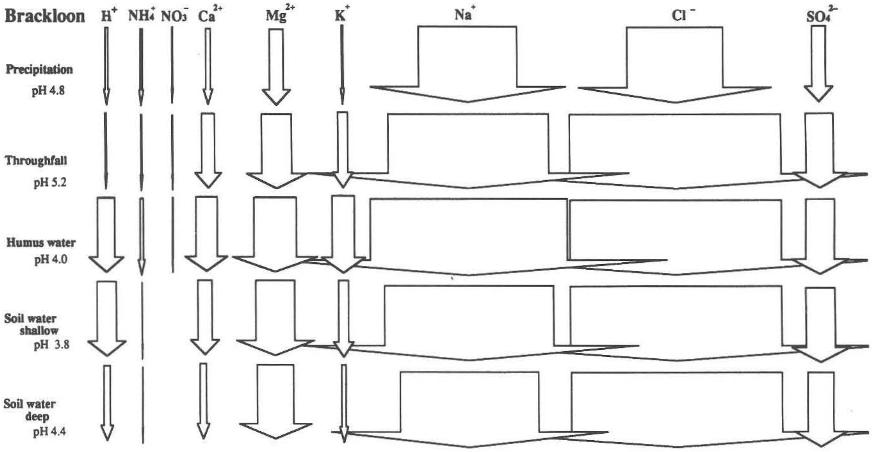

Figure 4: Ionic fluxes, Brackloon (mol_c ha^{-1} $year^{-1}$). Values are as in Table 4.

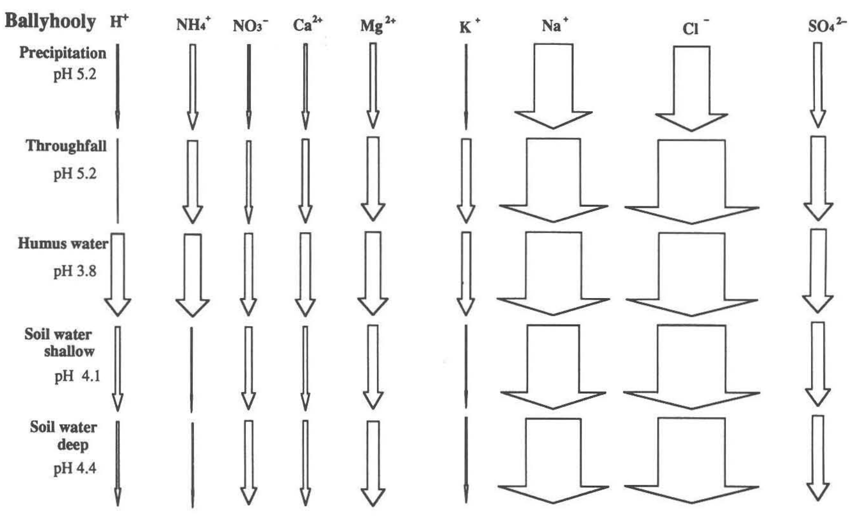

Figure 5: Ionic fluxes, Ballyhooly (mol_c ha^{-1} $year^{-1}$). Values are as in Table 5.

(N_2O)) may be significant (H. Papen, personal communication, 1993). The behaviour of nitrogen in ecosystems is very complex. The principal ionic species, ammonium (NH_4^+) and nitrate (NO_3^-) can both be taken up by plants. Ammonia gas (NH_3) is evolved from animal manure and slurry on the farms in the vicinity of Ballyhooly. Very high concentrations of both gaseous ammonia and of ammonium in throughfall have been detected on occasion. Ammonia neutralises acidity both in precipitation and throughfall, forming ammonium. However, this neutralisation is a short-lived benefit because the added ammonium reaching the soil increases soil acidification, either through plant uptake of ammonium, or through the microbial transformation of ammonium to nitrate (nitrification).

The significant contribution of nitrate to total nitrogen deposition at Roundwood, low throughfall pH, and the absence of intensive agriculture in the vicinity, all support the suggestion of a long-range pollution influence (Farrell, 1992). When levels of ammonium and nitrate in throughfall at all four sites are compared (Figure 6), it can be seen that total nitrogen deposition is greatest at Roundwood. Ammonium and nitrate levels are almost equal here, suggesting a mixing of pollutants from different sources during long-range transport. The correlation between ammonium and nitrate in precipitation (0.997, $p < 0.001$; Kramadisastra, 1993) supports this contention. Concentrations of ammonia in the atmosphere are lower at Roundwood than at Ballyhooly (Farrell *et al.*, in preparation). Consequently, the neutralising effect of ammonia is reduced and pH values are very low, particularly in throughfall.

In recent years, pollutant loads have been described in terms of critical load, *a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects to specified elements of the environment do not occur . . .* (Hettelingh *et al.,* 1991). Critical loads for coniferous forest

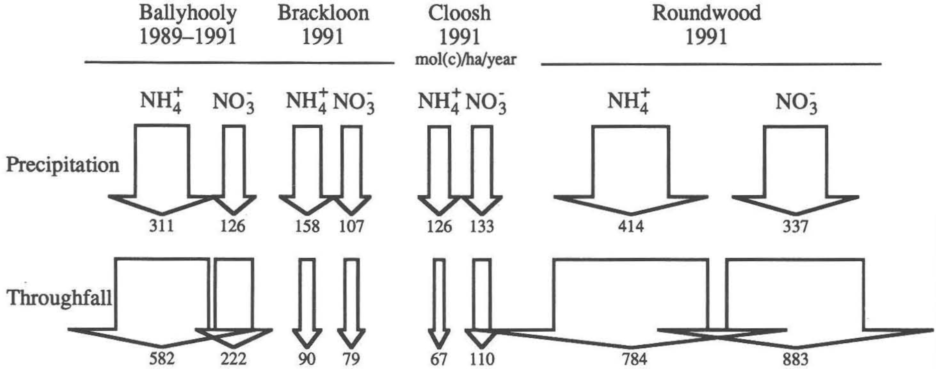

Figure 6: Ionic fluxes of ammonium and nitrate in precipitation and throughfall (mol$_c$ ha^{-1} year^{-1}) at the four monitoring sites. Values are as in Tables 2-5.

ecosystems in the Nordic countries are of the order of 3-11 kg N ha^{-1} $year^{-1}$ (Sverdrup *et al.*, 1992). Total nitrogen deposition at Roundwood in 1991 was about 24 kg N ha^{-1}, significantly higher than the admittedly crude estimates of critical load which are available to date.

High salt concentrations have been reported for rainfall and throughfall in western Ireland (Farrell, 1990b). Results from the monitoring sites at Cloosh and Brackloon confirm this finding (Tables 3, 4; Figures 3, 4). The principal marine ions are sodium and magnesium amongst the cations and the anions chloride and sulphate. By comparison with continental European sites (Rasmussen, 1990; Rasmussen *et al.*, 1992), salt concentrations are high even at Ballyhooly. This establishes clearly that the marine influence is strong throughout Ireland.

The uptake of both sodium and chloride by plants is negligible in comparison with inputs, in an oceanic region. Chloride, as stated earlier, is a very mobile ion, not involved in sorption processes in the soil to any significant extent. Sodium, however, as with all cations, can be adsorbed onto the exchange complex of soils. There, it is held in a form in which it may be easily exchanged for other cations. It is possible that following a major storm event, when inputs of sodium and chloride are particularly high, that a significant proportion of the sodium is held on the exchange complex, displacing other cations including hydrogen. This could lead to the export of acidity from the forest, resulting in a temporary acidification of streamwater. This phenomenon has been reported for maritime regions in Scotland (Langan, 1987). Evidence for its occurrence in Connemara has been put forward by Allot *et al.* (1990). Annual mean deposition quantities for the Cloosh and Brackloon sites (Tables 3, 4; Figures 3, 4) would seem to support this. They show a pronounced change in the Na^{+}:Cl^{-} ratio as the water moves from throughfall to the deeper soil. This imbalance, however, would seem to suggest a long-term storage of sodium in the soil. No other evidence is available to support this.

Sulphate has two major sources, combustion of fossil fuels and the sea. By correcting for marine contributions, according to the ratio of an ion such as chloride, to sulphate in sea water, it is possible to estimate the proportion of sulphate deposition arising from pollution. There is a significant marine contribution at all four sites but the proportion of non-marine (also called "excess") sulphate varies from about 25% of the total in the western sites to 50% at Ballyhooly and 75% in Roundwood. In some respects 25% excess sulphate at the western sites could be considered surprisingly high. In fact, it goes to confirm that there is a small but significant pollution influence in the region. Indeed, in Cloosh, precipitation pH was above the conventionally accepted 5.6 threshold for acid rain during only two weeks in 1991.

Calculation of ionic fluxes in the soil provides a useful indication of the export of pollutants to surface waters, adjoining streams or lakes, and groundwater. Potential pollution at these sites can come from acidity, from aluminium which is toxic to living organisms, and nitrate which can be toxic and also contributes to eutrophication. It is therefore interesting to look both at the concentration of ions such as hydrogen (measured as pH) and aluminium and nitrate in the deepest soil water samples and also the flux of nitrate and aluminium. Roots are rare or absent at this depth (75 cm) and the sample is considered to represent water exported from the site. The Cloosh site is different, in that there is significant surface runoff laterally through the forest floor.

Soil water is very acid at all sites. At Cloosh and Brackloon it is more acid in the forest than at the open site. At Cloosh, annual mean soil water pH at 25 cm is 3.6, compared to pH 4.2 in the surface water of the open bog (Farrell *et al.*, in preparation). At Roundwood, however, the open site soil water is more acid than in the forest (Table 2). Determination of the influence of the forest canopy on soil water is complicated by the difficulty in finding a comparable, non-forested site. At Roundwood and Ballyhooly, the open sites available were clearfells. In Brackloon, old forest land cleared for agriculture is used, and in Cloosh, an area of undrainable bog. Despite this difficulty in interpretation, the capacity for the forest to develop higher atmospheric deposition loads than occur on open land is clear. The interceptive capacity of the canopy is reflected in higher fluxes of most ions in the throughfall and soil water.

Conclusions

Over most of Europe, environmental concern is focused on the problem of forest decline. In Ireland, however, attention has been concentrated not on the influence of the environment on the forest, but on the impact of plantation forests on the environment.

The ability of trees to intercept pollutants from the atmosphere is well known. The establishment of a forest plantation results in a drastic alteration of the original ecosystem. In the case of natural and semi-natural ecosystems, this disruption carries an inevitable risk of environmental damage.

The evidence from four intensive monitoring plots in Ireland suggests that one, Roundwood, experiences significant pollutant deposition. It is at this site that forest damage is most likely to occur and it is here also that a negative impact on surface waters might be anticipated. At Cloosh, there is little evidence of pollution deposition, although soil water is more acid under the forest then in the open. Acid events may occur here as a result of occasional instances of acid deposition or due to the displacement of protons from the soil exchange complex by sodium ions. However, the data reported here should be treated with caution. While they do indicate evidence of long-term ecosystem degradation, particularly at Roundwood, this is based on only a single year's data. Changes in forest ecosystems generally occur slowly. Long-term monitoring is required to provide the level of understanding needed before management strategies to reverse or mitigate damaging effects can be developed.

The modern forest manager would do well to consider him or herself not as a manager of a timber crop but as a manager of a plantation forest ecosystem, the primary objective of which is to produce timber. This simple adjustment in attitude alters the ground rules considerably. It brings a recognition that forest management results in ecosystem disturbance and that precautions are necessary to ensure that this disturbance is controlled and its detrimental consequences minimised.

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