European Community Scheme for the Protection of the Community's Forests against Atmospheric Pollution
Council Regulations 3528/86 and 2157/92 and Commission Decision C (2002) 2674/8 of 18/07/2002

MONITORING OF FOREST ECOSYSTEMS IN IRELAND

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FOREM 9 Project

Project Number 2002.60.IR.

Final Report

Forest Ecosystem Research Group Report Number 72

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The FOREM projects have yielded data which will be of benefit to the Community's forest health monitoring. The quality of that information represents the best testimony to the efforts of all who have worked in the project. The names of those who participated are included in the research team.

Many others have also contributed to the success of the project, including members of the administrative and management staff the collaborating organisations. They cannot all be listed here, but some deserve special mention.

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Summary

Intensive monitoring has been carried out under EC Regulation 3528/86 (project number 8860 IR 001.0) at Ballyhooly, Co. Cork since 1988. In 1991, three new plots (Roundwood, Cloosh and Brackloon) were established (9060IR0030) to give a more comprehensive network of such plots in Ireland. Monitoring of these three plots continued under project numbers 9360IR0030, 9560IR0030, 9760 IR 0030 9860 IR 0030, 9960IR0030, 2000.60.IR, 2001.60.IR and the current project, focusing on atmospheric inputs and biogeochemical cycling. In 2001, a new plot, Ballinastoe was established, to replace the Roundwood plot, which was due to be clearfelled. This project, (FOREM9, 2002.60.IR**)** ran from January 2002 to December 2002. The monitoring is designed to improve understanding of the effects of atmospheric pollution on forest ecosystems, and is based on permanent sample plots located in important forest ecosystems in Ireland. The monitoring procedures followed those in the previous projects and closely follow the ICP Manual (UN/ECE, 1998 and updates). Measurements included: precipitation in an open-field plot; quantitative collection and chemical analysis of forest throughfall and stemflow; collection and chemical analysis of forest soil solution from zero-tension lysimeters below the forest floor, and from suction lysimeters at greater depths.

The health status of the forests in Ireland is generally good. The Roundwood and Ballinastoe sites are located in the east of Ireland. As such, they are it is subject to higher levels of atmospheric pollutants than the two sites located on the west coast. If there were to be a deterioration in the health of forests in Ireland due to atmospheric deposition, it would be expected to first appear on the east coast, where deposition is highest. Thus the Roundwood and Ballinastoe sites are very valuable for the intensive monitoring programme.

Atmospheric deposition in Ireland is dominated by marine ions, notably sodium and chloride. This is due to Ireland's location on the western seaboard of continental Europe. However, the country is exposed to pollutants during periods of easterly air flows. Evidence of these is seen particularly at the Roundwood and Ballinastoe sites, in eastern Ireland. These "pollution events" merit more comprehensive treatment, to ascertain both their frequency and intensity, and to make some estimation of their potential effects on the forest ecosystem. Soil water sampling is essential to the understanding of these events. Calculation of soil water fluxes carried out in this project, improves our insight into the longer-term environmental impacts of atmospheric deposition on these forests.

Research team

Researcher	Title	Special responsibility
Prof. Edward P. Farrell	Project director	Project inception and execution, reportibng.
Dr James F. Collins	Senior researcher	Technical advice.
Dr George W. Smillie	Senior researcher	Technical advice.
Ms Gillian M. Boyle	Project manager	Management, reporting, administration.
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Mr Martin Joyce	Research assistant	Sampling, Brackloon.
Mr Patrick McDonagh	Research assistant	Sampling, Cloosh.
Mr Peter Doyle	Research assistant	Sampling, Roundwood and Ballinastoe.

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Introduction

Project administration

Intensive monitoring has been carried out under EC Regulation 3528/86 (project number 8860 IR 001.0) at Ballyhooly, Co. Cork since 1988. In 1991, three new plots (Roundwood, Cloosh and Brackloon) were established (9060IR0030) to give a more comprehensive network of such plots in Ireland. Monitoring of these three plots continued under project numbers 9360IR0030, 9560IR0030, 9760 IR 0030, 9860 IR 0030, 9960 IR 0030 and 2000 60 IR, 2001.60.IR and the current project, focusing on atmospheric inputs and biogeochemical cycling. In 2001, a new plot, Ballinastoe was established, to replace the Roundwood plot which was due to be clearfelled. The two plots, Roundwood and Ballinastoe, were monitored concurrently for the duration of this project. This project, (FOREM 9, 2002.60.IR.) ran from January 2002 to December 2002.

The projects are managed by the Department of Environmental Resource Management of University College Dublin, through the Forest Ecosystem Research Group (FERG), headed by Professor Edward P. Farrell. These projects have been reported by Farrell *et al*., (1994a), Boyle *et al*., (1997a&b), Boyle *et al*. (2000) and Boyle and Farrell (2003).

Objective

The FOREM project was initiated to consolidate the base of understanding of biogeochemical deposition, fluxes and cycling in forest ecosystems in Ireland.

Background

Level I

The activities of the European Commission in the field of the protection of forests against atmospheric pollution started in 1987 with the adoption of the relevant Council Regulation 3528/86 (EEC, 1986). In close cooperation with the International Cooperative Programme on the Assessment of Air Pollution Effects (ICP Forest of UN-ECE) an extensive systematic large scale network (16 x 16 km) of forest sample points was established (Level I). Since 1988, annual crown assessments, as well as forest soil condition surveys and an analysis of the chemical contents of needles and leaves has been carried out. The main benefits received from the assessment on this large scale gridnet, which contains now almost 600 sample points, are a more accurate knowledge of the extent, dynamic and spatial distribution of the symptoms of forest damage in Europe, a database for time series analysis of crown defoliation, important information on forest soil condition and information on the nutrient balances in some forest areas. However, the large scale monitoring does not aim at a cause effect relationship research.

Level II

In order to contribute to a better understanding of the impact of air pollution and other stress factors which influence forest ecosystems, the large scale survey was extended by the intensive monitoring programme of forest ecosystems (Level II). In this context, more than 500 plots have been installed in the EU and around 860 in Europe in total. This second level of monitoring intensity was also carried out as a consequence of Resolution Number 1 of the Ministerial conference for the protection of forests in Europe (Strasbourg, 1990). The aim of this second level of monitoring intensity is defined as “intensive monitoring of forest condition aimed at the recognition of factors and processes, with special regard to the impact of air pollutants, on the more common forest ecosystems in Europe.” The intensive monitoring programme now consists of 9 assessments: crown condition, soil, foliage, forest growth, deposition, meteorology, soil solution, vegetation and remote sensing/aerial photography. The execution of this second level of monitoring is carried out in close cooperation with ICP Forests. Common assessment methods are defined and used.

University College Dublin is responsible for monitoring deposition, soil solution and meteorology at 3 of the 15 Level II plots in Ireland. Results of this monitoring are presented in this report.

Cycling of elements has been studied for several decades, particularly the nitrogen cycle. Hydrological cycling has been monitored for considerably longer (Genesis 8: 6–12). Ecosystem monitoring has developed from ecological studies which quantified biomass, food webs and parts of the carbon cycle, to more interdisciplinary studies. These latter studies incorporate interacting cycles of many elements, with complex biology and often sophisticated modelling of critical ecosystem processes over long time scales on capital-intensive sites (for example, at Hubbard Brook Experimental Forest—Likens and Bormann, 1995).

Biogeochemical cycling studies are important not only in the context of forest decline, but also as a key basis in the development of methods of sustainably managing ecosystems in the human landscape. The plantation forest area in Ireland is increasing rapidly. The proportion of the land under forest when this project was proposed in 1990 was quoted as 6%; now it is almost 10%. Natural and semi-natural ecosystems have been severely disrupted by afforestation. This has resulted in the interruption of nutrient cycles and the alteration of the ecology of ecosystems. Little quantitative information is available on the impact of specific disturbances on the properties of ecosystems which limit their productivity, biodiversity and sustainability. Long-term biogeochemical monitoring of important ecosystems provides essential background information on regional ambient deposition, and environmental noise. This baseline then gives a basis for quantification of impacts from such management and disturbance as clearfelling, cultivation or fire (Cunningham, 1996) and their long-term legacies in soil processes.

Biogeochemical monitoring also provides the necessary information for assessments of critical load exceedence (Aherne and Farrell, 1995), the current means for assessing the ability of soils to deliver ecosystem-sustaining services under current deposition regimes of acidifying substances.

Methods

The sampling for this project was principally of water. Samples were collected and analysed in accordance with the guidelines specified in the "Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests" (UN/ECE, 1998). Samples were analysed chemically for their content of a range of simple ions and elements. Measurements were also made of meteorological and hydrological phenomena.

Sampling objectives

The sampling objectives centred on estimating mass fluxes of the principal biogeochemicals through the plots. The emphasis was on water-borne fluxes, and on vertical flow from open atmosphere via throughfall/stemflow and humus water to deep soil water.

Sampling was continuous, or regular and frequent, so that any stratum sampled was adequately described for the period of sampling. Sampling was intensive, so that variation over relatively small times can be accounted for. Multiple sampling points were used within each stratum sampled, to provide samples representative of that stratum, and independent of local variation.

Sampling equipment was made of inert materials, which do not add or remove anything chemically from the samples, and which can withstand weathering in the field for several years' service. Sampling materials include polytetraflouroethylene (PTFE), polyethylene (PE), silicon rubber and polyvinylchloride (PVC). Sampler surfaces were initially scrupulously cleaned by acid-washing with 10% hydrochloric acid, distilled-water rinsing and ultra-pure-water (Milli-Q™) rinsing. Re-used vessels were given a multiple-rinse cleaning. Where this was impractical (stemflow gutters were the only case), a run-in period was given for the samplers to adjust to field conditions before the samples were analysed. Ceramic-cup soil water samplers were cleaned as described above for the other equipment, but were also given a run-in period, for equilibration with soil chemical conditions.

Sampling personnel followed a standard code of sample handling which minimises contamination, and simultaneously provides for recording of successful sampling, observed contamination or unusual events (Quality Control Section).

Sample sources, measurements, installation and collection

A description of how sampling was carried out in each of the strata selected follows, including the equipment used, the method of installation of equipment, the nature of the sample obtained and the frequency of collection.

Meteorology

A standard Meteorological Office design rain gauge (127 mm diameter, high rim, funnel-opening) was placed with its opening 30 cm above ground level over a short clipped sward on the open sites. Obstacles likely to produce turbulence such as buildings, bushes etc. were avoided. Precipitation amount was measured weekly (mm).

Precipitation and throughfall

"Precipitation", as used in this report, generally refers to samples of bulk precipitation collected for quantitative chemical analysis, as distinct from the hydrological measurement of precipitation amount. Collectors were 100 mm polypropylene open funnels, fitted with a custom-designed coarse-mesh nylon filter, leading directly into the sample bottles. Funnels were supported on a vertical stake driven into the ground, with the opening horizontal, at 1.3 m. The top of the stake was angled away from the collector to prevent splashing. Four precipitation collectors were used to sample open-land precipitation at each site.

Throughfall collectors were installed in numbers subjectively chosen, broadly in proportion to the variability of quantity expected, considering the tree canopy structure of the stand. Points for installation were chosen by simple random sampling along axes of a 0.1 × 0.1 m square grid aligned to the plot edges. Points falling within a tree, or the concentric area which would be covered by a stemflow gutter (were it installed), were excluded. All other points were considered acceptable. The bulk sample collected was taken to represent water falling freely in the inter-stem area of the stand, excluding the influence of low ground vegetation. Precipitation and throughfall were sampled weekly in 1000 or 500 mL bottles.

Stemflow

Eight trees per site were selected by simple random sampling of stems. Silicon rubber gutters were attached to these trees, with the gutter outlet about 1.3 m above ground level, and the inner surface of the gutter sealed to the bark with silicon mastic. The stemflow samples were collected in graduated 80 litre, PVC bins in the field, from which a subsample was collected. The stemflow bulk sample was taken to represent throughfall (ie. within-forest precipitation) which was not falling in the inter-tree space, but was constrained in its fall by tree stems, and had significantly greater physical contact with tree surfaces than the between-tree throughfall. This included water both actually flowing along the stem surface, and a narrow zone of more freely-falling water within a few centimeters of the stem surface. Stemflow was sampled weekly, sub-sampled into 500 mL bottles.

Humus water

Humus water collectors were polyethylene, zero-tension tray lysimeters, with a coarse mesh upper surface and a simple closed sloping tray underside draining into a sample bottle located nearby downhill. Seven such collectors were installed in each plot by simple random sampling on a grid as described for throughfall collectors. The selected point was where the collector was to sample, and installation proceeded from the downhill side of this point (all sites had a definite slope). A pit was dug and a rigid plate carefully inserted, horizontally, below most of the humus layer, and above all of the underlying soil. Roots were cut as needed. A little excavation was done below the plate, its underside cleaned, and the cleaned collector inserted before the plate was removed. The hole was deepened and lined with a top-opening pipe, to hold the sampling bottle. The sampler drained through a flexible pipe into the sample bottle. The pit was back-filled, leaving a disturbed area from which the bottle could be reached, and an undisturbed area of humus layer, through which the water to be sampled percolated. In Cloosh, because of the plough ribbons and furrows, humus lysimeters were restricted to those areas of undisturbed ground between the ribbons. The humus-water sample collected was water flowing under saturated conditions and through macropores. Water held under tension in the humus layer, which is important in the physiology of plants, was not collected by this technique. Humus water was sampled weekly, sub-sampled into 250 mL bottles.

Soil water

Ceramic cup suction lysimeters were initially installed at all three plots. Soil water samplers were tube-mounted ceramic cups, to which a sealed, partly evacuated chamber was connected. This caused water to flow into the sampler from the surrounding soil. The soil water sample was drawn from the sampler body at a later stage into a partially evacuated bottle. Sites for soil water collection were chosen to be associated with humus water collection. Thus soil water samplers were installed in groups, within 2 m uphill of the humus water collectors. Soil water samplers were installed vertically, in a hand-augered hole, to the required depth. Tubes were installed in duplicate, at each of two depths (nominally 25 cm and 75 cm below the base of the forest floor) in each group. A little of the soil removed from the hole at that depth was made into a slurry and applied to the cup by a suction on the sampling tube. The remaining slurry was poured down the hole immediately before the sampler was inserted and firmed into place. Disturbance was kept to a minimum during installation by use of mats, and when complete, access to the sampler areas was restricted. The sampling method used a portable 12 V vacuum pump to partially evacuate glass bottles (c. 400 hPa) attached to the samplers. This suction method allows sampling in both saturated and unsaturated soil water conditions. This is an important difference from the method of zero-tension lysimetry used to collect humus water. These samplers can continue to work in all but the driest (Irish) summer soil. Throughout this report, the term “soil water” is used to refer to soil water from the forest plots unless otherwise stated. Soil water was sampled at 2–4-week intervals, collected in 250 mL bottles.

In 1996, the ceramic cup lysimeters at the Brackloon plot were replaced with Teflon suction lysimeters. The ceramic cup lysimeters at the Cloosh and Roundwood sites were replaced with Teflon lysimeters in 2001.

Soil

The soil profiles of Brackloon and Roundwood were described at the beginning of 1991. Soil samples were taken from representative soil profile pits in 1991 and again in 1994. Both organic and mineral soil samples were collected by horizon.

Handling and storage of samples

Field handling of water samples

The field personnel had a weekly field observation sheet, on which they recorded which samples they had successfully collected, their volume (for samples where a graduated collector was used) and a record of which samples were suspected of being contaminated. Whenever contamination was suspected, this was noted on the field sheet and the bottle. The sample was still sent, clearly labelled as contaminated. Between collection and dispatch, all samples were kept cool and dark as far as possible.

Transport

Water samples were collected in the field between Sunday and Tuesday of each week and delivered to the laboratory by courier on the following morning. Planned delays were arranged around public holidays, samples remaining in the field and having minimum transit time.

Arrival at the laboratory

The day the water samples arrived, they were prepared as follows:

1. The samples that were sent, the date collected and the date received in the laboratory were recorded in each site data book.

2. The volume of each sample was recorded by weight.

3. Any samples that were contaminated (as noted on the field observation sheet) were discarded. The reason for discarding a sample was noted in the site data book.

4. Each sample for analysis was usually a composite sample, from a number of samplers in the field. The individual samples for each stratum were pooled for analysis, in proportion to their individual volume. Where the collecting apparatus had overflowed (thus not giving a true estimate of sample volume), the maximum volume was used for bulking (ie humus:2000 mL, stemflow:80 L, precipitation:1000 mL). Samples were bulked to 250 mL by stratum, according to the formula:

$$\frac{\text{Sample volume}}{\text{Total volume of samples of that stratum}} \times 250 = \text{mL for bulking}$$

5. Bulked samples were filtered through Whatman filter paper number 41, into clean, acid-washed, 250 mL HDPE bottles and labelled with the sample type and week number.

Soil

Soil samples were air dried on arrival in the laboratory and then sieved through a 2 mm sieve and stored in labelled, sealed plastic bags.

Storage and timing of analysis

Bulked, filtered water samples were stored at 4˚C in a cold room in the dark prior to analysis. pH and conductivity were measured on arrival in the laboratory. NH_4^+-N, P, dissolved organic carbon and alkalinity were measured within a week. Cations, anions (Na^+, K^+, Mg^{2+}, Ca^{2+}, Mn^{2+}, Cl^-, NO_3^-, HPO_4^{2-}, SO_4^{2-}), aluminium and total nitrogen, were generally measured on samples within a month.

Chemical analysis

	Method of Analysis
Water	
pH	Low-conductivity combination electrode
Conductivity	Conductivity meter (µS/cm)
Ammonium-nitrogen	Colorimetrically using the phenol–hypochlorite method (Solórzano, 1967), read on a UV at 635 nm
Phosphorus	Acid-antimony–molybdate method (Murphy and Riley, 1962), read on a UV at 880 nm
Calcium, magnesium, potassium, sodium, manganese and total monomeric aluminium	Inductively-coupled-plasma optical-emission spectrometry (ICP). If K <1 mg L-1, potassium was measured by atomic absorption spectrometry (AA)
Chloride, nitrate, sulphate and orthophosphate	Ion chromatography (IC), using an anion exchange column and conductivity detection
Dissolved organic carbon	UV at 320 nm (Gorham et al., 1985), after filtration through a 0.45 µm filter and calculation by regression equation
Alkalinity	Gran titration (Mackereth et al., 1978)
Total Nitrogen	Digestion and colourimetric measurement (Koroleff, 1973)
Soil	
pH	1:2 soil:distilled water slurry, and read on a pH meter with a standard laboratory probe. pH in 0.1 M KCl was measured in a similar way, using 0.1 M KCl instead of distilled water
Organic carbon	Walkley–Black (1934) titration method on the mineral horizons. Loss on Ignition (Ball, 1964) for the organic horizons
Total nitrogen	Kjeldahl digest by steam distillation and back-titration (Jackson, 1958)
Exchangeable calcium, magnesium, potassium, sodium, manganese, iron and aluminium	ICP following extraction with 0.5 M NH^4Cl
Extractable phosphorus	Dilute double acid extraction method of Olsen and Dean (1965) and read on a UV at 660 nm
Particle size	Deflocculation and settling method
Total calcium, magnesium, potassium, sodium, phosphorus, manganese, iron and aluminium on peat samples	ICP following digest with nitric-perchloric acid (Zasoski and Burau, 1977)

Calculations

Units

The Système International d'Unites is the accepted standard and is used.

Solute concentrations were measured in mg L^{-1} (often given by instruments as ppm). Conversion to moles of charge (often referred to as equivalents) allows a functional comparison of concentrations of different ions.

Water flows in precipitation or soil-water are expressed in millimetres per unit time, or litres per hectare per unit time. Precipitation water fluxes were calculated from the horizontal planar area of an open-funnel collector and the volume or mass of water collected in a known time. Stemflow water fluxes are the product of the mean volume of water collected from randomly selected single trees and the number of trees per hectare in a uniformly-stocked stand.

Solute flux densities (or simply "fluxes") are expressed in $mmol_{\pm}$ m-2 per unit time (millimoles of charge). The units % and ppm are given with the SI form (eg. g 100 g-1 or mg kg-1, or µg m-3 for gases) in cases where their ambiguity may be a problem. The SI allows l or L for the unit litre. L is preferred here as it avoids confusion with the number 1.

The system of week numbering is that recommended by the International Standards Organisation (ISO) according to which Week 1 is the first week containing four or more days in the new year. Monday is taken as the first day of the week.

Conversion equations

$\mu mol_{\pm}\ L^{-1}$ =	$mg\ L^{-1} \times 10^{3} \times$ charge / mass
$\mu mol_{\pm}\ L^{-1}$ =	$mol_{\pm}\ ha^{-1} \times 10^{2}$ / mm
$\mu mol_{\pm}\ L^{-1}$ =	$kg\ ha^{-1} \times 10^{5} \times$ charge / (mass × mm)
$mg\ L^{-1}$ =	$\mu mol_{\pm}\ L^{-1} \times 10^{-3} \times$ mass / charge
$mg\ L^{-1}$ =	$mol_{\pm}\ ha^{-1} \times 10^{-1} \times$ mass / (charge × mm)
$mg\ L^{-1}$ =	$kg\ ha^{-1} \times 10^{2}$ / mm
$mmol_{\pm}\ m^{-2}$ =	$\mu mol_{\pm}\ L^{-1} \times 10^{-3} \times$ mm
$mmol_{\pm}\ m^{-2}$ =	$mg\ L^{-1}$ ×mm ×charge / mass
$mmol_{\pm}\ m^{-2}$ =	$kg\ ha^{-1} \times 10^{2} \times$ charge / mass
$mmol_{\pm}\ m^{-2}$ =	$mol_{\pm}\ ha^{-1} \times 10^{-1}$
$mol_{\pm}\ ha^{-1}$ =	$\mu mol_{\pm}\ L^{-1} \times 10^{-2} \times$ mm
$mol_{\pm}\ ha^{-1}$ =	$mg\ L^{-1} \times 10 \times$ mm × charge / mass
$mol_{\pm}\ ha^{-1}$ =	$kg\ ha^{-1} \times 10^{3} \times$ charge / mass
$mol_{\pm}\ ha^{-1}$ =	$mmol_{\pm}\ m^{-2} \times 10$
$kg\ ha^{-1}$ =	$\mu mol_{\pm}\ L^{-1} \times 10^{-5} \times$ mm × mass / charge
$kg\ ha^{-1}$ =	$mg\ L^{-1} \times 10^{-2} \times$ mm
$kg\ ha^{-1}$ =	$mol_{\pm}\ ha^{-1} \times 10^{-3} \times$ mass / charge
$kg\ ha^{-1}$ =	$g\ m^{-2} \times 10$
$kg\ ha^{-1}$ =	$mmol\ m^{-2} \times$ mass $\times 10^{-2}$
$L\ ha^{-1}$ =	$mm \times 10^{4}$

Ratios of ions in seawater ($mol_{\pm}\ mol_{\pm}^{-1}$):

SO_4^{2-} : Mg^{2+} = 0.532 : 1
SO_4^{2-} : Na^{+} = 0.121 : 1
SO_4^{2-} : Cl^{-} = 0.103 : 1

DOC (mg/L), soil solution

$$= 100 \times ABS_{320} + 3.4$$

DOC (mg/L), stemflow and humus water

$$= 55.2 \times ABS_{320} + 24.4$$

Alkalinity (µmol±/L)

$$= \frac{\left[\dfrac{mL \times 0.02 \times 100.8 \times 1000}{Volume(mL)}\right] \times 1000 \times 2}{100.8}$$

Stemflow Volume (mm)

$$= \frac{\overline{L} \text{ / tree } \times \text{ trees per hectare}}{10{,}000}$$

Weighted means

Where mass flux densities of water are known, and are related to the volume of sample, it is appropriate to express mean concentrations as volume-weighted values. Examples of a weighted mean calcium concentration are given:

Volume	pH	$[Ca^{2+}]$
a	x	p
b	y	q
c	z	r
d	w	s

$$\text{Volume-weighted mean } [Ca^{2+}] = \frac{ap + bq + cr + ds}{a + b + c + d}$$

$$\text{Mean pH} = -\log_{10}\left[\frac{10^{-x} + 10^{-y} + 10^{-z} + 10^{-w}}{4}\right]$$

$$\text{Volume-weighted mean pH} = = -\log_{10}\left[\frac{a10^{-x} + b10^{-y} + c10^{-z} + d10^{-w}}{a + b + c + d}\right]$$

Quality Control

The Forest Ecosystem Research Group has prepared a FERG Procedure Manual that describes in detail our monitoring work and methods. This manual is in loose-leaf format, which facilitates its continual updating, as our methods are improved. The field and laboratory procedures are also on our Web page, at http://www.ucd.ie/~ferg/Methods.

Monitoring Plots

Brackloon, Cloosh, Roundwood, and Ballinastoe

Monitoring has been carried out continuously (apart from an enforced pause during the foot and mouth disease outbreak in the United Kingdom in 2001) at all three sites since 1991. A description of the forest stands at the monitoring sites follows. The monitoring sites, Brackloon and Cloosh are forest sites, with mature, closed-canopy high forest. A new plot was established at Ballinastoe, to replace the old Roundwood plot in the summer of 2001. It is located about 3km from the latter. The Ballinastoe stand is much younger than the previous Roundwood plot; it was planted in 1976 whereas Roundwood was planted in 1955. Both plots were included in the monitoring programme for the duration of this project.

At each site, non-destructive measurement and sampling is done on a plot within the forest. Each plot has an adjacent plot on open land without forest cover, at which further sampling and measuring is done. Site locations are shown in Figure 1, with co-ordinates given in Table 1.

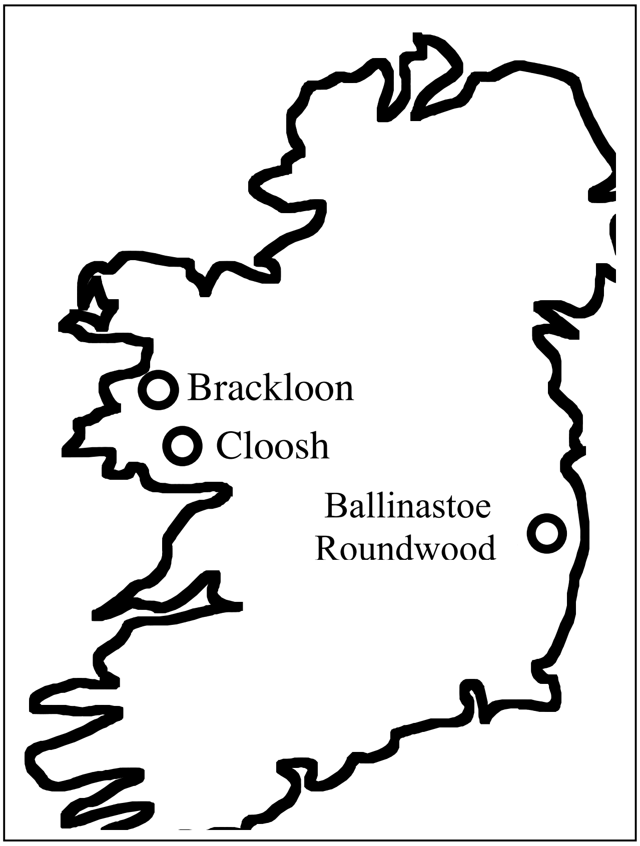

Figure 1. The FOREM forest ecosystem monitoring sites in Ireland (Roundwood and Ballinastoe are in close proximity to one another).

Table 1. Locations of the FOREM forest ecosystem monitoring sites.

Site	Latitude & Longitude	Irish Grid Reference	Elevation (m)
Brackloon	53°45.51'N 9°33.44'W	L 973 799	75
Cloosh	53°21.41'N 9°20.47'W	M 104 346	102
Roundwood	53° 6.20'N 6°14.28'W	O 180 073	395
Ballinastoe	53° 6.40'N 6°13.55'W	O 182 082	470

Site selection criteria

The sites in this project were chosen to represent important Irish forest ecosystems. The choice of a semi-natural oakwood (Brackloon) represents one major type of the primeval native woodland, though this site is much disturbed through centuries of exploitation (Little *et al.*, 1990). Sitka spruce is the clear choice for the other sites (Cloosh, Roundwood and Ballinastoe), since this species forms most of the Irish commercial plantation estate and continues to be planted on a large scale (Department of Agriculture, Food and Forestry, 1996). That one site is on a poor mineral soil and the other on deep peat further reflects contemporary Irish forestry.

Further criteria used in selecting the sites were: (1) that the canopies should be pure, full and even—this ruled out mixed stands, or line-thinned plantations; (2) that the stand was not threatened by clearfelling, grazing, fire or windthrow during the next ten years; (3) that soils were manageably uniform and slopes moderate at most and (4) that access was good.

Site access and protection

All plots were chosen to be conveniently accessible by road, without being so conspicuous as to attract unwarranted attention. The Roundwood, Ballinastoe, and Brackloon open and forest plots are enclosed with standard stock fencing. The low level of agriculture and population near the Cloosh site meant stock fencing was not needed, although spot-protection of soil water samplers with wire mesh became necessary due to repeated disturbance, possibly by a pine marten.

Climates

The climate of Ireland, and therefore of these study sites, is dominated by the westerly atmospheric circulation of middle latitudes, and the proximity of the North Atlantic Ocean (Rohan, 1975). Frontal systems travel eastwards over the country, giving strong winds and frequent precipitation, though only moderate daily and annual temperature ranges. A generalised seasonal pattern of Irish weather begins with rapidly eastward-moving depressions in December and January, bringing strong winds and much frontal rainfall, separated by periods of blustery showers. The cold anticyclone over Europe often extends eastwards in late January or February to give a spell of cold dry weather. During February to June, anticyclones from the east or Greenland keep rainfall down, but also tend to delay the spring temperature rise. Air frost is common inland at night even in May, though days are quite mild. Short dry periods are common in late spring. Westerlies increase in June–July, with increasing wind, cloud and rain. Thunderstorms are most likely in the humid late summer. Active depressions develop again in late August–September, interrupted in some years by a week or two of anticyclonic calm. Daytime weather in October–November can be pleasantly bright and calm. The frequency of anticyclones soon increases, followed by ever heavier showers, and as days shorten the wet and windy winter returns.

Brackloon Site

The Brackloon monitoring plot is located within Croagh Patrick Forest, 6 km from the town of Westport in County Mayo, western Ireland. The monitoring plot covers an area of 0.125 ha (50 x 25m). The site is at an altitude of 75 m. An associated non-forest plot is located on privately owned farmland nearby, approximately 400 m from the forest plot. Site details of the Brackloon monitoring plot are presented on Table 2.

Table 2. Site details of the Brackloon monitoring plot

Latitude & Longitude	Tree species	Age	Coillte Teoranta Inventory data	Geology	Soil type
53°45.51'N 9°33.44'W	*Quercus petraea*	> 150 years	Compartment 53277A Sub-compartment 1	Schist and gneiss	Peaty podzol (Spodosol)

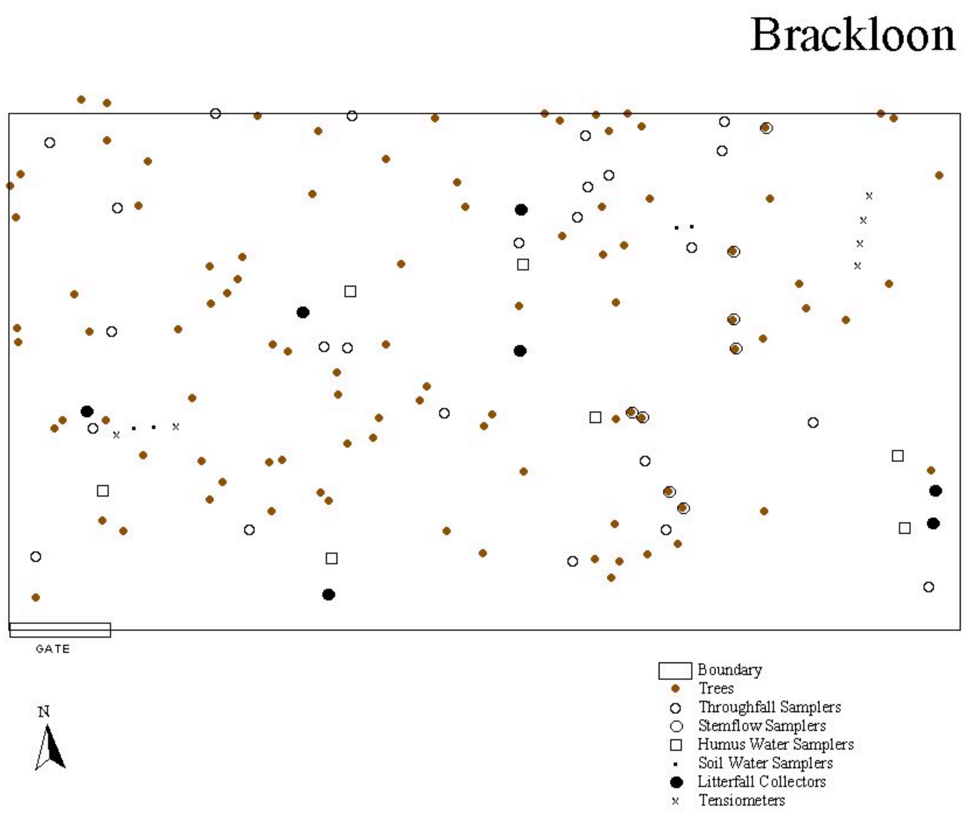

Figure 2. Location of trees and equipment at the Brackloon site.

Installations and measurements at the Brackloon site

Table 3 records the date of installation of equipment at the Brackloon monitoring site, and summary of the measurements taken, the sampling frequency and the analysis carried out on the samples. Figure 2 shows the locations of trees and equipment at this plot.

Table 3. Installations at the Brackloon monitoring plot

Sampling / measurement	Sampling / measurement dates (week–year)	Equipment	Sampling / measurement frequency	Measurement / Analysis
precipitation amount	8–1991 to 52–2002	127 mm Rain Gauge	Weekly	water flux, mm/week
precipitation	1–1991 to 52–2002	4 × 1000 mL bottles and 100 mm funnels	Weekly	pH, conductivity, NH_4^+, P, cations, anions, Alk
throughfall	1–1991 to 52–2002	24 × 1000 mL bottles and 100 mm funnels	Weekly	pH, conductivity, NH_4^+, P, cations, anions, Alk, total N
stemflow	48–1991 to 52–1993 & 10–1995 to 52–1997	8 × silicone gutters with 80 L bins	Weekly	pH, conductivity, NH_4^+, P, cations, anions, Alk, total N, DOC
humus water	1–1991 to 52–2002	7 × tray lysimeters with 2 L bottles	Weekly	pH, conductivity, NH_4^+, P, cations, anions, DOC
shallow and deep soil water at approx. 25 & 75 cm in the mineral soil	8–1991 to 20–1996	18 × ceramic cup suction lysimeters	4-weekly 8/91 to 12/92 2-weekly 14/92 to 52/93 4-weekly 1/94 to 20/96	pH, conductivity, NH_4^+, P, cations, anions, DOC
shallow and deep soil water at approx. 25 & 50 cm in the mineral soil	22–1996 to 52–2002	16 × teflon suction lysimeters	2-weekly	pH, conductivity, NH_4^+, P, cations, anions, DOC

Cations = Ca^{2+}, Mg^{2+}, K^+, Na^+, Mn^{2+}, total monomeric aluminium. Note: Mn^{2+} measured from 1993 only.
Anions = Cl^-, NO_3^-, SO_4^{2-}, HPO_4^{2-}
DOC: dissolved organic carbon, Alk: Alkalinity when pH>5.0

Soil

The Brackloon site is on a peaty podzol (Spodosol) and the soil is derived directly from weathered bedrock (schist and gneiss), with little or no overlying glacial drift. It is a very poor soil with little or no agricultural potential, except perhaps for low-input sheep grazing. The area is mapped as Association No. 1 by Gardiner and Radford (1980). This soil association includes peaty podzols over 75% of the mapped area, representing almost 5% of the total land area of the island of Ireland.

Soil profile description

Morphological soil profile descriptions for Brackloon are given, followed by analyses of physical properties, extractable chemical species and total chemical content of soil samples taken both in 1991 and 1994 in Tables 4–7.

Table 4. Site details and soil profile description for the soil on the forest plot at Brackloon

Brackloon forest site, soil profile description

Location:		Brackloon Wood, Brackloon townland, Knappagh, Westport, Co. Mayo. Coillte Teoranta compartment 53277A, subcompartment 1, Croagh Patrick Forest.
Altitude:		75–100 m.
Topography:		Rolling to hilly, gently sloping valley wall to river at base; hummocks and depressions with old river terraces.
Soil type:		Humus–iron podzol.
Soil parent material:		Weathered head containing schist (mainly phyllite) and gneiss.
Ground water:		Deep, locally shallow.
Vegetation:		Closed canopy with abundant, diverse ground cover. *Quercus petraea* dominates stand with *Betula pubescens*, *Ilex aquifolium* and *Sorbus aucuparia*; rich ground cover dominated by *Vaccinium myrtillus* and ferns; *Lobaria pulmonaria* and other lichens common; bryophtes abundant.
Root distribution:		Abundant to a depth of 50 cm.
Organic matter:		Fibrous layer of variable depth composed mainly of bilberry and woodrush overlain by the litter of oak and holly.
Slope:		8–14%, south-easterly aspect.
Horizon	**Depth**	**Description**
Oe	13–6 cm	very fibrous, undecomposed and layered organic matter; dark brown, 10YR 3/3–2/2; variable depth containing many fine roots; clear wavy boundary to;
Oa	6–0 cm	organic matter with some mineral material inter-mixed at base; greasy/plastic, very weak fine crumb structure; very dark brown, 10YR 2/2–3/2; abundant fine roots; clear wavy boundary to;
Ea	0–6/26 cm	very fine sandy silt loam; apedal massive structure; light grey, 10YR 7/2; stony; fine vertical and horizontal roots; clear wavy boundary to;
Bh	6–9 cm	(discontinuous horizon) very fine silty clay; apedal/massive structure; very dark brown to black, 10YR 2/1–2/2; stony; fine vertical and horizontal roots; abrupt boundary to;
Bs	9/26–48 cm	fine sandy silt loam; apedal/massive structure; reddish yellow (matrix) to strong brown (streaks), 7.5YR 5/8–6/8; stony/bouldery; many fine and coarse multi-directional roots; clear wavy boundary to;
C1	48–58/72 cm	fine sandy silt loam; apedal/massive structure; dark greyish brown, 10YR 4/2; moderately stony; few fine roots; diffuse wavy boundary to;
C2	58/72–75 cm	weathered bedrock mantle; coarse sandy silt loam; apedal/single-grain structure; pale brown to light yellowish brown, 10YR 6/3–6/4; no roots; abrupt boundary to;
R	>75 cm	weathered schist.

Comment: The forest site profile description above refers to an area of greater than 15 ha dominated by podzols.

Table 5. Site details and soil profile description for the soil on the open plot at Brackloon

Brackloon open site, soil profile description

Location:	Tawnynameeltoge townland, circa 1,000m south-west of the UCD/FERG monitoring site at Brackloon Wood, Brackloon townland.
Soil type:	Iron-pan podzol.
Soil parent material:	Weathered till of mostly schist with some shale and quartzite.
Topography:	River plain with occasional hillock containing rock outcrop.
Altitude:	75–100 m.
Slope:	5–20%, south-easterly aspect.
Ground water:	Occasionally deep (about 70 cm), mostly shallow.
Organic matter:	Thick fibrous layer of undecomposed grasses and heather.
Root distribution:	Predominantly in the O horizons with some in the Bh and Bs.
Stoniness:	Very stony/bouldery throughout (except in O).
Vegetation:	Heathy pasture dominated by grasses and *Calluna* species with lesser amounts of *Ranunculus* and *Sphagnum*.

Horizon	Depth	Horizon description
Oe	14/12–8 cm	organic matter, fibrous, layered and dry; firm *in situ*, disintegrates to large matted blocky lumps; dark brown, 10YR 2/2; abundant fine roots; diffuse wavy boundary to;
Oa	8–0 cm	organic matter, moist, amorphous and greasy, firm *in situ*, smears under pressure; black, 10YR 2/1; abundant fine roots; few medium coarse roots; abrupt wavy boundary to;
Ea	0–4/10 cm	very fine sandy silt loam; firm *in situ*, collapses under pressure, coarse angular blocky structure; light brownish grey, 10YR 6/2; abundant angular stones (mostly quartzitic); few roots; strong weathering features (schist) at abrupt wavy boundary to ;
Bh(f)	4/10–13/20 cm	fine sandy silt loam; loose coarse angular blocky to cemented, massive iron pan (at Ea–Bh and Bh–Bsh interfaces); very dark brown, 10YR 2/2 with a black wavy discontinuous pan, 10YR 2/1; stony/bouldery; abundant fine roots; locally abrupt (pan), generally diffuse boundary to;
Bsh	13/20–23/40 cm	fine sandy silt loam; firm *in situ*, yields under pressure, coarse angular blocky structure; reddish yellow to strong brown, 7.5YR 6/8–5/8 with strong brown tonguing, 7.5YR 4/2; very stony/bouldery; few fine roots at upper boundary; diffuse wavy boundary to;
B/Cx	23/40–45/70 cm	very moist sandy loam; indurated *in situ*, collapses under pressure, apedal/single grain structure; light yellowish brown, 2.5Y 6/4; extremely stony/bouldery; no roots; diffuse boundary to;
R	> 45/70 cm	weathered schist.

Comment: The soil profile was dug on an exposed hillock surrounded by very wet low lying peaty gleys the latter accounting for over 80% of the field area. Tillage was probably never practiced as the field in general is waterlogged. The O horizon is compacted possibly due to cattle congregating on this relatively dry area.

Soil chemical analysis

Table 6. Chemical analysis of soils at Brackloon forest and open sites, 1991 (Little, 1994).

Brackloon forest site

Horizon	pH	pH	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	Mn^{2+}	Fe^{3+}	Al^{3+}	CEC	Base Sat.	total N	extractable P	O.C.
	H_2O	KCl	mmol$_{\pm}$ 100g^{-1} (exchangeable)								%	%	mg kg^{-1}	%
Oe	4.3	3.8	19.4	11.6	2.9	2.5	0.8	0.04	0.27	37.5	97	1.78	23.4	—
Oa	3.7	3.4	5.8	12.0	1.6	2.9	0.03	0.12	0.54	23.0	97	1.40	16.3	29.5
Ea	4.2	3.2	0.26	0.42	0.09	0.13	0.003	0.02	0.93	1.9	49	0.04	1.5	1.6
Bs	3.9	3.7	0.22	0.42	0.08	0.46	0.002	0.11	4.2	5.5	21	0.13	0.16	4.6
Bs2/C	4.6	4.1	0.53	0.21	0.07	0.25	0.01	0.05	2.4	3.5	30	0.09	1.04	3.0

Brackloon open site

Horizon	pH	pH	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	Mn^{2+}	Fe^{3+}	Al^{3+}	H^{+}	CEC	Base Sat.	LOI	O.C.
	H_2O	NH_4Cl	mmol$_{\pm}$ 100g^{-1} (exchangeable)									%	%	%
Oe	4.2	3.2	7.5	5.2	1.3	1.0	0.2	0.2	1.3	1.93	18.6	81	59.1	32.5
Oa	4.0	2.9	26.3	18.6	1.9	3.2	0.2	0.2	1.7	3.98	56.1	89	90.6	45.1
Ea	4.7	3.5	0.5	0.4	0.1	0.1	—	—	0.6	0.55	2.2	49	2.4	0.9
Bh(f)	4.8	3.8	1.2	1.1	0.1	0.2	—	0.2	4.3	0.31	7.4	35	18.5	9.3
Bsh	5.1	4.2	0.6	0.5	—	0.2	—	—	2.7	0.13	4.1	31	9.5	4.0
B/Cx	5.4	4.7	0.1	—	0.1	0.1	—	—	0.3	0.34	0.9	32	1.8	0.3

CEC = Cation Exchange Capacity, by summation of all exchangeable cations analysed.
Base Sat. = Base Saturation
O.C. = Organic Carbon, determined by the Walkley–Black (1934) method.
LOI = Loss On Ignition

Table 7. Chemical analysis of the forest soil at Brackloon, 1994.

Horizon	pH	pH	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	Mn^{2+}	Fe^{3+}	Al^{3+}	CEC	Base Sat.	total N	extractable P	O.C.
	H_2O	KCl	mmol$_{\pm}$ 100g^{-1} (exchangeable)								%	%	mg kg^{-1}	%
Oi	4.5	4.1	21.9	10.8	5.1	2.6	3.1	0.05	0.55	44.1	92	0.92	25.0	92.2
Oe	3.6	3.3	10.5	9.9	3.3	1.9	0.5	0.17	0.6	26.9	95	1.59	21.9	93.7
Oa	4.3	3.3	6.9	8.8	1.2	2.0	0.04	0.04	0.3	19.3	98	1.50	26.7	90.4
E	4.6	3.1	0.27	0.43	0.09	0.15	0.003	0.03	1.1	2.1	45	0.04	1.6	1.5
Bhs	3.9	3.3	0.27	0.52	0.09	0.28	0.01	0.42	6.7	8.3	14	0.17	0.0	4.5
Bs	4.3	3.8	0.15	0.28	1.0	0.25	0.01	0.11	5.0	6.8	25	0.14	0.11	3.9
C	4.8	4.3	0.12	0.05	0.06	0.14	0.001	0.03	1.5	1.9	19	0.04	9.0	1.9

Both forest- and open-plot soils in Brackloon are acid, with a slight increase in pH with depth, more so in the open site. The pH in salt solution is 0.3–1.5 pH units lower than in water in the forest soil, and 0.7–1.2 units lower in the open-plot soil. This pH decrease represents the range of field soil-solution pH values which might be expected under different intensities of salt stress from atmospheric inputs or from concentration of the soil solution during dry periods.

Both soils are very infertile, with very low levels of exchangeable base cations, except in the surface organic-dominated horizons, which, despite being poorly-supplied themselves, are the most nutrient-rich layers of these two soil profiles. In the Bs and Bh horizons, there is a local increase in cation exchange capacity and organic carbon content. These are apparently due to translocated humic substances which have precipitated, forming these layers.

Soil physical analysis

Particle size analysis and bulk density measurements have been made on the mineral soils at Brackloon, and are presented in Table 8.

Table 8. Particle size analysis and bulk density of the forest soil at Brackloon, 1991.

			Horizon		
Fraction	Size	Units	Ea	Bs	Bs2/C
Coarse sand	2 - 0.5 mm	%	3	8	12
Fine sand	0.5 - 0.053 mm	%	36	34	20
Silt	53 - 2 μm	%	51	46	39
Clay	≤ 2 μm	%	9	12	28
Bulk density		$g\ cm^{-3}$	0.74	1.38	1.04

Field-saturated conductivity

Field-saturated conductivity data collected at the site at Brackloon are presented in Table 9. The data for the Ea horizon is the result of only one water addition. The time taken for this single addition of water to fully percolate out of the hole was such (493 minutes – i.e. 8 hours and 13 minutes), that it was not possible to repeat it. In general, the field-saturated conductivity at Brackloon was lower than at Roundwood. The time taken to obtain conductivity data was therefore much longer (Figures 3 and 8). Although the variation was greater in these soils than for the soils at Roundwood (e.g. Figures 3 and 8), the method was still considered useful for estimating field saturated conductivity.

Table 9. Field saturated conductivity measurements at Brackloon.

Horizon	Ks (m day^{-1})
Ea	0.051
Bs	0.204
C1	0.694
C2	0.284

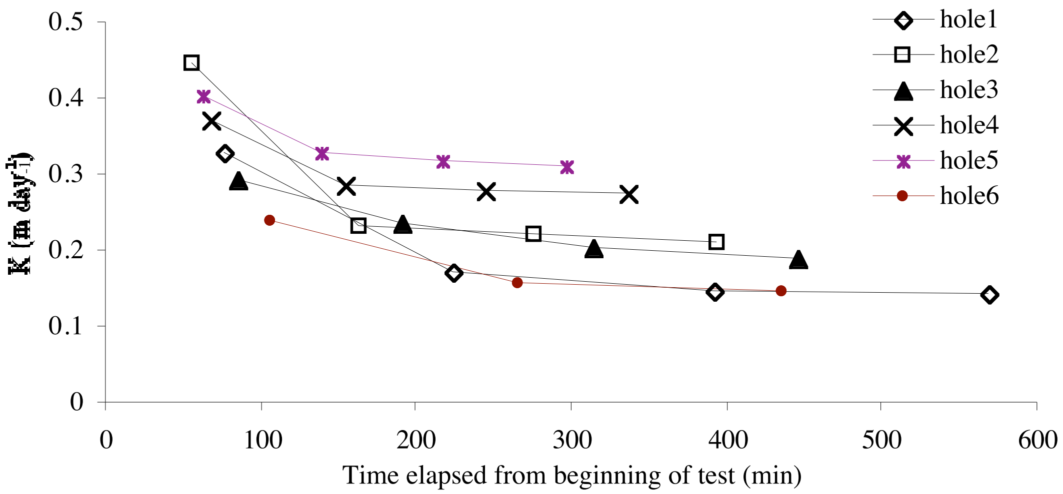

Figure 3. Hydraulic conductivity in 6 replicate holes in the Bs horizon at Brackloon. Constant or near constant values were obtained after periods of between 5 and 10 hours.

Soil water retention curves (pF curves)

Measurements of soil water content at different tensions (values for h) were made in triplicate for each horizon at Brackloon, except for the Bs horizon, from which 6 replicate measurements were made. The data obtained are presented in Table 10. Soil water retention curves (pF curves) were obtained by fitting equation 2 to the data points (Figure 4).

Table 10. Soil water tension data from different horizons at Brackloon.

Log (h)	Organic	Ea	Bs	C1	C2
Saturation	-	0.546	0.671	0.553	0.694
0.70	0.862	0.406	0.540	0.395	0.448
1.00	0.816	0.386	0.534	0.384	0.441
1.30	0.756	0.366	0.483	0.326	0.395
1.48	0.716	0.354	0.446	0.289	0.364
1.00	-	0.345	0.419	0.275	0.346
1.70	0.656	0.335	0.395	0.258	0.336
2.40	0.560	0.317	0.379	0.239	0.317
3.01	0.476	0.301	0.357	0.217	0.287
3.70	0.364	-	-	-	-
4.18	0.342	-	-	-	-

Data provided by Teagasc Research Station at Kinsealy

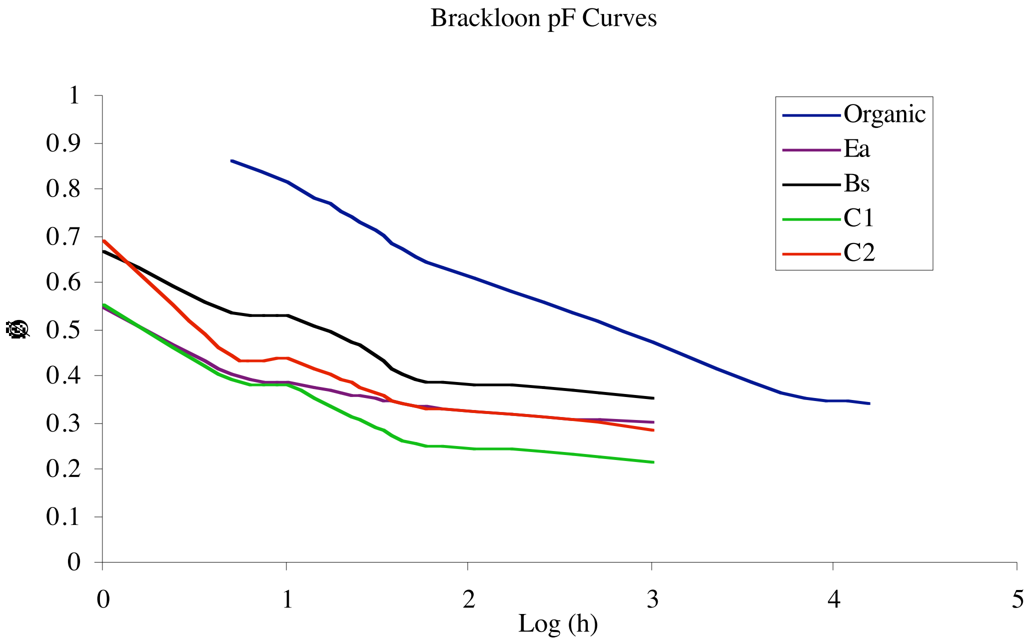

Figure 4. Soil water retention curves (pF curves) for the various soil horizons at Brackloon.

Vegetation

Fox *et al*. (2001) carried out a vegetation survey of Brackloon Wood in 1997, as part of a COFORD funded project at this site. They examined the vegetation in 112 quadrats in the forest. The vegetation community on the site has been classified as the *Blechno-Quercetum petraea* sub-association s*capanietosum* (Cross & Neff, 1982; Van Doorslaer & Mullinger, 1993; Daly, 1997), which is believed to be a woodland vegetation type particular to Ireland and not represented in other EU Member States. Variation in vegetation composition occurs as a result of varying soil, topographical and hydrological conditions, in particular. In addition, human impact, past and present, exerts a considerable influence.

Table 11 summarises the groundflora species that appeared most frequently in the survey data. By and large, they are typical oak woodland species. The fact that *Quercus petraea* appeared in only 10 of the 112 quadrats assessed, indicates the open nature of this woodland canopy. In fact, although there are a total of ten *Quercus* specimens in the survey, only one of these is a mature tree. Moreover, only three of the most common elements of the ground flora are trees, i.e. *Quercus*, *Sorbus* and *Ilex*, and these represent the 16th, 20th and 23rd most common elements of the ground flora respectively (Table 12).

Table 11. Groundflora species at the Brackloon forest plot (Fox *et al.*, (2001).

Ground Layer Species	Common Name	Number of Quadrats in which Species appears
Luzula sylvatica	Greater wood rush	104
Oxalis acetosella	Wood sorrel	90
Blechnum spicant	Hard fern	84
Vaccinium myrtillus	Bilberry	78
Thuidium tamariscinum	Wood feather moss	63
Rhytidiadelphus triquetrus	Teddy bear moss	50
Lonicera periclymenum	Honeysuckle	42
Eurynchium praelongum	Moss species	37
Melampyrum pratense	Cow wheat	33
Isothecium myosuroides	Oak trunk moss	29
Rubus species	Bramble	24
Rhytidiadelphus loreus	Soft Rhytidiadelphus	20
Anthoxanthum odoratum	Sweet vernal grass	18
Pteridium aquilinum	Bracken	17
Viola riviniana	Common violet	15
Sorbus aucuparia	Rowan	13
Dicranum majus	Moss species	10
Dryopteris dilatata	Broad buckler fern	10
Hedera helix	Ivy	10
Quercus petraea	Oak	10
Rhytidiadelphus squarrosus	Lawn moss	10
Dicranum scoparium	Moss species	9
Ilex aquifolium	Holly	8
Polytrichum commune	Moss species	7
Potentilla erecta	Tormentil	7
Frullania tamarisci	Liverwort species	5
Hypnum cupressiforme	Moss species	5
Lepraria incana	Lichen species	5
Corylus avellana	Hazel	4
Filipendula ulmaria	Meadowsweet	4

Total Number of Quadrats surveyed is 112. Species appearing in fewer than 4 quadrats have been omitted. All *Rubus* species/subspecies have been aggregated in this and subsequent tables.

Table 12. Summary of vegetation survey of Brackloon Wood (Fox *et al.*(2001).

Species frequency (Max.25)		**Greatest Cover (Max.100%)**		**Tallest Element of Ground Flora**	
Species	Frequency	Species	Cover	Species	Height (cm)
Luzula sylvatica	19	*Luzula sylvatica*	16	*Quercus petraea*	171
Vaccinium myrtillus	11	*Vaccinium myrtillus*	13	*Ilex aquifolium*	86
Blechnum spicant	10	*Blechnum spicant*	12	*Corylus avellana*	72
Oxalis acetosella	9	*Rhytidiadelphus triquetrus*	4	*Sorbus aucuparia*	67
Rhytidiadelphus triquetrus	5	*Pteridium aquilinum*	4	*Pteridium aquilinum*	64
Thuidium tamariscinum	3	*Lonicera periclymenum*	3	*Betula pubescens*	50
Lonicera periclymenum	2	*Oxalis acetosella*	3	*Juncus effusus*	50
Melampyrum pratense	2	*Isothecium myosuroides*	3	*Juncus inflexus*	50
Anthoxanthum odoratum	2	*Thuidium tamariscinum*	2	*Carex sylvatica*	43
Pteridium aquilinum	2	*Rhytidiadelphus loreus*	2	*Agrostis canina*	40
Rhytidiadelphus loreus	1	*Rubus* species	2	*Carex pulicaris*	40
Isothecium myosuroides	1	*Dryopteris dilatata*	2	*Cephalantera longifolia*	40
Rubus species	1	*Melampyrum pratense*	1	*Filipendula ulmaria*	39
Eurynchium praelongum	1	*Quercus petraea*	1	*Dryopteris dilatata*	36
Viola riviniana	1	*Sorbus aucuparia*	1	*Crepis paludosa*	35

Note: Species frequency is calculated as an average (based on all 112 quadrats surveyed) of how many of the twenty-five 100cm^2 subdivisions of each quadrat contained each species. Similarly, the greatest cover is an average of an estimate of the percentage of each quadrat covered by each species. The tallest elements of the ground flora is an average of the heights of each species found in each quadrat. In all three species lists, only the **tallest** 15 species are included.

Luzula sylvatica is a conspicuous component of the ground vegetation, reflecting the acid nature of the soil. On acid brown-earth soils, less acidophilus species such as *Geranium robertianum* and *Circaea lutelina* are dominant. The current assemblages of *Viola* and *Juncus* species in a section of the core zone may be outcompeted in future by more acidophilous species (e.g. *Luzula*) if nutrient flushing was to decrease and/or if soil acidification was accelerated.

Table 12 shows that the species with the highest frequency inside the quadrats (occupying the most number of quadrat grid-squares), are, unsurprisingly, very similar to those with the highest percentage cover. When the rank of a species in the frequency column is higher than its rank in the cover column in Table 11, it is usually because that species has a small leaf area, e.g. *Oxalis acetosella*, *Melampyrum pratense*. It is also unsurprising that *Quercus*, *Ilex*, *Corylus* and *Sorbus* are the tallest elements in the ground flora, since these are all tree species. Grasses also feature among the tallest species. The data for the height of *Quercus* is skewed due to the presence of one 15m tree in one of the quadrats. The other nine *Quercus* specimens present are seedlings and are of a more uniform height (average height of 23 cm).

The Brackloon open site is remarkably diverse (Table 13). This may be in part due to the survey method, which was not restricted by a plot boundary on the open site, and to its position on a rocky ridge with many micro-habitats. The large number of plants, and especially woody plants, which the open site has in common with the forest plot is significant. This, combined with its close proximity to the forest suggest a clearance of woodland similar to that on the forest plot, within historical times.

Table 13. Groundflora species at the Brackloon open plot.

Ground layer species	Common Name
Agrostis canina L.	velvet bent grass
Agrostis tenuis SIBTH.	common bent grass
Anthoxanthum odoratum L.	sweet vernal-grass
Bellis perennis L.	daisy
Betula alba L.	birch
Blechnum spicant L.	hard fern
Calluna vulgaris (L.) HULL	ling or heather
Centaurea nigra L.	black knapweed
Crataegus monogyna L.	hawthorn
Daboecia cantabrica (HUDS.) C. KOCH.	St. Daboec's heath
Dactylorhiza incarnata (L.) SOO	early marsh orchid
Dryopteris felix-mas (L.) SCHOTT	male fern
Erica cinerea L.	bell heather
Eriophorum angustifolium HONCK.	bog cotton or cotton grass
Festuca vivipara (L.) SM.	viviparous fescue
Galium saxatile L.	heath bedstraw
Hedera helix L.	ivy
Holcus lanatus L.	Yorkshire fog
Ilex aquifolium L.	holly
Isolepis setacea (L.) R. BR.	bristle scirpus
Juncus acutiflorus EHRH. EX. HOFFM.	sharp-flowered rush
Juncus effusus L.	soft rush
Luzula multiflora (RETZ.) LEJ	many-flowered woodrush
Molinia caerulea (L.) MOENCH.	purple moor-grass
Myrica gale L.	bog myrtle or sweet gale
Polypodium species L.	polypody fern
Polypodium vulgare L.	common polypody
Potentilla erecta (L.) RAUSCH.	tormentil
Primula elatior (L.) HILL	oxlip
Quercus petraea L.	sessile oak
Ranunculus acris L.	meadow buttercup
Rhododendron ponticum L.	rhododendron
Rubus fruticosus L.	bramble or blackberry
Rumex acetosa L.	common sorrel
Salix caprea L. (probably)	sally or goat willow
Scirpus maritimus L.	sea club-rush
Solidago virgaurea L.	golden-rod
Sorbus aucuparia L.	rowan or mountain ash
Succisa pratensis MOENCH	devil's-bit scabious
Taraxacum officinale WEBER.	dandelion
Trifolium repens L.	white clover

Forest stand

The Brackloon stand is a much disturbed remnant of the natural closed woodland climax of the region (Little *et al*., 1990). The monitoring plot is in a stand of semi-natural sessile oak (*Quercus petraea* (MATTUSCHKA) LIEBLEIN), with a sub-dominant layer of mountain ash (rowan) (*Sorbus aucuparia* L.) and an understory of holly (*Ilex aquifolium* L.). It is typical of the scattered remnants of native closed woodland vegetation now remaining (Little, D., personal communication), though these are not representative of the original post-glacial forest vegetation of Ireland, being generally on infertile soils, in remote areas.

Productivity and Management

Forest stand measurements for Brackloon, taken over the duration of the monitoring period are presented in Table 14. The age of the stand is uncertain, but estimated at over 150 years.

Table 14. Stand details of the Brackloon forest site.

	1991	1992	1993	1994	1995	1996	1997	1998
Mean diameter (cm) at 1.3 m	26	26	25	25	25	25	25	26
Basal area (m^2 ha^{-1})	36	37	38	38	39	38	38	38
Top height	—	17	14.5	18	—	—	—	—

An additional monitoring project has recently been completed at the Brackloon site. This project was funded by COFORD (Council for Forest Research and Development in Ireland) and ran from 1996–1998. It was being carried out at this site because of the monitoring work that has been continuous at Brackloon since 1991. This project funded an extension of the monitoring at Brackloon to include biological parameters in accordance with other monitoring network protocols. This monitoring can provide valuable additional information on the impact of low intensity pollution on a broadleaved forest ecosystem. The reports that were produced on the additional monitoring that was carried out at Brackloon, are listed at the beginning of this report.

Cloosh Site

The Cloosh monitoring site is located within the Cloosh Valley Forest, approximately 10 km from the town of Oughterard, County Galway, western Ireland. The monitoring plot is in a plantation of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (Figure 5). The Cloosh site is very remote, having no more than two houses within 5 km, although there is a livestock slatted house on the periphery of the forest block, approximately 300 metres east of the plot. The monitoring plot area is 0.0525 ha (35 × 15 m), is at an altitude of 102 m O.D. and is on blanket peat (Histosol). The plot is not fenced, although spot-protection of soil water samplers with wire mesh became necessary due to repeated disturbance, possibly by a pine marten. The open site is located approximately 600 m away, on an unplanted patch in the forest. Site details of the Cloosh monitoring plot are presented in Table 15.

Table 15. Site details of the Cloosh monitoring plot

Latitude & Longitude	Tree species	Planting year	Coillte Teoranta Inventory data	Geology	Soil type
53°21.41'N 9°20.47'W	*Picea sitchensis*	1958	Compartment 51530I Sub-compartment 6	Granitic acid intrusive rocks	Atlantic Blanket peat (Histosol)

Installations and measurements at the Cloosh site

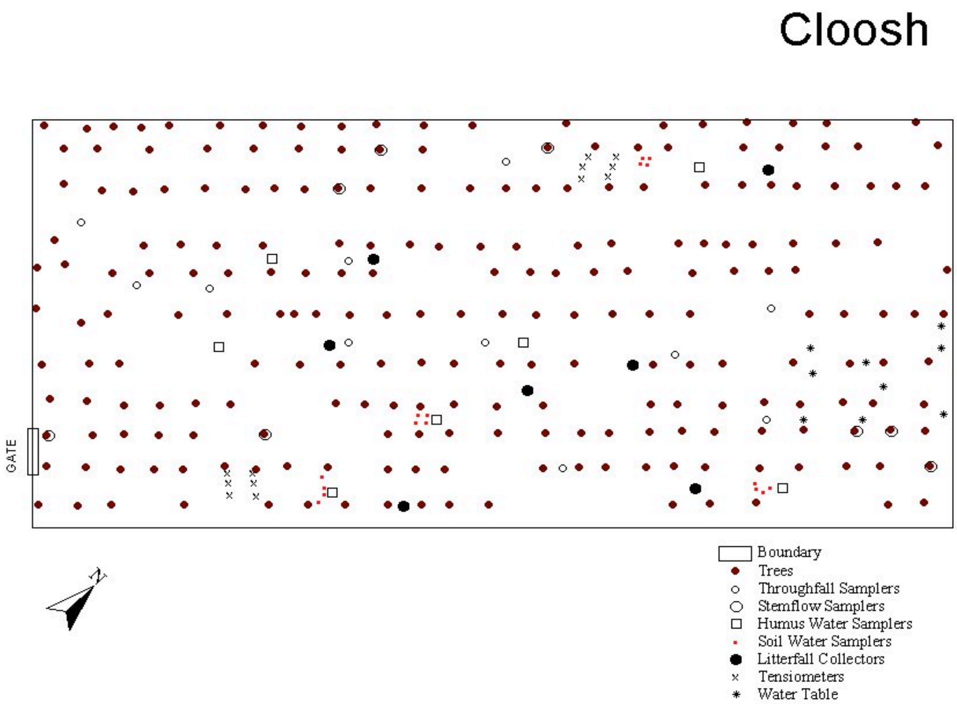

Figure 5. Locations of trees and equipment at the Cloosh site.

Table 16 records the installations in place and the date of installation of the equipment at the Cloosh monitoring plot. In addition, a summary of the measurements taken and analysis carried out on the samples is also presented.

Table 16. Installations at the Cloosh monitoring plot

Sampling / measurement	Sampling / measurement dates (week–year)	Equipment	Sampling / measurement frequency	Measurement / Analysis
precipitation amount	9–1991 to 52–2002	127 mm Rain Gauge	Weekly	water flux, mm/week
precipitation	1–1991 to 52–2002	4 × 1000 ml bottles and 100 mm funnels	Weekly	pH, conductivity, NH_4^+, P, cations, anions, Alk
throughfall	1–1991 to 52–2002	11 × 500 ml bottles and 100 mm funnels	Weekly	pH, conductivity, NH_4^+, P, cations, anions, Alk, total N
stemflow	48–1991 to 1–1994 & 18–1994 to 52–2002	8 × silicone gutters with 80 L bins	Weekly	pH, conductivity, NH_4^+, P, cations, anions, Alk, total N, DOC
humus water	1–1991 to 52–2002	7 × tray lysimeters with 2 L bottles	Weekly	pH, conductivity, NH_4^+, P, cations, anions, DOC
shallow and deep soil water at approx. 25 & 75 cm in the forest	8–1991 to 24–2001	16 × ceramic cup suction lysimeters	4-weekly 8/91 to 12/92 2-weekly 14/92 to 52/93 4-weekly 1/94 to 52/95 2-weekly 1/96 to ok 52/98 4-weekly 1/99 to 24/01	pH, conductivity, NH_4^+, P, cations, anions, DOC
shallow and deep soil water at approx. 25 & 75 cm beneath the humus layer	25–2001 to 52–2002	16 × teflon suction lysimeters	4-weekly 25/01 to 52/01	pH, conductivity, NH_4^+, P, cations, anions, DOC

Cations = Ca^{2+}, Mg^{2+}, K^+, Na^+, Mn^{2+}, total monomeric aluminium. Note: Mn^{2+} measured from 1993 only.

Anions = Cl^-, NO_3^-, SO_4^{2-}, HPO_4^{2-}

DOC: dissolved organic carbon, Alk: Alkalinity, when pH>5.0

Soil

The Cloosh site is on deep Atlantic (low-level) blanket peat (Histosol) underlain by granite or granodioritic acid intrusive rocks. The area is mapped as Association No. 24 by Gardiner and Radford (1980) and described in detail in Hammond (1981). This soil type covers approximately 5% of the land surface of Ireland, principally in western regions.

Soil chemical analyses

In Cloosh, the nature of the soil, being organic, required a different approach to nutrient analysis—in this instance, total elements were analysed on an acid digest, rather than exchangeable cations as was done for the mineral soils in Brackloon and Roundwood. The chemical analysis results are presented in Tables 17–18.

Table 17. Chemical analysis of soils at Cloosh forest and open sites, 1991 (Kelly, 1993).

Horizon	pH	Ca	Mg	K	Na	Fe	Al	P	N
	H_20	mg kg^{-1} (total)							%
Cloosh open site									
0–10 cm	4.4	1499	1249	543	662	553	637	345	1.88
10–20 cm	4.4	1466	1350	200	482	345	859	287	2.05
20–30 cm	4.5	2081	1800	121	457	361	797	223	2.13
30–40 cm	4.7	2357	2205	113	447	370	803	212	2.07
40–50 cm	4.8	2352	2279	127	489	326	775	198	1.97
50–60 cm	4.8	1176	1165	72	450	179	483	461	2.37
60–70 cm	4.8	1235	1298	73	444	159	468	451	2.12
Cloosh forest site									
O	—	1967	1081	1083	686	197	348	580	1.04
0–10 cm	4.1	595	857	420	671	783	1295	472	1.85
10–20 cm	4.1	679	838	182	468	692	1479	412	2.18
20–30 cm	4.3	626	846	163	391	724	1383	356	2.61
30–40 cm	4.5	603	987	178	396	924	1149	292	2.24

Table 18. Chemical analysis of the forest peat at Cloosh, 1994

Horizon	pH	pH	Ca	Mg	K	Na	Mn	Al	P	N	O.C.
	H_20	KCl	mg kg^{-1} (total)							%	%
Oi	4.7	3.7	6721	905	823	292	66	156	604	0.82	97.3
Oe	4.0	2.8	1208	1322	490	482	8	538	666	1.41	97.1
Oa	4.0	3.0	1009	1405	293	525	6	782	226	1.67	95.9
0–10 cm	4.1	3.1	477	799	379	396	8	1874	567	2.33	95.0
10–20 cm	4.2	3.2	578	768	103	410	3	580	320	2.10	97.9
20–30 cm	4.3	3.2	586	760	94	424	3	486	333	2.10	98.8
30–40 cm	4.5	3.3	497	1021	49	457	3	270	265	1.95	98.3
40-50 cm	4.5	3.5	268	888	67	500	3	627	262	2.08	98.6

Both forest and open plots in Cloosh have acid, fibrous, poorly humified peat, with slightly more acid conditions towards the surface. Concentrations of calcium and magnesium are higher in the open-plot peat, while potassium is more concentrated under the forest. There is little difference between the two soils in the case of sodium concentrations. Iron and aluminium are present in larger amounts in the forest peat, though not in the litter layer. Phosphorus is also present in greater concentration in the forest, while nitrogen contents of both areas are quite similar. The amounts of iron, aluminium and phosphorus are likely to be influenced by the somewhat uneven application of rock phosphate to this forest site around the time it was planted.

Vegetation

A list of vascular plants, including some mosses and lichens, was made at the Cloosh open and forest plots in 1991 (Table 19). The plants recorded are listed, with some comment on the associations.

Table 19. Groundflora species at the Cloosh forest and open plots (Burke, 1991)

Forest plot:	
Picea sitchensis (BONG.) CARR	Sitka spruce
Open plot:	
Molinia caerulea (L.)	purple moor-grass
Cladonia portentosa (DUFOR) ZAHLBR.	reindeer moss lichen
Calluna vulgaris (L.) HULL	heather or ling
Erica tetralix L.	heather or cross-leaved heath
Potentilla erecta (L.) RAUSCH.	tormentil
Sphagnum magellanicum BRID.	
Sphagnum fallax KLINGGR.	
Narthecium ossifragum (L.) HUDS	bog asphodel
Menyanthes trifoliata L.	bog bean
Schoenus nigricans L.	black bog rush
Polygala serpyllifolia HOSE	
Drosera rotundifolia L.	round-leaved sundew
Eriophorum vaginatum L.	bog cotton
Juncus effusus L.	rush
Pleurozia purpurea LINDB.	
Orthothecium rufescens BSG	
Aulocomnium palustre (HEDW.) SCHWRAEGR.	
Leucobryum glaucum (HEDW.) ANGSTR.	
Sphagnum capillifolium (EHRH.) HEDW.	
Sphagnum rubellum WILS.	
Sphagnum cuspidatum HOFFM.	
Sphagnum subsecundum (RUSS.) C. JENS	
Rhyncospora alba L.	white-beaked sedge
Drosera anglica L.	long-leaved sundew

The Cloosh forest plot has a healthy, fully-stocked, maturing Sitka spruce stand, and as such has virtually no ground vegetation, principally due to the lack of light. The thick, coarse, acid litter layer no doubt contributes to the lack of vegetation. Some lichens and algae occur on the spruce foliage.

The Cloosh site is Atlantic blanket peatland. This type of peatland is discussed by Hammond (1981), and is characterised by the presence of the black bog rush, *Schoenus nigricans*, which is not seen in the montane type, above about 150 m. Other characteristic plants of blanket bog include *Molinia caerulea*, *Eriophorum* spp., *Juncus* spp. and the heathers, *Calluna* and *Erica*, though these are not diagnostic of the Atlantic type. *Narthecium ossifragum* (bog asphodel) further confirms the extremely poor nutritional status of this ecosystem, particularly in phosphorus, due to its rain-fed condition.

A detailed survey of mosses was not available to the monitoring projects. Despite this, it was clear that there were both large quantities and a broad diversity of *Sphagnum* species on the Cloosh open site. Such a dominance of sphagna is not typical of Atlantic blanket peatland, it is more associated with the raised-type peatland.

Forest stand

The Cloosh monitoring plot is in a plantation of Sitka spruce (*Picea sitchensis* (Bong.) Carr.), which is part of one of the largest areas of forest in Ireland. It is a first-rotation plantation, established on former extensively-managed unenclosed hill land. The forest is representative of much of the afforestation carried out by the state Forest Service in the 1955–1975 period, being typically extensive blocks of pine and spruce on western blanket peatland. Management is often on a no-thin regime (as is the case in the monitoring plot) due to the high risk of windthrow.

Productivity and Management

Forest stand measurements for Cloosh, taken over the duration of the three monitoring projects, are presented in Table 20. The spruce stand is managed for commercial timber production and would be due for clearfelling about 2004 (Coillte management records). The no-thin regime leads to a high stocking of relatively small-diameter trees, with increasing numbers of standing dead trees due to crown competition.

Table 20. Stand details of the Cloosh forest site.

	1991	1992	1993	1994	1995	1996	1997	1998
Cloosh (planted 1958)								
Mean diameter (cm) at 1.3 m	15	15	—	17	17	18	—	18
Basal area (m^2 ha^{-1})	73	78	—	78	79	78	—	82
Top height	—	18	20	21	—	—	—	—

Roundwood Site

The Roundwood monitoring site is located within Ballinastoe Wood, approximately 4 km from the village of Roundwood, County Wicklow, eastern Ireland (Table 21). It is located in a plantation of Sitka spruce (*Picea sitchensis* (Bong.) Carr.). The monitoring plot covers an area of 0.125 ha (50 × 25 m), is at an altitude of 395 m O.D. and is fenced against deer and sheep (Figure 6). The open site is located approximately 300 m away.

Table 21. Site details of the Roundwood monitoring plot

Latitude & Longitude	Tree species	Planting year	Coillte Teoranta Inventory data	Geology	Soil type
53°6.20'N 6°14.28'W	*Picea sitchensis*	1955	Compartment 11854O Sub-compartment 4	Schist and quartzite	Peaty podzol (Spodosol)

Installations and measurements at the Roundwood site

Table 22 records the installations in place and the date of installation of the equipment at the Roundwood monitoring plot. In addition, a summary of the measurements taken, the sampling frequency and analysis carried out on the samples is also presented. Figure 7 records the locations of trees and equipment in the plot.

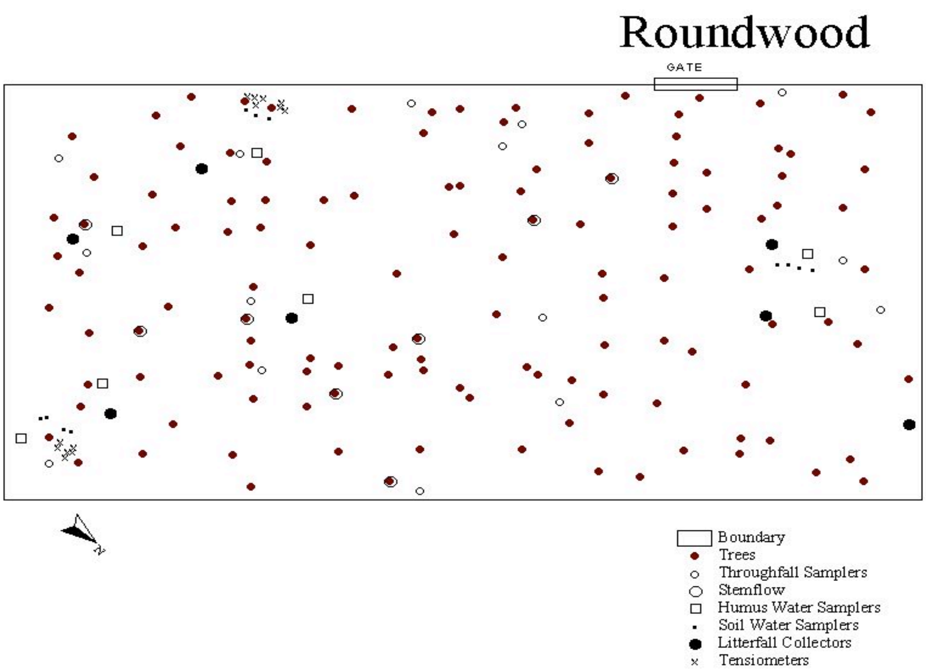

Figure 6. Location of trees and equipment at the Roundwood site.

Table 22. Installations at the Roundwood monitoring plot

Sampling / measurement	Sampling / measurement dates (week–year)	Equipment	Sampling / measurement frequency	Measurement / Analysis
precipitation amount	9–1991 to 52–2002	127 mm Rain Gauge	Weekly	water flux, mm/week
precipitation	1–1991 to 52–2002	4 × 1000 mL bottles and 100 mm funnels	Weekly	pH, conductivity, NH_4^+, P, cations, anions, Alk
throughfall	1–1991 to 52–2002	15 × 1000 and 500 mL bottles and 100 mm funnels	Weekly	pH, conductivity, NH_4^+, P, cations, anions, Alk, total N
stemflow	11–1992 to 52–2002	8 × silicone gutters with 80 L bins	Weekly	pH, conductivity, NH_4^+, P, cations, anions, Alk, total N, DOC.
humus water	1–1991 to 52–2002	7 × tray lysimeters with 2 L bottles	Weekly	pH, conductivity, NH_4^+, P, cations, anions, DOC.
shallow and deep soil water at approx. 25 & 75 cm in the mineral soil	21–1991 to 24–2002	10 × ceramic cup suction lysimeters	4-weekly 21/91 to 12/92 2-weekly 14/92 to 52/93 4-weekly 1/94 to 52/95 2-weekly 1/96 to 24/01	pH, conductivity, NH_4^+, P, cations, anions, DOC.
shallow and deep soil water at approx. 25 & 75 cm in the mineral soil	25–2001 to 52-2002	16 × teflon suction lysimeters	2-weekly 25/01 to 52/01	pH, conductivity, NH_4^+, P, cations, anions, DOC.

Cations = Ca2+, Mg2+, K+, Na+, Mn2+, total monomeric aluminium. Note: Mn2+ measured from 1993 only.
Anions = Cl-, NO3-, SO42-, HPO42-
DOC: dissolved organic carbon, Alk: Alkalinity, when pH > 5.01 All sampling was suspended from 04/03/2001 to 29/04/2001, due to foot and mouth disease restrictions.

Soil

The Roundwood site is on a peaty podzol (Spodosol); the soil is derived directly from weathered bedrock (schist and gneiss) or thin drift. As with Brackloon, the area is mapped as Association No. 1 by Gardiner and Radford (1980). This association represents almost 5% of the total land area of the island of Ireland.

Soil profile description

A morphological soil profile description for Roundwood is given, followed by chemical, physical and total analyses of destructive soil samples taken in 1991 and 1994 in Tables 23–26.

Table 23. Site details and soil profile description for the soil on the forest plot at Roundwood

Roundwood forest site, soil profile description.

Location:	Ballinastoe Wood, Roundwood, Co. Wicklow. Coillte Teoranta compartment 11854O, subcompartment 4, Roundwood Forest.
Altitude:	390 m.
Topography:	Mountain.
Slope:	23%, easterly aspect.
Soil type:	Peaty podzol.
Soil parent material:	Schist and quartzite.
Stoniness:	Occasional large granite erratics. Frequent medium and large stones in upper soil layers; many small, medium and large stones below.
Vegetation:	*Picea sitchensis* plantation, planted 1955, thinned twice, fully stocked; few ferns and poorly developed moss layer.
Root distribution:	Abundant in humus layer, few roots to c. 20 cm; common roots at 20–60 cm, few below this.
Organic matter:	Fresh over humified spruce litter; remnant peaty layer below (Oa/E).

Horizon	**Depth**	**Horizon description**
Oi	4–3 cm	organic; coarse fresh spruce litter matted with moss and sheets of white fungal hyphae; occasional large stones; common short branched roots in lower part protruding from below; abundant large angular pores; abrupt clear boundary to;
Oe	3–0 cm	organic; matrix of partly humified organic material (Von Post 5) between abundant fine roots; many medium long horizontal roots; reddish black, 10R 2/1; occasional large stones; weak horizontal layering; abrupt clear boundary to;
Oa/E	0–4/6 cm	organic clay loam; weak coarse angular blocky to weak fine prismatic structure; plastic and slightly sticky (moist); black, 5YR 2/1; occasional large stones; frequent small roots; common medium roots, confined to interped planes; frequent small–medium biopores; occasional short vertical fissures; gradual boundary to;
E/Bw	4/6–12/18 cm	loam; moderate fine subangular blocky structure; friable; very slightly sticky (moist); dark reddish-brown, 5YR 3/2; frequent medium and large stones; frequent fine and medium roots; common fine and coarse biopores; diffuse boundary to;
Bw/Bs	12/18–30 cm	stony clay loam; strong medium angular blocky and very fine crumb structure; friable; sticky when moist; dark yellowish-brown, 10YR 4/4 (2.5YR 3/2 in upper part—Bw—and around roots throughout); frequent large, medium and small stones; common medium and fine roots; abundant small and medium biopores; clear boundary to;
C	30–90+ cm	loamy sand; weak coarse angular blocky structure; slightly plastic when moist; olive, 5Y 4/3; many large, medium and small stones; occasional medium roots; common fine pores; bottom of pit.

Comment: Former organic matter accumulation in the form of a peaty layer has ceased and this layer is cracked even in wet weather. A new accumulation of spruce litter is clearly distinguishable above.

Soil chemical analyses

Soil chemical analyses for the Roundwood soil samples is given in Tables 24–25.

Table 24. Chemical analysis of soil at Roundwood forest site, 1991.

Horizon	pH H_2O	pH KCl	Ca^{2+}	Mg^{2+}	K^+	Na^+	Mn^{2+}	Fe^{3+}	Al^{3+}	CEC	Base Sat. %	total N %	extractable P mg kg^{-1}	O.C. %
			mmol$_\pm$ $100g^{-1}$ (exchangeable)											
Oi	3.5	2.9	3.0	4.3	0.71	0.81	1.7	0.52	7.2	18.2	48	1.44	—	—
Ah/Ea	3.3	2.8	1.6	0.29	0.26	0.17	0.7	0.37	3.3	6.7	35	0.11	1.4	6.0
Ea/A1	3.8	3.4	0.36	0.18	0.16	0.15	0.77	0.27	7.9	9.8	9	0.38	0.75	4.9
B	4.6	4.5	0.04	0.03	0.07	0.06	0.05	0.3	2.2	2.8	7	0.13	0.66	1.5
B_2/C	4.7	4.5	0.54	0.03	0.09	0.07	0.03	0.07	0.68	1.5	48	0.12	1.4	0.45

Table 25. Chemical analysis of soil at Roundwood forest site, 1994.

Horizon	pH H_2O	pH KCl	Ca^{2+}	Mg^{2+}	K^+	Na^+	Mn^{2+}	Fe^{3+}	Al^{3+}	CEC	Base Sat. %	total N %	extractable P mg kg^{-1}	O.C. %
			mmol$_\pm$ $100g^{-1}$ (exchangeable)											
Oi	4.4	4.0	6.3	3.8	4.8	0.84	6.0	0.11	0.73	22.6	70	1.55	38.8	84.0
Oe	4.0	3.4	6.2	3.5	1.5	0.78	5.6	0.07	0.76	18.4	65	1.50	21.5	90.5
Oa	3.5	2.8	5.3	4.9	0.76	0.82	4.2	0.24	2.4	18.6	63	1.61	11.3	92.5
Oa+O/E	3.4	2.7	0.48	0.85	0.21	0.27	0.48	0.44	3.8	6.5	28	0.72	3.15	11.6
O/E	3.5	2.7	0.21	0.34	0.13	0.19	0.42	0.38	3.9	5.6	16	0.37	0.74	5.6
E/B	4.0	3.3	0.15	0.17	0.11	0.12	0.96	0.09	6.0	7.6	7	0.33	0.11	3.9
Bs/Bw	4.5	4.3	0.46	0.02	0.08	0.08	0.08	0.02	2.1	2.8	23	0.22	0.05	1.8
C	4.6	4.5	0.04	0.01	0.04	0.06	0.02	0.001	0.79	0.96	16	0.10	0.33	0.61

CEC = Cation Exchange Capacity, by summation of all the cations analysed.
Base Sat. = Base Saturation.
O.C. = Organic Carbon, determined by the Walkley–Black (1934) method.

The Roundwood forest soil is very acid, even considering the slight rise in pH with depth. It is very low in exchangeable base cations, extremely low in some species at depth. The cation exchange capacity is low, indicating a severe limitation to the fertility of this site.

Soil physical analysis

Particle size analysis was carried out on the Roundwood mineral soil, and is presented in Table 26.

Table 26. Particle size analysis of the forest soil at Roundwood, 1991.

Fraction	Size	Horizon Ah/Ea %	Ea/A1 %	B %	B_2/C %
Coarse sand	2 - 0.5 mm	17	16	25	34
Fine sand	0.5 - 0.053 mm	18	19	32	22
Silt	53 - 2 µm	33	31	28	33
Clay	≤ 2 µm	34	33	16	11

Field-saturated conductivity

Mean field-saturated conductivity measurements for the Roundwood site are presented in Table 30. The logarithm of conductivity measurements was used to calculate mean values because saturated conductivity is log–normally distributed. The data in Table 30 suggest that under field-saturated conditions, water moved at a relatively constant rate through the O/E, E/B and B horizons. The ability of the C horizon to transmit water under field-saturated conditions was almost double that of the other mineral horizons. The saturated conductivity of the organic layer was an order of magnitude greater than the conductivity of the mineral horizons.

Figure 8 shows the evolution of the conductivity of the four replicate square holes in the C horizon. Saturation of the soil immediately below the hole was reached when the measurements of conductivity stabilised. The reasonable reproducibility of the measurements (Figure 7 and Table 30) suggests that the method was suitable for measuring field-saturated conductivity in the soil profile at this site. The smaller scale of the experimental set up used for measurements in the organic and O/E horizons might explain the higher standard errors found (Table 30).

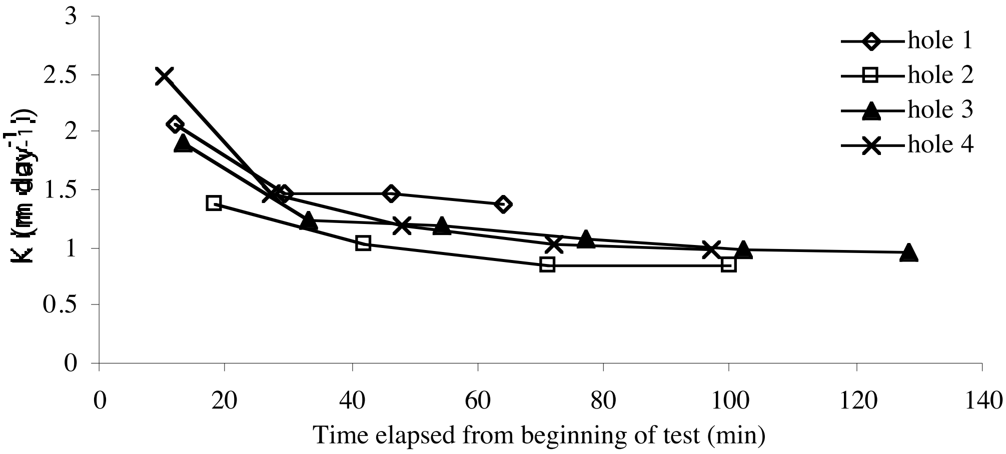

Figure 7. Hydraulic conductivity in 4 replicate holes in the C horizon at Roundwood. Constant or near constant values were obtained in under 2 hours.

Unsaturated conductivity

Means of duplicate measurements are presented in Table 27. The ability of horizons O/E and E/B to transmit water was less than that of the lower horizons (B and C). It should be noted that the unsaturated conductivity at all three tensions was higher in the B horizon than in the C horizon and that the contrary was found under field-saturated conditions (Table 30). This suggests that there was more macropore flow in the C horizon, as field-saturated conductivity measurements include both macropore and non-macropore flow, while measurements made with the tensions infiltrometer exclude macropore flow (Perroux and White, 1988).

Table 27. Field-saturated and unsaturated conductivities (m day^{-1}) at the Roundwood site

Horizon	Organic	O/E	E/B	B	C
Field-Saturated	18.87 (9.55)[a]	0.651 (1.203)	0.620 (0.150)	0.661 (0.149)	1.036 (0.116)
Unsaturated					
-5	nd [b]	0.00511[c]	0.0145	0.363	0.219
-10	nd	0.00204	0.00539	0.174	0.117
-17	nd	nd	0.00261	0.045	0.0291

[a] Means (standard error of the mean); [b] Not determined [c] Mean

Soil water retention curves (pF curves)

Measurements of soil water content at different tensions (values for h) were made in quadruplicate for each horizon. The data obtained are presented in Table 28. Soil water retention curves were obtained by fitting equation 2 to the data points (Figure 9).

Table 28. Water content of samples from each soil horizon at Roundwood, at a range of tensions.

Log (h)	Organic	O/E	E/B	B	C
Saturation	-	0.648	0.640	0.657	0.514
0.70	0.788	0.480	0.501	0.460	0.407
1.00	0.715	0.453	0.450	0.417	0.372
1.30	0.653	0.427	0.399	0.380	0.334
1.48	0.622	0.420	0.381	0.356	0.321
1.70	0.576	0.398	0.352	0.329	0.302
2.40	0.521	0.361	0.297	0.272	0.264
3.00	0.453	0.330	0.260	0.228	0.219
3.70	0.315	0.315	0.240	0.181	0.158
4.18	0.275	0.275	0.203	0.144	0.117

Data were provided by Teagasc research station at Kinsealy

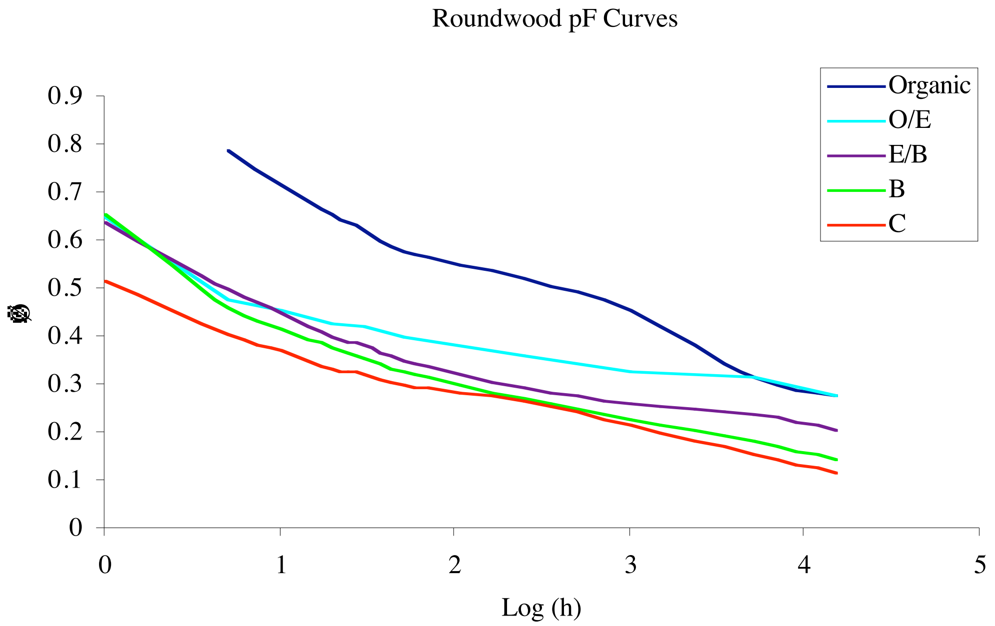

Figure 8. Soil water retention curves (pF curves) for the various soil horizons at Roundwood.

Soil hydraulic parameters

Soil hydraulic parameters were obtained by fitting the equation of Brooks and Corey (1964) to the soil water retention data. Where unsaturated conductivity was measured, the equations of Brooks and Corey (1964) and Mualem (1976) were fitted simultaneously to soil water retention data and unsaturated conductivity data, respectively (Figure 9).

Plant properties: Fine root density

The number of root intersections with the 0.5 x 0.5cm grid and the percentage of total root length found in each layer is shown in Table 33. Measurements were only made to a depth of 64 cm due to the stoniness of the soil. However, the measured root distribution in the C horizon was best fitted by a logarithmic function, from which it was possible to obtain estimates of root density below 64 cm by extrapolation (Figure 9). It is worth noting that a large proportion of the fine roots was found in the organic horizon (Table 29).

Table 29. Root density data from the Roundwood site.

Soil Horizon	Depth	Root intersections	% of total root length
Humus	0-4	2183	40.50
O/E	4-9	371	6.89
E/B	9-19	454	8.42
B	19-34	499	9.25
C	34-44	675	12.52
C	44-54	534	9.90
C	54-64	277	5.14
C	64-74	178	3.30
C	74-84	110	2.04
C	84-104	110	2.04

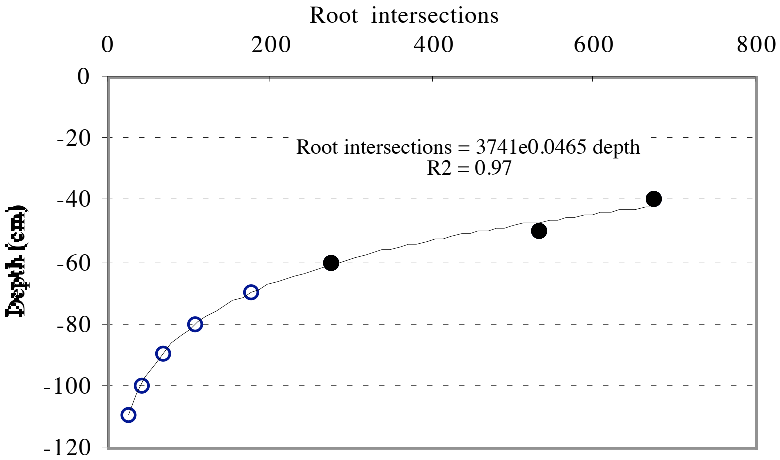

Figure 9. Root intersections in the C horizon. A logarithmic function was fitted to measured values (●) and used to estimate values of root density by extrapolation (o).

Other plant parameters were obtained from the literature or by model calibration. A value of 12% was set for the solar reflection coefficient (albedo) of vegetation of soil (Jarvis *et al*., 1976). The critical soil water tension (the soil water tension below which roots to not take up water) was set at –50kPa and the surface resistance when water is intercepted was set at 7 (Eckersten *et al*., 1995). Other parameters describing the canopy were deduced by calibrating model throughfall values against weekly throughfall measurements for the years 1992–1997.

Vegetation

A vegetation survey was carried out at Roundwood's forest and open plots in 1991 by the Forest Ecosystem Research Group (Burke, 1991). In 1997, a more intensive vegetation survey of the forest plot at Roundwood was carried out by Coillte (O'Brien *et al*., 1998). The plants recorded are presented in Tables 30–31, with some comment on the associations.

Table 30. Groundflora species at the Roundwood forest plot (O'Brien *et al.*, 1998).

Forest plot:	**% Cover**				
Quadrat	**1**	**2**	**3**	**4**	**5**
Canopy Layer					
Picea sitchensis	50	35	55	60	50
Shrub Layer					
Vaccinium myrtillus	+	<5	0	+	<5
Herb Layer					
Agrostis capillaris	<5	5	0	+	+
Galium saxatile	+	<5	0	0	0
Dryopteris felix-mas	0	+	0	0	0
Dryopteris dilatata	<5	<5	+	+	<5
Ground Layer					
Polytrichum formosum	12	20	5	<5	5
Platiothecium undilatum	25	15	10	0	10
Hypnum jutlandicum	30	15	10	5	<5
Thuidium tamariscinum	5	0	<5	<5	12
Eurhynchium praelongum	<5	<5	5	5	5
Mnium hornum	+	5	<5	<5	<5
Campylopus paradoxus	<5	<5	<5	0	+
Dicranum scoparium	<5	<5	<5	<5	<5
Rhytidiadelphus loreus	<5	0	0	0	0

+: Plant present
Data collected by Coillte Teoranta (O'Brien *et al.*, 1998)

The Roundwood open site has vegetation typical of peaty podzols in Wicklow. The forest plot has a very bare understory with a very poor shrub layer and a poor herb layer present. There is quite a lot of litter in the form of needles, branches and small dead trees. There is a moderate covering of bryophytes on the ground. There are very few ferns and only small patches of grass. It is rocky in places, and the rocks are mostly covered by litter or mosses. There is a very low epiphyte cover on the trees.

Table 31. Groundflora species at the Roundwood open plot (Burke, 1991).

Open plot:	**% Cover**					
Quadrat	**1**	**2**	**3**	**4**	**5**	**6**
Calluna vulgaris L.	85	62	40	40	15	0
Vaccinium myrtillus L.	<5	<5	40	40	0	0
Erica tetralix L.	<5	15	15	0	0	0
Grasses (spp below)	<5	<5	<5	<5	40	85
Molinia caerulea (L.)						
Agrostis tenuis SIBTH.						
Juncus acutiflorus EHRH. EX HOFFM.						
Deschampsia flexuosa (L.) TRIN						
Agrostis stolonifera L.						
Anthoxanthum odoratum L.						

Forest stand

The Roundwood forest stand is a first-rotation plantation established on former extensively-managed, unenclosed hill land. The monitoring plot is in a Sitka spruce plantation, part of about 100 ha of forest, mostly Sitka spruce, with Scots pine (*Pinus sylvestris* L.). It has been thinned several times.

Productivity and Management

Forest stand measurements at Roundwood, taken over the duration of the three monitoring projects, are presented in Table 32. The spruce stand has been managed for commercial timber production, and is scheduled for clearfelling about 1999 (Coillte management records). The monitoring-plot stand has been thinned twice. The first thinning was a systematic line thinning; the linear openings in the canopy had closed when monitoring began.

Table 32. Stand details of Roundwood forest site.

	1991	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**
Roundwood (planted 1955)								
Mean diameter (cm) at 1.3 m	24	24	25	26	26	27	27	28
Basal area (m^2 ha^{-1})	42	45	46	48	49	51	52	56
Top height	—	19	—	19	—	23	—	—

Ballinastoe Site

The Ballinastoe monitoring site is located within Ballinastoe Wood, approximately 4 km from the village of Roundwood, County Wicklow, eastern Ireland. It is located in a plantation of Sitka spruce (*Picea sitchensis* (Bong.) Carr.). The monitoring plot covers an area of 0.25 ha (50 × 50 m).

This plot was established as a replacement for the original, Roundwood plot. It is located about 3 km from this plot. The stands around the original plot have been decimated by wind. In addition, clearfelling in the area has left the plot exposed so that it is no longer representative of forest conditions in the region.

Originally it was intended to run the old plot in parallel with the new for a period of one year. The original open site, which is used for collection of bulk precipitation, is being maintained until the old forest plot has been cleared. It then will become the open site for the new, Ballinastoe, plot.

Table 33. Site details of the Ballinastoe monitoring plot

Latidtude & Longitude	Tree species	Planting year	Coillte Teoranta Inventory data	Geology	Soil type
53° 6.40'N 6°13.55'W	*Picea sitchensis*	1976	Compartment 11860F Sub-compartment 9	Schist and quartzite	Peaty podzol (Spodosol)

Installations and measurements at the Ballinastoe site

Table 34 records the installations in place and the date of installation of the equipment at the Ballinastoe monitoring plot. In addition, a summary of the measurements taken, the sampling frequency and analysis carried out on the samples is also presented.

Table 34. Installations at the Ballinastoe monitoring plot

Sampling / measurement	Sampling / measurement dates (week–year)	Equipment	Sampling / measurement frequency	Measurement / Analysis
Throughfall	35–2001 to 52–2002	30 × 500 mL bottles and 100 mm funnels	Weekly	pH, conductivity, NH_4^+, P, cations, anions, Alk, total N
Humus water	35–2001 to 52–2002	7 × tray lysimeters with 2 L bottles	Weekly	pH, conductivity, NH_4^+, P, cations, anions, DOC.
Shallow and deep soil water at approx. 25 & 75 cm in the mineral soil	35–2001 to 52-2002	16 × teflon suction lysimeters	2–weekly	pH, conductivity, NH_4^+, P, cations, anions, DOC.

Cations = Ca2+, Mg2+, K+, Na+, Mn2+, total monomeric aluminium.
Anions = Cl-, NO3-, SO42-, HPO42-
DOC: dissolved organic carbon, Alk: Alkalinity, when pH > 5.0

Forest stand

The Ballinastoe forest stand is a first-rotation plantation established on former extensively-managed, unenclosed hill land. The monitoring plot is in a Sitka spruce plantation, part of about 100 ha of forest, mostly Sitka spruce, with Scots pine (*Pinus sylvestris* L.). It has been thinned several times. The species composition of the plot is 100% Sitka spruce. The Yield Class of the stand, extracted from forest inventory data, is 16.

Results

Results are presented for each site for the reporting period, 2002.

Precipitation Amounts

Table 35. Annual rain gauge, precipitation, throughfall and stemflow volumes, where measured, and interception at Brackloon, Cloosh and Roundwood, 2002.

Source	Brackloon	Cloosh	Roundwood
Rain gauge (mm)	1510	2094	2076
Precipitation (mm)	1453	1651	1475
Throughfall (mm)	1309	973	858
Stemflow (mm)	-	122	42
% Interception (including stemflow)	10	34	39

Precipitation volumes are measured using a standard Meteorological 127 mm rain gauge. However, precipitation samples are collected separately, using 100 mm funnels. The precipitation volume as measured by the 100 mm funnels is lower that rain gauge readings by around 11% at Roundwood to 25% at the western sites on an annual basis. The source of this bias varies with weather conditions, as they affect splashing, turbulence and evaporation at the funnel openings. There is no estimate for the bias in throughfall measurements, although it is probably smaller.

Brackloon Water chemistry, Mean Values

Results for the monitoring period are presented in Table 36.

Table 36. Mean ionic concentrations (µmol± L-1), pH and dissolved organic carbon (mg L-1) in all ecosystem water strata sampled at Brackloon, 2002.

	pH	H^+	NH_4^+	NO_3^-	Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	SO_4^{2-}	Non-seasalt sulphate	Al^{3+}	Mn^{2+}	DOC
							µmol± L^{-1}							mg L^{-1}
Precipitation	5.18	6.6	13	5.6	20	59	7.8	296	366	47	*9.3*	1.4	0.11	nd
Throughfall	5.29	5.1	22	9.2	87	187	71	805	1002	141	*38*	1.7	3.8	nd
Humus water	3.99	103	1.6	0.74	55	213	35	912	954	99	*0.74*	21	0.63	81
SW shallow	4.55	28	2.2	1.7	39	212	7.1	789	903	96	*3.0*	89	0.35	34
SW deep	4.80	16	3.9	0.05	32	218	12	883	1057	127	*18*	61	0.33	12

nd: not determined,
Al3+ is total monomeric aluminium, quoted as if all was present as the tripositive aluminium ion.
DOC: Dissolved Organic Carbon
Non-seasalt sulphate is calculated using a Cl-:SO42- ratio of 0.103:1
SW= soil water; “shallow” and “deep” soil water samplers are at nominal depths of 25 and 50 cm respectively in the mineral soil.

Cloosh Water chemistry, Mean Values

Table 37. Mean ionic concentrations ($\mu mol_{\pm}\ L^{-1}$), pH and dissolved organic carbon ($mg\ L^{-1}$) in all ecosystem water strata sampled at Cloosh, 2002.

	pH	H^+	NH_4^+	NO_3^-	Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	SO_4^{2-}	Non-seasalt sulphate	Al^{3+}	Mn^{2+}	DOC
							$\mu mol_{\pm}\ L^{-1}$							$mg\ L^{-1}$
Precipitation	4.90	12	7.2	5.3	19	49	5.6	247	308	42	*10*	1.3	0.12	nd
Throughfall	4.83	15	11	6.5	77	159	60	692	887	119	*28*	3.2	0.97	nd
Stemflow	4.60	25	29	3.4	222	330	125	1382	1582	249	*86*	8.0	1.96	49
Humus water	3.83	148	17	0.72	36	106	3.3	681	629	121	*56*	11	0.25	68
SW shallow	4.00	101	104	16	51	175	5.3	762	910	100	*6.3*	36	0.21	66
SW deep	4.32	48	262	4.0	42	219	5.5	889	1155	69	*-50*	28	0.10	65

nd: not determined, †: below detection limit

Al^{3+} is total monomeric aluminium, quoted as if all was present as the tripositive aluminium ion.

DOC: Dissolved Organic Carbon

Non-seasalt sulphate is calculated using a Cl^-:SO_4^{2-} ratio of 0.103:1

SW= soil water; “shallow” and “deep” soil water samplers are at nominal depths of 25 and 50 cm respectively in the mineral soil.

Roundwood Water chemistry, Mean Values

Table 38. Mean ionic concentrations (µmol± L^{-1}), pH and dissolved organic carbon (mg L^{-1}) in all ecosystem water strata sampled at Roundwood, 2002.

	pH	H^+	NH_4^+	NO_3^-	Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	SO_4^{2-}	Non-seasalt sulphate	Al^{3+}	Mn^{2+}	DOC
							µmol± L^{-1}							mg L^{-1}
Precipitation	4.91	12	44	16	12	12	6.1	77	103	31	*20*	2.0	0.14	nd
Throughfall	4.64	23	54	61	51	79	60	330	404	108	*66*	3.8	15	nd
Stemflow	4.23	58	173	143	130	203	161	712	801	282	*199*	9.6	38	46
Humus water	3.59	255	18	104	56	138	29	431	471	141	*92*	45	30	65
SW shallow	4.17	68	3.5	80	62	113	11	388	445	151	*105*	89	83	26
SW deep	4.37	43	8.3	104	54	117	9.8	422	490	164	*114*	128	47	13

nd: not determined.
Al3+ is total monomeric aluminium, quoted as if all was present as the tripositive aluminium ion.
DOC: Dissolved Organic Carbon
Non-seasalt sulphate is calculated using a Cl-:SO42- ratio of 0.103:1
SW= soil water; “shallow” and “deep” soil water samplers are at nominal depths of 25 and 50 cm respectively in the mineral soil.

Ballinastoe Water chemistry, Mean Values

Results for the monitoring period are presented in Table 39 This new site is located close to the Roundwood plot which, it is intended ultimately to replace. At present, it shares the open site with Roundwood.

Table 39. Annual ionic concentrations (µmol± L^{-1}), pH and dissolved organic carbon (mg L^{-1}) in all ecosystem water strata sampled at Ballinastoe, 2002.

	pH	H^+	NH_4^+	NO_3^-	Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	SO_4^{2-}	Non-seasalt sulphate	Al^{3+}	Mn^{2+}	DOC
							µmol± L^{-1}							mg L^{-1}
Throughfall	4.55	28	26	34	40	53	40	216	276	77	*49*	3.4	3.7	nd
Humus water	3.91	122	19	16	40	69	28	288	338	87	*52*	24	2.5	67
SW shallow	3.85	143	12	19	41	65	11	400	476	139	*90*	105	3.9	54
SW deep	4.35	45	3.5	22	47	83	4.1	385	436	148	*103*	118	10	16

nd: not determined

Al^{3+} is total monomeric aluminium, quoted as if all was present as the tripositive aluminium ion.

DOC: Dissolved Organic Carbon

Non-seasalt sulphate is calculated using a Cl^-:SO_4^{2-} ratio of 0.103:1

SW= soil water; “shallow” and “deep” soil water samplers are at nominal depths of 25 and 50 cm respectively in the mineral soil.

Conclusions

Continued long-term monitoring at Brackloon, Cloosh and Roundwood is gradually improving our understanding of both the health of these ecosystems and the sustainability of all forest ecosystems in Ireland. The greatest threat to forest health is in the east of the country, where anthropogenic influences are greatest. However, the levels of pollution are relatively low by European standards and only those forests located on poorly buffered acid soils, principally those derived from quartzite and granite, should be considered susceptible. Sitka spruce comprises a high proportion of the total forest area in Ireland. Although this reliance on a single tree species is in many respects undesirable, its tolerance of acid stress gives some grounds for reassurance.

The health status of the forests in Ireland is generally good. The Roundwood and Ballinastoe sites are located in the east of Ireland. As such they are subject to higher levels of atmospheric pollutants than the two sites located on the west coast. If there were to be a deterioration in the health of forests in Ireland due to atmospheric deposition, it would be expected to first appear on the east coast, where deposition is highest. Thus the Roundwood site is and, in time, Ballinastoe will be very valuable components of the intensive monitoring programme.

Due to its location on the western seaboard of continental Europe, atmospheric deposition in Ireland is dominated by marine ions, notably sodium and chloride. However, the country is exposed to pollutants during periods of easterly air flows. Evidence of these is particularly seen at the Roundwood site, in eastern Ireland. These “pollution events” deserve more comprehensive investigation, to ascertain both their frequency and intensity, and thereby make some estimation of their potential effects on the forest ecosystem.

Nitrogen deposition is very low at the two western sites. The uptake of nitrogen by the canopy, as evidenced by a decreased nitrogen flux from precipitation to throughfall, suggests that these forests are nitrogen-limited. The situation at the Roundwood site in the east of the country is rather different. Nitrogen inputs are very much higher here and there is an increase in nitrogen flux from precipitation to throughfall. The flux of nitrate in the soil solution also increases with depth.

Calculation of soil water fluxes allows us to have a greater understanding of the longer-term environmental impacts of atmospheric deposition on the forests. This data can be used to predict the consequences of change within the ecosystem, the long-term influence of external factors and ultimately, the long-term sustainability of the ecosystem.

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