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# The use of ground vegetation and humus type as indicators of soil nutrient regime for an ecological site classification of British forests

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**Abstract**

In many countries ground vegetation and humus type are used as indicators of forest soil quality, especially nutrient regime. This paper reports the development of such methods for use in British forests, within a new Ecological Site Classification combining climate, soil moisture regime and soil nutrient regime.

To develop a field assessment method for soil nutrient regime, a study was made of soil chemistry, humus type and ground vegetation in British forests. Sites were selected in both mature plantations and semi-natural woodlands. Soil and humus profiles were described and the soil was sampled volumetrically for later chemical analysis. Vascular ground vegetation was recorded in quadrats by species cover fraction, and classified according to the existing British National Vegetation Classification. Soils were analyzed for a number of chemical variables. Vegetation data were treated by application of the species indicator values for soil reaction (*R*) and soil nitrogen (*N*), as proposed by Ellenberg [Vegetation Ecology of Central Europe, 4th Edition. Cambridge University Press, Cambridge]. Site mean indicator values *mR* and *mN* (weighted by species cover fraction) were then calculated. Multivariate statistical analysis techniques were applied to both the soil chemical and the vegetation sample data.

Soil nutrient regime was shown to be a composite gradient of several soil chemical variables, of which the pH value and the availability of mineral (especially nitrate) nitrogen, and of calcium, were of particular importance. The species composition of the ground vegetation was related to position on this soil nutrient gradient. The vegetation: soil nutrient correlation using the site mean Ellenberg values was satisfactory ($r$=0.89), but was improved by using indicator values generated from within the present data. The occurrence of the major humus types (mor, moder and mull) is broadly related to soil nutrient regime defined in this way. Both ground vegetation and humus type can therefore be used as soil nutrient indicators in British forests.

A division of the soil nutrient gradient into five classes (Very Poor, Poor, Medium, Rich and Very Rich) is proposed. Future sampling work may lead to the definition of an additional class of soils with carbonate nutrient regimes. The Ecological Site Classification will provide forest managers in Great Britain with an improved basis for the selection of tree species for planting, and the adoption of silvicultural methods best suited to the site. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* Forest site classification; Soil nutrients; Soil mineral nitrogen; Species indicator values; Humus types; Great Britain

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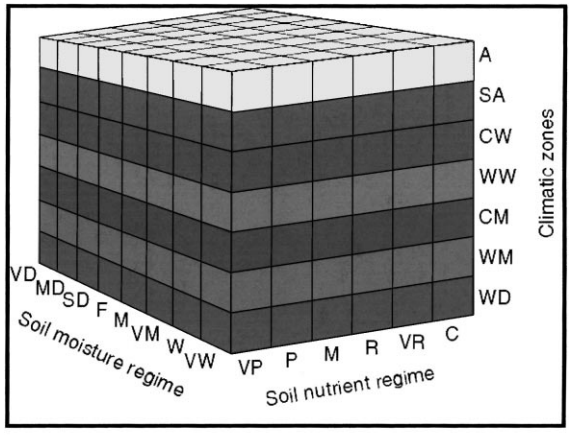
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## 1. Introduction

Most of Britain's forests consist of plantations dating from the 20th century, and often of introduced species. Sustainable forest management (Forestry Commission, 1998) requires a knowledge of how the ecological potential of the site should influence management, but the current growth performance of the plantations provides an inadequate guide to long-term prospects. Policy has been extended recently to promote the wide range of benefits to be derived from forests, and, in particular, to conserve and where appropriate to enhance biological diversity (Ratcliffe, 1993). For example, as plantations mature, the opportunity is being taken to increase structural diversity and to recreate woodlands composed of native species (Rodwell and Patterson, 1994). To help the forest manager take advantage of the many opportunities available, an Ecological Site Classification (ESC) is being developed, based on a number of indicators of climate, soil moisture regime and soil nutrient regime (Pyatt and Suarez, 1997).

The methods being developed for use within the ESC follow work done elsewhere in Europe and North America. Cajander (1926) and Duchaufour (1960) described the basic concepts of forest site classification. The use of ground vegetation to assess soil moisture and soil nutrients was taken forward by Central European ecologists, notably Ellenberg (1988), who proposed the use of species indicator values. In Britain, Anderson (1950) set out a classification of 'bare land' that considered soil moisture and soil nutrients as separate factors. The use of three 'principal components' to describe forest site quality or potential was pioneered in British Columbia, Canada by Krajina (1969), Klinka and colleagues (Klinka et al., 1984, 1989; Pojar et al., 1987) and has been adopted as the basis for ESC. Comparable schemes have been developed in other parts of North America, including Wisconsin (Coffman et al., 1983; Kotar et al., 1988; Kotar and Burger, 1989) for the management of semi-natural forests.

The Ecological Site Classification describes site types in terms of three independent components: climate, soil moisture regime (SMR) and soil nutrient regime (SNR). These can be represented visually by a site-type 'cube' or a soil quality 'grid' (Pyatt, 1995; Pyatt and Suarez, 1997) (see Figs. 1 and 2). Similar soil quality grids have been used in Europe (Ellenberg, 1988; Rameau et al., 1989, 1993; Anon., 1991a, b), Canada (Pojar et al., 1987) and the United States (Kotar and Burger, 1989)




**Key**

| Soil moisture regimes | Soil nutrient regimes | Climate zones |
|---|---|---|
| VD = very dry | VP = very poor | WD = warm dry |
| MD = moderately dry | P = poor | WM = warm moist |
| SD = slightly dry | M = medium | CM = cool moist |
| F = fresh | R = rich | WW = warm wet |
| M = moist | VR = very rich | CW = cool wet |
| VM = very moist | | SA = sub-alpine |
| W = wet | | A = alpine |
| VW - very wet | | |

Fig. 1. Ecological Site Classification site quality cube.

Seven climatic zones are defined within Great Britain using accumulated temperature (Birse and Dry, 1970) and moisture deficit (Bendelow and Hartnup, 1980) combined spatially in a Geographical Information System (GIS). Windiness (Quine and White, 1994), winter cold and continentality (Bendelow and Hartnup, 1980) are also used to evaluate climatic suitability for planting. Eight classes of SMR are defined on the basis of moisture deficit and soil moisture capacity and recognized by examination of the soil profile. Six classes of SNR have been provisionally defined following the example of the Biogeoclimatic Ecosystem Classification (BEC) in British Columbia (Klinka et al., 1984).

A pilot study in British forests showed that it might be possible to relate the composition of the ground vegetation to soil chemical properties (Hawkes et al., 1997) and thereby to assist in the field recognition of SNR classes. Hawkes et al. (1997) used Ellenberg indicator values for each vascular plant species to obtain a score for the vegetation related to SNR

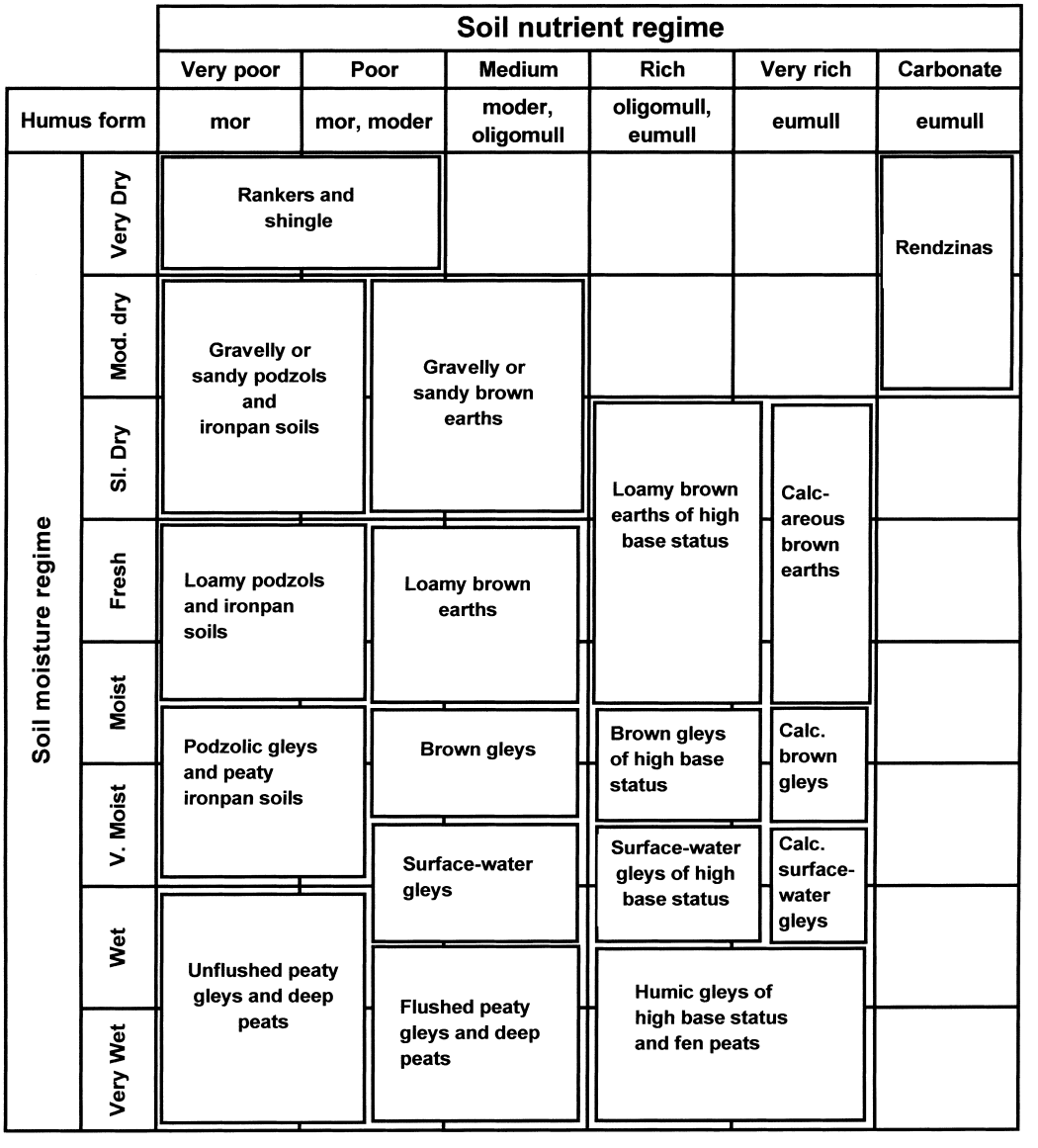



Fig. 2. Indicative distribution of soil types on the soil quality grid.

(Ellenberg, 1988; Ellenberg et al., 1992). Ellenberg produced and revised a set of indicator values referring to the ecological preferences of plant species growing in natural competition in Central Europe. Separate indicator values, each on an integer scale from 1 to 9, refer to individual ecological parameters such as light availability, continentality and soil moisture availability. These values were produced by largely subjective means, based on extensive experience of the ecosystems of Central Europe over many years. Specifically, the Ellenberg '*R*' value deals with a species' preference with regard to soil reaction (acidity), and the '*N*' value describes the preference with regard to soil nutrients, primarily nitrogen. In each case the lower values correspond to infertile soils and the higher values to fertile soils.

This paper reports recent work that has extended the methods of Hawkes et al. (1997), based on the

hypothesis that ground vegetation and humus form can be used as indicators of SNR. The specific objectives were to produce a quantitative definition of SNR for adoption within the ESC and to derive a statistical relationship between the species composition of the ground vegetation and measured SNR, defined in this way. This relationship, together with observations of soil type and humus type would then be used in the operational assessment of the SNR of forest sites. The work is fully described by Wilson (1998) (unpublished).

## 2. Methods

### 2.1. Selection of sampling sites

Seventy sites were deliberately chosen to include most of the major soil types used for forestry in Great Britain and many of the associated ground vegetation types. It was anticipated that these sites would also cover the range of soil nutrient conditions. Of these, 68 were selected within mature plantations (mainly of *Pinus*, *Larix* and *Quercus* spp.). More than half of these sites were located within Forestry Commission Permanent Sample Plots, maintained for yield modelling purposes and for which volume increment data were available. Two sites were in semi-natural *Quercus–Betula* woodlands. All sites were positioned in areas of apparently uniform soil type, with well-developed and reasonably consistent ground vegetation.

### 2.2. Field sampling

At each site a survey plot of some 0.1 ha was defined. Location and physical features of the site such as National Grid Reference, elevation, aspect, relative topographical position and solid geology were obtained from maps. Details of the stand itself (species, age and volume increment) were obtained from Forestry Commission records.

A pit was excavated in the centre of the plot, and the soil profile described by the method of Avery (1990) and classified according to the standard Forestry Commission scheme (Pyatt and Suarez, 1997). The humus type was described and classified using alternative methods from British Columbia (Green et al., 1993) and France (Jabiol et al., 1995). The soil was sampled volumetrically to a depth of 50 cm by power-assisted corer (using Eijelkamp equipment) in 6 to 9 locations spaced evenly across the plot. Each core sample was divided into three layer samples (by soil horizons where possible) whose thickness was noted. Where a separable organic layer was present, this was taken as the upper layer. The corresponding layer samples were aggregated for the plot, and their volume and total mass determined (from which bulk-density was calculated). Each aggregated layer sample was thoroughly mixed on-site and a small sub-sample was taken and kept chilled (<5°C) at field moisture content to await laboratory analysis.

The species composition of the ground vegetation was recorded in 2 m×2 m quadrats adjacent to the soil coring points. An estimate of ground cover fraction (abundance) was made for each vascular species in the shrub, field and ground layers separately. These descriptions of the ground vegetation were assigned to the semi-natural woodland communities of the National Vegetation Classification (NVC) using the keys provided by Rodwell (1991) and Whitbread and Kirby (1992). The ground vegetation was also allocated to one of 10 subjectively defined types depending on the two or three most abundant species. The quadrat data were used to calculate abundance-weighted mean Ellenberg indicator values *mR* and *mN*, using a computer spreadsheet and following the method of Hawkes et al. (1997). The tree canopy species were only included in the calculation if the woodland was semi-natural.

### 2.3. Laboratory analysis methods

For each layer, the bulk of the aggregated sample was air-dried and mechanically sieved to determine the mass-fraction of stones larger than 2 mm. The field-moist sub-sample was pushed through a 2 mm sieve and analysed for the following variables: (a) moisture content, (b) loss-on-ignition, (c) pH (both in water and in 0.01 M calcium chloride solution), (d) extractable calcium, magnesium and potassium individually, (e) total phosphorus and (f) $NO_3$-nitrogen and $NH_4$-nitrogen both before and after aerobic incubation.

Laboratory methods generally followed those of Allen (1989). Moisture content was determined by

measuring mass-loss from a 10 g sample after oven-drying for 24 h at 90°C. The dried samples were then ignited in a muffle furnace at 500°C overnight to give loss-on-ignition. Total carbon was not determined as a separate component of loss-on-ignition. pH was measured using a glass-electrode meter in a 1:2.5 w/v suspension of soil in de-ionised water and also in an 0.01 M aqueous solution of calcium chloride. Extractable cations were determined by atomic absorption spectrophotometry after extraction of a 10 g soil sample with 1 M aqueous ammonium acetate for 2 h. This same extract was also analysed colorimetrically for phosphorus, but the amounts determined were very low. For this reason a measure of total phosphorus by extraction with aqua regia was obtained. We followed Hawkes et al. (1997) in measuring plant-available nitrogen in both the nitrate and ammonium forms, before and after aerobic incubation. Similar methods were used for the BEC scheme in British Columbia (Fyles et al., 1990). The soil sample was incubated for 28 days at 30°C, with periodic irrigation with de-ionised water to maintain the original moisture content. The extraction was carried out on 10 g of soil using 1 M aqueous potassium chloride for 2 h, followed by colorimetric determination for $NO_3$-nitrogen and $NH_4$-nitrogen. The post-incubation values were treated separately, without subtraction of the pre-incubation values.

Soil chemical variables were expressed both spatially, aggregated to 50 cm depth (kg $ha^{-1}$), and as conventional oven-dry basis mass-fractions for each layer (mg $kg^{-1}$) but only the former values were used in the statistical analysis. pH was included as separate values for the three layers.

### 2.4. Statistical analysis

Prior to statistical analysis, and excepting the already logarithmic ($base_{10}$) pH values, the data were transformed by logarithms to the $base_{10}$. This transformation makes variability more equal across the set of individual variates. The statistical techniques employed do not require an underlying assumption of multivariate normality (Digby et al., 1989).

Principal Components Analysis (PCA) was applied to the soil chemical data, in order to identify the major gradients of between-site variation in soil chemistry (Jongman et al., 1987). Separate analyses were run using the alternative sets of pH values (in water and in calcium chloride solution). The analyses were performed on the covariance matrices, using the GENSTAT 5 program (Payne, 1993).

Canonical Correlation Analysis (COR) (Jongman et al., 1987) was applied to the combined soil chemical and vegetation datasets, again using the GENSTAT 5 program. The vegetation data were used in the form of the site mean Ellenberg indicator values *mR* and *mN*. The objective was to test the ability of these indicator values to predict soil nutrient regime in the manner suggested by Hawkes et al. (1997).

(De-trended) Canonical Correspondence Analysis (DCCA) (Jongman et al., 1987) was applied to the combined soil chemical and vegetation datasets, using the CANOCO program (ter Braak, 1991). The vegetation data were used directly in the form of mean species abundances across the set of quadrats for each site. The objective was to generate one or more gradients of soil nutrient regime on which the sites and species could be ordinated without reference to pre-determined species indicator values. This was considered essential as the Ellenberg values were not developed for use in British conditions and may not be as valid as they are in central Europe. The significance of the results of the [D]CCA was verified using a Monte Carlo simulation approach.

A de-trended correspondence analysis (DCA) (Jongman et al., 1987), without inclusion of the soil chemical data, was carried out for comparison with the DCCA. This employed the DECORANA program (Hill and Gauch, 1980). This was needed to test whether the major gradients in the species composition of the ground vegetation were inherently due to soil nutrient regime, independently of the variables selected for measurement in this study.

## 3. Results

### 3.1. Sampling sites

A wide range of geological parent materials and soil types were represented in the 70 sites. The sites also displayed a wide range of estimated soil moisture regime, but with few sites in the classes Very Moist to Very Wet (see Fig. 2). A summary of site details is provided in Table 1.

Table 1
Summary details of sampling sites[a]

| Site | Region | Geology | Soil type | Humus type | Vegetation |
|---|---|---|---|---|---|
| Brendon Chase | South west England | Devonian sandstone | Brown earth | Moder | Type 4/NVC W 11 |
| Okehampton | South west England | Carboniferous culm shale | Ironpan soil | Moder | Type 4/NVC W 16 |
| Stourton | South west England | Cretaceous greensand | Surface-water gley | Moder | Type 6/NVC W 11 |
| Well Wood, Liskeard | South west England | Devonian shale | Brown earth | Oligomull | Type 6/NVC W 10 |
| Blandford Forest | Southern England | Clay over cretaceous chalk | Argillic brown earth | Mesomull | Type 8/NVC W 8 |
| New Forest | Southern England | Tertiary sand | Brown earth | Mor | Type 4/NVC W 16 |
| Alice Holt Forest | South east England | Cretaceous gault clay | Surface-water gley | Moder | Type 4/NVC W 11 |
| Bedgebury Plantation | South east England | Cretaceous Hastings sand | Podzol | Mor | Type 4/NVC W 16 |
| Blackwood | South east England | Cretaceous chalk | Calcareous brown earth | Eumull | Type 9/NVC W 8 |
| Bramshill Plantation | South east England | Tertiary sand | Ground-water gley | Mor | Type 4/NVC W 4 |
| Chiltern Beechwoods | South east England | Clay over cretaceous chalk | Argillic brown earth | Mesomull | Type 7/NVC W 14 |
| Ladwell | South east England | Cretaceous london clay | Surface-water gley | Mesomull | Type 8/NVC W 10 |
| Liphook | South east England | Cretaceous greensand | Podzol | Mor | Type 4/NVC W 16 |
| Micheldever Forest | South east England | Clay over cretaceous chalk | Argillic brown earth | Mesomull | Type 8/NVC W 10 |
| Cwm Ystwyth Forest | Wales | Silurian shale | Upland brown earth | Oligomull | Type 3/NVC W 17 |
| Cwmcarn Forest | Wales | Carboniferous sandstone | Upland brown earth | Moder | Type 3/NVC W 16 |
| Gwydr Forest | Wales | Ordovician rhyolitic tuff | Ranker | Mor | Type 4/NVC W 16 |
| Gwydr Forest | Wales | Ordovician shale | Upland brown earth | Oligomull | Type 6/NVC W 11 |
| Pembrey Forest | Wales | Littoral sand | Littoral sand | Mor | Type 6/NVC W 10 |
| Pembrey Forest | Wales | Littoral sand | Littoral sand | Moder | Type 6/NVC W 10 |
| Forest of Dean (Pillowell) | Western England | Carboniferous sandstone | Brown earth | Oligomull | Type 4/NVC W 11 |
| Forest of Dean (Blaize Bailey) | Western England | Devonian sandstone | Brown earth | Mesomull | Type 5/NVC W 10 |
| Forest of Dean (Bunjups) | Western England | Devonian sandstone | Surface-water gley | Eumull | Type 8/NVC W 10 |
| Forest of Dean (Dymock) | Western England | Devonian sandstone | Brown earth | Oligomull | Type 7/NVC W 10 |
| Forest of Dean (Redbrook) | Western England | Devonian sandstone | Brown earth | Mesomull | Type 7/NVC W 10 |
| Forest of Dean (Ruspidge) | Western England | Devonian sandstone | Brown earth | Mesomull | Type 8/NVC W 10 |
| Wigmore Rolls | Western England | Silurian shale | Surface-water gley | Eumull | Type 9/NVC W 8 |
| Wyre Forest | Western England | Carboniferous sandstone | Brown earth | Oligomull | Type 8/NVC W 10 |
| Apethorpe Forest | Central England | Jurassic limestone | Surface-water gley | Eumull | Type 10/NVC W 8 |
| Cannock Chase | Central England | Triassic sandstone | Ground-water gley | Mor | Type 4/NVC W 16 |
| Fineshade Forest | Central England | Jurassic limestone | Argillic brown earth | Mesomull | Type 8/NVC W 10 |
| Sherwood Forest (Blidworth) | Central England | Triassic sandstone | Brown earth | Mor | Type 7/NVC W 11 |
| Sherwood Forest (Clumber Park) | Central England | Triassic sandstone | Brown earth | Mor | Type 7/NVC W 11 |
| Whitwell Wood | Central England | Permian magnesian limestone | Argillic brown earth | Eumull | Type 9/NVC W 8 |
| Thetford Forest (Kings) | Eastern England | Sand over cretaceous chalk | Argillic brown earth | Oligomull | Type 5/NVC W 10 |
| Thetford Forest (Brandon) | Eastern England | Sand over cretaceous chalk | Podzol | Mor | Type 3/NVC W 16 |
| Thetford Forest (High Bridgham) | Eastern England | Cretaceous chalk | Calcareous brown earth | Eumull | Type 10/NVC W 8 |
| Thetford Forest (Cockley Cley) | Eastern England | Sand over cretaceous chalk | Argillic brown earth | Moder | Type 7/NVC W 10 |
| Thetford Forest (Mundford) | Eastern England | Sand over cretaceous chalk | Argillic brown earth | Mor | Type 7/NVC W 10 |
| Thetford Forest (Redlodge) | Eastern England | Sand over cretaceous chalk | Brown earth | Moder | Type 4/NVC W 10 |
| Dodd Wood | North west England | Ordovician shale | Brown earth | Moder | Type 6/NVC W 11 |

| | | | | | |
|---|---|---|---|---|---|
| Thornthwaite Forest | North west England | Ordovician shale | Surface-water gley | Moder | Type 5/NVC W 11 |
| Grizedale Forest | North west England | Silurian shale | Brown earth | Oligomull | Type 5/NVC W 10 |
| Mabie Forest | South west Scotland | Silurian shale | Alluvial brown earth | Mesomull | Type 6/NVC W 11 |
| Forest of Ae | South west Scotland | Silurian greywacke | Alluvial brown earth | Oligomull | Type 6/NVC W 11 |
| Dalby Forest | North east England | Jurassic sandstone | Ground-water gley | Moder | Type 6/NVC W 10 |
| Stocksfield Estate | North east England | Carboniferous sandstone | Surface-water gley | Oligomull | Type 6/NVC W 10 |
| Glentress Forest | South east Scotland | Silurian greywacke | Brown earth | Oligomull | Type 6/NVC W 11 |
| Glentress Forest | South east Scotland | Silurian greywacke | Upland brown earth | Moder | Type 6/NVC W 17 |
| Ariundle Oakwood | Western Scotland | Granite | Peaty gley | Mor | Type 2/NVC W 4 |
| Kilmichael Forest | Western Scotland | Dalradian mica schist | Peaty gley | Mor | Type 6/NVC W 11 |
| Knapdale Forest | Western Scotland | Dalradian mica schist | Peaty gley | Mor | Type 1/NVC W 18 |
| Knapdale Forest | Western Scotland | Dalradian mica schist | Ironpan soil | Mor | Type 6/NVC W 11 |
| Leanachan Forest | Western Scotland | Granite | Ironpan soil | Mor | Type 3/NVC W 17 |
| Loch Ard | Western Scotland | Dalradian mica schist | Ironpan soil | Mor | Type 3/NVC W 17 |
| Drummond Hill Forest | Central Scotland | Dalradian mica schist | Upland brown earth | Oligomull | Type 5/NVC W 11 |
| Kinfauns Estate | Central Scotland | Devonian andesite | Brown earth | Eumull | Type 10/NVC W 8 |
| Balmoral Estate | North east Scotland | Granite | Alluvial brown earth | Mor | Type 1/NVC W 18 |
| Clashindarroch Forest | North east Scotland | Dalradian mica schist | Alluvial ground-water gley | Oligomull | Type 6/NVC W 11 |
| Culbin Forest | North east Scotland | Littoral sand | Littoral sand | Mor | Type 1/NVC W 18 |
| Culbokie Wood | North east Scotland | Devonian sandstone | Podzol | Mor | Type 1/NVC W 18 |
| Culloden | North east Scotland | Devonian sandstone | Upland brown earth | Oligomull | Type 5/NVC W 11 |
| Dinnet Oakwood | North east Scotland | Dalradian limestone | Brown earth | Oligomull | Type 4/NVC W 11 |
| Drumtochty Forest | North east Scotland | Devonian sandstone | Brown earth | Moder | Type 3/NVC W 16 |
| Drumtochty Forest | North east Scotland | Devonian sandstone | Ironpan soil | Mor | Type 3/NVC W 17 |
| Leschangie, Kemnay | North east Scotland | Granite | Brown earth | Moder | Type 6/NVC W 11 |
| Monaughty Forest | North east Scotland | Devonian sandstone | Brown earth | Moder | Type 1/NVC W 18 |
| Seafield Estate | North east Scotland | Moine schist | Podzol | Mor | Type 1/NVC W 18 |
| Teindland Forest | North east Scotland | Devonian sandstone | Ironpan soil | Mor | Type 1/NVC W 18 |
| Tentsmuir Forest | North east Scotland | Littoral sand | Littoral sand | Moder | Type 6/NVC W 11 |

[a] Geology from British Geological Survey 'Ten Mile Map', 1979. Soil types and humus types after Pyatt and Suarez, 1997 (Appendix 2 and Fig. 18 respectively). Vegetation types as in Table 2.

Table 2
Dominant ground vegetation types in British plantation forests and corresponding National Vegetation Classification woodlands

| Type | Characteristic species | Corresponding NVC woodlands |
|---|---|---|
| 1 | *Calluna vulgaris, Erica* spp. | W18 *Pinus sylvestris* with *Calluna vulgaris* |
| 2 | *Molinia caerulea* | W4 *Betula pubescens* with *Molinia caerulea* |
| 3 | *Deschampsia flexuosa* | W15 *Fagus sylvatica* with *Deschampsia flexuosa*<br>W16 *Quercus-Betula* with *Deschampsia flexuosa*<br>W17 *Quercus-Betula* with *Dicranum majus* |
| 4 | *Pteridium aquilinum* | W16 *Quercus-Betula* with *Deschampsia flexuosa* |
| 5 | *Agrostis* spp./*Holcus* spp. | W11 *Quercus-Betula* with *Oxalis acetosella* |
| 6 | *Rubus* spp./*Dryopteris* spp/ *O. acetosella* | W11 *Quercus-Betula* with *Oxalis acetosella* |
| 7 | *Rubus fruticosus* (+ *Pteridium aquilinum*) | W10 *Quercus* with *Rubus fruticosus*<br>W14 *Fagus sylvatica* with *Rubus fruticosus* |
| 8 | Species rich ground vegetation | W10 *Quercus* with *Rubus fruticosus* |
| 9 | *Mercurialis perennis* | W8 *Fraxinus-Acer* with *Mercurialis perennis*<br>W12 *Fagus sylvatica* with *Mercurialis perennis* |
| 10 | *Urtica dioica* | W7 *Alnus glutinosa* with *Urtica dioica*<br>W8 *Fraxinus-Acer* with *Mercurialis perennis* |

The range of ground vegetation types is shown in Table 2. It often proved difficult to match an individual plot with one NVC woodland community or sub-community. Particular problems were encountered with W17, W16, W11 and W10 (all *Quercus–Betula* woodlands) whose descriptions appear to overlap at both community and sub-community levels.

Some of the NVC woodland types were not encountered in this project, notably the 'wet woodlands' W1 to W7, and the base-rich upland woodland W9. Only one example of a mesotrophic beech woodland (W14) was included. However, the more restricted range of vegetation types that occurs frequently in plantations has been covered.

The observed range of Ellenberg *mR* values was 1.04 to 7.18 and for *mN* was 1.04 to 8.57. These compare with the range of 1 to 9 for the individual species indicator values.

### 3.2. Soil chemical analysis

The results of the soil chemical analyses are summarized in Table 3.

A number of notable features of the soil chemistry of these sites emerged from the analyses. With the exception of $NH_4$-nitrogen and loss-on-ignition, all the soil chemical variables were positively correlated. Most of the soils were strongly acid, with pH values from 3.5 to 4.5, especially in the surface layer. Those sites with pH greater than 5.0 formed a distinct group and mostly occurred over calcareous substrates. The two measures of pH (in water and in calcium chloride solution) gave similar results.

The measures of $NO_3$-nitrogen before and after incubation were positively correlated ($r$=0.83), but this was less pronounced for the $NH_4$-nitrogen measures. The sites could be divided into a number of groups as regards their mineral nitrogen status: (a) those with very low supplies in both forms, (b) those high in $NO_3$-nitrogen, with a wide range of $NH_4$-nitrogen supply (c) those high in $NH_4$-nitrogen but with low $NO_3$-nitrogen supply and (d) those with moderate supplies in both forms. The high $NO_3$-nitrogen soils were mainly those with the higher pH values (see Table 4).

### 3.3. Statistical analysis

#### 3.3.1. Principal Component Analysis (PCA)

The first principal component, which was strongly loaded by pH and extractable calcium, explained ~65% of the total variation. The second and third principal components, mainly reflecting $NO_3$-nitrogen and $NH_4$-nitrogen respectively, each explained ~9% of the total variation (see Fig. 3). The other chemical variables, including total phosphorus, had small loadings on the first three principal components. The results of the PCA were similar whether pH in water or in calcium chloride solution was used. It was observed that the three measures of soil pH in the

Table 3
Summary soil chemical data[a]

| | pH [$H_2O$] [Top] | pH [$H_2O$] [Middle] | pH [$H_2O$] [Bottom] | pH [$CaCl_2$] [Top] | pH [$CaCl_2$] [Middle] | pH [$CaCl_2$] [Bottom] | EXT Ca kg/ha | |
|---|---|---|---|---|---|---|---|---|
| Minimum | 2.8 | 3.0 | 3.1 | 2.8 | 2.6 | 2.9 | 45.0 | |
| Quartile 1 | 3.3 | 3.4 | 3.6 | 3.0 | 3.4 | 3.7 | 218.3 | |
| Median | 3.5 | 3.7 | 3.8 | 3.3 | 3.6 | 3.9 | 497.5 | |
| Mean | 3.6 | 3.9 | 4.3 | 3.5 | 3.8 | 4.3 | 4456.9 | |
| Quartile 3 | 3.8 | 3.9 | 4.5 | 3.6 | 4.0 | 4.3 | 3648.5 | |
| Maximum | 5.9 | 6.5 | 7.3 | 6.2 | 6.7 | 7.1 | 40990.0 | |
| | AV $NO_3$:N kg/ha | MIN $NO_3$:N kg/ha | AV $NH_4$:N kg/ha | MIN $NH_4$:N kg/ ha | Total P kg/ha | EXT K kg/ha | EXT Mg kg/ha | LOI Mg/ha |
| Minimum | 0.0 | 0.0 | 0.0 | 0.0 | 136.4 | 56.0 | 39.0 | 98.0 |
| Quartile 1 | 9.9 | 14.7 | 12.3 | 52.8 | 761.0 | 129.5 | 90.0 | 183.0 |
| Median | 24.9 | 43.7 | 26.0 | 79.3 | 1104.7 | 182.0 | 136.5 | 245.0 |
| Mean | 39.5 | 69.3 | 33.2 | 93.9 | 1349.8 | 254.2 | 388.5 | 252.1 |
| Quartile 3 | 46.1 | 87.2 | 49.3 | 119.0 | 1803.6 | 276.5 | 370.5 | 302.8 |
| Maximum | 274.2 | 311.1 | 135.5 | 363.7 | 3639.8 | 1328.0 | 3513.0 | 532.0 |

[a] EXT=Extractable, AV=Available, MIN=Mineralisable, LOI=Loss on ignition.

separate layers were correlated. Comparable results are obtained from the PCA if the pH data is entered in the form of a simple mean of the three layer values for each plot.

### 3.3.2. Canonical Correlation Analysis (COR)

The first canonical axis explained ~75% of the vegetation-soil chemistry variation, and was correlated with pH, the base cations and $NO_3$-nitrogen. It was correlated with both the *mR* ($r$=0.86) and *mN* ($r$=0.77) site indicator values. For the sites in this study the *mR* and *mN* values were themselves significantly correlated ($r$=0.88), emphasizing that reaction (base status) and $NO_3$-nitrogen supply may be components of a single major gradient of soil nutrient regime, at least in British woodlands. The second canonical axis explained ~25% of the variation. Its was correlated with total phosphorus but was not

Table 4
Allocation of sampling sites to mineral nitrogen regime categories in relation to overall soil nutrient regime

| Soil nutrient regime | Mineralisable nitrogen regime | | | | | |
|---|---|---|---|---|---|---|
| | High $NO_3$-N High $NH_4$-N | High $NO_3$-N Low $NH_4$-N | Moderate $NO_3$-N Moderate $NH_4$-N | Low $NO_3$-N High $NH_4$-N | Low $NO_3$-N Low $NH_4$-N | Total |
| Very Poor | 0 | 0 | 2 | 3 | 4 | 9 |
| Poor | 0 | 3 | 9 | 11 | 4 | 27 |
| Medium | 3 | 4 | 6 | 2 | 0 | 15 |
| Rich | 5 | 6 | 1 | 0 | 1 | 13 |
| Very Rich | 3 | 3 | 0 | 0 | 0 | 6 |
| Total | 11 | 16 | 18 | 16 | 9 | 70 |
| Basis of allocation[a] | | | | | | |
| Min $NO_3$-N | Quartile 4 | Quartile 4 | Quartile 2 | Quartile 1 | Quartile 1 | |
| Min $NH_4$-N | Quartile 3 or 4 | Quartile 1 or 2 | Quartile 2 or 3 | Quartile 3 or 4 | Quartile 1 or 2 | |
| | Or | Or | Or | Or | Or | |
| Min $NO_3$-N | Quartile 3 | Quartile 3 | Quartile 3 | Quartile 2 | Quartile 2 | |
| Min $NH_4$-N | Quartile 4 | Quartile 1 | Quartile 2 OR 3 | Quartile 4 | Quartile 1 | |

[a] For quartile values see Table 3.

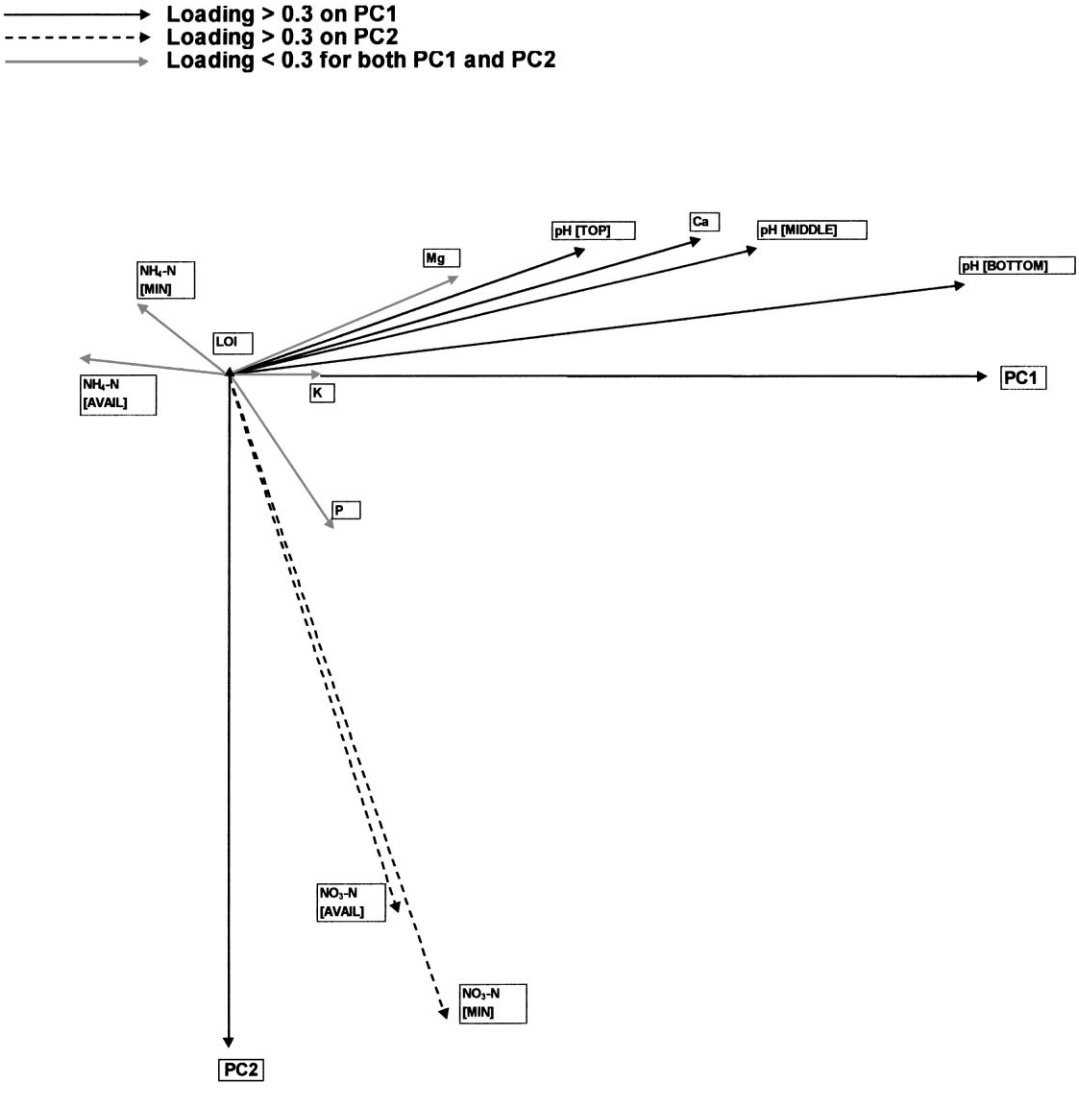



Fig. 3. Principal Components Analysis of soil chemistry — vector loadings on PC1 and PC2.

correlated with either the *mR* or *mN* site indicator values.

### *3.3.3. (De-trended) Canonical Correspondence Analysis (DCCA)*

The first canonical axis was very similar to that produced by COR, and had the same pattern of correlations with the individual soil chemical variables. The internal species-soil chemistry correlation was high ($r$=0.94) (see Fig. 4). The correlation of this component with the *mR* value was of comparable strength ($r$=0.89), suggesting that the Ellenberg species indicator values do have predictive effectiveness under British forest conditions. The next three canonical axes did not appear to be related to any of the soil chemical variables. The (de-trended) correspondence analysis (DCA) produced a first axis correlated with that from DCCA ($r$=0.84). This confirmed that the major trend in ground vegetation species composition was related to soil nutrient regime, independently of the chemical variables measured.

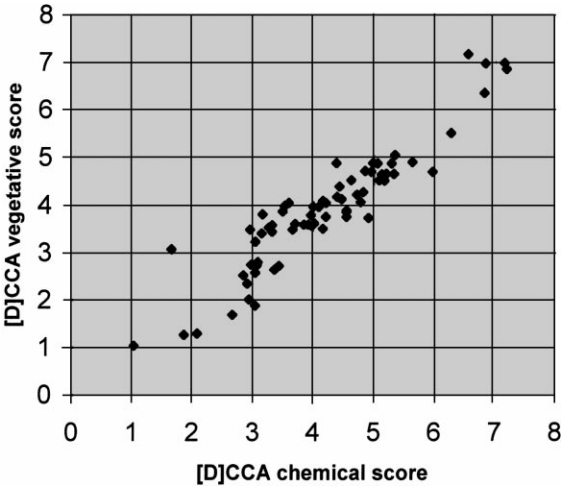



Fig. 4. [D]CCA chemical score v. vegetative score $r$=0.94.

Table 5
Humus types and corresponding soil nutrient classes

| Humus type | Soil nutrient class |
|---|---|
| Mor | Very Poor/Poor |
| Moder | Poor/Medium |
| Oligomull | Medium |
| Mesomull | Medium/Rich |
| Eumull | Very Rich |

### 3.4. Humus types

A wide range of mor, moder and mull humus types was recorded for the sampling sites. The occurrence of these was broadly related to soil nutrient regime as defined by the DCCA first canonical axis and summarised in Table 5. However, there were substantial overlaps in soil nutrient regime between the types, suggesting that other factors such as climate, soil moisture regime or litter chemical composition may influence humus type.

## 4. Discussion

### 4.1. Range of soil nutrient regime sampled

The recorded ranges for the mR and mN indicator values were as follows (as compared to an integer range of 1 to 9 for the individual species indicator values):

*mR* 1.04 to 7.18

*mN* 1.04 to 8.57

This confirmed that a wide range of soil nutrient conditions had been sampled. However, 'carbonate soils', which are expected have very high *mR* values, may have been missed. These were provisionally defined by Pyatt and Suarez (1997) as soils with pH values in the upper 20 cm of 7.5–8.5 but with only moderate $NO_3$-nitrogen supply (i.e. high *mR*, medium *mN*) and usually occurring over limestone or chalk (see also Pyatt (1996)). The highest pH values (in $H_2O$) recorded in the upper or middle layers were 6.5, although pH values over 7.0 were recorded in the lower layer for several of the soils examined.

### 4.2. Basis for the classification of soil nutrient regime

The first canonical axis produced by DCCA, positively correlated with all the individual soil chemical variables measured, excepting $NH_4$-nitrogen and loss-on-ignition, can serve as the gradient of SNR within ESC. It is proposed to divide this gradient into five classes of soil nutrient regime (Very Poor, Poor, Medium, Rich and Very Rich), with the possibility that an additional Carbonate class may be defined after further sampling. The number of classes chosen is essentially a matter of convenience, based on the experience of other comparable schemes (especially BEC), rather than an emergent property of the soil chemistry itself. The delineation of the boundaries between the soil nutrient classes could be based on the occurrence of the main vegetation types described above, on soil types, or on equal sectors of the soil nutrient axis. It is felt that a division based mainly on the occurrence of the National Vegetation Classification communities will facilitate the field recognition of the soil nutrient classes, and will make the integration of the two classifications more straight-forward. This is illustrated in Fig. 5.

The explicitly multivariate nature of the SNR axis is more in accordance with that of the British Columbian BEC, which stresses the importance of nitrogen as well as base status (Klinka et al., 1984, 1989), than

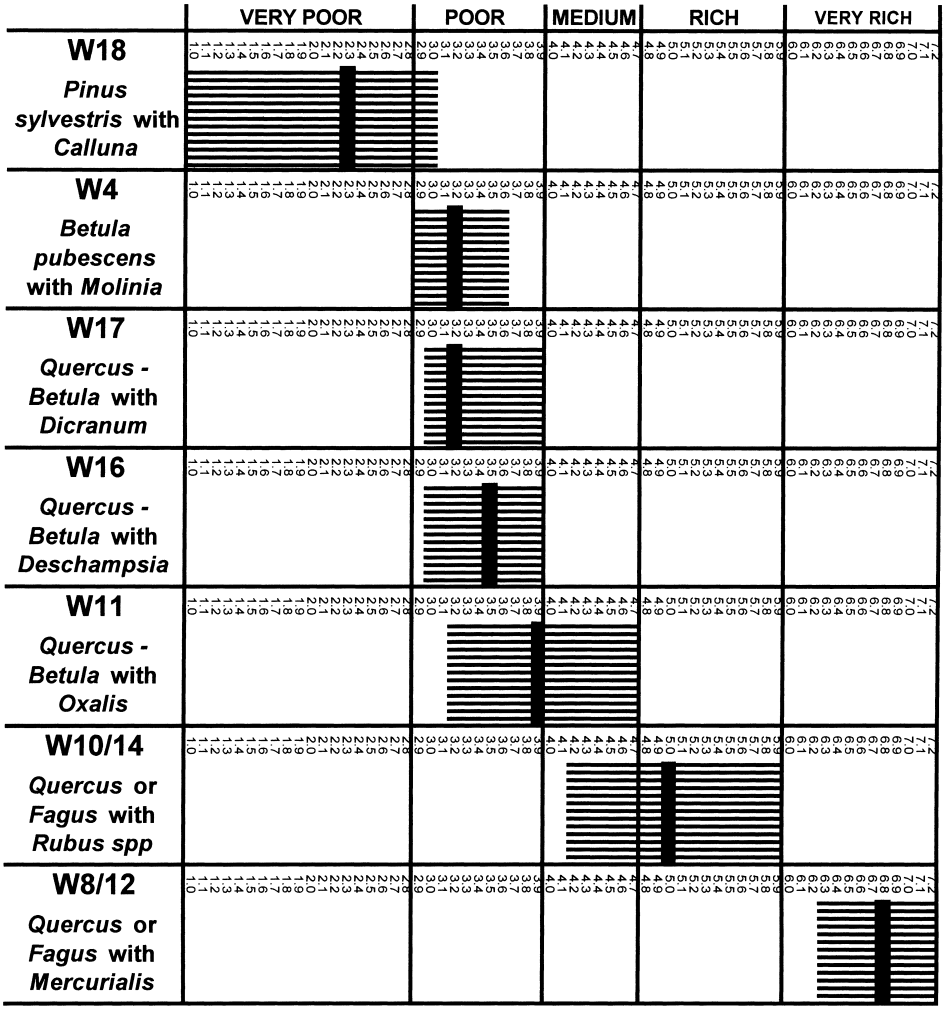



Fig. 5. Occurrence of selected NVC woodland communities in relation to soil nutrient regime.

with the equivalent axes of some European soil quality grids, which are gradients of base status alone (Ellenberg, 1988; Rameau et al., 1989, 1993; Anon., 1991a, b). The advantage of the multivariate nature of SNR is that it is all-encompassing and hence it is unnecessary to recognise separate soil chemical variables that influence plant ecology. For example, some Continental European schemes (e.g. Rameau et al., 1989, 1993) recognise distinct 'indicator plant groups', some of which are defined purely according to their position on an axis of base status, while others are groups of 'nitrophile' species with a high requirement for nitrogen, independently of base status. A possible disadvantage of a multivariate definition of SNR is that it may be difficult to place a given site on the axis on the basis of its soil chemistry alone, due to the overlapping ranges of each of the chemical variables in terms of overall SNR. It may be necessary to add the data for the new site to the existing dataset and carry out the statistical analysis (DCCA) for the whole set before the new site can be evaluated with certainty.

The inclusion of $NO_3$-nitrogen as well as $NH_4$-nitrogen in the evaluation of SNR extends the ideas of Klinka et al. (1989) and has been particularly informative. There appears to be a clear distinction between soils that produce $NO_3$-nitrogen and those

that do not and this is only partly related to base status [see Table 4]. The importance of incubating soils prior to measurement of mineral N had been suggested by previous work; however it was interesting to note that the measures of mineral N made *before* incubation were similarly informative. There is clearly scope for further research into the nitrogen status of forest soils to elucidate the conditions under which different amounts of $NH_4$-nitrogen and $NO_3$-nitrogen are produced.

The correlation between multivariate SNR and the soil pH values was similar, whether the pH was measured in water or calcium chloride. This confirmed the findings of the pilot project (Hawkes et al., 1997) in this regard. No evidence emerged to support the view, held by some soil scientists, especially in Continental Europe, that the pH measure in calcium chloride is inherently more reliable. In British forests, the variability of soil moisture status during the summer may be less than in continental Europe with the result that soil pH is less dependent on the overall ionic concentration of the soil solution.

### *4.3. Use of ground vegetation to predict soil nutrient regime*

The species composition of the ground vegetation can be used to assess soil nutrient regime by the calculation of an abundance-weighted site mean indicator value, in the manner described by Hawkes et al. (1997). The calculations required will be facilitated by a computer 'Decision - Support System' being developed for ESC (Ray et al., 1998). The species indicator values generated by this project, or those provided by Ellenberg et al. (1992), can be used. Indeed there may be an advantage in using both sets of indicator values because only the commonest 40 species encountered in this project are considered to have reliable indicator values (see Fig. 6). To improve the applicability of ESC these scores require to be refined and a greater range of species included. Where the ground vegetation includes substantial amounts of other species, Ellenberg indicator values may give more reliable predictions of soil nutrient regime. Recently Diekmann and Falkengren-Grerup (1998) have offered alternative *N* values for common species in Sweden, values that seem to be more in accord with ours than Ellenberg values.

Subjectively-defined ground vegetation types as listed in Table 2, or alternatively, the NVC communities, can also be used to estimate site position on the soil nutrient gradient, prior to detailed vegetation description (see Fig. 5). The difficulties encountered in matching plots to a single NVC community or sub-community may have resulted from a lower diversity of ground vegetation species within plantations than is often found in more structurally diverse semi-natural woodlands (Peterken, 1993). In the central part of the soil nutrient gradient the characteristic species tend to have broad tolerance ranges, e.g. *Pteridium aquilinum* (L.) Kuhn, *Rubus fruticosus* agg. (L.), *Dryopteris dilatata* (Hoffm.) A. Gray and *Oxalis acetosella* (L.), which makes their association with an individual soil nutrient class less clear. Use of the NVC is therefore more likely to be effective in the Very Poor and Very Rich classes of nutrient regime than in the central three classes. Key indicator species can also be overlaid on the soil quality grid of Fig. 2 to assist in initial site assessment (see Table 7 of Pyatt and Suarez (1997)).

### *4.4. Use of humus type to assess soil nutrient regime*

For our sites, the French humus typology (Jabiol et al., 1995) appeared to be more effective than that from British Columbia (Green et al., 1993), due to its finer resolution of the mull types. A basic classification of humus type can contribute to soil nutrient assessment (Table 5), particularly when taken together with soil type (Fig. 2). This will be most useful where ground vegetation is sparse due to canopy shade conditions or disturbance. Pyatt and Suarez (1997) provided a simplified version of the French typology for this purpose.

The present work has confirmed the broad relationship of humus type to soil nutrient regime as defined here, but there is much scope for further research. In British plantations the humus has rarely reached a state of equilibrium with the mineral soil and litterfall. Ex-arable sites are still accumulating humus layers at the same time as nutrient levels may be falling; heathland or peatland sites have inherited thick humus layers that are now better aerated and breaking down. It is therefore difficult given the present state of knowledge to use humus type as a reliable soil nutrient indicator.

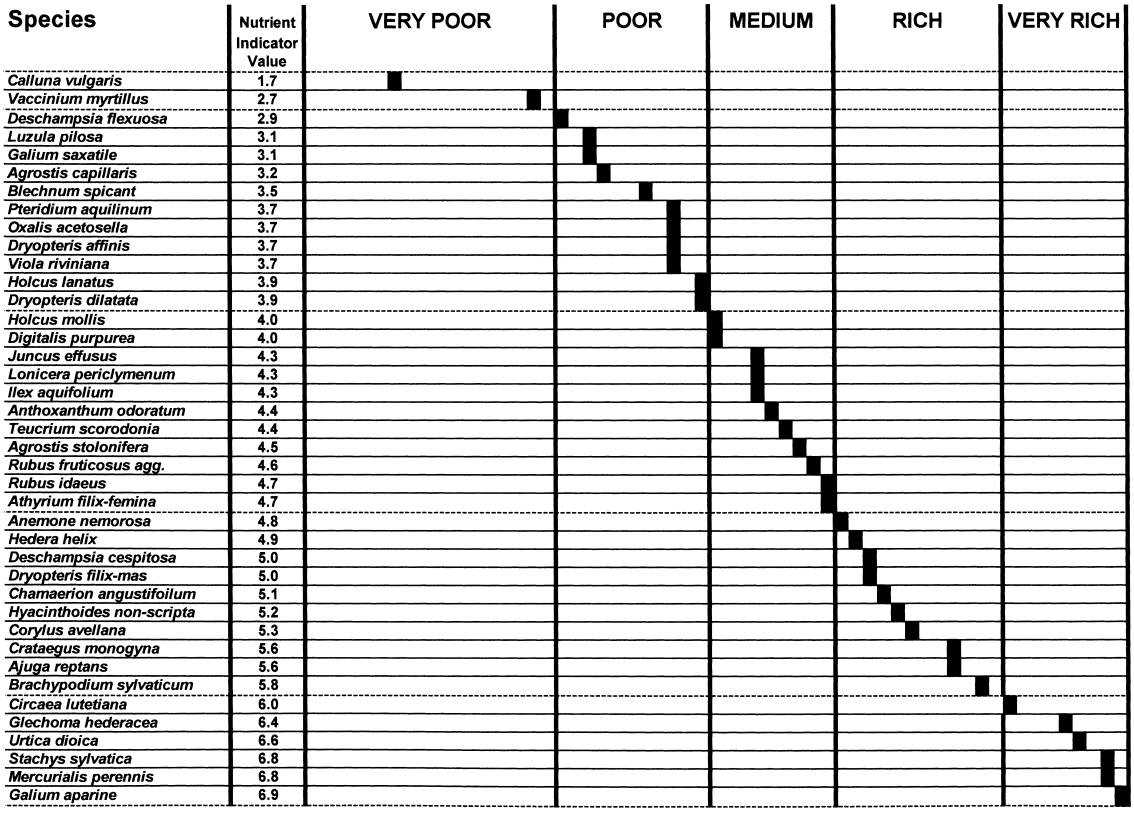



Fig. 6. Common indicator species with soil nutrient indicator values and classes.

## 5. Conclusion

Soil nutrient regime is one of the three 'principal components' of the ESC for British forests and it is desirable that it should be defined on a sound quantitative chemical basis. The work reported in this paper has shown that this is indeed possible. The most important variables within SNR are pH and $NO_3$-nitrogen, at least where phosphorus is in adequate supply. Further, the relative abundance of a small number of common species in the ground vegetation on a site offers a convenient quantitative method of predicting the soil nutrient regime without recourse to soil sampling and chemical analysis. The method can be used either with a new set of species indicator values or Ellenberg indicator values. The nature of the humus layer can give additional support to the estimate of soil nutrient class, especially where ground vegetation is sparse. The relationship of the NVC woodlands to soil nutrient regime has been clarified, although some *Quercus–Betula* and *Fagus* woodlands appear to have overlapping soil nutrient regimes. Further sampling work is required to clarify the relationships between the NVC and the ESC. More research would be beneficial further to elucidate soil nitrogen status, to improve applicability near the extremes of the range of soil nutrient regime and to add to the number of reliable species indicator values.

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