A CLUSTER ANALYSIS APPROACH TO CLASSIFYING IRISH NATIVE WOODLANDS

Philip M. Perrin, James R. Martin, Simon J. Barron and Jenni R. Roche

ABSTRACT

The National Survey of Native Woodlands in Ireland, which was initiated in 2003, will provide two key resources identified in the National Biodiversity Plan: an inventory of native woodlands and a woodland classification system. The project has taken advantage of recent advances in GIS and remote sensing to develop a GIS-based inventory of potentially native woodland sites. Field survey and characterisation of a large subset of these sites is currently ongoing. In this paper, a proposed methodology is presented for developing a national woodland classification based on data from this field survey using current best practice in statistical techniques. The applicability of this method is demonstrated using the data gathered thus far. The method uses hierarchical agglomerative cluster analysis and indicator species analysis with validation using multi-response permutation procedure (MRPP) and non-metric multidimensional scaling ordination (NMS). A two-tier classification system has been produced, with five broad groups of woodland being each divided into a number (between five and eight) of more specific woodland types. The five main vegetation groups were named, using the results of indicator species analysis, as: *Quercus petraea* – *Luzula sylvatica*, *Quercus robur* – *Hedera helix*, *Corylus avellana* – *Thamnobryum alopecurum, Alnus glutinosa* – *Filipendula ulmaria* and *Betula pubescens* – *Molinia caerulea*. This classification defines a greater number of woodland types than previous studies based on the more subjective central European phytosociological approach. However, for applied purposes any evaluation based on the statistical significance of these groups may need to be tempered by ecological significance. It is apparent that the identification of native woodland communities may be hampered by the modified nature of Irish woodlands and the presence of non-native species in particular. With the dataset still expanding, the results must be regarded as preliminary, but it is concluded that this is an effective method for the objective classification of Irish native woodlands.

Philip M. Perrin (corresponding author e-mail: pperrin@botanicalenvironmental.com), James R. Martin, Simon J. Barron and Jenni R. Roche, BEC Consultants Ltd, 27 Upper Fitzwilliam Street, Dublin 2.

INTRODUCTION

Ireland is one of the least forested countries in Europe, with about 9% of its area under forest cover, the majority of which is composed of commercial conifer plantations (Gallagher *et al.* 2001). Only around 1.1% of the country is covered by native woodland, that is woodland dominated by native tree species, and much of this is highly fragmented and modified (Higgins *et al.* 2004). However, a recently launched initiative, the Native Woodland Scheme, seeks to increase this national resource by grant-aiding woodland creation and conservation. The National Biodiversity Plan has set a target for this scheme of 15,000ha of new native woodland, in addition to setting a broader target of increasing the broadleaf component of total annual afforestation to 30% by 2007 (Department of Arts, Heritage, Gaeltacht and the Islands 2002). Other recent projects have looked at the potential for woodland development through natural succession on conifer clearfells (Perrin 2003; Smith *et al*. 2003) and various aspects of native woodland ecology and conservation (e.g. Kelly 2002; Perrin 2002; Coroi *et al*. 2004).

The formulation of national native woodland strategies is, however, hindered by the lack of a detailed and extensive inventory of sites. Previous woodland surveys have concentrated on sites with commercial potential (O'Flanagan 1973; Purcell 1979) and sites of designation quality (An Foras Forbartha 1981) resulting in a lack of knowledge of the smaller or less economically valuable woods, which constitute the vast majority of the country's fragmented resource (Higgins *et al*. 2004). Similarly, ecological research projects have largely been concentrated in a handful of well-known, high conservation status sites, such as the woodlands of the Killarney National Park, Co. Kerry.

Classification of Irish woodlands has essentially followed the phytosociological work of Braun-Blanquet and Tüxen (1952). Subsequent classification studies have each addressed specific types of woodland, for example, acidophilous oak woods (Kelly and Moore 1975; Kelly 1981), woodlands over limestone substrate (Kelly 1981; Kelly and Kirby 1982), esker woodlands (Cross 1992) and wet woodlands (Kelly and Iremonger 1997; Cross and Kelly 2003). These studies have also largely followed the central European phytosociological approach, and an overview of phytosociological associations in Ireland was provided by White and Doyle (1982). In a recent discussion, Jörg (2003) outlined the criticisms of the phytosociological approach, which come largely from population ecologists who question firstly the viability of formally classifying vegetation communities given the individualistic response of plant species to environmental variation, and secondly the subjectivity of the methodology and analysis. However, the potential irrelevance of the first issue from an applied viewpoint was suggested by Erjnæs *et al.* (2004) who stated: 'Today, most researchers acknowledge the individualistic behaviour of plant species, yet admit the usefulness of the study of community and community classification for providing references for ecological studies, vegetation mapping and conservation'. Jörg (2003) urged vegetation scientists to interact with contemporary analytical methods and to look beyond classification for its own sake. In Ireland, Fossitt (2000) developed a relatively simple classification encompassing the range of known woodland types, with an emphasis on ease of application in the field. This 'user-friendly' classification has found considerable favour and has subsequently been refined by Cross (2005). It is, however, largely and subjectively based on the datasets and results of the phytosociological studies previously mentioned. There remains, therefore, the lack of a detailed woodland classification system objectively based on a large dataset that encompasses the breadth of national woodland diversity.

The need for these two key resources, an inventory and a classification system, has been identified in the National Biodiversity Plan (Department of Arts, Heritage, Gaeltacht and the Islands 2002), and in response to this the National Survey of Native Woodlands (NSNW) was initiated in 2003. This project has taken advantage of recent advances in GIS and remote sensing to develop an inventory of potentially native woodland sites. Field survey and characterisation of a large subset of these sites is currently ongoing. In this paper we present a proposed methodology for developing a national woodland classification based on data from this field survey using current best practice in statistical techniques. The applicability of this method is demonstrated using the data gathered thus far; it should be emphasised that this is the primary purpose of this paper and that the results as they pertain to vegetation types are very much preliminary. The method uses hierarchical cluster analysis, an objective technique that has long been applied to a wide variety of ecological scenarios (e.g. Williams *et al*. 1966; Stocker *et al.* 1977; Baeur 1989; Yom-Tov and Radmon 1998; Hupalo *et al.* 2000; Miserere *et al.* 2003), but has yet to be used extensively in the study of Irish vegetation.

METHOD

SITE SELECTION

The Forest Inventory Planning System 1998 (FIPS) was used as the primary data source for the site selection process. FIPS is a GIS platform running in ArcView that has digitally mapped all forested areas (parcels) ≥ 0.2ha in Ireland (Fig. 1a; Gallagher *et al*. 2001). It was developed using a combination of satellite (Landsat Thematic Mapper) imagery taken between 1993 and 1997 and a series of ortho-corrected panchromatic aerial photographs taken in 1995 (Gallagher *et al*. 2001). To focus in on putative native woodland sites, a modification to FIPS was developed (Fig. 1b; Higgins *et al*. 2004). This comprised three main steps. Parcels labelled with non-relevant class categories (mainly 'Conifer forest' or 'Cleared') were removed, leaving only parcels designated as either 'Broadleaf' or 'Mixed forest'. For each of these class categories, contiguous parcels were joined using a conventional dissolve procedure. Finally, parcels falling below the minimum threshold for inclusion in this survey (0.98ha in area and 40m in width) were removed.

From this modified FIPS platform a subset of sites was selected for field survey within each of the counties chosen for inclusion in the first two years of the project. These were counties in the east and north of the country, where information on native woodlands was relatively scarce. Sites were selected to encompass a range of sizes and to ensure a wide geographical spread, and sites of various ownership and designation status were included. In addition, a small number of non-FIPS sites were identified by manual inspection of aerial photographs or in the field; this was to compensate for the degree of inaccuracy that is inherent in FIPS (Gallagher *et al.* 2001).

FIELD SURVEY

Fieldwork was conducted between April and September 2003 and between July and September 2004. At each site a general site-level survey was conducted (for details see Higgins *et al.* 2004), during which areas of different woodland type were identified and mapped. This was a broad-scale procedure such that areas of markedly different species composition or tree structure were differentiated. Within each area, a $10\text{m} \times 10\text{m}$ relevé was subjectively placed to represent the vegetation of that woodland type. Within each relevé, vascular plants and bryophytes were

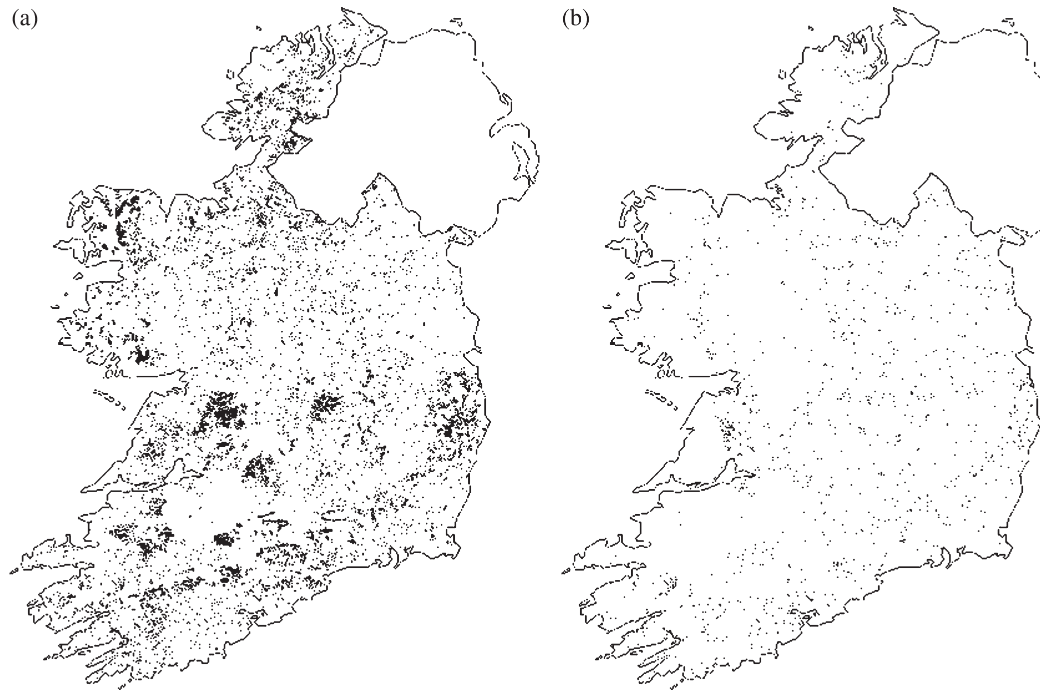

Fig. 1 — (a) Total forest cover in the Republic of Ireland as defined by FIPS 1998 (Gallagher *et al.* 2001); (b) broadleaf and mixed woodland cover in the Republic of Ireland as modified from FIPS 1998 by Higgins *et al.* (2004).

recorded and scored on the Domin cover scale and a habitat type was assigned using Fossitt (2000). Vascular plant nomenclature followed Stace (1997), while bryophyte nomenclature followed Smith (2004) for mosses and Paton (1999) for liverworts. Soil type was recorded following the Great Soil Groups of Gardiner and Radford (1980). Slope and altitude were recorded and five 10cm deep soil samples were taken from each relevé and bulked in the field. Soil pH was recorded using field-fresh material, while total P and % organic content were subsequently measured in the laboratory after air-drying. Total plant species richness was calculated for each relevé.

The dataset was supplemented with the inclusion of relevés from two pilot studies to the NSNW. These consisted of a survey of the eastern half of County Offaly conducted in summer 2001 (van der Sleesen and Poole 2002) and a survey of woodlands in three SACs (Lough Forbes Complex, Co. Longford; River Barrow – River Nore, Co. Wexford and Co. Kilkenny; Unshin River, Co. Sligo) conducted in summer 2000 (Browne *et al*. 2000). Site selection for these two studies was conducted using 1:50,000 and 1:10,560 maps, aerial photography and field observations; FIPS was not used. However, the field methodology used in the pilot studies is directly comparable with that being used in the main survey, with the exception that no *a priori* classification using Fossitt (2000) was conducted.

Data preparation and analysis

The analysed dataset consisted of 518 relevés (145 from the two pilot studies and 373 from the main survey). Outlier analysis had indicated that a small number of samples (approx. five relevés) could be regarded as outliers. These all consisted of riparian or lakeshore sites containing unusual combinations of *Salix* spp. As these fell within the target population of the survey and the methodology includes measures to reduce their influence, they were retained at this preliminary stage. To reduce noise within the dataset, species occurring in less than three relevés were deleted, reducing the total number of species from 467 to 307.

A suite of complementary statistical techniques was used to analyse the dataset. Analysis was conducted using PC-ORD 4 (MjM Software, Oregon).

The main method selected for grouping the data into vegetation types was hierarchical, polythetic, agglomerative cluster analysis. From a data matrix of n samples $\times\, p$ species, an $n \times n$ distance matrix is calculated by measuring the dissimilarity (or similarity) between each pair of samples. The most similar samples, which are selected using a predetermined criterion of minimum distance (linkage method), are merged into a group and their attributes are combined. The procedure is repeated $n-1$ times until the samples have been merged (clustered) into two groups, with the results being displayed as a dendrogram (McCune and

Grace 2002). Quantitative Sørensen (Bray-Curtis) was selected as the distance measure, as it has been shown to be one of the most effective measures for ecological community analysis, being less prone to exaggerating the influence of outliers and retaining greater sensitivity with heterogeneous datasets (McCune and Grace 2002). Flexible beta was used as the linkage method with $\beta = -0.25$ (Lance and Williams 1967). This option is compatible with Sørensen distance and is space-conserving, i.e. properties in theoretical space defined by the original dissimilarity matrix are preserved as groups form during the cluster procedure. Space-distorting strategies can lead to undesirable effects such as high levels of chaining—the sequential addition of single items to existing groups (Legendre and Legendre 1998; McCune and Grace 2002).

Hierarchical clustering was chosen over two other popular classification methods: TWINSPAN (Two Way Indicator Species Analysis) and K-means clustering. Serious weaknesses in the TWINSPAN method have previously been highlighted, not least its poor performance with heterogeneous datasets containing more than one important gradient and the loss of information from quantitative data inherent in the 'pseudospecies' concept (Belbin and McDonald 1993; Legendre and Legendre 1998). The lack of dimensionality in dendrograms resulting from hierarchical clustering is, conversely, an advantage when dealing with heterogeneous datasets (McCune and Grace 2002). A more valid alternative is K-means clustering, a non-hierarchical cluster technique. The K-means method is not suitable for directly clustering most ecological datasets, however, as it employs the Euclidean distance measure (Legendre and Legendre 1998).

Indicator Species Analysis (ISA; Dufrene and Legendre 1997) was used as an objective tool to determine at what level the dendrogram resulting from the hierarchical clustering should be cut, i.e. what is the optimal number of final groups. ISA produces percentage indicator values (IndVals) for species and works on the concept that for a predetermined grouping of samples, an ideal indicator species will be found exclusively within one group and will be found in all the samples in that group. IndVals are thus a simple combination of measures of relative abundance between groups and relative frequency within groups. At any given level of clustering, species are assigned to the group for which their IndVal is maximal; the significance of this assignment is tested using Monte Carlo randomisations. Dufrene and Legendre (1997) concluded that ISA was more sensitive at identifying indicator species than TWINSPAN and also suggested that this method could be used as a stopping rule for clustering, as IndVals will be low when groups are too finely or too broadly defined, peaking at some intermediate, most informative level of clustering. ISA was run on the output from the hierarchical clustering cycles yielding 2–30 groups with 1000 randomisations used in the Monte Carlo tests. Number of significant indicators ($p \leq 0.05$) and average p-value were selected as criteria (McCune and Grace 2002).

To test for significant differences between the groupings determined by the hierarchical clustering and ISA, multi-response permutation procedure (MRPP) was employed. This is essentially a non-parametric multivariate test and thus avoids the normality requirements of parametric multivariate tests such as discriminant analysis (McCune and Grace 2002). As it is statistically inappropriate to test for differences between groups using the same variables used to define them, MRPP was run on a matrix of five environmental variables: pH, total P, % organic content, slope and altitude. In addition to a p-value, MRPP produces a statistic A that describes chance-corrected within-group heterogeneity. $A = 1$ when all samples within groups are identical, $A = 0$ when heterogeneity within groups equals expectation by chance and $A < 0$ when within-group heterogeneity is less than that expected by chance. Euclidean distance was used following relativisation of columns to standard deviates (McCune and Grace 2002).

Non-metric multidimensional scaling (NMS) was used to illustrate the relationships between relevés and between relevés and environmental variables. This iterative ordination technique is particularly well suited for analysis of ecological community data as it works well with non-normal datasets, allows the use of non-Euclidean distance measures and does not assume that species have linear or unimodal responses to environmental gradients (McCune and Grace 2002). Being based on ranked distances, NMS is less prone to distortion due to outliers. For ecological analysis, NMS has been recommended over the more widely used Detrended Correspondence Analysis (DCA) method, which has been seriously criticised by several authors (e.g. Minchin 1987; Legendre and Legendre 1998; McCune and Grace 2002). The 'slow and thorough' option in PC-ORD was used with Quantitative Sørensen (Bray-Curtis) distance and varimax rotation. The use of this distance measure permits ready comparison of the results with those of the hierarchical cluster analysis.

To produce a more detailed analysis of the diversity of native woodland vegetation, the hierarchical cluster analysis/ISA approach was then repeated in turn for each of the relevé subsets defined by the groups achieved through the first round of clustering. Thus a two-tier classification was produced with several broad groups each divided into a number of more detailed sub-groups.

RESULTS

MAIN GROUPS

ISA indicated that the five group stage of the cluster analysis was the most informative, as this was the level with the maximum number of significant indicators and the lowest average p-value (Fig. 2). MRPP indicated that there were significant differences between these groups in the environmental matrix ($A = 0.1545$; $p < 0.001$). Abbreviated floristic tables for these five groups together with summary environmental data are presented in Tables 1–5. Each group was named after the tree species and non-tree species with the highest IndVals within that group; these names are simply intended to succinctly distinguish and describe the related vegetation data: no direct reference to other classification systems is implied. A brief description of each group follows:

Quercus petraea–Luzula sylvatica **group** (Table 1): This vegetation type generally occurs on acid soils of medium organic content and low total P on sloping ground. Predominant soil types are brown earths, grey brown podzolics and brown podzols. The most frequent tree species are *Ilex aquifolium*, *Fagus sylvatica*, *Quercus petraea*, *Corylus avellana* and *Betula pubescens*. Frequent and potentially dominant species (maximum Domin score ≥ 8) in the field layer are *Hedera helix*, *Rubus fruticosus*, *Dryopteris dilatata*, *Hyacinthoides non-scripta*, *Luzula sylvatica* and *Vaccinium myrtillus*. Other frequent field layer species are *Lonicera periclymenum*, *Oxalis acetosella*, *Blechnum spicant* and *Pteridium aquilinum*. Frequent bryophytes include *Isothecium myosuroides*, *Kindbergia praelonga* and *Eurhynchium striatum*.

Quercus robur–Hedera helix **group** (Table 2): This vegetation type generally occurs on mildly acidic to basic soils of low organic content and medium total P on flat or shallowly sloping ground. Predominant soil types are grey brown podzolics and brown earths. The most frequent tree species are *Fraxinus excelsior*, *Quercus robur*, *Crataegus monogyna*, *Ilex aquifolium*, *Corylus avellana*, *Fagus sylvatica* and *Acer pseudoplatanus*. Frequent and potentially dominant species in the field layer are *Hedera helix*, *Rubus fruticosus*, *Circaea lutetiana*, *Hyacinthoides non-scripta* and *Polystichum setiferum*. Other frequent field layer species are *Lonicera periclymenum*, *Dryopteris dilatata*, *Arum maculatum* and *Viola riviniana/reichenbachiana*. Frequent bryophytes are *Thuidium tamariscinum*, *Kindbergia praelonga* and *Eurhynchium striatum*. Compared to the other four groups this group is less well defined by ISA, with indicators being few and with low IndVal scores.

Corylus avellana–Thamnobryum alopecurum **group** (Table 3): This vegetation type shares many of the environmental characteristics of the *Quercus robur–Hedera helix* group but is generally found on more base-rich soils. *Fraxinus excelsior* is still the most frequent tree species. *Corylus avellana* and *Crataegus monogyna* are more frequent than in the previous group, while *Quercus robur*, *Fagus sylvatica* and *Acer pseudoplatanus* occur less often. The field layer is broadly similar, with *Hedera helix*, *Rubus fruticosus*, *Circaea lutetiana*, *Geranium robertianum* and *Oxalis acetosella* frequent and potentially dominant. Other frequent field layer species are *Geum urbanum*, *Viola riviniana/reichenbachiana*, *Dryopteris dilatata*, *Veronica montana* and *Primula vulgaris*. *Lonicera periclymenum* is still frequent but markedly less so than in the previous group. Frequent and potentially dominant in the ground layer are *Thamnobryum alopecurum*, *Thuidium tamariscinum*, *Eurhynchium striatum* and *Kindbergia praelonga*. This group is characterised by higher species richness than the previous two groups.

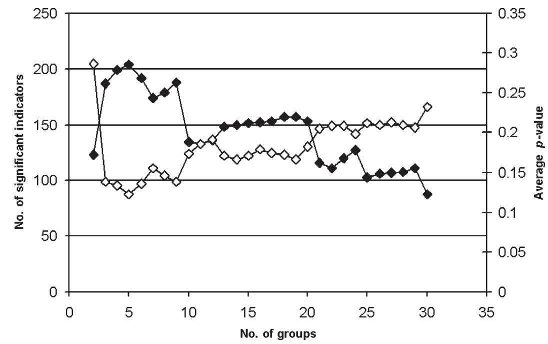

Fig. 2—Variation in the number of significant indicators (closed diamonds) identified by ISA and the average p-value of all species (open diamonds) at each step of hierarchical cluster analysis of the main dataset.

Alnus glutinosa–Filipendula ulmaria **group** (Table 4): This species-rich vegetation type generally occurs on base-rich, gleyed soils with medium organic content and high total P, on fairly flat ground. The most frequent tree species are *Alnus glutinosa*, *Fraxinus excelsior*, *Salix cinerea* and *Crataegus monogyna*. Frequent and potentially dominant species in the field layer are *Filipendula ulmaria*, *Carex remota*, *Galium palustre*, *Urtica dioica*, *Phalaris arundinacea*, *Circaea lutetiana* and *Caltha palustris*. *Hedera helix* and *Rubus fruticosus* are still common but markedly less frequent than in the other four groups. Other frequent field layer species are *Ranunculus repens*, *Angelica sylvestris*, *Mentha aquatica*, *Dryopteris dilatata*, *Chrysosplenium oppositifolium*, *Rumex sanguineus* and *Senecio aquaticus*. The most frequent bryophytes are *Kindbergia praelonga*, *Calliergonella cuspidata* and *Rhizomnium punctatum*. This group is particularly well defined by ISA with a number of high IndVal scores.

Betula pubescens–Molinia caerulea **group** (Table 5): This vegetation type generally occurs on acidic basin peats with high organic content and low total P, on fairly flat ground. *Betula pubescens* is almost ubiquitous. Other frequent trees are *Ilex aquifolium*, *Salix cinerea*, *Sorbus aucuparia* and

Fraxinus excelsior. Frequent and potentially dominant field layer species are *Rubus fruticosus*, *Hedera helix*, *Dryopteris dilatata* and *Molinia caerulea*. Other frequent field layer species are *Lonicera periclymenum*, *Pteridium aquilinum*, *Blechnum spicant* and *Potentilla erecta*. Frequent bryophytes include *Thuidium tamarascinum*, *Kindbergia praelonga*, *Pseudoscleropodium purum*, *Eurhynchium striatum*, *Hypnum cupressiforme*, *Lophocolea bidentata* and *Frullania dilatata*.

Table 1—Abbreviated floristic table and mean environmental data for the *Quercus petraea* – *Luzula sylvatica* group.

Species	*Freq.*	*Max.*	*IndVal*
Hedera helix	93.3	9	
Rubus fruticosus	90.7	10	
Dryopteris dilatata	90.7	8	28
Lonicera periclymenum	86.7	6	27
Ilex aquifolium	85.3	9	34
Thuidium tamariscinum	66.7	6	
Isothecium myosuroides	61.3	4	29
Fagus sylvatica	58.7	10	25
Quercus petraea	48.0	10	39
Kindbergia praelonga	46.7	5	
Oxalis acetosella	45.3	7	16
Hyacinthoides non-scripta	42.7	9	
Luzula sylvatica	41.3	10	29
Corylus avellana	37.3	8	
Betula pubescens	36.0	8	
Sorbus aucuparia	36.0	6	
Blechnum spicant	36.0	5	14
Acer pseudoplatanus	33.3	6	
Eurhynchium striatum	33.3	7	
Pteridium aquilinum	33.3	6	
Quercus robur	32.0	9	
Hypnum andoi	32.0	4	11
Hypnum cupressiforme	32.0	4	
Mnium hornum	32.0	3	12
Polytrichastrum formosum	30.7	4	
Fraxinus excelsior	29.3	8	
Vaccinium myrtillus	29.3	8	17
Dryopteris affinis	29.3	4	
Crataegus monogyna	28.0	5	
Polypodium vulgare	24.0	3	

	Mean	*Soil type*
Species richness	20	
pH	4.6	45% brown earths
% organic content	29	20% grey brown podzolics
Soil total P (mg g^{-1})	0.68	
Altitude (m)	80	19% brown podzols
Slope (°)	16	16% others

Freq. indicates % frequency occurrence.
Max. indicates maximum Domin score.
IndVal indicates % indicator value as determined by ISA.
$n = 75$.

A reasonable overall correlation is shown by a comparison of these groups with the *a priori* assignments using Fossitt (2000) (Table 6). Within the *Quercus robur* – *Hedera helix* group, 58% of relevés had been classified as oak–ash–hazel woodland (WN2), but 34% had been classified as significantly modified (WD1 or WD2). Similarly, while 61% of the *Quercus petraea* – *Luzula sylvatica* relevés had been classified as oak–birch–holly woodland (WN1), 23% had been classified as modified, due primarily to the presence of beech (*Fagus sylvatica*). Of the *Corylus avellana* – *Thamnobryum alopecurum* group, the majority of relevés (68%) had been classified as WN2, but this group included a very broad range

Table 2 — Floristic table and mean environmental data for the *Quercus robur* – *Hedera helix* group.

Species	*Freq.*	*Max.*	*IndVal*
Hedera helix	96.7	10	27
Fraxinus excelsior	90.1	10	
Rubus fruticosus	89.0	10	
Quercus robur	78.0	10	39
Lonicera periclymenum	71.4	6	
Crataegus monogyna	59.3	8	
Thuidium tamariscinum	58.2	7	
Dryopteris dilatata	54.9	7	
Ilex aquifolium	53.8	7	
Corylus avellana	50.5	10	
Fagus sylvatica	50.5	10	
Kindbergia praelonga	50.5	7	
Acer pseudoplatanus	48.4	9	21
Circaea lutetiana	45.1	8	
Hyacinthoides non-scripta	45.1	9	21
Eurhynchium striatum	42.9	6	
Polystichum setiferum	42.9	8	19
Arum maculatum	36.3	3	19
Viola riviniana/reichenbachiana	33.0	5	
Geum urbanum	33.0	3	
Thamnobryum alopecurum	29.7	6	
Dryopteris filix-mas	28.6	5	
Dryopteris affinis	28.6	5	9
Geranium robertianum	27.5	7	
Veronica montana	23.1	3	
Neckera complanata	23.1	3	
Rosa canina	22.0	5	21
Carex remota	18.7	7	
Sambucus nigra	18.7	7	8
Phyllitis scolopendrium	18.7	3	

	Mean	*Soil type*
Species richness	21	
pH	5.8	51% grey brown podzolics
% organic content	18	
Soil total P (mg g^{-1})	0.81	31% brown earths
Altitude (m)	71	12% gleys
Slope (°)	11	6% others

Freq. indicates % frequency occurrence.
Max. indicates maximum Domin score.
IndVal indicates % indicator value as determined by ISA.
$n = 91$.

of *a priori* assignments. Most of the wet pedunculate oak–ash woodland relevés (WN4) are shared between this group and the *Alnus glutinosa* – *Filipendula ulmaria* group, which also includes the majority (68%) of relevés classified as either riparian (WN5) or wet willow–alder–ash (WN6). It can be seen that the *Betula pubescens* – *Molinia caerulea* group includes relevés from woodlands on cutover raised bog (WN7) and WN1. Note that WN3 is absent from this table, as this is the rare *Taxus baccata* woodland type found at only a few sites in the west of Ireland (Perrin 2002).

Table 3—Abbreviated floristic table and mean environmental data for the *Corylus avellana* – *Thamnobryum alopecurum* group.

Species	*Freq.*	*Max.*	*IndVal*
Hedera helix	95.2	10	
Fraxinus excelsior	91.7	10	32
Rubus fruticosus	85.5	9	
Crataegus monogyna	82.1	10	31
Corylus avellana	77.9	10	37
Geum urbanum	72.4	5	40
Thamnobryum alopecurum	71.0	8	42
Thuidium tamariscinum	71.0	8	
Viola riviniana/reichenbachiana	65.5	5	34
Eurhynchium striatum	64.1	8	22
Kindbergia praelonga	62.8	7	16
Dryopteris dilatata	58.6	5	
Circaea lutetiana	56.6	8	23
Geranium robertianum	53.1	8	23
Ilex aquifolium	52.4	8	
Hypnum cupressiforme	50.3	5	18
Lonicera periclymenum	49.7	5	
Neckera complanata	49.0	4	23
Veronica montana	45.5	4	23
Quercus robur	39.3	9	
Oxalis acetosella	38.6	8	
Primula vulgaris	38.6	6	30
Plagiomnium undulatum	38.6	4	16
Polystichum setiferum	38.6	9	
Carex sylvatica	36.6	4	17
Hyacinthoides non-scripta	34.5	10	
Arum maculatum	33.1	3	
Filipendula ulmaria	31.7	8	
Acer pseudoplatanus	31.0	10	
Potentilla sterilis	31.0	4	18

	Mean	*Soil type*
Species richness	30	
pH	6.3	63% grey brown podzolics
% organic content	19	
Soil total P (mg l^{-1})	0.78	17% brown earths
Altitude (m)	75	14% gleys
Slope (°)	10	6% others

Freq. indicates % frequency occurrence.
Max. indicates maximum Domin score.
IndVal indicates % indicator value as determined by ISA.
$n = 145$.

NMS found a two-dimensional solution (Fig. 3). The two axes represent 70% of variance in the dataset (axis 1: $r^2 = 0.379$; axis 2: $r^2 = 0.318$). Stress on this solution was 23.54%, which is rather high, but probably indicates a good solution given the large size of the dataset (McCune and Grace 2002). There is, overall, good separation of the five broad groups

Table 4—Abbreviated floristic table and mean environmental data for the *Alnus glutinosa – Filipendula ulmaria* group.

Species	*Freq.*	*Max.*	*IndVal*
Alnus glutinosa	85.9	9	64
Filipendula ulmaria	80.0	9	54
Fraxinus excelsior	76.5	9	
Salix cinerea	75.3	9	41
Hedera helix	64.7	5	
Rubus fruticosus	61.2	9	
Carex remota	58.8	8	30
Ranunculus repens	54.1	6	36
Kindbergia praelonga	54.1	7	
Galium palustre	52.9	8	36
Iris pseudacorus	49.4	7	48
Crataegus monogyna	48.2	5	
Angelica sylvestris	44.7	5	35
Urtica dioica	43.5	8	30
Mentha aquatica	42.4	4	38
Dryopteris dilatata	41.2	7	
Agrostis stolonifera	37.6	10	18
Phalaris arundinacea	37.6	8	36
Chrysosplenium oppositifolium	36.5	7	20
Circaea lutetiana	35.3	8	
Rumex sanguineus	34.1	6	20
Calliergonella cuspidata	34.1	8	21
Senecio aquaticus	32.9	5	29
Polypodium vulgare	30.6	3	10
Thuidium tamariscinum	30.6	6	
Geum urbanum	29.4	3	
Caltha palustris	29.4	8	29
Hypnum cupressiforme	28.2	4	
Rhizomnium punctatum	28.2	7	21
Geranium robertianum	27.1	4	

	Mean	*Soil type*
Species richness	30	
pH	6.5	51% gleys
% organic content	33	12% basin peats
Soil total P (mg g^{-1})	1.11	11% grey brown podzolics
Altitude (m)	52	11% brown earths
Slope (°)	2	15% other

Freq. indicates % frequency occurrence.
Max. indicates maximum Domin score.
IndVal indicates % indicator value as determined by ISA.
$n = 85$.

particularly for the *Alnus glutinosa* – *Filipendula ulmaria* and *Betula pubescens* – *Molinia caerulea* groups. The greatest degree of overlap occurs between the *Quercus robur* – *Hedera helix* and *Corlyus avellana* – *Thamnobryum alopecurum* groups.

SUB-GROUPS

ISA cannot be used when one of the clusters contains a single sample: as this point was reached at different stages in the clustering cycle for each of the main groups, the range of clustering steps

Table 5—Abbreviated floristic table and mean environmental data for the *Betula pubescens* – *Molinia caerulea* group.

Species	*Freq.*	*Max.*	*IndVal*
Betula pubescens	99.2	10	64
Rubus fruticosus	94.3	10	23
Thuidium tamariscinum	86.9	10	27
Hedera helix	82.8	8	
Dryopteris dilatata	78.7	9	
Ilex aquifolium	67.2	7	
Kindbergia praelonga	62.3	9	
Salix cinerea	59.0	8	
Lonicera periclymenum	57.4	5	
Pseudoscleropodium purum	50.8	8	45
Molinia caerulea	50.0	10	45
Sorbus aucuparia	44.3	8	22
Eurhynchium striatum	43.4	7	
Hypnum cupressiforme	41.8	4	
Pteridium aquilinum	39.3	5	17
Polytrichastrum formosum	39.3	6	21
Lophocolea bidentata	38.5	2	15
Frullania dilatata	35.2	2	12
Fraxinus excelsior	31.1	8	
Blechnum spicant	29.5	5	
Crataegus monogyna	25.4	7	
Potentilla erecta	24.6	3	21
Juncus effusus	23.8	4	
Viola riviniana/reichenbachiana	23.0	3	
Hypnum jutlandicum	23.0	5	11
Agrostis stolonifera	22.1	6	
Ulota bruchii/crispa	21.3	2	8
Galium palustre	21.3	4	
Anthoxanthum odoratum	20.5	6	16
Oxalis acetosella	20.5	6	

	Mean	*Soil type*
Species richness	24	
pH	4.9	66% basin peats
% organic content	71	11% gleys
Soil total P (mg g^{-1})	0.66	23% others
Altitude (m)	81	
Slope (°)	3	

Freq. indicates % frequency occurrence.
Max indicates maximum Domin score.
IndVal indicates % indicator value as determined by ISA.
n = 122.

examined for definition of the sub-groups varied (Fig. 4). The optimal step of the clustering procedure was not clear-cut for some of the subsets due to the non-unimodal response of the criteria (e.g. the *Corlyus avellana* – *Thamnobryum alopecurum* subset, Fig. 4c). Using a combination of the two criteria, the following number of sub-groups was decided upon: *Quercus petraea* – *Luzula sylvatica*, 5; *Quercus robur* – *Hedera helix*, 5; *Corylus avellana* – *Thamnobryum alopecurum*, 5; *Alnus glutinosa* – *Filipendula ulmaria*, 8; *Betula pubescens* – *Molinia caerulea*, 7. It is, however, beyond the scope of this paper to present the details of each of these groups.

DISCUSSION

CLASSIFICATION

Comparison of the groupings defined by this preliminary analysis can be made with relevant existing classifications. The *Quercus petraea* – *Luzula sylvatica* group corresponds largely with the acidophilous high forest of the *Blechno*–*Quercetum* association described for Ireland by Kelly and Moore (1975), chiefly the *coryletosum* sub-association with some minor elements of the *typicum* subassociation. The *scapanietosum* sub-association, which is confined to higher rainfall areas in the west of the country, is not present. Comparable groups within the British National Vegetation Classification (NVC; Rodwell 1991) are W10 *Quercus robur* – *Pteridium aquilinum* – *Rubus fruticosus*, W11 *Quercus petraea* – *Betula pubescens* – *Oxalis acetosella*, W14 *Fagus sylvatica* – *Rubus fruticosus*, W15 *Fagus sylvatica* – *Deschampsia flexuosa* and W16 *Quercus* spp – *Betula* spp – *Deschampsia flexuosa* woodland.

Both the *Quercus robur* – *Hedera helix* group and the *Corylus avellana* – *Thamnobryum alopecurum* groups are comparable to the *Corylo*–*Fraxinetum* association described by Kelly and Kirby (1982). The former group is similar to the species-poor high forests of the *typicum* subassociation and the latter has some affinities with the scrub woodlands of the *neckerotosum* subassociation; both groups have elements that may be related to the *veronicetosum* and *deschampsietosum* sub-associations. Within the NVC these groups are referable to W7 *Alnus glutinosa* – *Fraxinus excelsior* – *Lysimachia vulgaris,* W8 *Fraxinus excelsior* – *Acer campestre* – *Mercurialis perennis*, W9 *Fraxinus excelsior* – *Sorbus aucuparia* – *Mercurialis perennis* and W12 *Fagus sylvatica* – *Mercurialis perennis* woodland, with the noteworthy difference that *Mercurialis perennis* is of limited distribution and uncertain native status in Ireland (Preston *et al*. 2002).

The *Alnus glutinosa* – *Filipendula ulmaria* group contains many of the wet woodland associations described in Kelly and Iremonger (1997) and Cross and Kelly (2003): the *Salicetum albae* association of riparian communities, the *Osmundo* – *Salicetum* association of stagnant carr, the broader *Carici remotae* – *Fraxinetum* association and some elements of the *Corylo* – *Fraxinetum deschamp-sietosum*. This group comprises elements of several NVC communities: W1 *Salix cinerea* – *Galium palustre*, W2 *Salix* cinerea – *Betula pubescens* – *Phragmites australis*, W3 *Salix pentandra* – *Carex rostrata*, W5 *Alnus glutinosa* – *Carex paniculata* and W6 *Alnus glutinosa* – *Urtica dioica*. Wetter elements of W7 *Alnus glutinosa* – *Fraxinus excelsior* – *Lysimachia vulgaris* woodland are also referable to this group.

Finally, the *Betula pubescens* – *Molinia caerulea* group, which consists largely of stands on degraded raised bogs, is readily comparable to the W4 *Betula pubescens* – *Molinia caerulea* community of the NVC. Drier stands on milled bogs correspond well with the

Table 6—Confusion table comparing group assignment of relevés using hierarchical clustering with *a priori* classification using the woodland categories of Fossitt (2000). Figures are number of relevés.

	Quercus petraea – *Luzula sylvatica*	*Quercus robur* – *Hedera helix*	*Corylus avellana* – *Thamnobryum alopecurum*	*Alnus glutinosa* – *Filipendula ulmaria*	*Betula pubescens* – *Molinia caerulea*
WN1 Oak–birch–holly	35	2	1		12
WN2 Oak–ash–hazel	8	38	77	1	4
WD1 Modified mixed broadleaf	11	17	10		1
WD2 Modified mixed conifer	2	5	6	1	
WN4 Wet pedunculate oak–ash		2	5	6	
WN5 Riparian			3	12	4
WN6 Wet willow–alder–ash		1	9	40	7
WN7 Bog woodland	1		1		46
WS Scrub & Immature woodland			1		4

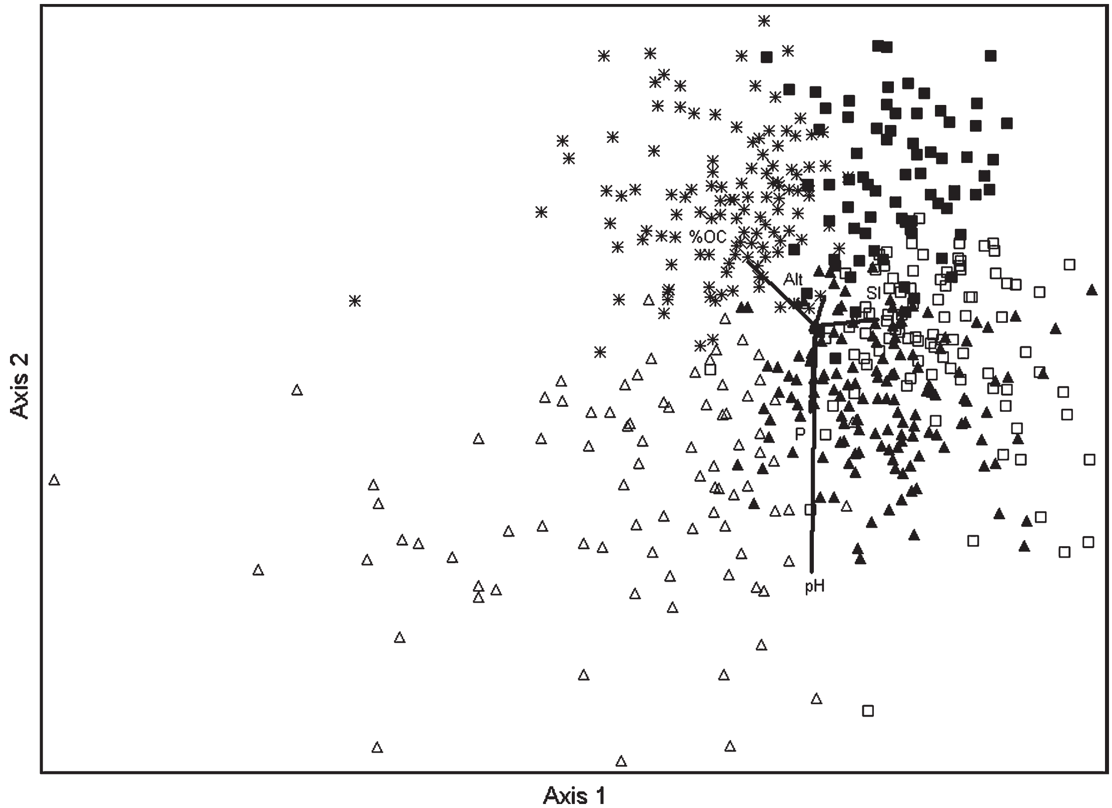

Fig. 3 — NMS ordination of 518 woodland relevés. Symbols indicate broad groups defined by hierarchical clustering and ISA: *Quercus petraea* – *Luzula sylvatica* = closed squares, *Quercus robur* – *Hedera helix* = open squares, *Corylus avellana* – *Thamnobryum alopecurum* = closed triangles, *Alnus glutinosa* – *Filipendula ulmaria* = open triangles, *Betula pubescens* – *Molinia caerulea* = stars. Lines indicate correlation with environmental variables with length of lines indicating strength of correlation. % OC = % organic content; Alt = altitude; Sl = slope; P = total P (mg l^{-1})

W4a *Dryopteris dilatata* – *Rubus fruticosus* sub-community. Cross and Kelly (2003) refer these to the *Vaccinio uliginosi* – *Betuletum pubescentis* association. However, this group also contains relevés from many wetter stands, often on smaller bog sites that have been damaged in the past from hand-cutting. These tend to be more species diverse with a strong *Salix cinerea* component and correspond with the W4b *Juncus effusus* sub-community.

In an international context, the definition of only five broad groups of woodland vegetation may at first appear to be somewhat low. There are several factors that may be of influence here. Firstly, there are undoubtedly deficiencies in the dataset, as only a portion of the country has been surveyed to date. Upland regions and the oceanic woods of the western parts of the country are presently poorly represented. Secondly, Ireland has a relatively limited range of environmental conditions, varying in altitude from 0m to 1041m and in latitude from 51.43°N to 55.38°N. It may, therefore, lack the range of ecological niches present in, for example, Italy (altitudinal range: 0–4807m), Norway (where latitude ranges from 57.58°N to 71.11°N) or even Britain (latitudinal range: 49.57°N to 58.40°N; altitudinal range: 0–1344m). Thirdly, due to its geographical location off the extreme west of the continental landmass, repeated glaciation events have left Ireland with an impoverished native flora in comparison to mainland Europe (Webb 1983). This means that there is a relatively small number of tree species available to fill available niches. Lastly, modification and the common occurrence of non-native species with broad ecological tolerances, such as beech, may have led to some blurring of native communities.

Conversely, with the definition of possibly thirty sub-groups this approach has identified greater diversity of Irish woodland types than Fossitt (2000) or Cross (2005). A sign of a good classification technique should be the ability to tease out more than is obvious and not simply reaffirm existing notions. For applied purposes, however, any evaluation based on statistical significance may need to be tempered by reference to ecological significance. Rodwell (1991) emphasised the need for the 'ecological integrity' of defined vegetation communities. It is important, therefore, that the methodology presented is viewed as the first step in a two step process: firstly, accurately and

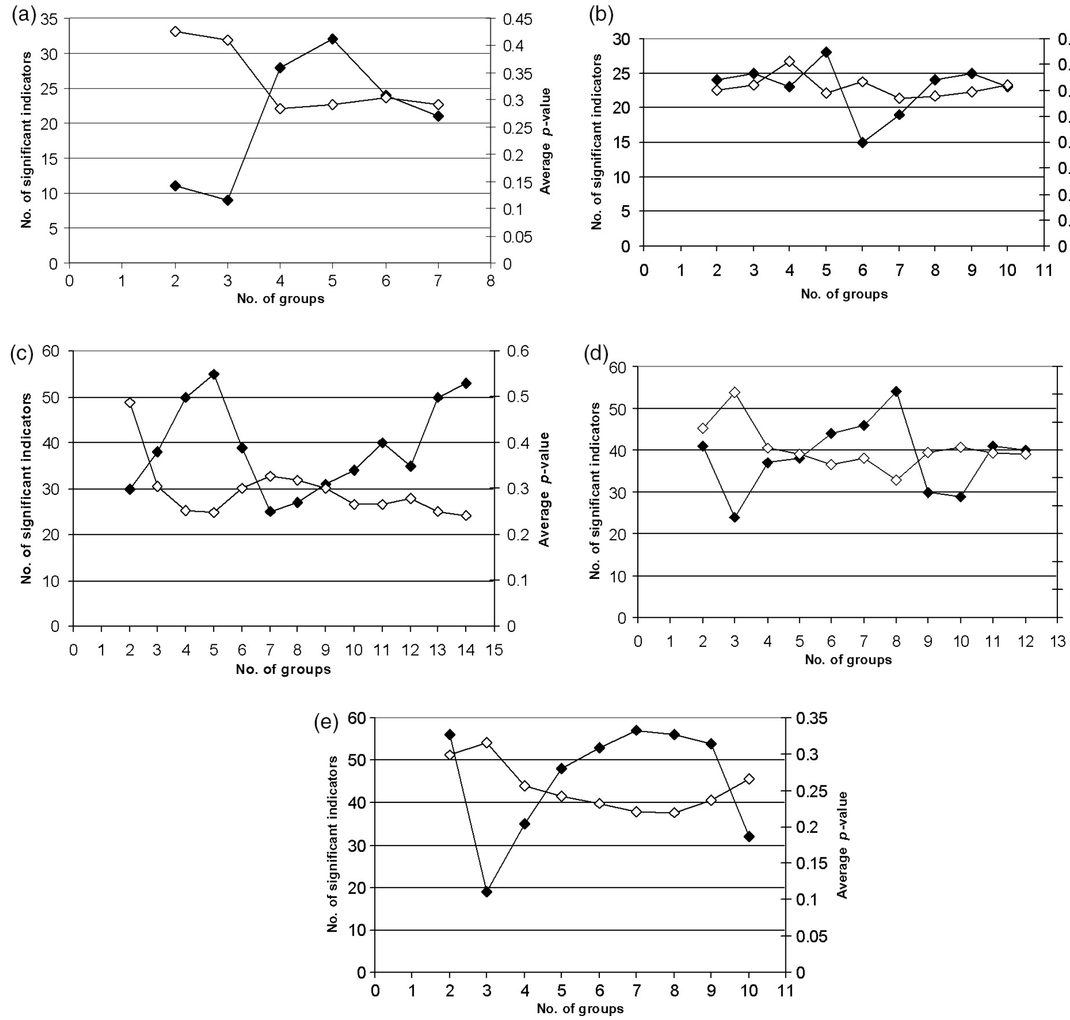

Fig. 4 — Variation in the number of significant indicators (closed diamonds) identified by ISA and the average *p*-value of all species (open diamonds) at each step of hierarchical cluster analysis for each of the five broad groups. (a) *Quercus petraea – Luzula sylvatica* group (b) *Quercus robur – Hedera helix* group (c) *Corylus avellana-Thamnobryum alopecurum* group (d) *Alnus glutinosa – Filipendula ulmaria* group (e) *Betula pubescens – Molinia caerulea* group

objectively defining and describing the diversity of Ireland's woodland vegetation communities; and secondly, translating this information into a classification that is readily applicable in the field. This is a procedure that awaits the completion of the survey and could involve either the definition of a new scheme or refinement of an existing one. A two-tier classification, such as produced by the current approach, would permit recording to be conducted at different levels depending on the practical and/or scientific purposes of any given study.

METHODOLOGICAL CONSIDERATIONS

The preliminary analysis reported here raises several pertinent methodological considerations. ISA offers a quantitative method for choosing the optimum number of end groups from cluster analysis (Dufrene and Legendre 1997; McCune and Grace 2002). It does not always yield clear unimodal results, however. Furthermore, there does not as yet appear to be any consensus on which is the best criterion to employ (McCune and Grace 2002; Lookingbill and Urban 2005). While some degree of judgement is required to interpret ISA results, ISA cannot be regarded as wholly objective.

The NSNW is seeking to survey a large number of woodland sites across the country. For practical considerations, subjectively placed relevés rather than randomly located plots have been used, as the latter approach would require much greater replication at each site. It is important that the limitations of relevé data are acknowledged in interpreting the results. Jörg (2003) points out that subjective sampling tends to overemphasise what is regarded by the surveyors as typical vegetation, at the expense of less well characterised transitional vegetation. As a result it is improper to draw conclusions about continuity or discreteness of vegetation communities from such datasets (McCune and Grace 2002), and again there is a danger of simply reaffirming existing ideas. This problem of subjectivity may in some degree be mitigated, however, by the initial selection of survey sites that may be described as 'arbitrary but without preconceived bias' (McCune and Grace 2002). This is an interesting concept because, owing to the highly fragmented nature of woodland in Ireland, remaining sites may in themselves be regarded as samples of previous or potential vegetation (Cross 1998).

Legendre and Legendre (1998) highlight the importance of validating the results of hierarchical clustering. A problem with hierarchical clustering is that it will always reveal groups even when the dataset is essentially unstructured (Pillar 1999); the strength of the results therefore needs assessing in some fashion. In this paper, an MRPP test with environmental variables was used to externally validate the partition of the dataset into the five broad groups. Visual inspection of the ordination plot gave weaker, non-statistical support. Internal validation via the jacknife or bootstrap resampling methods has been suggested as a more robust assessment (Legendre and Legendre 1998). Bootstrapping is widely used in the fields of phylogenetics and DNA microarray analysis, but has hitherto been seldom applied to ecological clustering. Pillar (1999) and McKenna (2004) have recently produced software for this purpose, but unfortunately neither gives the option of using the Sørensen distance measure with flexible beta linkage, as recommended for hierarchical clustering by McCune and Grace (2002). An alternative approach is that of sequential randomisation tests, which could strengthen the interpretation of groups and sub-groups produced by cluster analysis (Hunter and McCoy 2004).

Finally, it must be emphasised again that the classification and approach detailed in this paper are preliminary at this stage and will undoubtedly be refined as the dataset expands during the course of the National Survey of Native Woodlands. Nevertheless, it represents the first attempt to produce a national-scale vegetation classification system in Ireland, using a range of complementary methods and current best practice in statistical techniques.

ACKNOWLEDGEMENTS

This project has principally been funded by the National Parks and Wildlife Service, with additional funding from the Forest Service and COFORD. We are grateful to John Cross of the National Parks and Wildlife Service for much helpful advice. Thérèse Higgins, Naomi Kingston and Deirdre Lynn contributed to development of the field methodology, and George Smith provided important statistical advice. For assistance in integrating data from the two pilot studies we extend our thanks to Amanda Browne, Fiona Dunne, Sasha van der Sleesen and Niamh Roche. For technical support we would like to thank Andrew Fitzgerald and Guy McGrath. Several of these people also conducted part of the fieldwork. We are also very grateful to the other fieldworkers: Edwina Cole, Kieran Connolly, Jenny Dowse, Steve McCormack, Mark McCorry, Saoirse O'Donoghue, Alan Poole and Louise Scally. Thanks are due to two anonymous referees who made several constructive comments during preparation of this paper.

REFERENCES

Baeur, L.J. 1989 Moorland beetle communities on limestone 'habitat islands'. I. Isolation, invasion and local species diversity in carabids and staphylinids. *Journal of Animal Ecology* **58**, 1077–98.

Belbin, L. and McDonald, C. 1993 Comparing three classification strategies for use in ecology. *Journal of Vegetation Science* **4**, 341–8.

Braun-Blanquet, J. and Tüxen, R. 1952 Irische Pflanzengesellschaften. In W. Ludi (ed.), *Die Pflanzenwelt Irlands*, 224–415. Veröffentlichungen des geobotanischen Institutes Rübel no. 25. Zurich. Institutes Rübel.

Browne, A., Dunne, F. and Roche, N. 2000 A survey of broadleaf woodlands in three SACs: Barrow-Nore, River Unshin and Lough Forbes. Unpublished report, Dúchas, The Heritage Service, Dublin.

Coroi, M., Sheehy Skeffingtion, M., Giller, P., Smith, C., Gormally, M. and O'Donovan, G. 2004 Vegetation diversity and stand structure in streamside forests in the south of Ireland. *Forest Ecology and Management* **202**, 39–57.

Cross, J.R. 1992 The distribution, character and conservation of woodland on esker ridges in Ireland. *Proceedings of the Royal Irish Academy* **92**B, 1–19.

Cross, J.R. 1998 An outline and map of the potential natural vegetation of Ireland. *Applied Vegetation Science* **1**, 241–52.

Cross, J.R. 2005 Irish native woodland classification. In *Native woodland manual*, 41–50. Dublin. Forest Service, Department of Agriculture and Food.

Cross, J.R. and Kelly, D.L. 2003 Wet woodlands. In R. Otte (ed.), *The wetlands of Ireland*, 160–72. Dublin. University College Dublin Press.

Department of Arts, Heritage, Gaeltacht and the Islands 2002 *National Biodiversity Plan*. Dublin. Department of Arts, Heritage, Gaeltacht and the Islands.

Dufrene, M. and Legendre, P. 1997 Species assemblages and indicator species: the need for a flexible assymmetrical approach. *Ecological Monographs* **67**, 345–66.

Erjnæs, R., Bruun, H.H., Aude, E. and Buchwald, E. 2004 Developing a classifier for the Habitats Directive grassland types in Denmark using species lists for prediction. *Applied Vegetation Science* **7**, 71-80.

An Foras Forbartha 1981 Areas of scientific interest in Ireland: natural heritage inventory. Dublin. An Foras Forbartha.

Fossitt, J.A. 2000 *A guide to habitats in Ireland*. Kilkenny. The Heritage Council.

Gallagher, G., Dunne, S., Jordan, P. and Stanley, B. 2001 Ireland's forestry and planning system. Unpublished report, Department of Marine and Natural Resources, Wexford.

Higgins, G.T., Martin, J.R. and Perrin, P.M. 2004 National survey of native woodland in Ireland: interim report. Unpublished report, National Parks and Wildlife Service, Dublin.

Hunter, J.C. and McCoy, R. A. 2004 Applying randomization tests to cluster analyses. *Journal of Vegetation Science* **15**, 135-138.

Hupalo, R., Culver, D. and Doyle, G. 2000 Comprehensive statewide wetlands classification and characterization. Unpublished report, Colorado Department of Natural Resources. http://www.cnhp.colostate.edu/reports.html (2 August 2005).

Jörg, E. 2003 A critique of phytosociology. *Journal of Vegetation Science* **14**, 291–6.

Kelly, D.L. 1981 The native forest vegetation of Killarney, south-west Ireland: an ecological account. *Journal of Ecology* **69**, 437–72.

Kelly, D.L. 2002 The regeneration of Quercus petraea (sessile oak) woods in south-west Ireland: a 25-year experimental study. *Forest Ecology and Management* **166**, 207–26.

Kelly, D.L. and Moore, J.J. 1975 A preliminary sketch of the Irish acidophilous oakwoods. In J.-M. Géhu (ed.), *Colloques phytosociologiques III: La végétation des forêts caducifoliées acidophiles*, 375–87. Vaduz. J. Cramer.

Kelly, D.L. and Kirby, E.N. 1982 Irish native woodlands over limestone. *Journal of Life Sciences of the Royal Dublin Society* **3**, 181–98.

Kelly, D.L. and Iremonger, S.F. 1997 Irish wetland woods: the plant communities and their ecology. *Proceedings of the Royal Irish Academy* **97**B, 1–32.

Lance, G.N. and Williams, W.T. 1967 A general theory of classification sorting strategies. II. Clustering strategies. *Computer Journal* **10**, 271–7.

Legendre, P. and Legendre, L. 1998 *Numerical ecology*. 2nd edn. Amsterdam. Elsevier.

Lookingbill, T. and Urban, D. 2005 Gradient analysis, the next generation: towards more plant-relevant explanatory variables. *Canadian Journal of Forest Research* **35**, 1744–53.

McKenna, J.E. Jr. 2004 An enhanced cluster analysis program with bootstrap significance testing for ecological community analysis. *Environmental Modelling and Software* **18**, 205–20.

McCune, B. and Grace, J.B. 2002 *Analysis of ecological communities*. Oregon. MjM Software Design.

Minchin, P.R. 1987 An evaluation of the relative robustness of techniques for ecological ordination. *Vegetatio* **69**, 89–107.

Miserere, L., Montacchini, F. and Buffa, G. 2003 Ecology of some mire and bog communities in the Western Italian Alps. *Journal of Limnology* **62**, 88–96.

O'Flanagan, L.P. 1973 *Inventory of woodlands of the Forest and Wildlife Service*. Dublin. Stationery Office.

Paton, J.A. 1999 *The liverwort flora of the British Isles*. Colchester, England. Harley Books.

Perrin, P.M. 2002 The ecology of yew (*Taxus baccata*) in Ireland. Unpublished PhD thesis, University of Dublin.

Perrin, P.M. 2003 Establishment of long-term monitoring transects on conifer clearfells, Unpublished report, Woodlands of Ireland, Dublin.

Pillar, V.D. 1999 How sharp are classifications? Ecology **80**, 2508-2516.

Preston, C.D., Pearman, D.A. and Dines, T.D. 2002 *New atlas of the British and Irish flora*. Oxford. Oxford University Press.

Purcell, T.J. 1979 Inventory of private woodlands, 1973. Dublin, Stationery Office.

Rodwell, J.S. (ed.) 1991 *British plant communities. Volume 1. Woodlands and scrub*. Cambridge. Cambridge University Press.

Gardiner, M.J. and Radford, T. 1980 *Soil associations of Ireland and their land use potential*. Dublin. An Foras Talúntais.

Smith, A.J.E. 2004 *The moss flora of Britain and Ireland*. 2nd edn. Cambridge. Cambridge University Press.

Smith, G.F., Kelly, D.L. and Mitchell, F.J.G. 2003 Establishing native woodlands in former upland conifer plantations in Ireland. In J. Humphrey, A. Newton, J. Latham, H. Gray, K. Kirby, E. Poulsom and C. Quine. (eds), *The restoration of wooded landscapes*, 37–46. Edinburgh. Forestry Commission.

Stace, C. 1997 *New flora of the British Isles*. 2nd edn. Cambridge. Cambridge University Press.

Stocker, M., Gilbert, F.F. and Smith, D.W. 1977 Vegetation and deer habitat relations in southern Ontario: classification of habitat types. *Journal of Applied Ecology* **14**, 419–32.

van der Sleesen, S. and Poole, A. 2002 Inventory of semi-natural woodlands in the eastern part of County Offaly: a pilot study for the national inventory of native woodlands. Unpublished report, Dúchas, The Heritage Service, Dublin.

Webb, D.A. 1983 The flora of Ireland in its European context. *Journal of Life Science of the Royal Dublin Society*, 143–60.

White, J. and Doyle, G.J. 1982 The vegetation of Ireland: a catalogue raisonné. *Journal of Life Sciences of the Royal Dublin Society* **3**, 289–368.

Williams, W.T., Lambert, J.M. and Lance, G.N. 1966 Multivariate methods in plant ecology. V. Similarity analysis and information analysis. *Journal of Ecology* **54**, 427–45.

Yom-Tov, Y. and Kadmon, R. 1998 Analysis of the distribution of insectivorous bats in Israel. *Diversity and Distributions* **4**, 63–70.