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RESEARCH PAPER

A climatic stratification of the environment of Europe

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ABSTRACT

Aim To produce a statistical stratification of the European environment, suitable for stratified random sampling of ecological resources, the selection of sites for representative studies across the continent, and to provide strata for modelling exercises and reporting.

Location A 'Greater European Window' with the following boundaries: 11° W, 32° E, 34° N, 72° N.

Methods Twenty of the most relevant available environmental variables were selected, based on experience from previous studies. Principal components analysis (PCA) was used to explain 88% of the variation into three dimensions, which were subsequently clustered using an ISODATA clustering routine. The mean first principal component values of the classification variables were used to aggregate the strata into Environmental Zones and to provide a basis for consistent nomenclature.

Results The Environmental Stratification of Europe (EnS) consists of 84 strata, which have been aggregated into 13 Environmental Zones. The stratification has a 1 km^2 resolution. Aggregations of the strata have been compared to other European classifications using the Kappa statistic, and show 'good' comparisons. The individual strata have been described using data from available environmental databases. The EnS is available for noncommercial use by applying to the corresponding author.

Main conclusions The Environmental Stratification of Europe has been constructed using tried and tested statistical procedures. It forms an appropriate stratification for stratified random sampling of ecological resources, the selection of sites for representative studies across the continent and for the provision of strata for modelling exercises and reporting at the European scale.

Keywords
Bioclimatic classification, climate, Countryside Survey, environmental classification, Europe, monitoring, statistical stratification, stratified random sampling.

INTRODUCTION

In order to place field observations into the European context, it is necessary to find standardized methods of synthesizing environmental data into strata that will permit objective aggregation. The development of a statistical classification of environmental conditions is the first step in the production of a tool for deriving stratified random samples because it allows areas and situations to be compared in a reproducible way (Bunce *et al.*, 1996a). On a continental scale of spatial research, e.g. biodiversity monitoring, data comparisons and scenario building for the European Union (EU), a stratification of land into more or less homogeneous regions would provide a valuable framework because statistical inference requires sample data to be representative of a defined population (Cochran, 1977).

Within a stratum, or subpopulation, changes or effects can, as far as possible, be analysed separately from environmental heterogeneity by using standard statistical procedures (Bunce *et al.*, 1996a; Cochran, 1977). For example, agricultural land abandonment can affect species abundance and it could be important to assess the impact of this process on biodiversity in Europe. However, because species abundance is also dependent on wider-scale,

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more stable aspects of the environment, it is difficult to assess whether changes in species abundance are indeed caused by abandonment or by inherent differences in environments. Environmental stratification will provide a context within which analyses of dynamic change can be extrapolated safely. In the example, this makes it possible to determine whether differences in species abundance are the result of real change rather than background noise, using standard statistical routines (Haines-Young *et al.*, 2000). In addition, an environmental stratification provides a basis for stratified random sampling and enables samples to be placed consistently within the context of the entire continent, with robust statistical estimates and associated error terms. In contrast, studies that rely on expert judgement to select samples cannot be extrapolated statistically.

It is essential, however, that the environmental stratification has a sufficiently fine resolution and that it is derived statistically so that the strata are determined unambiguously by specific variables. The stratification is therefore reproducible and, as far as possible, independent of personal bias. This is of particular importance where large-scale continuous gradients are involved over thousands of kilometres, e.g. from Britain to Denmark, Sweden and Finland. No clear boundaries between zones are present in such cases, but statistical analysis provides robust divisions based on the balance between the variables that make up the database.

The need for statistical environmental stratification was first recognized by field ecologists at the Institute of Terrestrial Ecology (ITE) [now Centre for Ecology and Hydrology (CEH)] in the UK in the 1970s. These scientists realized that strategic stratified random sampling was the only feasible way of assessing ecological resources, such as habitats and vegetation, and enabling monitoring schemes to be developed for large, heterogeneous areas (Bunce *et al.*, 1996a,b,c; Haines-Young *et al.*, 2000; Firbank *et al.*, 2003). Sheail & Bunce (2003) have recently described the history and development of environmental classification and strategic ecological survey in the UK. Several other countries and regions have also adopted quantitative classifications as the basis for survey, monitoring and management, e.g. Australia (Mackey *et al.*, 1988), Spain (Elena-Rosselló, 1997; Regato *et al.*, 1999), Austria (Wrbka *et al.*, 1999), New Zealand (Leathwick *et al.*, 2003a,b), and Senegal (Tappan *et al.*, 2004).

Two earlier European statistical stratifications have been produced. In the first, Jones & Bunce (1985) defined eleven classes on a 50 × 50 km grid for Europe. More than a decade later, improved data availability, software and computing power allowed the classification of 64 classes on a 0.5° grid (approximately 50 × 50 km) (Bunce *et al.*, 1996d). Although this latter classification was used in a range of studies (Bunce *et al.*, 1996e, 1997; Duckworth *et al.*, 2000; Petit *et al.*, 2001), the coarse resolution limited its application for ecological sampling. At this resolution, some of the grid cells are relatively heterogeneous for climate and altitude. For example, the grid cell with the Picos de Europa in the Cantabrian Mountains in north-western Spain contains an elevation range from sea level to mountain summits at an altitude of 2500 m, with associated contrasting climate regimes. The classification was therefore too coarse to be used for monitoring programmes for land use change and for developing detailed scenarios.

Other European classifications with a higher resolution, e.g. maps of Potential Natural Vegetation (Noirfalize, 1987; Bohn *et al.*, 2000), biogeography (EEA, 2002) or ecoregions (Olson *et al.*, 2001) have classes that have not been defined statistically. They depend on the experience and judgement of the originators and rely upon the intuition of the observer in interpreting observed patterns on the basis of personal experience. These classifications, while important as descriptions of environmental regions, are not suitable for statistical stratification. Some bioclimatic classifications are quantitative and reproducible, e.g. those used in dynamic global vegetation modelling (Woodward & Rochefort, 1991; Prentice *et al.*, 1992). However, they distinguish too few classes at the European scale to provide suitable stratification for random sampling of ecological resources.

In this paper, an Environmental Stratification of Europe (EnS) is presented that has 84 strata with a 1 km^2 resolution. The stratification is based on statistical clustering, so that subjective choices are explicit, their implications are understood and the strata can be seen in the context of Europe as a whole. By demonstrating this new stratification approach, and by making the EnS public, a tool is now available for European ecologists to use for stratified random sampling of ecological resources and the selection of sites for representative studies across the continent. The strata can also be used for modelling exercises, scenario development and reporting.

MATERIALS AND METHODS

The construction of the Environmental Stratification has entailed three major stages (Fig. 1): (i) the selection of the relevant environmental variables; (ii) the extraction of the main environmental gradients using principal components analysis (PCA) and subsequent statistical clustering; and (iii) post-processing to minimize isolated groups of grid cells. Finally, in order to give the EnS more credibility, the EnS is compared to other available classifications, and correlations with other environmental data are calculated. All spatial calculations were carried out using ArcGIS 8.2 (ESRI, 2002).

Selecting relevant variables

In order to determine which variables are best suited for stratification of the European environment, some form of conceptual model is needed. This must be a simplified model that includes the relationship between abiotic and biotic components with ecological relevance. Figure 2 shows such a conceptual model, based on work by Klijn & de Haes (1994), which creates a functional hierarchy between different ecosystem components (e.g. climate, soil, vegetation). The lower components are relatively dependent on higher components (downwardly directed arrow). For instance, plant species are associated with specific soil conditions; major soil groups are formed under different climatic conditions. Furthermore, changes in the relatively independent higher components will have unavoidable influences on lower

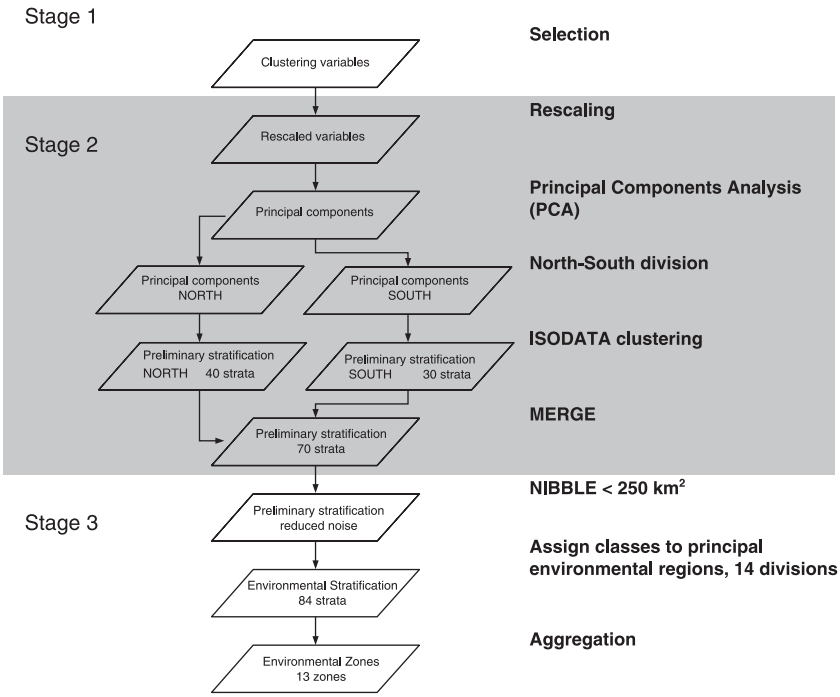

Figure 1 Flow chart of the creation of the Environmental Stratification in three major stages. (1) Variable selection; (2) clustering of the selected variables into strata; (3) some post-processing. All calculations were performed in ArcGIS 8.2 (ESRI, 2002).

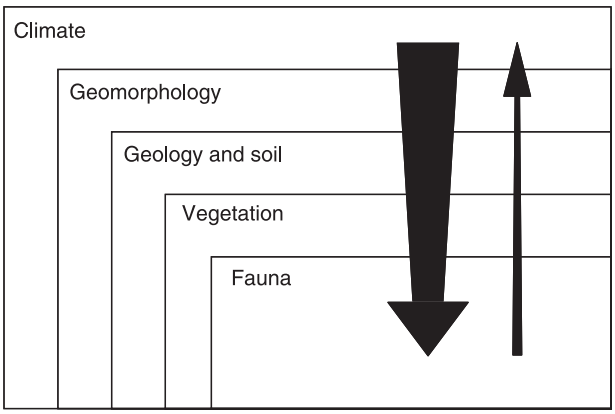

Figure 2 Conceptual model of an ecosystem, showing a hierarchy of relative dependence between major components (after Klijn & de Haes, 1994).

components (e.g. climate change will affect species distribution). Influences in the other direction are also recognized (upwardly directed arrow), but the model can be seen as a spatial and temporal hierarchy, with a global, relatively stable component at the top.

Others have also recognized the spatial hierarchy described in Klijn's model (Walter, 1973; Leser, 1976, 1991; Van der Maarel, 1976; Odum, 1983; Bailey, 1985; Bailey, 1987; Godron, 1994; Klijn & de Haes, 1994; Breckle & Walter, 2002). Walter, for instance, distinguished climatic zonobiomes, and in mountainous regions orobiomes, determined by altitudinal steps. These biomes are conditional for the formation of soils which usually show a more fine-grained pattern, with regional heterogeneity caused by, for instance, hydrological processes, erosion or human activity (Breckle & Walter, 2002). Vegetation superimposes an even finer pattern of local variation, consisting of various succession stages and human land use. For example, zonobiome VI, with a temperate climate and short periods of frost, is associated with forest brown earths and grey forest soils. The natural climax vegetation, associated with this climate and these soil conditions is a nemoral broad-leaf–deciduous forest (Breckle & Walter, 2002).

Of course, at field level there is large heterogeneity in environmental conditions, as well as land cover. Furthermore, there are feedbacks in the other direction (upwardly directed arrow in Fig. 2). For example, vegetation also influences soil properties and can even influence local climate. Nevertheless, in the continental or global context, ecosystem patterns are caused by the above-mentioned hierarchy (Klijn & de Haes, 1994). Bunce *et al.* (1996a, 2002) have shown that this hierarchy applies even on a national scale for large countries such as Great Britain and Spain. This hierarchy, therefore, is a suitable starting point for selecting relevant variables for creating a European environmental stratification.

Climate

The most comprehensive high-resolution climate data set available for Europe is the CRU_TS1.2 (Mitchell *et al.*, 2004), developed by the Climatic Research Unit (CRU) at the University of East Anglia. It has a 10′ × 10′ resolution (approximately 16 × 16 km) and contains monthly values for five variables during the period 1900–2000. Depending on the variable and year, between 200 and 1600 stations were interpolated using trivariate thin-plate spline surfaces, making use of a 1-km elevation database as a copredictor. The CRU_TS1.2 data set is based on the CRU CL2.0, which contains global climatologies for 1969–90 (New *et al.*,

Table 1 Comparison between the variables selected for the Environmental Stratification (EnS) and the ITE classification (Bunce *et al.*, 1996d). The variables represent mean monthly values for each grid cell. For the EnS slope and altitude, data are from the HYDRO1k data set (http://edcdaac.usgs.gov/gtopo30/hydro/) and the climate data are from CRU TS1.2 (Mitchell *et al.*, 2004). The ITE classification used an earlier CRU data set (Hulme *et al.*, 1995)

EnS (1 km^2 resolution)	ITE classification (0.5° × 0.5° resolution)
Altitude	Maximum altitude
	Mean altitude
	Minimum altitude
Slope	
Northing (latitude)	Northing (latitude)
Oceanicity	Oceanicity
Minimum temperature January	
Minimum temperature April	
Minimum temperature July	Frost days in July
Minimum temperature October	Frost days in November
Maximum temperature January	
Maximum temperature April	
Maximum temperature July	Maximum temperature in September
Maximum temperature October	Maximum temperature in October
Precipitation January	Rain days in December
Precipitation April	
Precipitation July	Precipitation in June
Precipitation October	Precipitation in October
Precipitation in November	
	Rain days in November
Percentage sunshine January	
Percentage sunshine April	Sun hours in May
Percentage sunshine July	Sun hours in June
Percentage sunshine October	
	Wind speed in April

2002), but is restricted to the 'greater European window' (11° W, 32° E, 34° N, 72° N) and uses an updated climate database. For the latter data set, generalized cross-validation (GCV) was performed for different regions of the world. In Europe, the average predictive error for precipitation stations used in fitting the surface varies between 12 and 15% of the monthly rainfall, while prediction errors for mean monthly temperature range between 0.8 and 1.1 °C (New *et al.*, 2002). Hutchinson & Gessler (1999) give a good description on the methodology used for fitting climate surfaces.

The data set used, CRU_TS1.2, contains mean monthly values for temperature, precipitation, percentage sunshine, vapour pressure and daily temperature range. From the daily temperature range and the mean temperature, the average minimum and average maximum temperature can be calculated. From the total data set, 1971–2000 climatologies were calculated as 30-year averages.

The 10′ × 10′ resolution, while nine times more detailed than the earlier ITE classification on a 0.5° grid (Bunce *et al.*, 1996d), is still coarse, especially for sampling 1 km^2 squares. Meanwhile, at the local level, environmental patterns are relatively independent of wider climate patterns and are dependent on local topography (Bunce *et al.*, 1998). The climate parameters were therefore resampled from the 10′ × 10′ grid of the CRU_TS1.2 data set in a 1 km^2 grid, for which topographic data are available. From the resampling techniques available in ArcGIS, bilinear interpolation was chosen to best represent climatic gradients between grid cells. This downscaling procedure ignores elevation as a copredictor. As a result, excess smoothing of the climate variables occurs in grid cells that are heterogeneous in elevation, resulting in some inaccuracies in the final stratification. In part this is counteracted by inclusion of high-resolution elevation data (see next section). In stratified sampling exercises these inaccuracies will be reflected in the standard errors of the sample mean (see Discussion).

To reduce the computational load it was necessary to select a subset of the total available data (seven variables × 12 months). For this purpose, in the earlier ITE classification, a thorough statistical analysis was carried out (Bunce *et al.*, 1996d) leading to the selection of 15 variables. In the present project a comparable set of variables was selected from the total available data (Table 1). In order to reflect the overall seasonal climate variation, data were selected for 4 months in the year, January, April, July and October. This was performed for the four available variables that were closest to those used in the 1996 ITE classification, namely mean monthly minimum and maximum temperature, precipitation and percentage sunshine. Table 1 lists the variables of the original ITE classification and the EnS.

Geomorphology

Geomorphology encompasses the formation and shapes of landforms, e.g. alluvial flats and alpine valleys. No consistent European geomorphological map exists. However, detailed digital elevation models (DEMs) are available, which convey a high proportion of the information required, i.e. altitude and slope. These data act as surrogates for geomorphological information. The best data set available is the United States Geological Survey

(USGS) HYDRO1k global digital elevation model, with a resolution of 1 km^2. It was created by projecting the USGS GTOPO30 data set, which has a 30″ resolution, onto an equal area Lambert Azimuthal projection. Slope, aspect and flow properties were also calculated for the data set. HYDRO1k is distributed by the Land Processes Distributed Active Archive Center (LP DAAC), located at the US Geological Survey's EROS Data Center (http://lpdaac.usgs.gov).

Oceanicity and northing

In the ITE classification northing, in the form of latitude, as well as oceanicity were included. By including northing in the stratification, differences in day-length and radiation are incorporated as well as a degree of locational information. Oceanicity expresses the buffering influence of the ocean, resulting in cooler summers, milder winters and a lower degree of interseasonal variability. In the ITE classification, oceanicity was defined by climatic criteria as the mean annual temperature range adjusted for latitude, as recommended by CRU. In the EnS, oceanicity was defined as the July–January temperature range divided by the sine of the latitude. Large mean annual temperature ranges (20–25 °C) are found in Eastern Europe, small ranges on the Atlantic coast (10–15 °C). Because the relative influence of the annual temperature range differs from north to south, the indicator is divided by the sine of the latitude.

Geology and soil

An investigation was conducted to assess whether it would be possible to include some geological or soil variables into the stratification. Known landscape patterns resulting from soils and geology (e.g. fluvial deposits and peat formations) are not present in a stratification based on bioclimatic variables alone, although there will be strong associations. For example, all permafrost soils are in arctic and alpine climates, podzols are predominantly found in boreal climates, and forest brown earths in temperate climates (Breckle & Walter, 2002).

Unfortunately, currently no European geological map is available and the available soil maps are difficult to include in statistical clustering due to the classification method that is used for mapping soils: it is based on expert knowledge of soil scientists, without specified critical thresholds. Furthermore, the higher aggregation levels do not show an equal distribution of soil properties. While these groups provide a sound descriptive base, they are of limited value in statistical analysis. A second problem arises because soil maps contain nominal data, which are not easily incorporated into the statistical clustering that is based on continuous data. Transformation is possible, but results in individual vectors for each soil type, which would unbalance the final set of variables, as discussed by Bunce *et al.* (1996a). Finally, soil variables derived from pedo-transfer functions (e.g. pH and water-holding capacity) can be incorporated into the clustering, but because the climate variables vary at a broader scale than the soil variables, the resulting map is fragmented and shows little internal consistency and little relation to climate zones. In principal, this could be overcome by weighing the soil variables down to allow broader-scale climate to remain dominant (cf. Belbin, 1991). However, considering inconsistencies in the soil data, and the lack of experience in assigning weights to the soil properties, it was decided not to include soil information in the stratification. Detailed regional soil information could eventually prove valuable in deriving local strata (see Discussion).

The variables selected

The variables selected are comparable to those used in the original ITE classification (Table 1), although the original statistical selection procedure for the climate variables was not repeated. As Bunce *et al.* (2002) have shown, using the European ITE classification, two British and a Spanish classification, the core patterns of statistical environmental classifications are stable regardless of details pertaining to the variables and algorithms used. Differences in detailed strata distribution are likely to occur along large-scale continuous gradients where no clear boundaries are present (e.g. from Britain to Denmark, Sweden and Finland). However, such differences will have minimal impact in any estimates derived from the strata because the gradient in ecological parameters will also be continuous and relatively homogeneous over large distances.

Running the classification

PCA allows redundant data to be compacted into fewer dimensions that are noncorrelated and independent and are often more readily interpretable than the source data (Faust, 1989; Jensen, 1996). The *ERDAS IMAGINE field guide* (ERDAS, 1997), available at http://support.erdas.com/documentation/documentation.html, gives a clear description of the process. In ArcGIS, PCA is carried out on the matrix of covariances between the variables, implicitly centering and standardizing by the input variables, as required when analysing variables that are measured in different units (Jongman *et al.*, 1995). In order to reduce file size and increase calculation speed, the variables were converted integers with a 0–10,000 range.

The Iterative Self-Organizing Data Analysis Technique (ISODATA) (Tou & Conzalez, 1974) was used to cluster the principal components into environmental strata. This technique is used widely in image analysis fields, such as remote sensing and medical sciences, e.g. Banchmann *et al.* (2002) and Pan *et al.* (2003). ISODATA is iterative in that it repeatedly performs an entire classification and recalculates statistics. Self-organizing refers to the way in which it locates clusters with minimum user input. The ISODATA method uses minimum Euclidean distance in the multi-dimensional feature space of the principal components to assign a class to each candidate grid cell. The process begins with a specified number of arbitrary cluster means. The (Euclidian) environmental distance between the candidate grid cell and each cluster mean is calculated. The grid cell is then allocated to the cluster whose centroid is the closest. The iterations are terminated when percentage of grid cells whose assignments are unchanged reaches 100%. The ITE classification distinguished

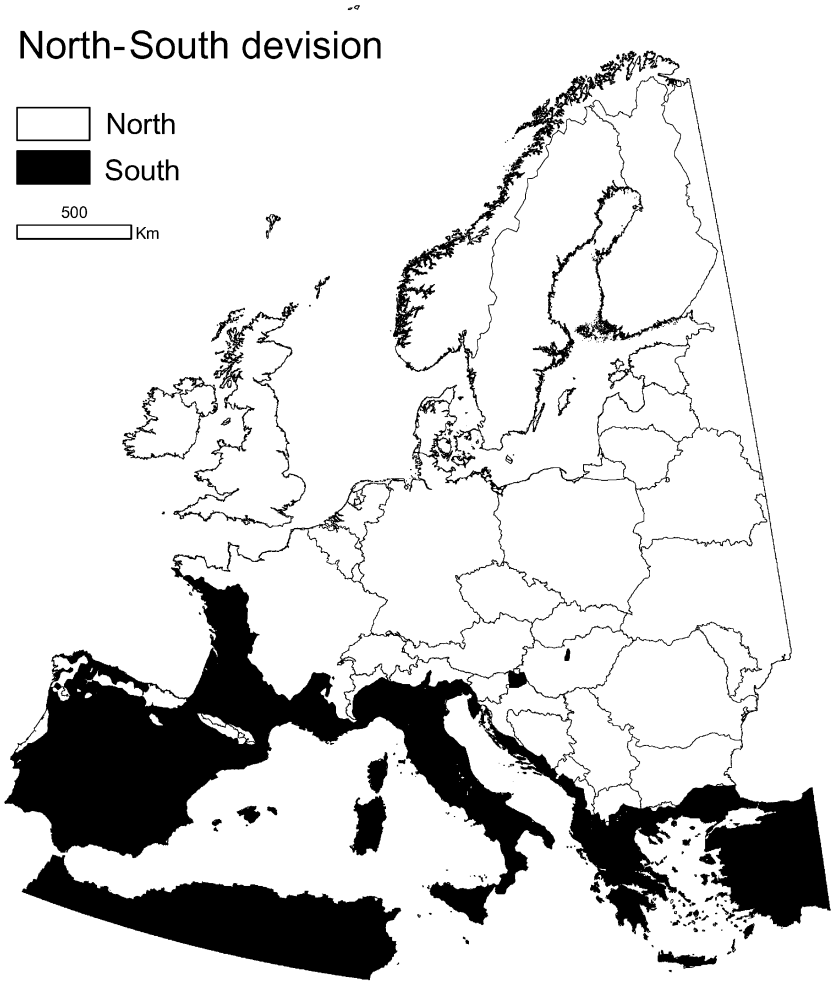

Figure 3 The European environment was classified into two classes, northern and southern Europe, based on ISODATA clustering of the first three principal components of only the climate variables. National borders are indicated for reference purposes.

64 strata using an arbitrary stopping rule. In the new stratification, classification into seventy strata was chosen, a number which makes characterization of the strata feasible.

The original ITE classification showed that the Mediterranean region is distinct from northern Europe. When the clustering was first preformed a relatively large number of small strata were present in the Mediterranean region and several large strata in northern Europe. Many strata (> 120) would be needed to divide northern Europe, creating too many strata for practical purposes overall. This problem was solved by using a stepwise procedure to divide Europe in two zones, based on a PCA of the climate variables and clustering into two classes. The northern class covers 70% of Europe and the southern (Mediterranean) class covers 30%, as shown in Fig. 3. The division is comparable to that of the original ITE classification, with only minor differences in the northern boundaries, and it is also close to the divisions described by Kendrew (1953). In the next stage of the analysis, the principal components of the full set of variables were used to classify northern and southern Europe separately. Northern Europe was clustered into 40 strata and southern Europe into 30 strata. In this way, environmental heterogeneity in Northern Europe is emphasized, while recognizing the greater variability in the Mediterranean region. Compared to the northern class, it has almost 50% (30/70) of the number of strata, but covers only 30% of the spatial extent.

Post-processing

In the original map of the environmental strata, there is a dispersed scatter of small regions of only a few square kilometres. For most applications, such fragmentation is not useful on a European scale. Therefore, all regions smaller than 250 km^2 were identified and assigned to the strata of the neighbouring grid cells. This procedure eliminates most of such noise, much improving the clarity of the map, but simultaneously introducing a bias that could lead to higher statistical errors in sample means. The procedure of removing noise is analogous to the use of the discriminant function procedure in the original ITE classification. The original output is also available for studies that require such a level of detail.

In some cases EnS strata occurred in two distant regions, e.g. in the Atlantic as well as Adriatic regions. Climatically these regions are indeed comparable, but they are very different in biogeography and therefore species composition. As a consequence, sampling these strata for habitats, vegetation and landscapes would produce estimates with large standard errors. Furthermore,

aggregation and naming of the strata would be extremely complicated. For these reasons all strata were assigned to one of six main environmental regions: Alpine, Boreal, Continental, Atlantic, Mediterranean and Anatolian. Strata that occurred in two such regions were separated. Arguably, for some applications this division is not desirable. For instance, the original strata could be used as an explanation of similar vegetation structure in distant regions. For this reason the original 70 strata are also available in the EnS data set.

Relation to other data sets

In order to give the EnS more credibility, both to the scientific community as well as to policy advisers, it is important to show its relationship to other widely used European data sets. This was conducted in three ways: (i) by comparing the EnS to other classifications; (ii) by assessing correlations between the EnS and other data sets; and (iii) by describing the EnS strata with other available data. Some important properties of the data sets used in this paper are summarized in Table 2.

Comparison

As mentioned in the Introduction, several classifications of the European environment exist that are not appropriate for stratified sampling in the field due to their spatial resolution (the ITE classification), the limited number of classes that are distinguished (biomes) or ambiguous definitions of class boundaries (e.g. WWF ecoregions). Although these classifications are not suitable for statistical sampling, there are many similarities in the environmental patterns detected by these classifications and the EnS. To test these similarities, the strength of agreement between the EnS and three other available data sets was determined by calculating Kappa statistics (Monserud & Leemans, 1992). This is identical to the approach used by Lugo *et al.* (1999) to 'verify and evaluate' their classification for the United States.

For the Kappa analysis, the data sets that are compared must have the same spatial resolution and distinguish the same classes. To meet these requirements, the EnS was resampled to the resolution of the alternative classification and the two classifications were clipped to the largest overlapping extent. A contingency matrix was calculated to determine the best way to aggregate the EnS strata to the classes of the alternative classification. Kappa could then be calculated using the default settings of the Map Comparison Kit (Visser, 2004). The three alternative classifications used in this comparison were: the ITE classification [0.5° resolution, 64 classes (Bunce *et al.*, 1996d)]; global biomes determined by the IMAGE model for 1990 [0.5° resolution, nine classes (IMAGE team, 2001)]; and WWF ecoregions [polygons resampled to 1 km^2, 28 classes (Olson *et al.*, 2001)].

Correlation

Based on the conceptual hierarchy used to determine the variables used to construct the EnS (Fig. 2), the EnS should show correlations with other environmental data sets, including those lower in the conceptual hierarchy, e.g. those for soil, vegetation, species distributions. Even European land-cover maps can be expected to

Table 2 Summary of data sets that were available to (a) compare and (b) correlate with the EnS. While it is impossible to discuss the quality of these data sets at length, this table provides insight into the spatial scale, data scale and extent of the data sets. The number of classes or types distinguished by the data sets gives further insight into the level of detail provided by the data sets

(a)

Data set	Reference	Spatial scale	Data scale	Extent	Number of classes in Europe
IMAGE 1990 biomes	IMAGE-team 2000	0.5°	nominal	World	9
WWF ecoregions	Olson *et al.* (2001)	? 1 : 5,000,000	nominal	World	23
ITE European land classification	Bunce *et al.* (1996d)	0.5°	nominal	European window	64

(b)

Data set	Reference	Spatial scale	Data scale	Extent	Number of types in Europe
Atlas Flora Europaea — *Quercus* species	Jalas & Suominen (1976)	50 km	binary	Pan-Europe	25 species
CORINE land cover	EEA (2000)	250 m	nominal	European Union (15)	44 types
PELCOM land cover	Mücher *et al.* 2001	1 km	nominal	Pan-Europe	14 types
Potential Natural Vegetation	Bohn *et al.* (2000)	1 : 2,500,000	nominal	Pan-Europe	740 types
FAO Digital Soil Map of the World	FAO 1991	1 : 5,000,000	nominal	World	345 types at level 3
FAO Agro-ecological Zones	FAO/IIASA 2000	5′	nominal	World	7
HYDRO1k DEM and slope	[http://edcdaac.usgs.gov/]	1 km	ratio	World	not relevant
CRU TS1.2 climate	Mitchell *et al.* (2004)	10′	interval/ratio	European window	not relevant
MARS agronomic variables	[http://agrifish.jrc.it]	50 km	ratio	Pan-Europe	not relevant
IGBP soil variables	Global Soil Data Task 2000	5′	interval/ratio	World	not relevant

correlate with the EnS; after all, the distribution of several principal land-cover types (e.g. coniferous forest, deciduous forest, rain-fed cropland, vineyards) are determined by broad climatic patterns.

For quantitative variables (e.g. length of the growing season, soil pH), with a ratio or interval data scale, the correlation was calculated between the mean score of the first principal component of the classification variables, and the response variable.

For nominal environmental data sets (e.g. those for potential natural vegetation, soils and land cover), it is necessary to calculate a multivariate proxy that indicates the association of the various classes in the data set with each EnS stratum. This was achieved by determining the area-percentages of each nominal class (e.g. soil type) within each EnS stratum. For example, boreal EnS strata are expected to score high values for the podzol soil types, but low scores for Mediterranean brown earths. From this multivariate data set, the first principal component is calculated for each EnS stratum, using the default settings in SPSS (SPSS, 2001). This result can then act as the required proxy, and can be correlated with the mean first principal component of the classification variables.

For binary species distribution data sets, detrended correspondence analysis (DCA) can be used to analyse inherent gradients in the data set (Hill & Gauch, 1980). The default settings of CANOCO (Ter Braak & Šmilauer, 1998) were used to calculate the first DCA axis, which was then correlated with the mean first principal component of the classification variables.

Description

Finally, for each stratum, zonal statistics were calculated for the variables on which the stratification is based. These statistics help understand stratum boundaries and provide a general description of the strata. Box plots can be used to summarize the spread of values in each stratum. Other environmental data sets (i.e. soil, potential natural vegetation and land cover) provide a more complete description of the strata.

RESULTS

The Environmental Stratification of Europe

The first three principal components (Fig. 4) explain 88% of the variation in the 20 input variables. The subsequent two-tier clustering procedure produced 70 classes. Regions smaller than 250 km^2, less than 0.12% of the total extent, were identified and assigned to neighbouring strata. In 14 cases a class occurred in two distant environmental regions. In these cases the classes were split, resulting in a final stratification of 84 strata.

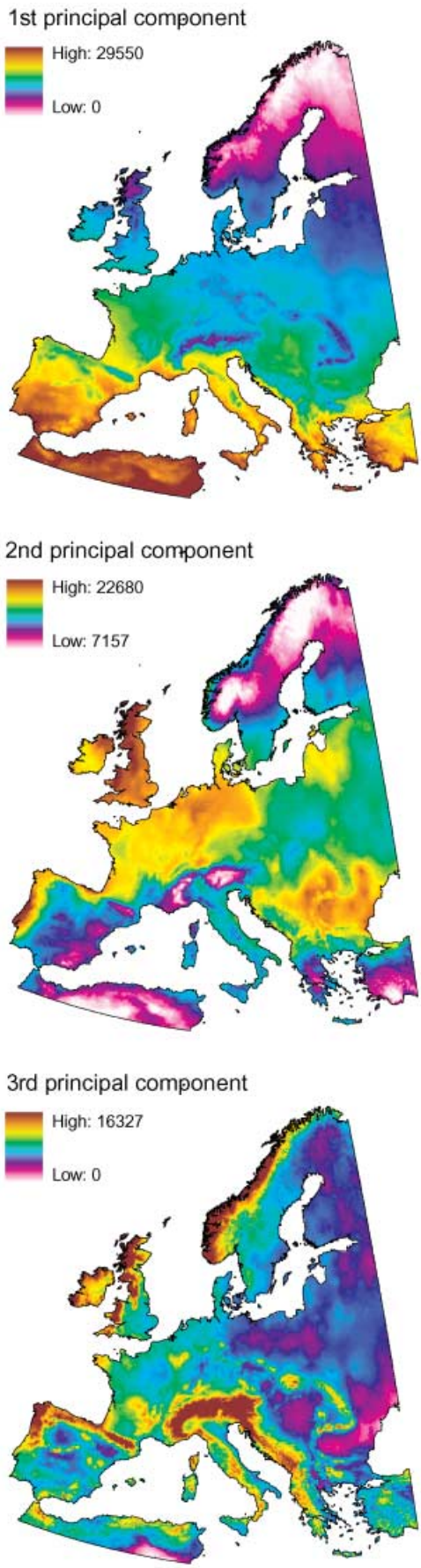

Figure 4 Maps of the first three principal components of the stratification variables, together explaining 88% of the total variation in the variables. The first principal component, explaining 65% of the variation, expresses the temperature gradient across Europe. The second component, an oceanicity gradient, and the third component, a precipitation pattern, express 15% and 8% of the variation, respectively.

The 84 EnS strata provide a convenient set for a continent as diverse as Europe and are appropriate for stratified sampling and analysis of environmental data. However, there are too many strata for summary reporting and presentation of the principal characteristics of Europe. An aggregation of the strata into a limited number of Environmental Zones (EnZs) was created to facilitate communication based on the experience of a similar situation in Great Britain, where 32 land classes were reduced to six zones for reporting purposes. The main environmental regions mentioned above (Alpine, Boreal, Continental, Atlantic, Mediterranean and Anatolian) were subdivided on the basis of the mean first principal component score of the strata in the regions. In order to distinguish the Mediterranean Mountains zone (MDM), an extra rule was required. All Mediterranean strata with altitudes above 1000 m were assigned to MDM. The remaining southern strata were assigned to Mediterranean North (MDN) or South (MDS) based on mean first principal component scores of the strata.

Consistent naming is important to emphasize the statistical approach and prevent misleading interpretations. The EnZs have, therefore, been ordered by the mean value of the first principal component of the classification variables, which expresses the north–south environmental gradient across Europe. In the same way, the EnS strata that fall within the EnZs are also numbered by the mean value of the first principal component. The EnS strata have been given systematic names based on a three-letter abbreviation of the EnZ to which the stratum belongs, and an ordered number based on the mean first principal component score. For example, the EnS stratum with the highest mean first principal component score within the Alpine North EnZ is named ALN1 (Alpine North one). The Environmental Stratification can now be mapped by colouring the EnS strata according to their EnZ and labelling them with their consistent names, as shown in Fig. 5. Because a numerical label is sometimes more convenient, all EnS strata are also numbered based on first principal component score. A high-resolution image of Fig. 5, which will allow for zooming in any image processing software, as well as a table with a broad geographical description of the location of the strata, are available as online appendices to this paper (see Figure S1 and Table S1 in Supplementary material).

Table 3 Strength of agreement, expressed by the Kappa statistic, between the EnS and three other European classifications: the ITE classification (Bunce *et al.*, 1996d); global biomes determined by the IMAGE model for 1990 (IMAGE team, 2001); WWF ecoregions (Olson *et al.*, 2001); Monserud & Leemans (1992) gave an indication of the quality of the comparison for different ranges of Kappa

Data set	Kappa	Quality of the comparison
ITE classification	0.55	good
1990 IMAGE biomes	0.72	very good
WWF ecoregions	0.60	good

Relation to other data sets

Comparison

Table 3 shows that the Kappa values for the comparison of the EnS with available data sets range between 0.55 and 0.72, indicating 'good' or 'very good' comparisons, according to Monserud & Leemans (1992). The Kappa values are higher than those reported by Bunce *et al.* (2002) in a comparison of biogeographical classifications of Europe.

Correlation

Table 4 and Fig. 6 show that all data sets available show a significant correlation with the Environmental Stratification (Pearson's

Table 4 Significant correlations were found between the mean first principal component of the classification variables per EnS stratum and available ecological data sets using Pearson's correlation coefficient at the 0.01 level. Binary and nominal data cannot be directly correlated to the principal component scores, therefore orthogonal regression and detrended correspondence analysis (DCA) were used for nominal and binary data respectively (see Materials and methods for details). The statistics were calculated for the European part of the stratification, since this is the area of interest and some data sets used for comparison do not cover northern Africa. Table 2 gives a summary of the data sets used in this analysis. Figure 5 shows the regressions of three data sets

Data set	Data scale	Reference	R^2 of the regression	Pearson's correlation coefficient
MARS annual temperature sum	ratio	[http://agrifish.jrc.it]	0.95	0.978
Potential Natural Vegetation	nominal	Bohn *et al.* (2000)	0.85	0.920
MARS growing season (no. of days ≥ 5 °C)	ratio	[http://agrifish.jrc.it]	0.83	0.911
Quercus species distribution	binary	Jalas & Suominen (1976)	0.72	−0.848
DSMW, all soil types	nominal	FAO 1991	0.59	0.771
IGDP soil pH first 100 cm	interval	Global Soil Data Task 2000	0.59	0.768
Agro-Ecological Zones	nominal	FAO/IIASA 2000	0.45	0.671
DSMW, main soil groups	nominal	FAO 1991	0.43	0.659
IGDP soil organic carbon first 100 cm	ratio	Global Soil Data Task 2000	0.42	−0.652
PELCOM land cover	nominal	Mücher *et al.* 2001	0.34	0.585
CORINE land cover	nominal	EEA (2000)	0.23	0.477

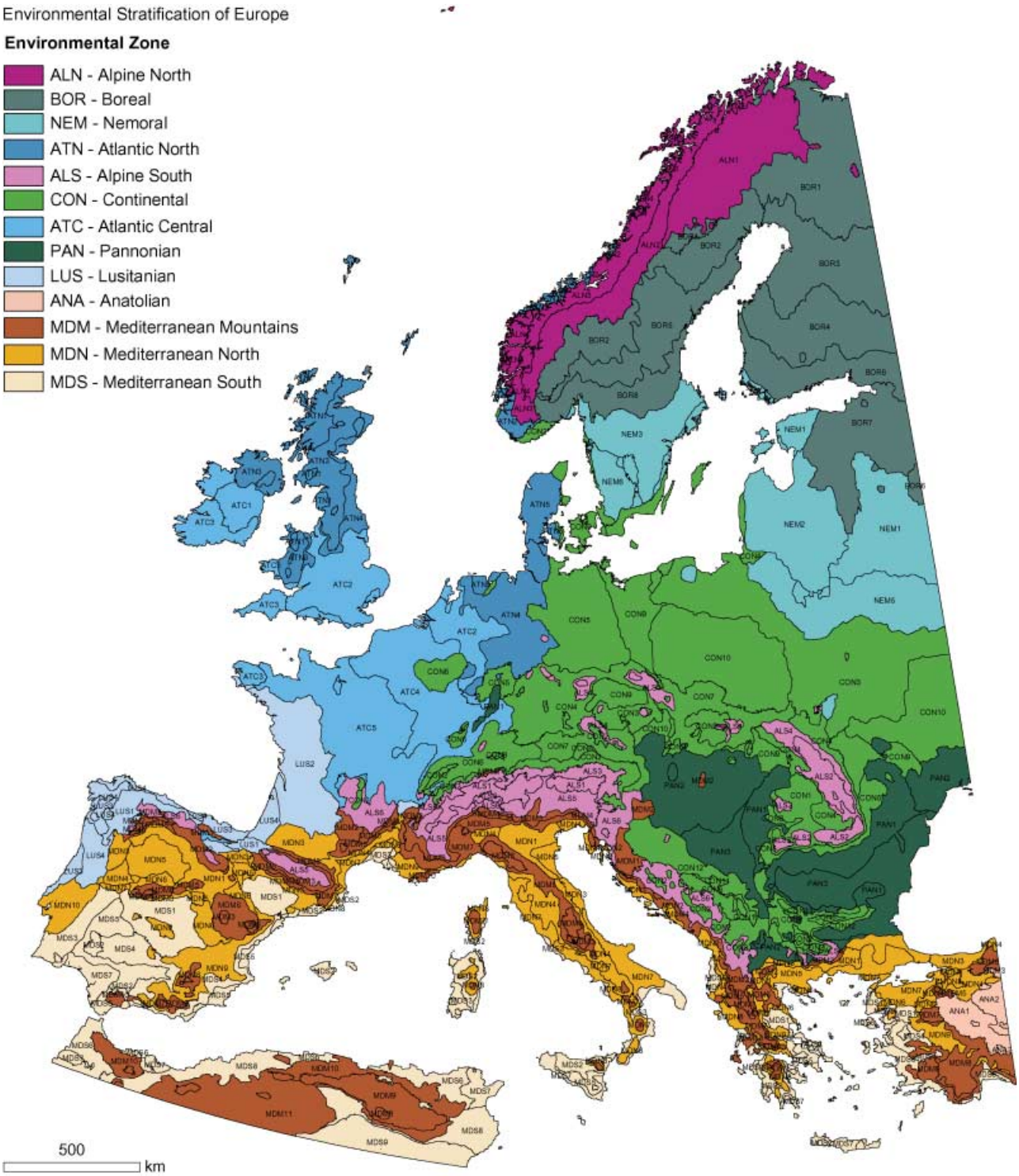

Figure 5 The Environmental Stratification of Europe in 84 strata. Where the size of the stratum permits, the individual strata are labelled within the main Environmental Zones. The stratification extends from 11° W to 32° E and from 34° N to 72° N. It is projected in a Lambert Azimuthal equal area projection. Because certain strata do not necessarily fit traditional experience, in this stratification strict statistical rules have been maintained, recognizing these apparent inconsistencies, e.g. PAN1 in the Vosges and Schwartzwald and CON2 in southern Norway.

correlation coefficient at the 0.01 level). Especially for the land-cover maps (CORINE and PELCOM), a considerable amount of the variation is not explained by the EnS. This is not surprising for the following two reasons.

1 These data sets include broad categories that do not differentiate across the European environment. For instance, categories such as pastures, coniferous forest and shrub land occur across Europe as one category, while in the field

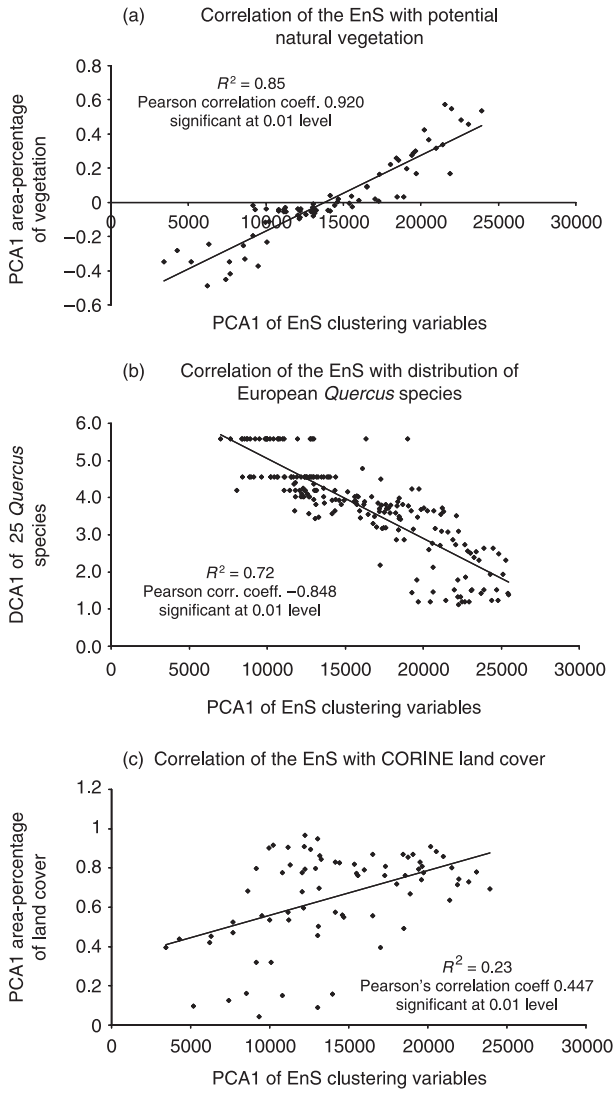

Figure 6 Significant correlations were found between the mean first principal component of the classification variables per EnS stratum and available ecological data sets using Pearson's correlation coefficient at the 0.01 level. Binary and nominal data cannot be directly correlated to the principal component scores, therefore orthogonal regression and detrended correspondence analysis (DCA) were used for nominal and binary data, respectively (see Materials and methods for details). The statistics were calculated for the European part of the stratification, as this is the area of interest and some data sets used for comparison do not cover northern Africa. Table 2 gives a summary of the data sets. (a) Potential natural vegetation (Bohn *et al.*, 2000); (b) *Quercus* species in the *Atlas Flora Europaea* (Jalas & Suominen, 1976); and (c) CORINE land cover (EEA, 2000).

there are differences in the species composition of the vegetation.

2 Land cover is influenced directly by human decisions that do not necessarily follow regional patterns. For instance, in the vicinity of Newmarket (East Anglia, Eastern England) the predominance of racing stables has resulted in several square kilometres of grassland in a region otherwise dominated by crops.

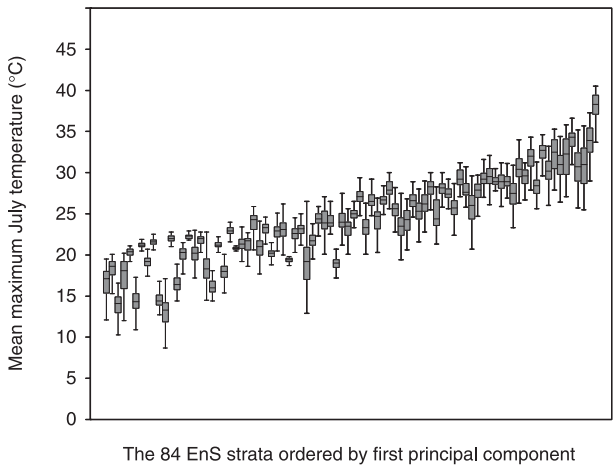

Figure 7 Box plots of the mean maximum temperature in July summarize the spread of the variable in each stratum. The strata are ordered by the mean value of the first principal component for each EnS stratum, which depicts the north–south environmental gradient across Europe. The climate data were derived from the CRU_TS1.2 data set (Mitchell *et al.*, 2004).

Description

The EnS is a multivariate stratification. The strata show overlapping ranges for most variables because the differences between them are multi-dimensional. Nevertheless, description of the strata with available data sets helps to understand the division of the strata. Each stratum has been described using the data sets listed in Table 2. An example of such a description for the mean maximum July temperature is given in Fig. 7.

DISCUSSION

Quality of the stratification

The aim of the Environmental Stratification of Europe is to form a sufficiently detailed statistical stratification of Europe's environment that can be used for strategic random sampling and for the comparison and analysis of diverse ecological spatial data. Taking into account the functional hierarchy in ecosystem components, discussed previously, it is appropriate to construct an environmental stratification for Europe using mainly climatic variables. In order for the stratification to be functional, it should show sufficient detail and it should correlate well with ecological data. Keeping these requirements in mind, it follows that it should be possible to select the best stratification from a suite of possible candidates, based on different variables and clustered into different numbers of strata and then choosing the stratification which holds the highest correlation with independent ecological data sets. This was the approach that had originally been envisaged, but it was not followed for several reasons. Firstly, by not being able to incorporate soil variables, possible combinations of variables were reduced. Secondly, it proved difficult to obtain ecological data sets to correlate with the stratification. However, as Bunce *et al.* (2002) have shown, statistical environmental

classifications will have much in common and decisions between them are arbitrary in any case and judgement is not involved in determining boundaries between the strata. Finally, in practice, there is a limitation to the number of strata that are convenient to handle, analyse and describe.

Analyses of the EnS with available data sets cannot be seen as a true validation of the stratification, but do indicate that the EnS forms an appropriate stratification of environmental variability in Europe. The comparisons with other classifications are good (Table 3), considering that two of the classifications (the WWF ecoregions and the IMAGE biomes) were constructed from different perspectives. Furthermore, the significant correlations between the EnS and various ecological data (Table 4 and Fig. 6), justify its wider application. The final test is through the application of the strata to field survey and the subsequent derivation of estimates and correlations.

The data used in the present study have limitations, but are the best available at the current time. Future improvements in data layers, when available, could improve the efficiency of the stratification. However, comparisons with available classifications, as described above, show that the main environmental boundaries in the Europe are relatively stable. It is therefore likely that any changes in the boundaries will affect the eventual estimates only to a small degree. Instability of the classified strata due to misclassification is discussed in Bunce *et al.* (1996a,b), where the clustering procedure had to be carried out in two stages. In the present study such instabilities were overcome by classifying all 1 km^2 sample squares in a single analysis. Any change in the databases used for classification, or in the classification procedure, will cause some squares to change class, but will not alter the overall pattern. However, any inefficiencies of the stratum will eventually be incorporated in the standard errors attached to the field estimates (Firbank *et al.*, 2003).

In mountainous regions steep environmental gradients occur over short distances. Although the EnS picks up these gradients more accurately than the ITE classification did, it still shows insufficient detail in most mountainous strata to form a good basis for defining distributions of predicted parameters at a lower level. The stratum ALS1 (Alpine South one), for instance, covers a range of altitude from 630 m to 4453 m. This lack of detail can be solved with an algorithm dividing all mountainous strata into three substrata that are equal in area, e.g. ALS1-high, ALS1-mid and ALS1-low. These strata are named altitude environmental strata (AEnS). AEnS strata created for the Alps distinguish valleys, slopes and mountain summits. Although the method of creating AEnS strata is arbitrary it offers a consistent division of mountainous strata, as is required for definition at a regional level (Jongman *et al.*, in press). Alternatively, more detailed regional stratifications could be used to disperse samples within an EnS stratum, e.g. based on regional information about geomorphology, soils or hydrology. As long as the samples are dispersed randomly, they can still be aggregated to the European context using the EnS.

While the 1 km^2 resolution may be considered coarse within Alpine environments, variation at lower resolutions can only be determined by field survey using procedures described by Firbank *et al.* (2003) for standardized sampling of, among others, vegetation, linear and freshwater features. Furthermore, all major monitoring exercises in the Alpine region, e.g. Wrbka *et al.* (1999) have also used 1 km^2 samples, supported by field surveys.

A hierarchical framework and its applications

The procedure described by Bunce *et al.* (1996a) for the GB land classification uses the first principal component to construct a hierarchy, but it was not as deterministic as the aggregation approach used in creating the EnS, which is entirely rule-based. The 84 EnS strata have been aggregated into 13 Environmental Zones, and even into seven generic Environmental Regions, but the EnS strata can also be disaggregated into approximately 200 AEnS strata. This hierarchical framework will allow for aggregation of local data into a European context. Alternatively it can be used to disaggregate regional data, as Petit *et al.* (2001) have shown for the distribution of habitats in Europe. In addition, different aggregations of the strata are possible to suit specific objectives. For instance, the EnS strata have been aggregated into European Mountain zones for analysis of European transhumance systems (Bunce *et al.*, 2004), and into principal biomes to aggregate global change impacts (Metzger *et al.*, in press).

The EnS is currently used within the EU Fifth Framework project BioHab (Coordination of *Bio*diversity and *Hab*itats in Europe) to provide the stratification for a framework for consistent monitoring of the occurrence and distribution of habitats in Europe. The EU Fifth Framework project ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling) has used the EnZs as a basis for summarizing and comparing outputs from a suite of global change impacts models (Metzger *et al.*, 2004). Smith & Bunce (2004) have also used the strata from the Atlantic zone to estimate the number of veteran trees by field survey of over 90 1 km^2 samples. Other parallel examples quoted in the present paper, e.g. Haines-Young *et al.* (2000), have shown that the EnS would be appropriate for the assessment of ecological resources and change. A range of modelling exercises involving the assessment of consequences resulting from environmental change (e.g. Petit *et al.*, 2001), scenario testing and modelling change (e.g. Parry *et al.*, 1996; Ewert *et al.*, 2005) have also been conducted. The application of the EnS to other comparable studies is currently under discussion.

CONCLUSION

The Environmental Stratification of Europe has been constructed using tried and tested statistical procedures and shows significant correlations with principal European ecological data sets. As shown in comparative studies, such a stratification can be used for strategic random sampling for resource assessment, for the measurement of change and for modelling. The hierarchy of the EnS framework allows regional applications to be aggregated into continent-wide assessments, thus facilitating the growing demand for coherent European ecological data to assist EU policy and global state of the environment assessments such as

the EU State of the Environment Report and the Millennium Ecosystem Assessment. The EnS will not replace existing classifications, but will provide a framework for integration between them and subsequent estimates of habitat and vegetation when field data become available. The Environmental Stratification is available for noncommercial use by applying to the corresponding author.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article online at www.blackwell-synergy.com

Figure S1. High-resolution map of the Environmental Stratification of Europe.

Table S1. Description of the location of the EnS strata.

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Marc Metzger is finishing his PhD within the EU-funded ATEAM project, where he developed a comprehensive approach to quantify the vulnerability of society to changes in ecosystem service provision under global change.

Bob Bunce has developed a methodology of land classification, using statistical analysis and stratified random sampling that has been used for assessing vegetation, habitat and landscape change in Great Britain. He is now working on extending the methodology for Europe.

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John Watkins was database manager, working on the earlier 0.5° climatic classification.