Ecological Indicators 33 (2013) 26–35

Contents lists available at SciVerse ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Environmental stratifications as the basis for national, European and global ecological monitoring

M.J. Metzger[a,*], D.J. Brus[b], R.G.H. Bunce[c], P.D. Carey[d], J. Gonçalves[e], J.P. Honrado[e], R.H.G. Jongman[b], A. Trabucco[f,g], R. Zomer[h]

[a] The University of Edinburgh, School of GeoSciences, Drummond Street, Edinburgh EH8 9XP, Scotland, UK
[b] Alterra, Wageningen Univeristy and Research Centre, The Netherlands
[c] Estonian University of Life Sciences, 51041 Tartu, Estonia
[d] Department of Plant Sciences, University of Cambridge, UK
[e] CIBIO, University of Porto, Portugal
[f] Euro-Mediterranean Center on Climate Changes, IAFENT Division, via de Nicola 25, 07100 Sassari, Italy
[g] KULeuven, Division Forest, Nature and Landscape, Celestijnenlaan 200E, 3001 Leuven, Belgium
[h] Centre for Mountain Ecosystems Studies, Kunming Insitute of Botany, China

ARTICLE INFO

Article history:
Received 31 March 2012
Received in revised form 7 November 2012
Accepted 11 November 2012

Keywords:
Environmental stratification
Biodiversity monitoring
GEO BON
General Habitat Categories

ABSTRACT

There is growing urgency for integration and coordination of global environmental and ecological data and indicators required to respond to the 'grand challenges' the planet is facing, including climate change and biodiversity decline. A consistent stratification of land into relatively homogenous strata provides a valuable spatial framework for comparison and analysis of ecological and environmental data across large heterogeneous areas. We discuss how statistical stratification can be used to design national, European and global biodiversity observation networks. The value of strategic ecological survey based on stratified samples is first illustrated using the United Kingdom (UK) Countryside Survey, a national monitoring programme that has measured ecological change in the UK countryside for the last 35 years. We then present a design for a European-wide sampling design for monitoring common habitats, and discuss ways of extending these approaches globally, supported by the recently developed Global Environmental Stratification. The latter provides a robust spatial analytical framework for the identification of gaps in current monitoring efforts, and systematic design of new complementary monitoring and research. Examples from Portugal and the transboundary Kailash Sacred Landscape in the Himalayas illustrate the potential use of this stratification, which has been identified as a focal geospatial dataset within the Group on Earth Observation Biodiversity Observation Network (GEO BON).

1. Introduction

There is growing urgency for integration and coordination of global environmental and biodiversity data required to respond to the 'grand challenges' the planet is facing, including climate change and biodiversity decline (Parr et al., 2003; MA, 2005; Pereira and Cooper, 2006; Scholes et al., 2008, 2012; Mooney et al., 2009; Metzger et al., 2010, in press; Pereira et al., 2010). On-going and new programmes are gathering valuable data through a profusion of projects at regional, national and international scales, e.g. the Long Term Ecological Research (LTER) programmes (Parr et al., 2003), and activities related to the Global Earth Observation System of Systems (GEOSS; e.g. Muchoney, 2008). Nevertheless, major challenges remain, including data aggregation across scales, consistent monitoring of global biodiversity change, and linking in situ and earth observations (Bunce et al., 2008; Scholes et al., 2008, 2012; GEO BON, 2010). Progress in these fields is essential to improve future assessments and the evaluation of policy targets relating to the stock and change of global ecosystem resources and biodiversity (Scholes et al., 2008, 2012), including efforts to support the recently launched Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES; Larigauderie and Mooney, 2010) and the United Nations Convention on Biological Diversity (CBD) Aichi targets (Nayar, 2010).

Consistent classification, or stratification[1], of land into relatively homogenous strata provides a valuable spatial framework for

* Corresponding author. Tel.: +44 131 651 4446; fax: +44 131 650 2524.
E-mail address: marc.metzger@ed.ac.uk (M.J. Metzger).

[1] When classes are not meant as descriptive units, but specifically designed to divide gradients into relatively homogeneous subpopulations we prefer to use the statistical term *stratification*.

1470-160X/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ecolind.2012.11.009

comparison and analysis of ecological and environmental data across large heterogeneous areas (Paruelo et al., 1995; Lugo et al., 1999; McMahon et al., 2001; Leathwick et al., 2003; Metzger et al., 2005). Stratifications can be used for targeting research and monitoring efforts (cf Metzger et al., 2010), aggregating observations (cf Firbank et al., 2003), and for the comparison of trends within similar environments (cf Mooney, 1977). This paper will discuss their role as the basis for monitoring ecological indicators across large areas with major environmental gradients. In these cases it is important that sample units are geographically spread across the domain and that representivity of the diversity of environmental conditions is ensured. The value of strategic ecological survey based on stratified samples is first illustrated using the United Kingdom (UK) Countryside Survey, a national monitoring programme that has measured ecological change in the UK countryside for the last 35 years (Sheail and Bunce, 2003; Norton et al., 2012). This is followed by presenting the recent development of a European-wide sampling design for statistical monitoring of common habitats. Finally, the potential of developing a global biodiversity observation network is discussed, along with initial applications of a new global stratification. The paper concludes with a vision of the way forward for global monitoring of ecological indicators.

2. Countryside Survey: 35 years of strategic ecological survey in the UK

2.1. Background

Countryside Survey (CS) provides scientifically reliable evidence about the state or 'health' of the UK countryside. The most recent survey was carried out in 2007 and the findings can be compared against the findings of previous surveys from 1998, 1990, 1984 and 1978, allowing changes (and the relative rate of change) in ecological indicators to be quantified. This evidence is used to inform and develop policies that influence management of the countryside, both now and in the future (Norton et al., 2012; Maskell et al., 2010; Chamberlain et al., 2010; Smart et al., 2005).

A unique strength of CS has been that data have been collected from permanently sited vegetation plots with integrated landscape scale habitat mapping, soil samples, and freshwater sampling from the same 1×1 km square at the same time. This landscape scale approach allowed groundbreaking linkages to be made between the causes of change over a 35 year period in land-use, vegetation, soil and freshwater (Sheail and Bunce, 2003). CS has become a programme with multiple government funders and has had to adapt to the needs of users whilst maintaining its scientific integrity. This has been achieved by having a rigid backbone of information that is collected at each survey date, to which other elements have been added when financial resources were available. Details of the methods of data collection are available at www.countrysidesurvey.co.uk from where all reports can be downloaded.

Importantly, CS uses a stratified random sample of the whole country, and does not target areas of conservation importance and can therefore be considered to be a census of the countryside as a whole. However, areas of conservation interest are found within the sample and ecological surveys following CS protocols have been used in other projects to target areas of conservation interest and agri-environment schemes, which have then been compared to the countryside as a whole (e.g. Carey et al., 2002)[2].

CS findings are used to:

- contribute to Government's reporting of biodiversity through several key biodiversity indicators
- assess progress against target indicators in Biodiversity Strategies for the UK and the devolved countries (England, Wales, Scotland, Northern Ireland)
- improve scientific understanding of the countryside's landscape, vegetation, freshwater and soils
- assess changes in the area and distribution of habitats and some habitat features of special interest (e.g. hedgerows, arable field margins and upland heath)
- examine how the countryside's natural resources respond to changes in land use, climate change and government policy

2.2. UK stratification and network design

The guiding principle underpinning CS is the policy need for reliable statistical estimates of indicators of stock and change in the countryside. This required a statistical sampling design that provides reliable national statistics and also, crucially, ensures that the sample was representative of the range of different environments found in Great Britain (and later Northern Ireland). The spatial sampling design was therefore based on an environmental stratification of Great Britain that divides the major environmental gradients across the country (Bunce et al., 1996). A similar approach was used to create the sample for Northern Ireland. The stratification was initially developed using multivariate TWINSPAN analysis (Hill, 1979) of environmental variables. Climatic, topographic, geological and anthropogenic data were recorded from 1200 out of the 240,000 161 km squares of the National Grid of Great Britain (GB) laid out at the intersections of a 15 km square grid. Logistic regression and discriminant functions were subsequently used to assign all the remaining squares to the original strata but also to reassign the squares from the initial grid sample. The full procedure is described in Bunce et al. (1996).

Once the stratification had been constructed a probability sample[3] of 1 km squares (the sample units) was selected from each of the 32 strata. The first survey was carried out in 1978 and 8 sample units from each stratum were visited, giving a total of 256. In 1984, 12 squares from each stratum were surveyed, and in 1990 16 squares. Resource availability determined the number of sample units initially. In subsequent surveys the need for greater replication was noted but again, ultimately it was financial resources that limited the sample size. By 1998, devolution had begun to take place in the UK and the Scottish government wished to report results separately. To achieve this, further strata had to be created to allow Scotland to be split from England and Wales and by 2007, Wales also wished to report separately from England and again further strata were required. In 2007 there were 40 strata and the aim was to survey 16 sample units from each.

In statistical terms, a monitoring network is a spatial and temporal collection of sampling units from the full population. In CS the same locations are resurveyed whenever possible to obtain the most reliable (precise) estimates of change. Such a space-time design is referred to as a static-synchronous design (De Gruijter et al., 2006) or pure panel. Serially alternating designs, where sampling effort is spread over a number of years, were discussed as this would have operational benefits because survey effort and project

[2] Because these studies were designed to assess particular conservation actions, the ability to compare with CS was a side-effect. Should a project be required to compare a conservation action to the countryside as a whole from the beginning, it should be designed accordingly with appropriate levels of sampling.

[3] We use the term probability sampling instead of random sampling, because the latter tem is also used to describe the arbitrary selection of sampling units. Only probability sampling allows for design-based estimation of target parameters, resulting into model-free, unbiased and valid estimates of the target parameters and their standard errors (De Gruijter and Ter Braak, 1990; Brus and De Gruijter, 2011).

management could then be spread over time. However, at the time, statistical methods for analysis were not developed for such a procedure and the ad hoc funding of the programme meant that a static-synchronous design was most suited design.

2.3. Lessons for large scale monitoring

CS illustrates the value of statistically designed monitoring to provide reliable indicators to support policy. A good example are the observed trends in hedgerow decline that were observed between 1984 and 1990, leading to legislation to halt the destruction of these important landscape features. The immediate policy effect was subsequently noted in the 1998 survey. CS was a pioneering endeavor that has inspired other large scale monitoring projects (e.g. in Spain (Elena-Rossello et al., 2005) and Sweden (Ståhl et al., 2011) and has had to adapt to new advances in technology and changes in policy interest. However, the general underlying principles have proved extremely successful and provide the basis for the following five lessons for designing large-scale ecological monitoring programmes:

1. **Environmental stratification is essential to ensure representivity.** Without environmental stratification the biogeography of the UK would not have been adequately covered with over representation of the arable lowlands and under representation of the hyper-oceanic and oceanic north-west.
2. **Probability sampling is needed to provide robust statistical estimates of change.** The statistical rigor of the CS indicators for hedgerow decline was crucial to convince the UK government to adopt protective legislature. Without probability sampling statistical inference extremely challenging, as discussed for Europe below.
3. **A flexible and simple sampling design is important.** Over time additional samples were added, separate reporting for Scotland and Wales became a requirement, and some sample units could no longer be recorded. The relatively simple sample design allowed for these changes to be accommodated, despite challenges, e.g. because the initial stratification and sampling design were based on a systematic grid.
4. **Collect disaggregated data.** By collecting disaggregated data for all elements (e.g. vegetation, invertebrates, habitats, soils and water) it had been possible to construct aggregated indicators tailored to the most recent policy questions, and provide historic time series for these indicators. For example, in the 1998 it was possible to report on the newly developed Broad Habitats (Firbank et al., 2003), and in 2007 survey it was possible to include an analysis of ecosystem services (Norton et al., 2011).
5. **Collect species level data.** Although time consuming to collect, vegetation plots with species level data are required to address quality change within the landscape. For example, although the extent of heathland and bog has not changed drastically, the species richness has declined considerably (Norton et al., 2012).

3. Towards a European-wide sampling design for monitoring of common habitats

3.1. Background

Biodiversity assessments to underpin EU policy and report to the CBD, as well as European ecological research concerning global change impacts on ecological resources, are both hindered by the lack of coherent data and institutional barriers to data availability (Bunce et al., in press-a; Jongman, in press). Currently, the Natura 2000 network of protected sites is the EU's main mechanism to protect biodiversity, with legal protection for rare and threatened species and habitats. However, monitoring, and therefore data collection, is not collected using standardised methods or indicators, and data is stored nationally and not generally available for scientific use (Jongman, in press). Outside Natura 2000, there are no reporting requirements to the EU and national efforts vary greatly. Status and trends reporting (e.g. EEA, 2010) and scientific ecological research therefore currently rely on coarse and indirect biodiversity indicators, for example based on the EU Corine land cover map or coarse species distribution maps.

In recent years new field protocols and harmonized indicators have been developed based on the General Habitat Categories (GHCs) described by Bunce et al. (2008). An updated field protocol, relying heavily on experience in CS, has been developed to consistently map European habitats within 1 km square sample units to assess habitat change (Bunce et al., 2011). Habitats are important indicators of biodiversity in their own right, but they are also linked to species and assemblages both of plans and other taxa, as discussed in detail by Bunce et al. (in press-a). Examples include the relation between patterns of animal occurrence in different forms of tree cover in agricultural landscapes (Harvey et al., 2006) and butterfly abundance that can be influenced by vegetation structure (Hinsley and Bellamy (2000). Recent work has shown how the GHCs can be combined with ancillary information to consistently record Habitats Directive Annex 1 habitats in the field (Bunce et al., in press-b).

Ultimately, a full scale European Biodiversity Observation Network (Euro BON) could be developed in which existing monitoring and Long Term Ecosystem Research (LTER) activities (Parr et al., 2003; Metzger et al., 2010) are complemented by a statistical monitoring programme that can provide estimates of stock and change in GHCs and other major ecological indicators. The following section explore the statistical network design, which would fit within the wider Group on Earth Observation Biodiveristy Observation Network (GEO BON) initiative to collate comprehensive information about the world's biological resources to support the efforts of policymakers and managers to set priorities, elaborate strategies and assess the effectiveness of their actions (Scholes et al., 2008, 2012).

3.2. European stratification and network design

The specific aim in this example is to develop a provisional sampling design to monitor the size (spatial extent) and quality indicators of common, widespread habitats in EU27 supplemented by Norway and Switzerland (EU27+), and report at the EU level to assist in the evaluation of the EU biodiversity targets. The design was developed following the structured approach of De Gruijter et al. (2006). Although it is unlikely to be adopted in the immediate future, it illustrates the considerations and plausibility of such a monitoring network. Full details of the proposed sampling design are described by Brus et al. (2011).

Similar to CS, the sampling units are 1 km squares, within which GHCs and vegetation plots are recorded based on in situ observations, following the procedures described by Bunce et al. (2011). Reporting units are the target area in its entirety (EU27+) and the twelve Environmental Zones (EnZs) defined by Metzger et al. (2005; see Appendix A). This implies that sufficient samples will be needed to obtain separate estimates of stock and change for the twelve EnZs, but reliable estimates for the separate environmental strata (EnS, subdivisions of the environmental zones), or for individual countries are not foreseen for the core design described here. However, the proposed sample could be combined with additional national data to obtain more reliable estimates of habitat properties at the national level.

A first choice in designing a space-time sample is on the pattern of revisits of 1 km squares. For instance, CS adopted a static-synchronous or pure-panel design (described in Section 2.2) where

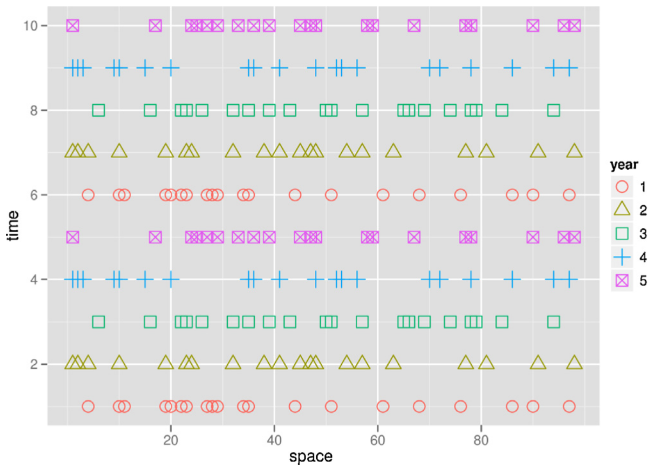


Fig. 1. Serially alternating space-time design with a periodicity of five years.

all sample units are revisited in each survey, while in an independent synchronous design no squares are revisited. Here, a serially alternating design is proposed, with a periodicity of five years (Fig. 1). In simulation experiments this type of space-time design has shown to be relatively efficient for estimating a linear temporal trend of spatial means (i.e. totals) (Urquhart and Kincaid, 1999; Ter Braak et al., 2008; Brus and De Gruijter, 2011). The proposed design implies that the sets of 1 km squares observed in the first five years differ between the years. In the sixth year the 1 km squares of the first year are revisited et cetera (Fig. 1). This design was also chosen for the National Inventory of Landscapes in Sweden (NILS; Ståhl et al., 2011), in part because of the operational convenience of spreading monitoring activities over time. It is important that the sample units of a given year are selected from the *entire* study area, not from a part of it (for instance from a subset of the strata). This enables unbiased estimation every year of the statistical parameters (area of habitat types et cetera) of the study area in its entirety, allowing for the detection and analysis of inter and intra annual variability in the target parameters.

As with CS, the spatial sampling units are selected by probability sampling. This allows for design-based or hybrid design and model-based estimates of *space-time* parameters, such as the temporal mean of the area of GHCs or the linear temporal trend of the area of GHCs (Brus and De Gruijter, 2012). To make statistical estimates of the target parameters with non-probability sampling in space, a statistical model of the variation in space and time is required for the target properties. Calibrating such model for the EU would be demanding and involve assumptions on stationarity, isotropy et cetera that will affect the quality of the monitoring result. Valid quantification of the uncertainty of the monitoring result, e.g. in standard error or confidence intervals, is important to avoid discussions on the statistical significance of estimated time trends in quality indicators and other target parameters.

Stratified simple random sampling (Brus and De Gruijter, 1997; De Gruijter and Ter Braak, 1990) is proposed as the spatial sampling design. The 78 EnS strata (see Appendix A) in the target population (EU27+) served as the primary stratification, but are further subdivided into compact geographical substrata, hereafter shortly referred to as geostrata, using the method proposed by Brus et al. (1999). This geographical substratification ensures good spatial coverage of the EnS by the km squares observed in a given year. In this method all 1 km squares within a given EnS are clustered by the k-means algorithm into $L_{\mathrm{EnS}} = n_{\mathrm{EnS}}/5$ clusters (n_{EnS} is the number of 1 km squares to be selected from environmental stratum EnS). The two spatial coordinates of the centre of the 1 km squares are used as classification variables in k-means clustering. The R-package spcosa

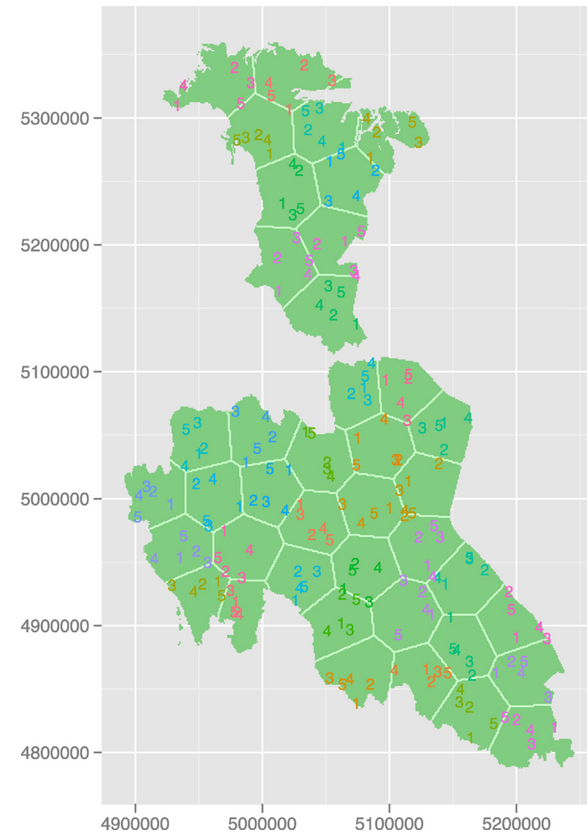


Fig. 2. Compact geographical substratification of EnS 2 with five (one per year) 1 km squares per geostratum. Numbers indicate the year of observation. Coordinates are from the EU INSPIRE coordinate reference system.

was used to construct the geostrata (Walvoort et al., 2010a,b). With $L_{\mathrm{EnS}} = 5$, within each geostratum five 1 km squares are selected by simple random sampling without replacement (Fig. 2). The order of selection of the 1 km squares is registered. The set of 1 km squares of the same order are sampled in the same year. The size (area) of the geostrata within a given EnS is not constant. The reason for not restricting the geostrata to equal area is that many environmental strata are not contiguous areas, but consist of several isolated polygons. Constraining the geostrata to equal area may lead to non-contiguous geostrata, which is clearly suboptimal. The differences in size (area) of the geostrata must be accounted for in the statistical estimation of target parameters.

The proposed sampling is design flexible and relatively simple. Additional samples can be added if greater accuracy is required, or national estimates are desired. Furthermore, the existing national programmes NILS (Ståhl et al., 2011) and CS (Norton et al., 2012) can be integrated into the suggested design (Brus et al., 2011). Calculations of the required sample size (number of locations per sampling time) can be calculated based on prior estimates of the spatial variance (population variance) of the target parameters (i.e. the habitat indicators) within the main strata and geostrata known (Brus et al., 2011). However, computation of these spatial variances of the indicators from currently available data is not straightforward because they need to be representative for the target area.

As an initial suggestion, based on experience in CS, a total sample size of 10,000 samples was used to provide an indication of the division of samples among European countries and approximate the total personnel time to carry out the survey based on the 10 person days per sample unit experienced during the testing of the protocol. The median number of sample units to be visited in each country is 43 per year, equaling around 0.5 Full-Time

Equivalent (FTE; 200 work days). Small countries have a smaller sampling effort (1 sample unit per year for Luxemburg and Malta, 21 sample units per year for The Netherlands), while large and diverse countries have a larger sampling effort (e.g. 347 samples/1.7 FTE per year for France). The total European effort of recording 2500 sample units per year would equate to 12.5 FTE.

3.3. Discussion and challenges ahead

The presented sampling design, in combination with the field protocol for the GHCs, form a robust of strategy for monitoring common and widespread habitats in Europe. Before implementation the design will need to be aligned further with funders' requirements and expectations, and the required accuracy of the estimates will need to be agreed (and sampling intensity adjusted accordingly). Nevertheless, over recent years the sample design and field protocols have been developed to a level where these are now ready for implementation.

The proposed observation network, based on monitoring habitat indicators, would provide data on biodiversity trends in Europe in far greater detail than current land cover based approaches (e.g. EEA, 2010). Habitats are seen here as an aggregated level of biodiversity, consisting of mixtures of vegetation types that in turn comprise of species assemblages and taxa (Bunce et al., in press-a). However, rare habitats and species, or those with specific ecological niches requirements, will not be recorded accurately with a probability sample (Bunce et al., 2008; Brus et al., 2011), and will require a targeted and tailored monitoring approach designed for the habitat or species of interest (see also Section 4.4). For example, to assess the distribution of *Ramonda pyrenaica* would require targeted surveying of 1 km squares containing canyons in the Pyrenees. In addition, vegetation or species that show great inter annual variability (e.g. annuals in xeric environments) will require methods that are targeted in time (Bunce et al., 2011).

The sampling design presented here focused on providing estimates for the EU as a whole, and will only be able to provide reliable regional results at the EnZ level (see Appendix 1). However, biodiversity reporting is currently a national responsibility, and historic and current national differences in nature conservation, land use planning et cetera mean that national trends can deviate significantly from the European trends. To be able to quantify these distinctions, and to be able to support national policy, the described method can be easily adapted by adding additional probability samples in individual countries. Countries with an existing monitoring network based on probability samples, e.g. the UK and Sweden, can integrate these surveys into the proposed design (Brus et al., 2011).

The need for reliable and consistent ecological data is widely reported, but the significant costs associated with data collection make it extremely challenging to initiate new monitoring programmes. The EU has invested in major research programmes to develop the science needed to implement a European monitoring network (e.g. BioHab, EuMON, AlterNet, EBONE), and is continuing investments in the Group on Earth Observations (GEO) initiative[4] and the development of a European Biodiversity Observation Network (Euro BON). It is especially important that Euro BON fits within existing institutional frameworks, making optimal use of exiting effort and funding (Parr et al., 2003). It should provide meaningful data and statistics, whilst linking to ongoing activities conducted by governmental agencies and NGOs at EU, national and regional level. The sampling design presented here, along with the field protocol (Bunce et al., 2011) form a solid basis that demonstrates the potential for strategic ecological survey to produce statistical estimates of stock and chance in key ecological indicators related to common habitats and their associated biodiversity. However, ultimately, the final implementation will be a matter of political will.

[4] www.earthobservations.org

4. Stratification to support a global biodiversity observation network

4.1. Background

A global stratification system would provide a flexible instrument for the coordination and analysis of global biodiversity observation efforts (Paruelo et al., 1995; Lugo et al., 1999; Leathwick et al., 2003; Pereira and Cooper, 2006). Furthermore, a robust global stratification into ecologically representative areas will be crucial under the CBD Aichi targets to increase terrestrial nature reserves from 13% to 17% of the world's land area by 2020 (Nayar, 2010) and would provide a valuable tool for environmental assessments, such as those required by IPBES (Larigauderie and Mooney, 2010).

The GEO BON vision is to support these needs by initiating a coordinated, global network that gathers and shares information on biodiversity, provides tools for data integration and analysis, and contributes to improving environmental management and human well-being (Scholes et al., 2012). A first task will be to establish a global community of practice that will facilitate collaboration, harmonization and integration of existing time series of ecological indicators (including those for genetic diversity, species diversity and habitat extent) that are collected around the world. To support these activities, the GEO BON implementation plan (GEO BON, 2010) explicitly refers to the need for a global stratification to support gap analysis in exiting biodiversity observations, and target additional observation effort and research.

Although many global climate or biome maps exist, and they have been used as summarising units for biodiversity change (e.g. global biomes in the Millennium Assessment), these maps are generally coarse, distinguishing no more than 10–30 classes. More detailed approaches to describe global ecoregions (Olson et al., 2001) rely heavily on expert judgement for interpreting class divisions, making it difficult to ensure reliability across the world and limiting their use in scientific analysis (Lugo et al., 1999). A new global stratification and its potential contribution to GEO BON is summarised below, followed by two examples of its application.

4.2. Global stratification and potential network design

The construction of the recently developed Global Environmental Stratification (GEnS; Metzger et al., in press) is based on the tested statistical methods used to develop the EnS (Metzger et al., 2005; Appendix A) to make subjective choices explicit, their implications understood and the strata representative in the global context. Statistical screening produced a subset of relevant bioclimate variables, which were compacted in uncorrelated dimensions using principal components analysis. Statistical clustering was subsequently used to classify the principal bioclimate gradients in temperature, aridity and seasonality into relatively similar biophysical environments. To provide structure and support a consistent nomenclature these strata were aggregated into global environmental zones based on the attribute distances between strata (Fig. 3). The GEnS delineates of 125 strata, which have been aggregated into 18 global environmental zones and has a 30 arcsec resolution ($0.93 \times 0.93 = 0.86\,km^2$ at the equator). Added value of the GEnS compared to existing global classifications include the rigorous statistical methods used to delineate strata, the high spatial resolution which allows for the identification of regional gradients, and the increased number of strata (e.g. in major mountain systems where altitudinal gradients are subdivided, as

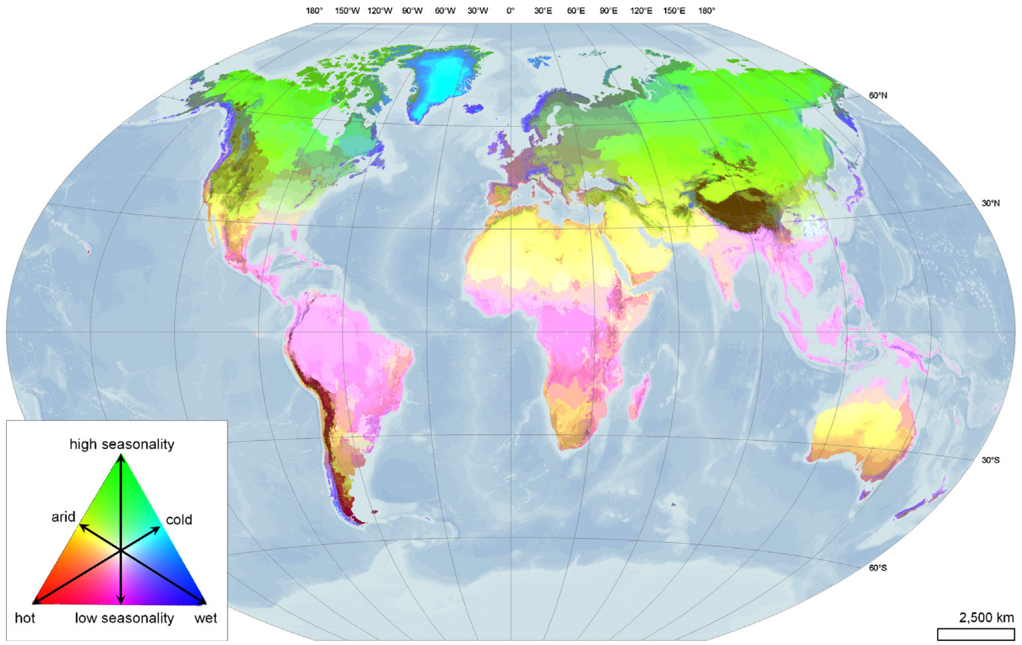


Fig. 3. Recently developed Global Environmental Stratification (after Metzger et al., 2013).

demonstrated in Section 4.3). Comparison with existing global continental, and national stratifications confirms that it successfully partitions important environmental gradients (as discussed in more detail in Section 4.4).

Developing a global biodiversity observation network that integrates existing activitis is not straightforward. Ecological data is collected in many different ways. Statistical surveys like CS are rare and much of the current data used to calculate global ecological indicators (e.g. the Living Planet indicator (Collen et al., 2009)) is collected in site based LTER stations (cf Parr et al., 2003). But there is also an increasing availability of ecologically interpreted satellite imagery (Muchoney, 2008), and citizen science is proving a promising and cost effective way to gather data (e.g. Thackeray et al., 2010). It is therefore important to find ways to collate and harmonise these diverse sources of data and develop appropriate statistical methods of data analysis to make optimal use of existing data. Furthermore, there is likely to be significant bias in the types of ecological indicators that are monitored, and in the spatial coverage or representativeness of these observations (Pereira et al., 2010). A spatial and thematic gap analysis will therefore be essential to establish the coverage of the existing biodiversity observation effort, and target future monitoring and research effort.

Environmental stratification helps in the comparison between sites across large heterogeneous areas (Jongman et al., 2006; Metzger et al., in press), and the GEnS has therefore been identified as a crucial dataset to support the assessment of spatial representiviy of existing monitoring activity (GEO BON, 2010). Specific methods for these analyses will need to be developed, and will depend on the level of desired detail and accuracy. However, even simple analyses assessing the number of sites providing observations for selected groups of indicators (e.g. birds, plants or habitats) can support decisions to add further observation to existing sites or to decide on locations for observations in those regions that are currently poorly represented.

In addition to these global analyses, the GEnS also provides sufficient detail to support the design of regional monitoring programmes that can be nested within the global network. Two such applications of the GEnS are discussed below.

4.3. *Ecological monitoring in the Kailash Sacred Landscape*

The Kailash Sacred Landscape Conservation Initiative (KSLCI) is the first cooperation of its kind among China, India, and Nepal. It seeks to conserve the unique, highly diverse and ecologically fragile Kailash Sacred Landscape (KSL) through the application of transboundary ecosystem management and enhanced regional cooperation. The transboundary KSL region is comprised of remote portions of the south-western Tibetan Autonomous Republic of China, and adjacent portions of northern India and north-western Nepal and covers over 31,000 km^2. The KSL harbours high levels of natural and agricultural biodiversity, and provides a broad array of ecosystem services to the more than one million people living within it boundaries (Zomer and Oli, 2011). Due to steep altitudinal gradients and extreme variations in topography, the ecosystems of the region vary widely from moist subtropical to temperate, alpine, and cold high altitude desert types.

The KSLCI, initiated in 2008 and envisioned as a long-term conservation initiative, has a priority focus on knowledge generation and capacity building for community based conservation and sustainable development. Long-term ecological monitoring and ecological research will create a regional knowledge–base and help develop a regional expertise. A comprehensive monitoring plan (KSL-CEMSP) has been developed as one of the core framework documents (ICIMOD, 2011a) supporting the KSL Conservation Strategy (ICIMOD, 2011b). The KSL-CEMSP outlines a common approach and transboundary framework for ecological monitoring and a broad range of ecological, socio-ecological, and socio-economic research, with an emphasis on biodiversity conservation and management, as well as local livelihoods and adaptation to climate change. It outlines and provides the framework for coordination among the three KSL countries, regional harmonization of monitoring and environmental research efforts, and the sharing and analysis of data, information, and knowledge. As this framework builds a common approach based upon standardized protocols, it creates the foundation for, and facilitates knowledge dissemination at all levels, and knowledge sharing between regional partners and with the international global science community.

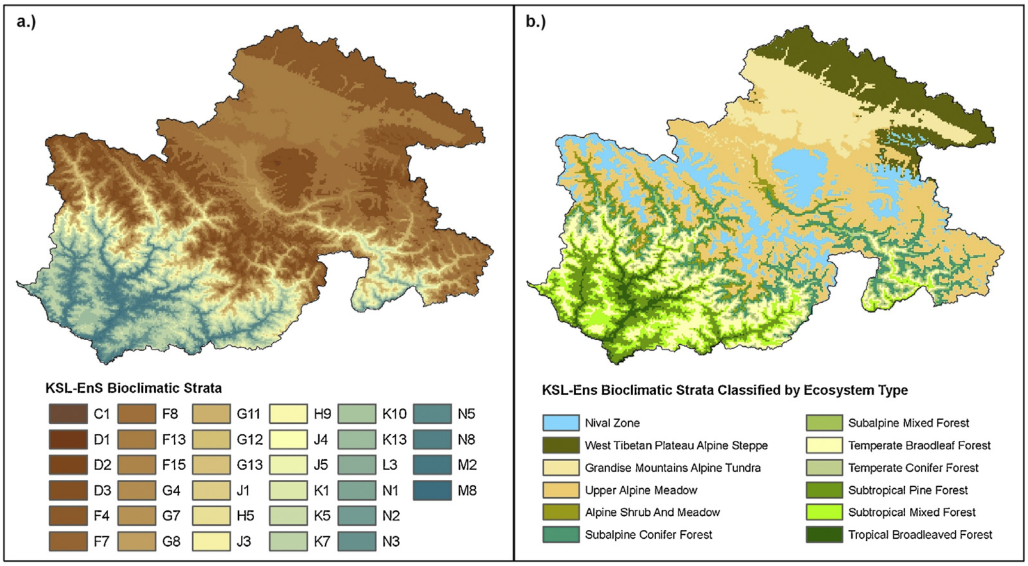


Fig. 4. The KSL-EnS stratified the KSL into ten zones and 34 strata (a). Twelve major ecosystem types (or ecotopes) were distinguished and used to aggregate the strata (b).

In support of the implementation of the KSL-CEMSP, the GEnS was applied within the KSL region (Zomer et al., in press) to provide an environmental stratification (KSL-EnS) that would allow for and facilitate comparative approaches amongst the three countries, as well as providing a globally comparative context. The KSL-EnS stratified the KSL into nine zones and 33 strata (Fig. 4a). The various parameters and biophysical characteristics of the KSL-EnS bioclimatic zones and strata were characterized by their existing primary land cover or land use, vegetation type, and "ecosystem" classification. Twelve major ecosystem types (or ecotopes) were distinguished and used to aggregate the strata (Fig. 4b), which were then labeled based on their "ecoregion" designation (Olson, 2001). The KSL-EnS was also used for the analysis of projected impact of climate change on terrestrial ecosystems (Zomer et al., in press), which indicates that, by the year 2050, a significant and substantial change in the distribution, extent, and productivity of these strata can be expected. The results of KSL study show that the GEnS approach can be applied regionally across the Hindu Kush–Himalaya region to develop a stratified frame for comparing climate change impacts, and that adopting this approach more generally can provide the structure for comparative ecosystems studies throughout the Asian Highland mountain region.

4.4. *Combining the GEnS and Species Distribution Models to improve the design of monitoring networks*

Whilst stratification ensures an adequate spatial dispersion of sampling units to support the monitoring of diversity indicators and common species and habitat types, it is less suited for rare or ecologically specialized species and habitat types with scattered occurrences. This is of particular relevance when designing observation networks to report on the condition and trends of rare species and habitat types of high conservation interest, such as many of those listed under EU's Habitats Directive (Alexandridis et al., 2009; Mücher et al., 2009; Velázquez et al., 2010).

In northern Portugal, a regional biodiversity observation network (SIMBioN) is being developed to support the management of natural parks and the reporting on international conservation goals and biodiversity indicators. Designing an efficient sampling network for rare species and habitat types forms a key objective of the SIMBioN network, which will collect field data to obtain robust estimates for predefined reporting indicators (e.g. range and abundance of rare species, range and area of rare habitat types).

Following Guisan et al. (2006) and Singh et al. (2009), a combination of Species Distribution Models (SDMs) and environmental stratifications was used to design the SIMBioN monitoring network. In a first step, SDMs were used to reduce the spatial population of sampling units to a set of units that enhances detectability of species or habitat types, and in a second step a stratified random sampling was applied on those previously selected units. This way, estimates are obtained for the subpopulation selected in the first step only, i.e. all sampling units above an occurrence probability threshold in SDMs, therefore demanding that these are robust and representative. If statistical estimates for the entire population are required, then a design or model-based estimate would also have to be obtained for the non-sampled part of the population.

To develop a regional monitoring network for riparian forests (priority habitat type 91E0*: "Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior*"; Annex I of the Habitats Directive) a predictive distribution model was developed for this habitat type using the maximum-entropy species habitat modeling software Maxent (Phillips and Dudík, 2008; Elith et al., 2011). Maxent calculates a statistical model of the potential range of the habitat from their current observed locations and a set of environmental variables for the whole region. The GEnS strata (Metzger et al., in press) were used for the stratified sampling performed in the second step, in this case only in the subpopulation above the probability threshold provided by the SDM (Fig. 5).

Results from field campaigns suggest that the proposed sampling design has led to an increase in habitat detectability (attained through the use of SDMs) while simultaneously allowing samples to be dispersed along robust climatic gradients, thus maximizing the diversity of environmental conditions in the samples. Complementary simulation analyses also confirmed that using the GEnS as the stratification layer increased the accuracy of the estimation of the areal extent of forest and agro-forestry land cover types (Corine Land Cover categories 243–"*agriculture with natural and semi-natural habitats*", and 313–"*mixed coniferous/broadleaf forests*") in the region, further highlighting its potential value for ecological assessment and monitoring.

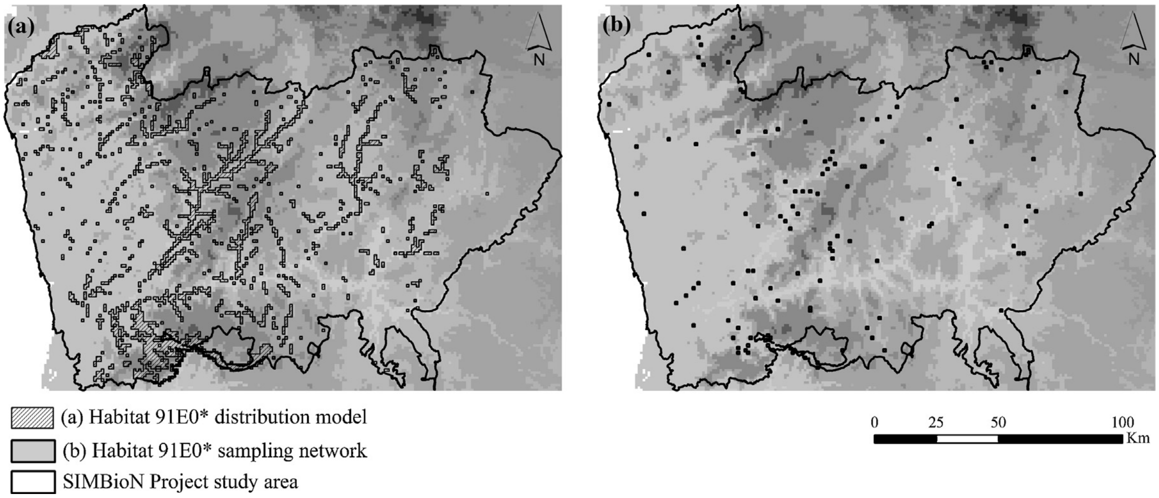


Fig. 5. Designing a monitoring network for the 91E0* priority habitat (Annex I of the Habitats Directive) in northern Portugal: (a) representation of units selected with an SDM in the first step; (b) the final monitoring network with sampling units selected in the second step (stratified random sample on the sub-population selected by the SDM).

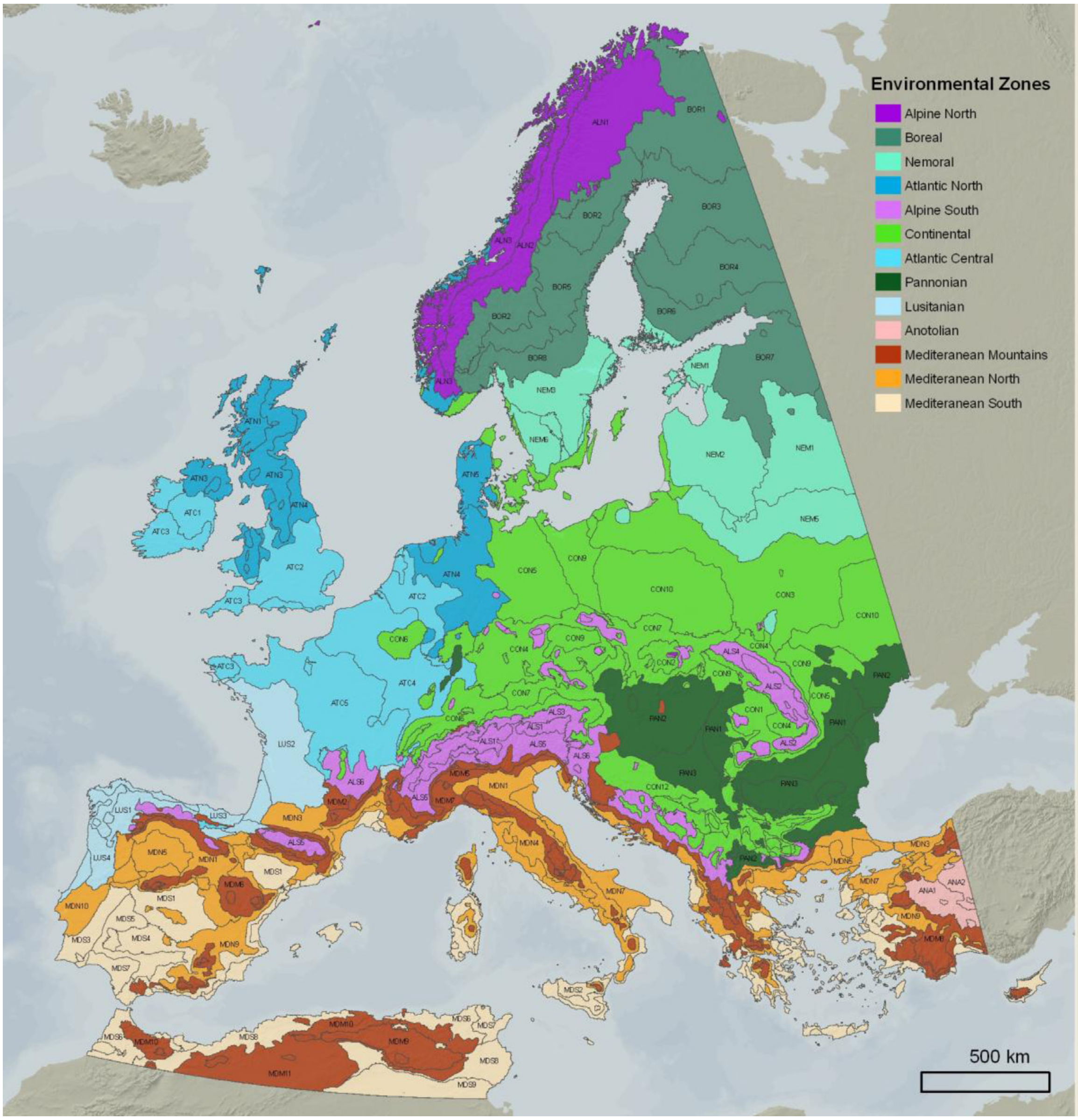
5. The way foreword

International collaboration is crucial to develop consistent data to develop reliable ecological indicators to assess progress towards biodiversity targets, including the CBD Aichi targets and support assessments under IPBES. With continued support, GEO BON can form an international community of practice that supports this process by providing the infrastructure and supporting the development of tools and methods to make optimal use of current observation effort (Scholes et al., 2012). This integration and combination of existing in situ observations, from site based LTER and statistical ecological surveys, remote sensing imagery and citizen science approaches forms a major challenge, and environmental stratification will be essential to ensure representivity of observations. In addition, stratification will also provide a valuable spatial framework for the further statistical design of monitoring networks and the analysis of the status and trends in ecological indicators across large and environmentally heterogeneous regions. The GEnS provides a promising tool to support the coordination and analysis of global biodiversity observations under GEO BON and can also provide support for nested national or regional networks.

Acknowledgements

The European sampling design and the Global Environmental Stratification were developed as part of the EU-funded FP7 research project EBONE (European Biodiversity Observation Network, contract 212322). We acknowledge Dennis Walvoort for his help in constructing the geostrata, described in Section 3.2. JG and JH developed the Portuguese sampling design with financial support from QREN/ON2 (project SIMBioN; 3–2–14–1-1192) and from FCT (through FEDER/COMPETE, project EcoSensing; PTDC/AGR-AAM/104819/2008). The authors would also like to acknowledge the work of the Kailash Sacred Landscape Conservation Initiative and the International Centre for Integrated Mountain Development in Kathmandu, Nepal, and to thank German Technical Cooperation-Nepal (GIZ) for funding and support of the research in the Kailash Sacred Landscape. MJM would like to thank Daumas Gassac for inspiration and support.

Appendix A. European environmental stratification



The European Environmental Stratification (after Metzger et al., 2005) delineates 84 strata, which are aggregated to 13 Environmental Zones (EnZs). Where the size of the stratum permits, the individual strata are labeled within the EnZs.

References

Alexandridis, T.K., Lazaridou, E., Tsirika, A., Zalidis, G.C., 2009. Using earth observation to update a Natura 2000 habitat map for a wetland in Greece. J. Environ. Manage. 90, 2243–2251.

Brus, D.J., De Gruijter, J.J., 1997. Random sampling or geostatistical modelling? Choosing between design-based and model-based sampling strategies for soil (with Discussion). Geoderma 80, 1–59.

Brus, D.J., De Gruijter, J.J., 2011. Design-based Generalized Least Squares estimation of status and trend of soil properties from monitoring data. Geoderma 164, 72–180.

Brus, D.J., De Gruijter, J.J., 2012. A hybrid design-based and model-based sampling approach to estimate the temporal trends of spatial means. Geoderma 173-174, 241–248.

Brus, D.J., Spatjens, L.E.E.M., De Gruijter, J.J., 1999. A sampling scheme for estimating the mean extractable phosphorus concentration of fields for environmental regulation. Geoderma 89, 129–148.

Brus, D.J., Knotters, M., Metzger, M.J., Walvoort, D.J.J., 2011. Towards a European-wide sampling design for monitoring of common habitats. Alterra report 2213, Alterra, Wageningen.

Bunce, R.G.H., Metzger, M.J., Jongman, R.H.G., Brandt, J., de Blust, G., Elena-Rossello, R., Groom, G.B., Halada, L., Hofer, G., Howard, D.C., Kovar, P., Mucher, C.A., Padoa-Schioppa, E., Paelinx, D., Palo, A., Perez-Soba, M., Ramos, I.L., Roche, P., Skanes, H., Wrbka, T., 2008. A standardized procedure for surveillance and monitoring European habitats and provision of spatial data. Landscape Ecol. 23, 11–25.

Bunce, R.G.H., Barr, C.J., Clarke, R.T., Howard, D.C., Lane, A.M.J., 1996. The ITE land classification of Great Britain. J. Biogeogr. 23, 625–634.

Bunce, R.G.H., Bogers, M.M.B., Roche, P., Walczak, M., Geijzendorffer, I.R., Jongman, R.H.G., 2011. Manual for Habitat and Vegetation Surveillance and Monitoring: Temperate, Mediterranean and Desert Biomes. Alterra report 2154, Alterra, Wageningen.

Bunce, R.G.H, Bogers, M.M.B., Evans, D., Halada, L., Jongman, R.H.G., Mucher, C.A., Bauch, B., de Blust, G., Parr, T.W., Olsvig-Whittaker, L. The significance of habitats as indicators of biodiversity and their links to species. Ecol. Indicat. http://dx.doi.org/10.1016/j.ecolind.2012.07.014, (Special issue, in press).

Bunce, R.H.G., Bogers, M.B.B., Evans, D., Jongman, R.H.G. Field identification of Habitats Directive Annex 1 Habitats as a major European biodiversity indicator. Ecol. Indicat. http://dx.doi.org/10.1016/j.ecolind.2012.10.004, (special Issue, in press).

Carey, P.D., Barnett, C.L., Greenslade, P.D., Hulmes, S., Garbutt, R.A., Warman, E.A., Myhill, D., Scott, R.J., Smart, S.M., Manchester, S.J., Robinson, J., Walker, K.J., Howard, D.C., Firbank, L.G., 2002. A comparison of the ecological quality of land between an English agri-environment scheme and the countryside as a whole. Biol. Conserv. 108, 183–197.

Chamberlain, P.M., Emmett, B.A., Scott, W.A., Black, H.I.J., Hornung, M., Frogbrook, Z.L., 2010. No change in topsoil carbon levels of Great Britain 1978-2007. Biogeosci. Discuss. 7, 2267–2311.

Collen, B., Loh, J., Whitmee, S., McRae, L., Amin, R., Baillie, J.E., 2009. Monitoring change in vertebrate abundance: the Living Planet Index. Conserv. Biol. 23, 317–327.

EEA, 2010. The European environment — state and outlook 2010: synthesis. European Environment Agency, Copenhagen.

Elena-Rossello, R., Bolaños, F., Gómez, V., González, S., Ortega, M., García del-Barrio, J.M., 2005. The SISPARES (Spanish Rural Landscape Monitoring System) experience, in: Bunce, R.G.H., Jongman, R.H.G. Jongman (Eds.), Landscape ecology in the Mediterranean: inside and outside approaches. Faro: Proceedings of European IALE conference.

Elith, J., Phillips, S.J., Hastie, T., Dudík, M., Chee, Y.E., Yates, C.J., 2011. A statistical explanation of MaxEnt for ecologists. Divers. Distrib. 17, 43–57.

De Gruijter, J.J., Brus, D.J., Bierkens, M.F.P., Knotters, M., 2006. Sampling for Natural Resource Monitoring. Springer, Berlin.

De Gruijter, J.J., Ter Braak, C.J.F., 1990. Model-free estimation from spatial samples: a reappraisal of classical sampling theory. Math. Geol. 22, 407–415.

Firbank, L.G., Barr, C.J., Bunce, R.G.H., Furse, M.T., Haines-Young, R.H., Hornung, M., Howard, D.C., Sheail, J., Sier, A.R.J., Smart, S.M., 2003. Assessing stock and change in land cover and biodiversity in GB: an introduction to the Countryside Survey 2000. J. Environ. Manage. 67, 207–218.

GEO BON, 2010. Group on Earth Observations Biodiversity Observation Network (GEO BON) Detailed Implementation Plan. http://www.earthobservations.org/documents (accessed 23.03.12).

Guisan, A., Broennimann, O., Engler, R., Vust, M., Yoccoz, N.G., Lehmann, A., Zimmermann, N.E., 2006. Using Niche-based models to improve the sampling of rare species. Conserv. Biol. 20, 501–511.

Harvey, C.A., Medina, A., Sánchez, D.M., Vílchez, S., Hernández, B., Saenz, J.C., Maes, J.M., Casanoves, F., Sinclair, F.L., 2006. Patterns of animal diversity in different forms of tree cover in agricultural landscapes. Ecol. Appl. 16, 1986–1999.

Hill, M.O., 1979. TWINSPAN: a FORTRAN Program for Arranging Multivariate Data in an Ordered Two-Way Table by Classification of the Individual and Attributes. Cornell University Press, Ithaca, New York.

Hinsley, S., Bellamy, P.E., 2000. The influence of hedge structure management and landscape context on the value of hedgerows for birds. J. Environ. Manage. 60, 33–49.

ICIMOD, 2011. Kailash Sacred Landscape Conservation Strategy. International Centre for Integrated Mountain Development. Kathmandu, Nepal.

ICIMOD, 2011. Kailash Sacred Landscape Comprehensive Environmental Monitoring Strategic Plan (KSL-CEMSP). International Centre for Integrated Mountain Development. Kathmandu, Nepal.

Jongman, R.H.G., Bunce, R.G.H., Metzger, M.J., Mücher, C.A., Howard, D.C., Mateus, V.L., 2006. Objectives and applications of a statistical environmental stratification of Europe. Landscape Ecol. 21, 409–419.

Jongman, R.H.G. European and global coordination in biodiversity monitoring. Ecol. Indicat. (Special issue, in press).

Larigauderie, A., Mooney, H.A., 2010. The Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services: moving a step closer to an IPCC-like mechanism for biodiversity. Curr. Opin. Environ. Sustain. 2, 9–14.

Leathwick, J.R., Overton, J.M., Mcleod, M., 2003. An environmental domain classification of New Zealand and its use as a tool for biodiversity management. Conserv. Biol. 16, 1612–1623.

Lugo, A.E., Brown, S.L., Dodson, R., Smith, T.S., Shugart, H.H., 1999. The Holdridge life zones of the conterminous United States in relation to ecosystem mapping. J. Biogeogr. 26, 1025–1038.

MA, 2005. Millennium Ecosystems Assessment Synthesis report. Washington DC.

Maskell, L.C., Smart, S.M., Bullock, J.M., Thompson, K., Stevens, C.J., 2010. Nitrogen deposition causes widespread loss of species richness in British habitats. Global Change Biol. 16, 671–679.

McMahon, G., Gregonis, S.M., Waltman, S.W., Omernik, J.M., Thorson, T.D., Freeouf, J.A., Rorick, A.H., Keys, J.E., 2001. Developing a spatial framework of common ecological regions for the conterminous United States. Environ. Manage. 28, 293–316.

Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Mucher, C.A., Watkins, J.W., 2005. A climatic stratification of the environment of Europe. Global Ecol. Biogeogr. 14, 549–563.

Metzger, M.J., Bunce, R.G.H., Van Eupen, M., Mirtl, M., 2010. An assessment of long term ecosystem research activities across European socio-ecological gradients. J. Environ. Manage. 91, 1357–1365.

Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Sayre, R., Trabucco, A., Zomer, R. A high resolution bioclimate map of the world: a unifying framework for global biodiversity research. Global Ecol. Biogeogr. http://dx.doi.org/10.1111/geb.12022, in press.

Mooney, H., Larigauderie, A., Cesario, M., Elmquist, T., Hoegh-Guldberg, O., Lavorel, S., Mace, G.M., Palmer, M., Scholes, R., Yahara, T., 2009. Biodiversity, climate change, and ecosystem services. Curr. Opin. Environ. Sustain. 1, 46–54.

Mooney, H.A., 1977. Convergent evolution in Chile and California: Mediterranean climate ecosystems Dowden, Hutchinson and Ross Stroudsburg, PA.

Mücher, C.A., Hennekens, S.M., Bunce, R.G.H., Schaminée, J.H.J., Schaepman, M.E., 2009. Modelling the spatial distribution of Natura 2000 habitats across Europe. Landscape Urban Plan. 92, 48–159.

Muchoney, D.M., 2008. Earth observations for terrestrial biodiversity and ecosystems. Remote Sens. Environ. 112, 1909–1911.

Nayar, A., 2010. World gets 2020 vision for conservation. Nature 468, 14.

Norton, L.R., Inwood, H., Crowe, A., Baker, A., 2011. Trialling a method to quantify the 'cultural services' of the English landscape using Countryside Survey data. Land Use Policy 29, 449–455.

Norton, L.R., Maskell, L.C., Smart, S.S., Dunbar, M.J., Emmett, B.A., Carey, P.D., Williams, P., Crowe, A., Chandler, K., Scott, W.A., Wood, C.M., 2012. Measuring stock and change in the GB countryside for policy–key findings and developments from the Countryside Survey 2007 field survey. J. Environ. Manage. 113, 117–127.

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P., Kassem, K.R., 2001. Terrestrial ecoregions of the world: a new map of life on earth. Bioscience 51, 933–938.

Parr, T.W., Sier, A.R.J., Battarbee, R.W., Mackay, A., Burgess, J., 2003. Detecting environmental change: science and society-perspectives on long-term research and monitoring in the 21st century. Sci. Total Environ. 310, 1–8.

Paruelo, J.M., Lauenroth, W.K., Epstein, H.E., Burke, I.C., Aguiar, M.R., Sala, O.E., 1995. Regional climatic similarities in the temperate zones of North and South America. J. Biogeogr. 22, 915–925.

Pereira, H.M., Belnap, J., Brummitt, N., Collen, B., Ding, H., Gonzalez-Espinosa, M., Gregory, R.D., Honrado, J.O., Jongman, R.G.H., Julliard, R., Mcrae, L., Proenãsa, V.N., Rodrigues, P.C., Opige, M., Rodriguez, J.P., Schmeller, D.S., Van Swaay, C., Vieira, C., 2010. Global biodiversity monitoring. Front. Ecol. Environ. 8, 459–460.

Pereira, H.M., Cooper, D.H., 2006. Towards the global monitoring of biodiversity change. Trends Ecol. Evol. 21, 123–129.

Phillips, S.J., Dudík, M., 2008. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. Ecography 31, 161–175.

Sheail, J., Bunce, R.G.H., 2003. The development and scientific principles of an environmental classification for strategic ecological survey in Great Britain. Environ. Conserv. 30, 147–159.

Scholes, R.J., Mace, G.M., Turner, W., Geller, G.N., Jurgens, N., Larigauderie, A., Muchoney, D., Walther, B.A., Mooney, H.A., 2008. Toward a global biodiversity observing system. Science 321, 1044–1045.

Scholes, R.J., Walters, M., Turak, E., Saarenmaa, H., Heip, C.H.R., Tuama, E.O., Faith, D.P., Mooney, H.A., Ferrier, S., Jongman, R.H.G., Harrison, I.J., Yahara, T., Pereira, H.M., Larigauderie, A., Geller, G., 2012. Building a global observing system for biodiversity. Curr. Opin. Environ. Sustain. 4, 139–146.

Singh, N., Yoccoz, N., Bhatnagar, Y., Fox, J., 2009. Using habitat suitability models to sample rare species in high-altitude ecosystems: a case study with Tibetan argali. Biodivers. Conserv. 18, 2893–2908.

Smart, S.M., Bunce, R.G.H., Marrs, R., LeDuc, M., Firbank, L.G., Maskell, M.C., Scott, W.A., Thompson, K., Walker, K.J., 2005. Large-scale changes in the abundance of common higher plant species across Britain between 1978, 1990 and 1998 as a consequence of human activity: tests of hypothesised changes in trait representation. Biol. Conserv. 124, 355–371.

Ståhl, G., Allard, A., Esseen, P.-A., Glimskar, A., Ringvall, A., Svensson, J., Sundquist, S., Christensen, P., Torell, A.G., Hogstrom, M., Lagerqvist, K., Marklund, L., Nilsson, B., Inghe, O., 2011. National Inventory of Landscapes in Sweden (NILS)-scope, design, and experiences from establishing a multiscale biodiversity monitoring system. Environ. Monit. Assess. 173, 579–595.

Thackeray, S.J., Sparks, T.H., Frederiksen, M., et al., 2010. Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. Global Change Biol. 16, 3304–3313.

Ter Braak, C.J.F., Brus, D.J., Pebesma, E.J., 2008. Comparing sampling patterns for kriging the spatial mean temporal trend. J. Agric. Biol. Environ. Stat. 13, 159–176.

Urquhart, N.S., Kincaid, T.M., 1999. Designs for detecting trend from repeated surveys of ecological resources. J. Agric. Biol. Environ. Stat. 4, 404–414.

Velázquez, J., Tejera, R., Hernando, A., Victoria Núñez, M., 2010. Environmental diagnosis: Integrating biodiversity conservation in management of Natura 2000 forest spaces. J. Nat. Conserv. 18, 309–317.

Walvoort, D., Brus, D., and de Gruijter, J., 2010a. Spatial Coverage Sampling and Random Sampling from Compact Geographical Strata. R package version 0. 2-3.

Walvoort, D.J.J., Brus, D.J., De Gruijter, J.J., 2010b. An R package for spatial coverage sampling and random sampling from compact geographical strata by k-means. Comput. Geosci. 36, 1261–1267.

Zomer, R.J., Oli, K.P., 2011. Kailash Sacred Landscape Conservation Initiative: Feasibility Assessment Report. ICIMOD: Kathmandu. SBN: 978 92 9115 211 7.

Zomer, R.J., Trabucco, A., Oli, K.P. Environmental Stratification and Projected Climate Change Impacts on Ecosystems in the Kailash Sacred Landscape of China, India, Nepal. International Centre for Integrated Mountain Development. Kathmandu, Nepal, in press.