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A multivariate approach to the selection of biological reserves

LEE BELBIN
CSIRO Division of Wildlife & Ecology, P.O. Box 84, Lyneham, ACT 2602, Australia

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Multivariate analysis provides an effective context for the examination of some significant aspects of biodiversity and conservation. The framework is a multidimensional space that integrates sample sites, taxa and environments. This approach enables terms such as representativeness, complementarity and irreplaceability to be integrated within an intuitive and practical framework for reserve design. Cluster analysis is proposed to determine 'what is there' by defining a set of complementary clusters. These clusters are sampled in a representative manner; from the core outward. The degree of irreplaceability of a site is defined as the multivariate distance of each potential reserve site to its nearest neighbour.

Keywords: reserve design; multivariate analysis; complementarity; representativeness; irreplaceability; dissimilarity

Introduction

The terminology of conservation is burgeoning. Scientific research is responding to society's recognition of the significance of its remaining landscape and biological heritage. New perspectives are giving rise to the need for new terms to identify and if possible, quantify key issues and processes. The problem however with any area of investigation at the cutting edge is that the terminology is often adapted from other disciplines or experiences, coined but misunderstood by all but the 'elite' or simply defined in different ways by different scientists. 'Biodiversity' has become a classic case in point.

Three concepts that have a capacity to be used effectively in the area of biological conservation are representativeness (Austen and Margules, 1984, 1986), complementarity (Vane-Wright *et al.*, 1991), and irreplaceability (Pressey *et al.*, 1993; 1994). Such terms are playing a useful role in focusing the debate over the alternative mechanisms for biological and landscape reserve design, for example, Woinarski and Norton (1993). As with diversity however, representativeness, complementarity and irreplaceability are giving rise to subtly different interpretations (Pressey *et al.*, in press).

Hill (1973a) provides an instructive lesson based on measures of diversity: 'There is an almost unlimited scope for mathematical generality in relation to measures of diversity and taxonomic difference. Simple and well-understood indices should be used.' Hill used this argument to rationalize diversity indices, rejecting those that were difficult or impossible to conceptualize. A similar approach is attempted here in providing simple definitions of complementarity, representativeness and irreplaceability using a multivariate framework.

A framework

What are the units of conservation and the associated attributes? One could define practical units of reservation as parcels of land (or water) while the features of these units are its biotic (species) and abiotic (environment/landscape/water quality) components. Alternatively, taxa, assemblages or functional groups may be the prime unit of conservation (call them objects) while location could be a key attribute. In other words, one conservationist's objects may be another's attributes. Multivariate analysis does appear to provide a mechanism where any of the above units can be placed in a broader, integrating context. Conservation implications can then be examined from a biotic, environmental or site-based orientation.

Multivariate analysis covers a range of techniques that are often deemed exploratory. Such techniques accept and integrate many variables. Some multivariate methods are designed to generate hypotheses (pattern analytic in the sense of Williams, 1976; Belbin, 1987a) while others test hypotheses (statistical). Some methods can be used in either context. For example, discriminant analysis can be used as an exploratory tool (seeking a simplifying definition of groups) or a confirmatory tool (determining the probability of assignment of objects between a set of groups).

Consider a basic multivariate premise: a set of objects are described by a set of attributes. A simplifying notion is to conceive a visual representation that shows as much as possible of the information contained within and between this set of objects. In multivariate analysis, such a useful conceptualization is of the set of objects represented by points distributed in a multidimensional space. In this space each attribute forms an axis at right angles to all other attributes. If more than three attributes are involved, this concept may at first be uncomfortable, but is none the less mathematically straightforward. As defined, this space is Euclidean, for example, given precipitation (p), temperature (t), radiation (r) and nutrient-level (n) as a set of attributes, the distance between any two points (call them sample sites 1 and 2) in this space is simply:

$$d_{12} = \sqrt{(p_2 - p_1)^2 + (t_2 - t_1)^2 + (r_2 - r_1)^2 + (n_2 - n_1)^2}$$

Multivariate techniques generally operate on distances as measured in this space. Clustering methods define boundaries around a set of objects to form a set of groups or clusters. Such clusters aim to minimize within-group heterogeneity and maximize between-group differences. Ordination methods attempt to locate another set of axes in this space that together account for most of the variation in the distribution of the objects. For example, principal components attempt to align the primary ordination axis in the direction of greatest variation. Methods such as discriminant analysis and classification trees start with the membership of the groups pre-defined and aim at operational definitions of those groups. Multivariate methods are not perfect in the sense that optimality is rarely if ever guaranteed. That many thousands of objects measured on thousands of attributes can be sifted and summarized bears testimony that multivariate strategies are powerful tools for extracting useful information from complex data. It is in this context that representativeness, complementarity and irreplaceability as well as other terms may be usefully defined.

What are the significant underlying dimensions of the multivariate space; the fundamental ecological processes controlling variation in the data? This has been determined both from the experience of ecologists noting that environmental changes parallel changes in community composition. Information has also come from multivariate techniques such as ordination that are designed to address this question. In the case where environmental attributes or species (coded as presence or absence, abundance or biomass) form the axes, the predominant underlying factors are environmental. Consider a data set comprising species abundances at various survey sites. In multivariate analysis, differences in species composition and abundance can be largely explained by differences in environmental factors. Attributes such as temperature, moisture availability, nutrients, solar radiation and evapotranspiration would now be perceived as significant factors controlling biological distributions (e.g. Nix, 1982; Austin *et al.*, 1984; Busby, 1986; Currie, 1991; Wylie and Currie, 1993).

While species can generally be viewed as distinct in the sense of reproductive isolation or morphological difference, the same cannot be said of site-based units. This implies that there will be a continuous change in environment (albeit steep in places) and species composition as one moves spatially away from any given geographic location. This spatial movement is mirrored in multivariate space and is fundamentally continuous (see Whittaker, 1978; Austin *et al.*, 1983; Austin, 1985). It is continuous in the sense that given any two points representing surveyed sites in the multidimensional space, a site of intermediate character could be assumed to exist. This analogy would not generally be true of species.

The multivariate space can be conveniently interpreted in environmental terms, regardless of whether the variables are environmental such as mean annual temperature, or measures of such as taxa presence, abundance or biomass. This does not however imply that sites, taxa and environmental attributes can easily be interchanged in multivariate analysis. Multivariate methods such as correspondence analysis/reciprocal averaging (Benzecri, 1973; Hill, 1973b) and a number of techniques based on this approach assume this in the face of ecological realities.

Sites can usually be represented by a point in multidimentional space. Survey sites are defined at least in part by the assumption of environmental homogeneity. Unless species have an extremely narrow niche, they are anticipated in a number of sites covering a range of environments/habitats. Species are more realistically considered in multidimensional space to occupy a volume greater than a site (e.g. Austin *et al.*, 1984, 1990). Similarly, an environment is usually taken to cover at least a small range of physical attributes rather than an explicit combination of values that do not vary.

In this framework, the use of site-based units of conservation as objects with taxa or environments as attributes holds few limitations. Such an approach does not preclude a focus on taxa as the primary units of conservation. For example, conservation prioritizing algorithms such as taxonomic (Vane-Wright *et al.*, 1991) or phylogenetic difference (Faith, 1992) can be more readily understood and evaluated in such a framework.

Complementarity

The term complementarity was not used explicitly until recently (Vane-Wright *et al.*, 1991). The notion of a set of complementary samples has however been used by a number of ecologists in procedures for biological reserve selection (e.g. Wright, 1970; Tubbs and Blackwood, 1971; Gelbach, 1975; van der Ploeg and Vlijm, 1978; Kirkpatrick, 1983; Margules *et al.*, 1988). Vane-Wright *et al.* (1991) used complementarity to refer to a procedure that extracted a conservation site/area and then examined the remaining sites/areas that were deemed complementary to the original in terms of features. The initial site is eliminated from further examination and only those remaining sites that are complementary to the original are examined by the selection criteria. In this sense, if site x has been sampled, sites that are complementary in terms of composition to x may be $(1 - x)$ or less. Vane-Wright *et al.* (1991) note that the complementarity approach is applied in procedures as proposed by Kirkpatrick (1983), Margules *et al.* (1988) and Pressey and Nicholls (1989a, b). The significance of complementarity is both an acknowledgement of the complete set or universe of variation and the relation of any component to the whole.

Belbin (1993) suggested that cluster analysis may be used to provide a foundation for complementarity. Given a set of sites and attributes, clustering provides an explicit mechanism to sort variation in the data into discrete, nameable units. By definition, this process aims to produce a set of groups that are complementary; each group represents a unique portion of the complete domain. Such groups can be defined in terms of biotic or environmental composition within the overall range of biomes or environments. Clustering is proposed as a mechanism for ensuring complementarity via a set of clusters (Fig. 1). The classification of objects embedded in a continuous multivariate space into discrete, identifiable units facilitates communication. For example, making sense out of a scatter of points in an ordination diagram is facilitated by superimposing a classification by lines or colour.

Groups generated by supervised or unsupervised clustering that are adjacent in multidimensional space retain distinct properties. But are any pair of groups for example, complementary? Complementary implies a totality or the process of completing. For example, two groups selected from a cluster analysis that produced ten groups may be distinct, but are deemed complementary given the context of the universe of ten groups. Things are either complementary in the sense that, when taken together, they form a whole or they do not. In this context, ten or 20 clusters derived from 100 samples are deemed equally complementary. Ten groups would exhibit a greater degree of distinctiveness than the 20 groups, but each set is equally complementary.

Are there degrees of complementarity? One referee was adamant that there was not, another was equally adamant that there was. The multivariate framework does provide an ideal environment for estimating overlap between a pair of objects in terms of attribute composition. Such pair-wise differences could be interpreted as degrees of complementarity. For example, two sites, each with ten unique taxa would be evaluated as having maximal difference (dissimilarity) and would be correctly perceived as being compositionally disjunct. These sites could be considered complementary but would only be so in a 'dictionary' sense if there were a total of 20 taxa. If there were 30 taxa, it could be argued that the two sites were not totally complementary in that both excluded the remaining 10 taxa. If desired, distance in multivariate space, as estimated by dissimilarity measures can be used to estimate complementarity as a continuous measure of the degree of over or underlap between objects or groups of objects.

Vane-Wright *et al.* (1991) and Faith (1992) approach complementarity with an emphasis on taxa. They suggested that complementarity can be quantified by genetic/phylogenetic difference. Both attempt to answer the question 'given a set of taxa, what would be the identity of the subset of k most-diverse taxa (in terms of genetic or phylogenetic differences)'. Applied to sites in multivariate space, this would amount to asking for the subset of sites that exhibit maximal difference; those sites that were at environmental extremes. As the number of sites in the sample is increased, other extrema would be sampled until at some point, sites that were intermediate in terms of environment (or species composition) would be sampled.

The first phase (of four) of the clustering algorithm (ALOC; Belbin, 1987b) used in environmental representativeness (Belbin, 1993) also pursues a subset of objects that could be deemed complementary. ALOC locates a set of objects that have at least a user-defined degree of separation using a dissimilarity measure. These objects are designed to provide an adequate coverage of the multivariate space. Such objects would generally be only partially complementary in having some attributes in common. As the size of the sample decreases, the degree of complementarity increases. There is an algorithmic limitation to the notion of maximal distinctiveness used by Vane-Wright *et al.* (1991) and Faith (1992). All pair-wise differences need to be searched for the identification of the k most diverse objects. This could be computationally demanding for more than a few thousand objects. By comparison, the ALOC approach need only examine object-seed differences. It is, therefore, computationally efficient for millions of objects.

Complementarity in a reserve design context suggests completeness or the totality of objects of interest. Any subset of sites or species can be complementary only in the context of the complete set. Complementarity is an effective concept in conservation because it emphasises the need to comprehend the whole. Clustering is an efficient procedure to define the whole by identifying a complement of nameable components; the groups or clusters. Complementarity based on clustering provides a mechanism of 'divide and conquer'; understanding the whole by naming the parts. Complementarity is a necessary, yet not sufficient step toward the design of a biological reserve network. The impossibility of reserving 100% of a region or preserving 100% of the biota raises the need for a definition of a representative sample.

Representativeness

Margules and Usher (1981) provided a useful summary of the issues and related terms in the field of conservation at that time. In their paper, they refer to 'typicalness or representativeness' and rank the ecological significance of the concept as used either implicitly or explicitly in four of the nine published studies they review. Austin and Margules (1986) provided a review of representativeness and suggested that the term referred to an assessment of the adequacy of a reserve network in sampling the biological variation in a region. Mackey *et al.* (1988) used representativeness 'to provide an environmental context; that is, to demonstrate how a place is related to the surrounding region, continent or globe'. They went on to say that representativeness 'implies that a subset of the population is taken such that all or most of the characteristics found in the total population are present' and that the practicalities of a representative sample were 'ill-defined'. Margules *et al.* (1994) argue that a representative reserve network is one that encompasses a true sample of the biota or environments of a region; a sample with the same mean and variance as the wider population. In this, Margules *et al.* refine the definition of representativeness to identify the range of variation, rather than just a typical sample. These could be identified as two different goals that if pursued, would result in two different reserve networks.

Representativeness stems from the practical limitations in reserving 100% of the land/water or the species or environments that they contain. A basic requirement is,

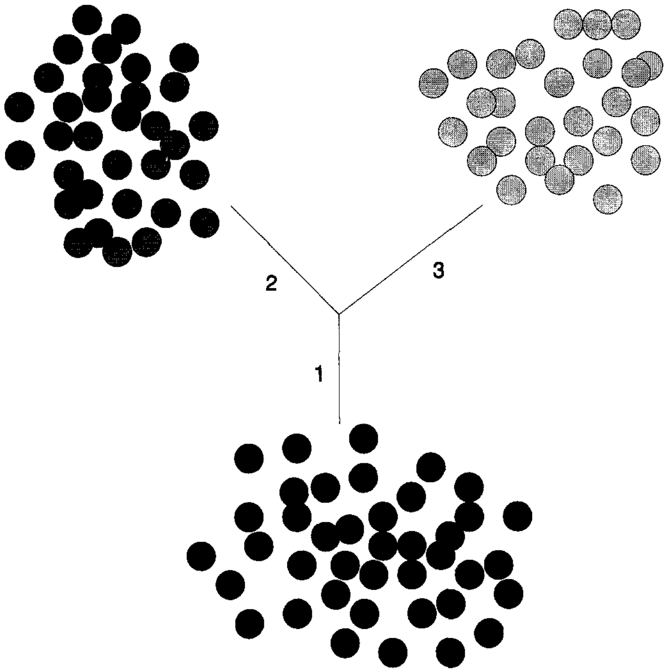

Figure 1. A diagrammatic representation of three distinct and complementary groups of survey sites defined by clustering and displayed in a three-dimensional space.

therefore, a sample that could be judged to be a good representation of the landscape and natural resources currently available. By what criterion should this judgement be made? Numerical or statistical criteria appear necessary. The continuous nature of change in biological or environmental composition does not appear to offer more discrete units of representation.

Belbin (1993) suggested that the problem was similar to asking for a single value (or statistic) that provided the best summary of a set of data. In the univariate case, this would correspond to one of the measures of central tendency; the mean, median or mode. In a multivariate context, this measure corresponds to the cluster centroid. the most representative object of a group of objects is therefore the one that is closest to the group centroid. Conversely, the further an object is from its centroid, the less representative it is of that group (Fig. 2). This is equivalent in a univariate situation to dismissing a value that is for example beyond the 95th percentile from the mean as not being a good representative of the sample as a whole.

Using this model, representativeness can be viewed as a set of concentric shells about the group centroids. The most representative samples are located at or close to the centroids while the least representative samples are located around the peripheries. If the units of reservation in this procedure were land parcels considered biologically sustainable in their own right, then the units closest to the group centroids would form a complementary and representative reserve network. In this paper, the general case is assumed; the sample units within any cluster require aggregation to form sustainable units.

Margules, C.R. (personal communication) pointed out that what is required for a

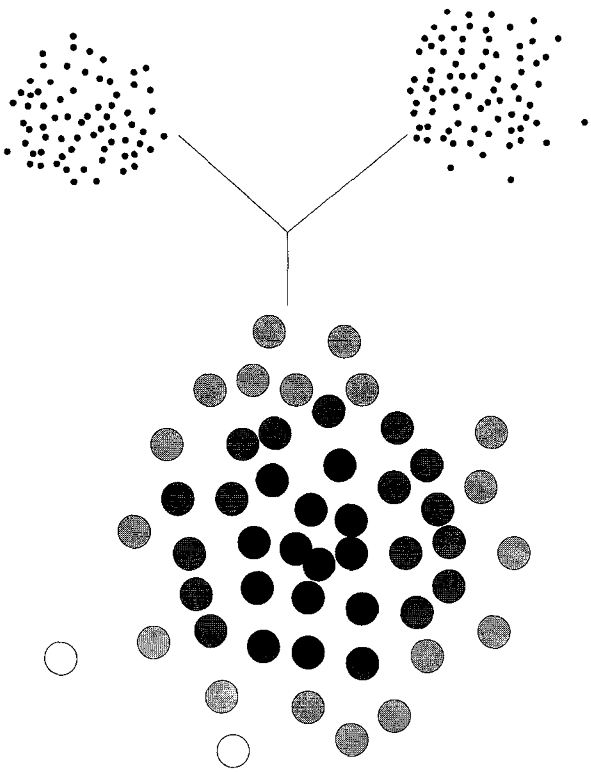

Figure 2. Representation of the degree of representativeness of objects in one of the three groups from Fig. 1.

representative sample is a 'subset of objects that together, statistically, represent the population'. Consider as an example the use of the mean and variance. In theory, there could be many ways of sampling a group so as to produce the same mean and variance. Anything from a single pair of objects up to nearly 100% of the objects in the group could, in theory, be sampled so as to also achieve the same mean and variance. This presents considerable theoretical and practical problems. An alternative statistical approach would be to take a random sample of the objects within each of the clusters. While this would provide a tractable procedure for sampling the variation, the approach is confused with the clustering step that ensures complementarity.

The use of clustering to define what is there and then a separate step to define a representative sample of that universe is appealing. I would argue that representative sampling outward from the cluster centroids provides an explicit representation of the population that also provides a controllable degree of 'replication' as a safety net. Such replication appears a conservative strategy in reserve design (e.g., Austin and Margules, 1986; Margules *et al.*, 1988; Pressy *et al.*, 1993). As with all known conservation algorithms, the question of the size of the sample (a stopping rule) is not addressed directly here either.

Consider a hypothetical reserve design scenario based on the Batemans Bay region of the south coast of New South Wales (CSIRO, 1990; Belbin, 1993). The reservation units are 3439 grid cells of 1 km^2 land parcels forming a grid. Each grid cell was sampled for environmental information. Local and state government agencies have decided to establish a minimum of 10% of the region in a reserve network. The grid cells are first classified into a suite of groups. The number of groups is user-definable and in this case, three groups are selected on their ability to form identifiable bio-environmental sub-regions. The second step identifies the 10% of samples within each group that are closest to the group centroids. Fig. 3 identifies the most representative 10%, the next most representative 20% and the remainder of the coastal sub-group. There is a reasonably high degree of spatial contingulty associated with all zones (as expected from the degree of spatial auto-correlation of the environmental attributes). It is interesting however to note that there is a significant 'most-representative' area on the coast that is not surrounded by cells of intermediate representativeness.

A situation could occur where a particular group did not have a sufficient number of samples within a reasonable radius of the centroid. This insufficiency could be identified for example as an inadequate (unsustainable) spatial coverage of representative sites from this group. The onus would then be on the ecologist to flag the problem and search for more representative sites as defined by species and/or environmental composition of the group centroid.

Irreplaceability

Explicit definitions and practical mechanisms for defining complementary groups and representative sampling provide a large part of a scientific reserve design strategy. Realistically, factors such as acquisition costs associated with different land tenure, access or manageability may be significant practical issues that require integration into the reserve design.

Pressey *et al.* (1993) defined irreplaceability as '(i) the potential contribution of a site to a reserve goal; and (ii) the extent to which the options for reservation are lost if the site is lost'. Some concept of the value of a site (or species) to a reserve network appears a necessary, if not totally palatable constraint in reserve design.

Multivariate space discriminates between objects only on the basis of location in this space. Location amounts to differences in species and environmental composition. An assemblage of species at a particular site may be unique. This site may be given a high conservation value and priority in any reserve network design; it may be irreplaceable. Classification may or may not identify this site as being in any way unique. If classification identified the site as an outlier, it would become part of the reserve network because it would be the only representative of its group. Another site may have an assemblage of species that is interpreted by classification as being intermediate in composition between two groups. An ecologist may however deem the site to be valuable because it contains a unique combination of species that have environmental optima at other environmental locations. In this case, classification and subsequent representative sampling may not identify such a site. It would be fair to say that the same is true of other selection algorithms such as those of Kirkpatrick (1983) and Margules *et al.* (1988), as well as those of Vane-Wright *et al.* (1991), Faith (1992) and Faith and Walker (1994). Can the multivariate approach help?

Irreplaceability of a potential reserve site (or species or environment) can be defined as the degree of isolation of that site from other surrounding sites in the multivariate space. For example, sites with similar composition are by definition, going to be close to one

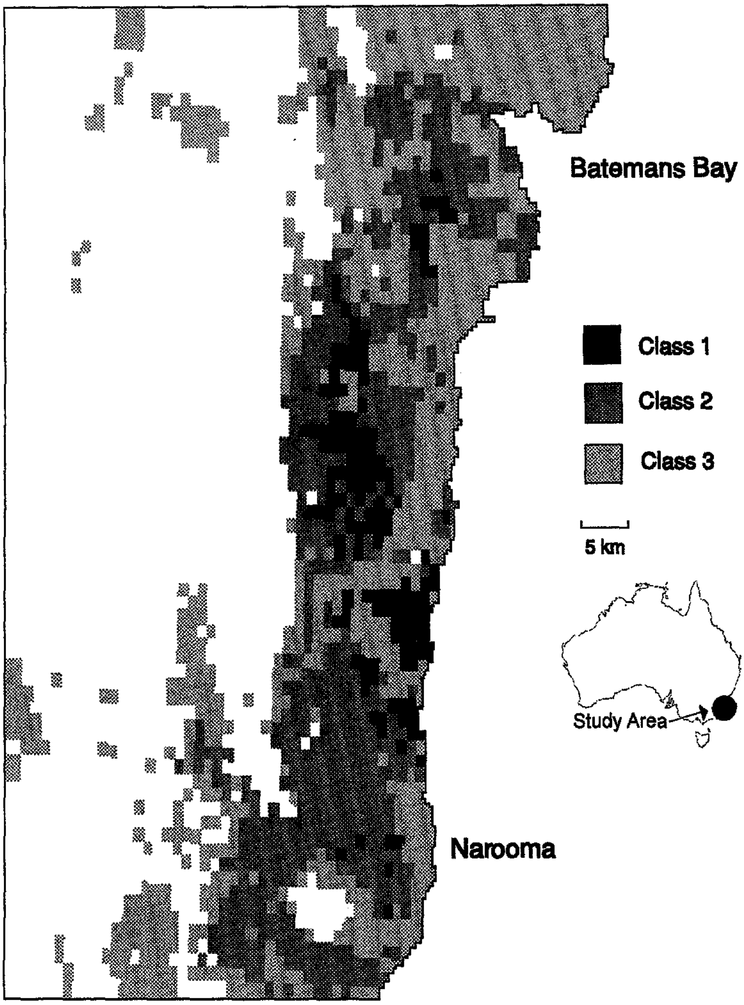

Figure 3. The most representative 10% of the coastal group of 3439 bio-environmental samples in the Batemans Bay region of New South Wales.

another in multivariate space. On the other hand, outliers defined by classification are isolated and therefore probably irreplaceable. The degree of irreplaceability of any site is therefore defined simply as the distance in multivariate space to its nearest neighbour. Faith and Norris (1989) suggested that an average of the distances in the multivariate (ordination) space of a potential reserve site to its nearest neighbours in the reserve network could be used as an estimate of a gain in representativeness of a new sample to an existing network. Irreplaceability simply takes the degree of isolation from the closest neighbour as an estimate of ecological distinctiveness or isolation as a check on the complementarity (clustering) and representativeness (sampling) processes.

If for pragmatic or other reasons, a site is unavailable for selection in the reserve network, the best alternative candidate is another site that is closest in multivariate space. In some instances, no candidates may be close enough. This may result in either a hunt for a

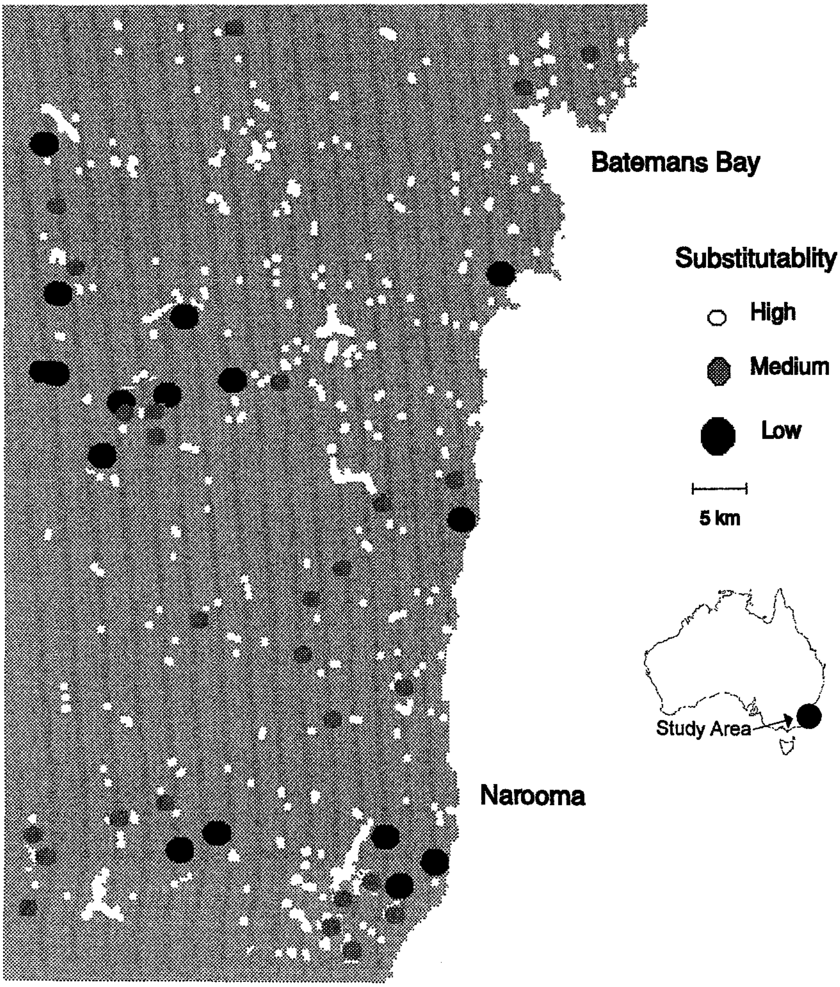

Figure 4. Map of the degree of irreplaceability of 884 vegetation sites in the Batemans Bay region of New South Wales.

site which is similar and/or an increase in the perceived significance of the unavailable site. The same procedure may be applied to species with the reservation as noted above; ordination techniques display species as points that do not indicate the volumes they may occupy in the space. Irreplaceability can be displayed on maps as point values or, if the coverage justified, as an interpolated landscape displaying the degrees of irreplaceability.

Fig. 4 shows an example of a map of irreplaceability values. The points displayed are 884 vegetation survey sites included in a study of the Batemans Bay region of south eastern New South Wales (CSIRO Divison of Wildlife and Ecology, 1990). The irreplaceability value for each site was determined as the distance, using the Czekanowski coefficient (Czekanowski, 1913; Belbin, 1987a; Faith *et al.*, 1987) to its closest neighbour. The histogram of these coefficients was examined and two cut-points applied to display three classes of irreplaceability on this map; low (high conservation value), moderate and high.

Discussion

Clustering is a convenient mechanism for identifying the range of variation in biotic or environmental data, breaking the continuous change composition into discrete and complementary groups. Complementarity could however be defined in continuous terms in exactly the same way as irreplaceability has been defined here, using dissimilarity measures from multivariate analysis. The further two sites or taxa are separated in terms of multivariate distance, the greater their complementarity. Similarly, as a site or taxon becomes more isolated in multivariate/environmental space, it becomes increasingly unique and presumably irreplaceable.

Clustering, as well as the concept of irreplaceability has been used here to provide an approach to reserve design that has implications for management. It is feasible to use the multivariate context to define and evaluate a set of complementary and representative samples independent of clustering. The utility of clustering is that it provides a consistent mechanism for building networks that may have a controllable degree of necessary redundancy or replication. If complementarity is defined at the sample level, a separate and potentially inconsistent mechanism for aggregation appears necessary in many reserve design situations.

Defining complementarity at the group level sets up a framework for representative sampling. If an individual group is examined, representative sampling can be defined as sampling objects that are most typical of that group. Taken across all groups, such sampling approaches a definition of representativeness that is aware of the extent of variation. In either approach, the multivariate framework is helpful in providing a context for evaluating conservation strategies.

Conclusion

The multivariate context offers a practical means of defining and evaluating reserve design strategies. An asset of this environment is its ability to integrate and simplify complex concepts. Useful conservation terms such as complementarity, representativeness and irreplaceability can be placed into an environmental space where they can be examined, more clearly comprehended and potentially further refined. Differences between sites or taxa in this contextual space are expressed as distances. The continuous nature of this space emulates the continuous nature of change in environment and species composition.

While clear, unambiguous distinctions would be convenient for conservation decision making, the reality is that the best we can hope for is an explicit mechanism of defining thresholds on a continuum. Hopefully, this framework provides more than an environment in which to hang existing concepts. Such an approach does provide a simple context for the comparison and refinement of conservation strategies.

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