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Identifying regional landscapes for conservation planning: a case study from KwaZulu-Natal, South Africa

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Abstract

The application of landscape ecology in conservation biology has rarely occurred in the context of defined landscapes. Conservation planning has focussed on representation of species diversity patterns and assumed that ecosystems, landscapes and their associated processes will be equally protected. The long-term persistence of biodiversity in the face of land transformations and global change requires the representation and retention of all elements of biodiversity. This biodiversity includes landscapes, and the landscape structure and processes that maintain patterns of biodiversity. We developed a method of classifying landscapes for the KwaZulu-Natal province of South Africa. The process entailed the use of 1 km^2 grid data from climate and terrain databases. Principal components analysis coupled with a cluster classification method and spatial overlay techniques were used to identify two hierarchical levels of landscapes. Validation analysis showed that landscapes are identifiable with a classification accuracy of 86.8%. The derived landscapes can be combined separately with data on vegetation and soil to describe landscape ecosystems that potentially differ in species composition, successional dynamics, and potential productivity. The surrogate use of the landscapes in conjunction with other strategic data, for the identification of priority conservation areas, is demonstrated. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Landscape ecology has made a significant contribution to conservation biology (Noss, 1983, 1990; Hansson and Angelstam, 1991; Forman, 1995). However, much of the landscape ecological research that investigates biological conservation problems has not occurred within appropriately defined landscapes, rather relying on arbitrary ecoregion delimitations (as discussed Host et al., 1996; Wright et al., 1998). For planning purposes, a representative landscape approach to conservation could potentially be used as a spatial surrogate to ensure the long-term maintenance of biodiversity. The maintenance of processes that sustain ecosystem structure and functioning is essential for achieving persistence goals for systems of conservation areas (Baker, 1992; Noss, 1996). If a landscape approach to conservation biology is to be effective, the landscape units need to be properly defined. At present, the only system that exists within South Africa is for the Kruger National Park (Gertenbach, 1983). This is understandable considering the

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relatively recent international emergence of landscape ecology as a discipline (Wiens, 1992), the importance placed on species systematics and inventorying in southern Africa (Huntley, 1989), and the emphasis placed on poorly sampled species databases for reserve selection (e.g. Rebelo and Siegfried, 1990; Freitag and van Jaarsveld, 1995; Lombard, 1995). The first step in developing a successful landscape level conservation plan is identifying and locating the landscapes of a region.

The goals and objectives of environmental management frequently require the classification of regions based on measurable environmental characteristics. Delineation of ecological landscapes is useful in a variety of contexts, for example, in the assessment of the regional representation of conservation areas (Margules et al., 1988; Bedward et al., 1992; Franklin, 1993; Pressey et al., 1994a,b), defining zones for sustainable ecological management (Forman, 1995), and as a framework for assessing the diversity of species and processes within landscapes (Lapin and Barnes, 1995).

An ecological framework that can integrate multiple environmental characteristics diminishes problems of duplication among government land resource agencies, and it can assist in the exchange of information and research results. Towards this end, the utility of ecoregional classifications, developed for the conterminous US (Omernik, 1987; Gallant et al., 1995; Omernik, 1995) and Canada (Wiken, 1986), have been successfully demonstrated (e.g. US Environmental Protection Agency: Environmental Monitoring and Assessment Program).

There are two broad approaches to classifying landscapes: human landscape-based classification approaches mainly applied in European countries (Blankson and Green, 1991; Green et al., 1996), and biophysical approaches (Christian and Stewart, 1953; De Agar et al., 1995; Bailey, 1996; Bernert et al., 1997) which combine climate, soils, vegetation and landform into observable and definable land units (e.g. Omernik, 1987). Methods vary from visual assessments using elements like scenery, to quantitative procedures which group areas with similar values for a set of mapped variables (Benefield and Bunce, 1982; Blankson and Green, 1991; Host et al., 1996; Bernert et al., 1997). These methods are not completely objective, as variables for consideration have to be chosen, but are less judgmental than visual methods.

We used the biophysical approach because the aim was to identify natural landscapes and then assess their conservation status by examining both the degree of protection and the amount of human-induced transformation that has occurred. This study presents a landscape classification system for the province of KwaZulu-Natal (South Africa) by using biophysical data and a combination of principal component analysis, clustering and spatial overlay techniques. A preliminary analysis is also undertaken to illustrate the important role that this kind of information can and should play in identifying conservation worthy areas.

2. Materials and methods

2.1. Study area

KwaZulu-Natal province is located on the east coast of South Africa and borders the countries of Lesotho, Swaziland and Mozambique (Fig. 1). The province is an important sub-tropical agricultural and plantation forestry production region, and over the last 20 years has seen increased pressure for industrial development in direct conflict with its emphasis and active expansion of conservation based tourism. KwaZulu-Natal province is characterized by the influence of the Indian Ocean, especially the warm Agulhas current, on its climate. This creates a wide coastal region of subtropical climate, characterized by high humidity, high temperatures and high summer rainfall (900–1200 mm). The climatic transition from the coast to the westerly plateau is gradual. Consequently, the region has warm, wet summers and cool, dry winters. KwaZulu-Natal's western border is defined by the Drakensberg Escarpment that forms a marked climatic gradient due to the influence of physiographic relief and altitude on temperature and moisture (Fig. 1). The province is primarily covered by grasslands, savanna woodlands, bush thickets and forest (see Table 1).

2.2. Explanatory variables

The variables used were those commonly used in the description of ecological regions (Omernik, 1987; Omernik, 1995; Bailey, 1996). The set of variables

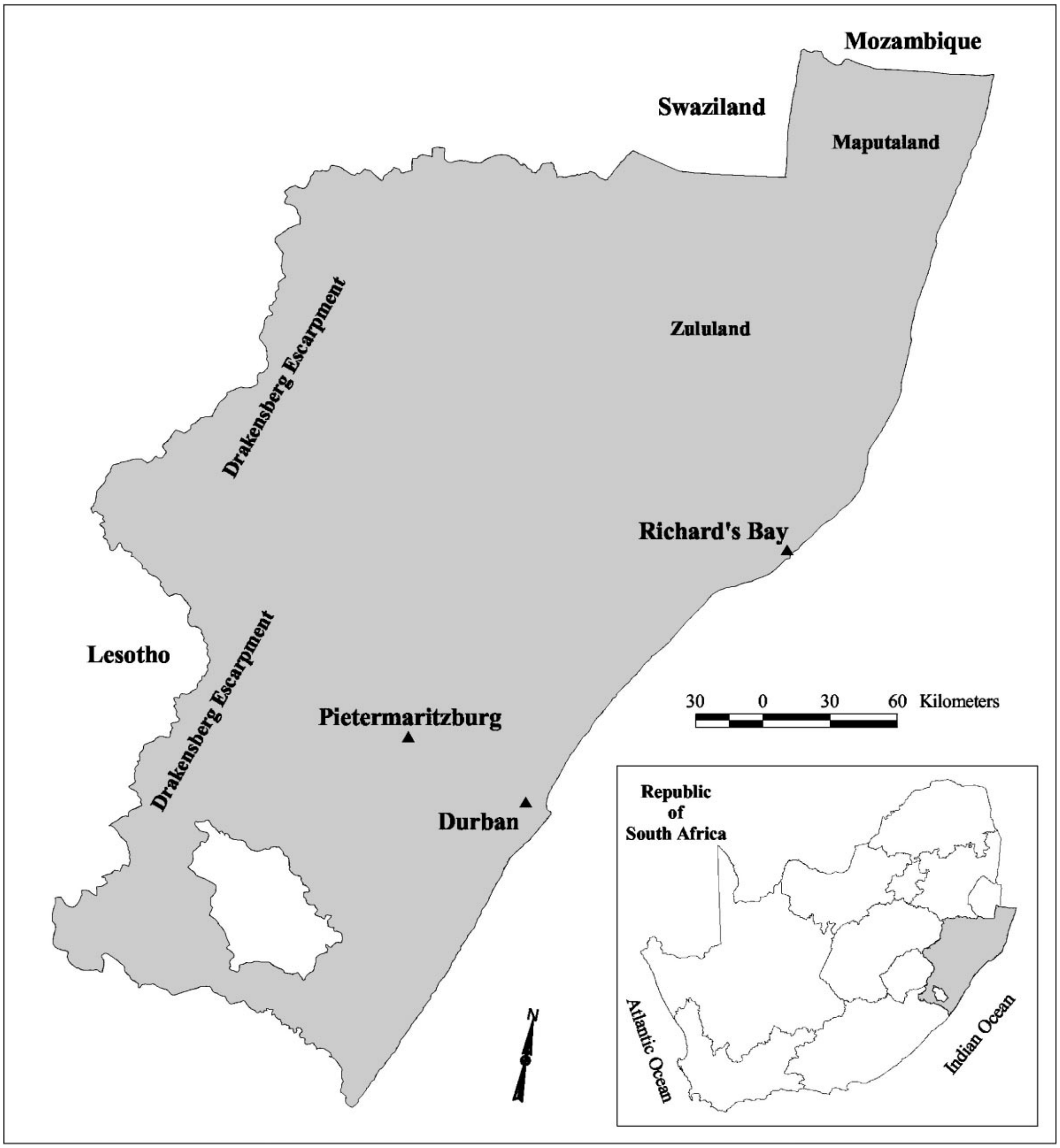

Fig. 1. The location of KwaZulu-Natal province within South Africa.

was broad, and included those describing the physical (topography, landform, geology and climate) and biological environments (vegetation) and was integrated into a geographic information system (GIS). Only the topography, landform and climate variables were used in the classification analysis, the geologic and vegetation maps were not used directly in the demarcation of landscapes (as proposed by Omernik, 1987; Bailey, 1996). Rather, they are used to derive a typology of attributes within the landscapes which allows the landscapes to be described according to the vegetation types and geological substrates found in

Table 1
Functional vegetation classification of the 1:500 000 National Botanical Institute Vegetation of South Africa, Lesotho and Swaziland (Low and Rebelo, 1996)[a]

Original potential vegetation types	Functional classification
Afromontane forest	Montane forest
Coastal forest	Coastal forest
Sand forest	Coastal forest
Eastern thorn bushveld	Arid woodland
Lebombo arid mountain bushveld	Arid woodland
Mixed lowveld bushveld	Arid woodland
Natal lowveld bushveld	Arid woodland
Sour lowveld bushveld	Arid woodland
Subarid thorn bushveld	Arid woodland
Sub-humid lowveld bushveld	Arid woodland
Sweet lowveld bushveld	Arid woodland
Coastal bushveld-grassland	Moist woodland
Coastal-hinterland bushveld	Mixed woodland
Natal central bushveld	Mixed woodland
Valley thicket	Thicket
Coastal grassland	Upland/lowland grassland
Moist upland grassland	Upland/lowland grassland
Short mistbelt grassland	Upland/lowland grassland
Afro mountain grassland	Highland grassland
Alti mountain grassland	Highland grassland
Moist clay highveld grassland	Highland grassland
Moist cold highveld grassland	Highland grassland
Moist cool highveld grassland	Highland grassland
Moist sandy highveld grassland	Highland grassland
North-eastern mountain grassland	Highland grassland
Wet cold highveld grassland	Highland grassland

[a] Endemic vegetation types to KwaZulu-Natal are in bold.

each unit. This adds considerably to the conservation planning objective by not subjectively combining the unit boundaries of vegetation and geology with landscapes to create arbitrary units (Host et al., 1996) and thus mask the landscape heterogeneity into a coarser ecoregional unit (Wright et al., 1998).

2.2.1. *Topography*

Topographic position has been found in other studies to significantly influence ecosystem variability patterns, especially the control of water movement (Kratz et al., 1991; Forman, 1995). A digital elevation model (DEM) of South Africa was available from the US Geological Survey (1996) with a horizontal resolution of 1 km^2 and a vertical resolution of 20 m. This was used to derive elevation information and a topographic landform index (ridge, valley, slope) using standard GIS routines. The percent slope surface was transformed to a surface representing flat-undulating (<4%) and ridge landscapes (>35%) and then a linear function scaled the slope data between the two extremes.

2.2.2. *Climate*

The principal controlling factor in southern African ecosystems is the soil water balance (Cowling et al., 1997; Scholes and Scholes, 1997). The mean number of days per annum on which sufficient water is available to permit plant growth was considered a biologically meaningful index of water availability. Ellery et al. (1992) developed such a water balance index, which calculates the water budget from available climatology data. The index, called ‘growth days’ (GD), is defined as the sum of the monthly ratios of precipitation to potential evaporation, where the ratio is not permitted to exceed 1 in any given month (i.e. if rainfall is larger than evaporation, it is not carried over into subsequent months, but is assumed to have been lost as runoff). This is achieved by multiplying the monthly ratios by the number of days in the month and summing over the year.

$$\mathrm{GD} = \sum_{12} \left(\frac{P}{E} d \right); \qquad \frac{P}{E} \le 1$$

where P is the long-term mean monthly rainfall, E the monthly open water potential evaporation (‘lake evaporation’, calculated using Lineacres’ equation (Linacre, 1989) which uses maximum and minimum temperature, altitude and latitude), and d the number of days in the month. Intuitively, it can be thought of as the number of days per year when soil moisture does not limit plant growth.

The GD index was calculated on the 1 km^2 grid covering the entire country, from monthly mean rainfall (1960–1990) and the monthly means of maximum and minimum daily temperatures (Dent et al., 1989).

The annual mean of the monthly mean temperature weighted by the monthly growth days was recorded as ‘growth temperature’ (GT), giving an indication of energy supply during the growing season (Ellery et al., 1992). The GT was calculated from available mean monthly temperature surfaces (Schulze, 1998).

Other bioclimatic variables considered for comparison for possible inclusion within the landscape model included median annual precipitation, summed mean minimum and maximum rainfall for the driest and wettest quarters, mean annual temperature, and mean minimum and maximum temperatures for the coldest and hottest months.

2.2.3. *Geologic origin and soil fertility*

The ecology and distribution of savanna woodlands and grasslands in South Africa is largely determined by soil fertility (Scholes and Walker, 1993; Ellery et al., 1995), which affects species composition patterns, production, and stability. Since soil maps for the whole of South Africa are not available, the geological material from which the soil was formed was used as an indicator of whether the soil types within the landscape are generally nutrient-rich, nutrient-poor or intermediate (Bell, 1982).

KwaZulu-Natal portion of South Africa's 1:1 000 000 scale geological map was reclassified according to origin and chemical composition using primary lithologies (Visser, 1989), and three landscape fertility classes (high, medium, low) reflecting their capacity to supply nutrients to plants and herbivores.

2.2.4. *Potential vegetation*

Vegetation type is a prime determinant of ecosystem type (Peters, 1992), playing a major role in determining the associated fauna and soil microbiota. Two potential vegetation map products are available for South Africa: Acock's (1953) vegetation types, which is largely based on the agricultural potential of the vegetation, and Low and Rebelo's (1996) vegetation types which is based on both structure and floristics, but is really a reassessment of Acocks (1953). The potential map of Low and Rebelo (1996) was mapped at a scale of 1:500 000. The 26 vegetation types that occur in KwaZulu-Natal were classified into functional community groupings (Table 1) (Low and Rebelo, 1996; Cowling et al., 1997) for analysis (Fig. 2).

2.3. *Approach*

We developed a systematic approach (Fig. 3) for delineating landscapes within the KwaZulu-Natal province that could be applied to any geographical region. To prevent landscapes occurring along the KwaZulu-Natal border from being defined by arbitrary political boundaries, the study area was extended across the borders using catchment boundaries (DWAF, 1996). This overlap will also allow for easier edge-matching of future landscape classifications developed by neighboring provinces.

The analysis was raster grid cell based. The analysis cell size was partly determined by the largest cell size of the already rasterised data sets and a logical cell size for future integrative work, in this instance 1 km^2. All data sets were converted to Lamberts Azimuthal Equal-Area projection for analysis.

To reduce the amount of data to be analysed, a stratified random sampling of data sets was conducted. The 167 South African Surveyor General 1:50 000 map sheets covering KwaZulu-Natal were used to stratify a random sample selection, with 25 cells being chosen from each sheet (i.e. a total of 4675 samples).

Pearson correlation coefficients were used to examine multicolinearity and thus minimise the duplication of variable information, and make decisions with regard to variables being recorded in the field. Principal component analysis (PCA) was performed on the resulting variables, which allows the important descriptors to be standardized against each other for interpretation into spatial objects (see Legendre and Legendre, 1998).

Pattern and cluster analysis was undertaken on the PCA results in ArcView GIS (ESRI, 1997) using bivariate map plots of the axes factor scores produced by the PCA analyses and then applying a natural breaks clustering classification technique. This method identifies breakpoints by looking for groupings and patterns inherent in the data using Jenk's optimization, which minimizes the variation within each class (Jenks, 1963). Using these techniques the data sets responsible for the greatest amount of variation, as identified by the PCA, were classified. The classified data sets were then subjected to class boundary cleaning by smoothing transitions between classes. This procedure removes class border roughness which is caused by inaccuracies in the coarse resolution data (ESRI, 1997).

Landscapes were constructed by combining the classified terrain and climatic data sets in a stepwise manner using Arc/Info GRID GIS (ESRI, 1997), and smoothing the intermediate derived data sets with a 3×3 grid cell neighbourhood majority class filter. This

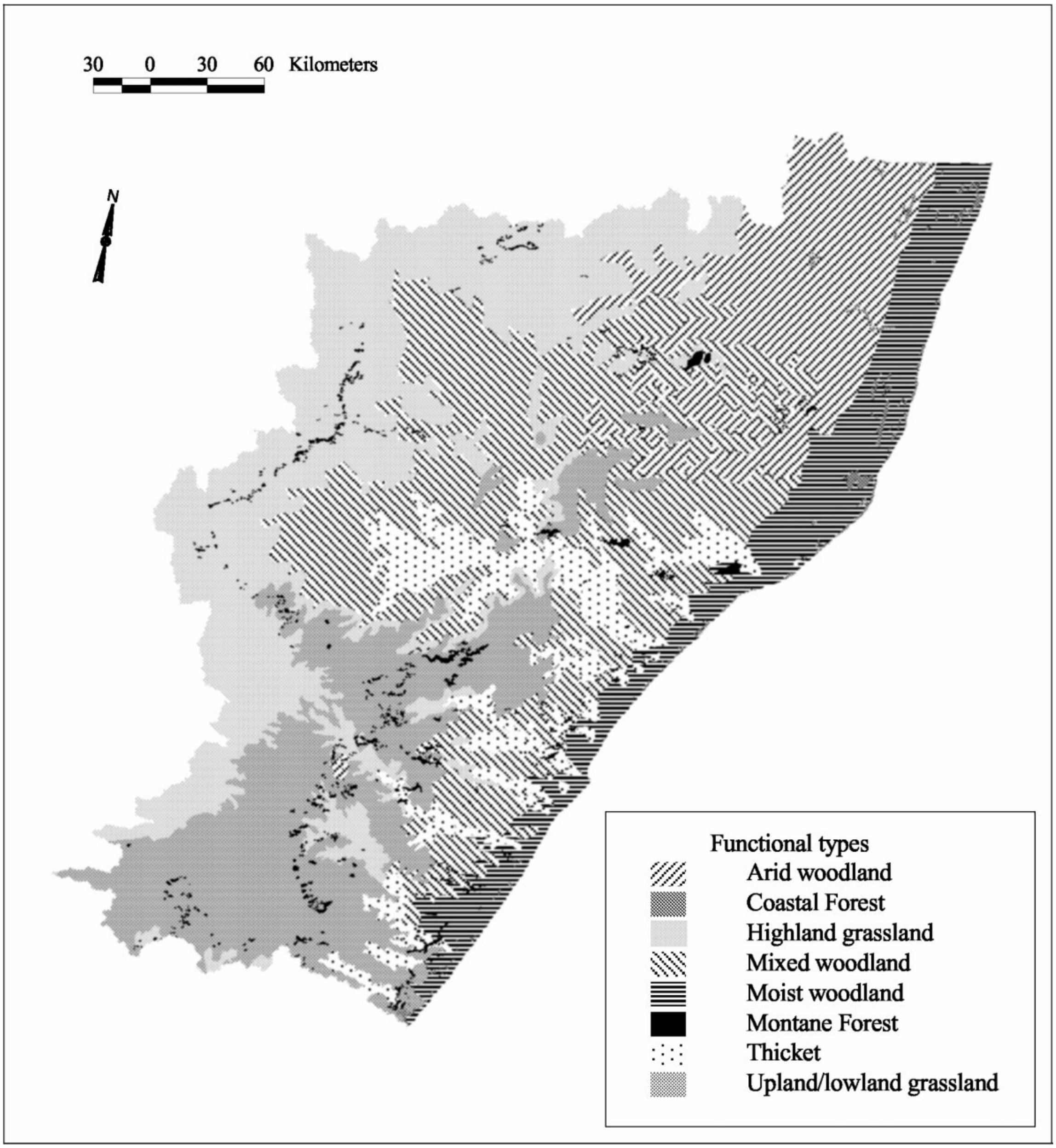

Fig. 2. Map of the functional vegetation types found within KwaZulu-Natal.

transformation reassigned pixel values based on the most prevalent class membership within a 3×3 cell moving window. Scarpace et al. (1981) found that majority filtering actually increased classification accuracy by reducing 'random' noise in classification results. When applying this method over large regions the errors average out, so the landscape estimates are probably quite accurate even if the cell by cell estimates may be less accurate.

A validation exercise was performed using the South African National Land-Cover Database accuracy assessment points (Fairbanks and Thompson,

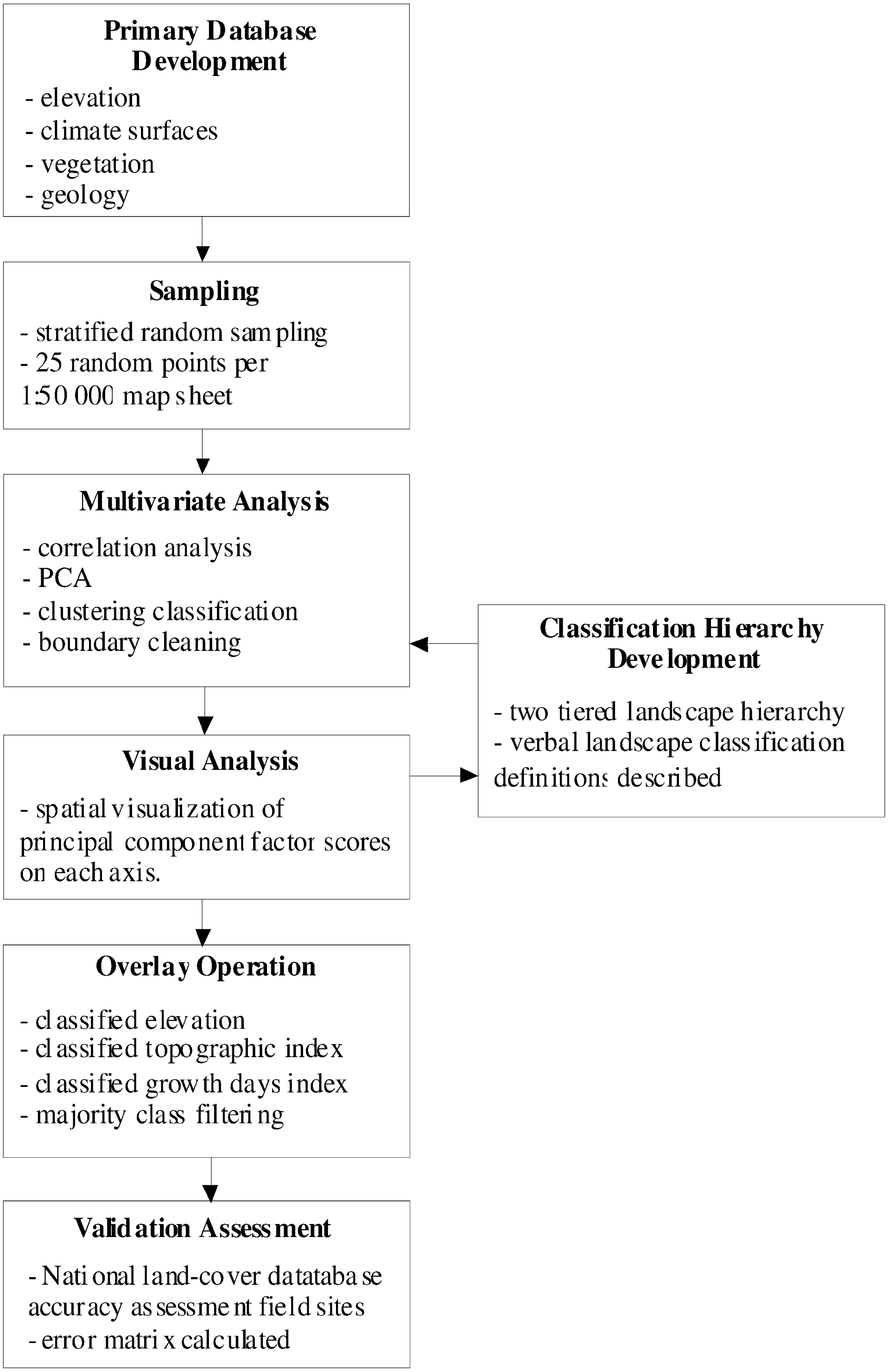

Fig. 3. Analysis framework used to classify and identify the landscapes.

1996). The overall accuracy of the landscape classification map was tested using 530 stratified random field locations. Actual class membership for the sample locations was assigned on majority area coverage of a class within a cell. A combination of using the extra attributes collected in the field (e.g. topography, position, and vegetation) per point and inspection of the fixed ground photography of the area around a point was used to determine actual landscape class membership. This helped to ensure that the derived landscape types were recognisable ecological units for conservation analysis and planning.

2.4. Landscape conservation analysis

A crucial consideration in maximizing the protection of biodiversity is the assignment of priorities for protection in the face of real-world constraints (Pressey et al., 1996a,b). The concepts of irreplaceability (Pressey et al., 1994a,b) and vulnerability (Pressey et al., 1996a,b) were developed to explicitly define conservation value and priority for representative areas. In its simplest form, irreplaceability is a measure of the likelihood that an area will be needed to achieve a conservation goal; vulnerability is a measure of the imminence or likelihood of the biodiversity in an area being lost to current or impending threatening processes. Thus, irreplaceability is a measure of conservation value whereas conservation priority is the value of an area combined with some assessment of the urgency with which it should be conserved (Pressey, 1997). Areas of high irreplaceability and high vulnerability are highest priorities for conservation action (Pressey et al., 1996a,b). Focusing conservation resources on such areas will maximize the extent to which representation goals will be achieved on the ground.

To demonstrate the value that landscapes add to the analysis of conservation goals, by helping identification of conservation worthy regions, we conducted an analysis of the derived landscapes with the South African National Land-Cover database (Fairbanks and Thompson, 1996; Fairbanks et al., 2000) and a protected area database for KwaZulu-Natal. The land-cover database contains spatial information on natural land-cover and identifiable human land-use mapped from Landsat TM imagery at 1:250 000 scale (Fairbanks et al., 2000). The land-use classes are essentially a measure of transformation status in the context of threats to biodiversity. The protected area database described the boundaries of provincial reserves, digitized from 1:50 000 maps.

The land-cover data was used to assess the vulnerability of the landscapes to future human transformation based on the diversity of land-uses in each landscape. The rationale being that landscape types with several land uses are more vulnerable to future transformation than areas of single land uses because of their unique and favorable environment to a variety of human development potential options. The level of irreplaceability was determined using a linear weighted combination of the extent of transformation, representation in protected areas and rarity (measured as the relative areal contribution of each class).

$$\begin{aligned}\text{Irreplaceability} = \sum_{3} &(\text{rarity} \times \text{weight})\\ &+ (\text{transformation} \times \text{weight})\\ &+ (\text{representation} \times \text{weight})\end{aligned}$$

The classification of the measures was derived using the natural breaks classification technique (Jenks, 1963). The vulnerability and irreplaceability scores were scaled from 0 to 100% as calculated from classifications and weights (Table 2) as defined by KwaZulu-Natal Nature Conservation Services (KZNNCS).

Table 2
Landscape rarity, transformation and protection status classification rules and importance ratings

Total % (rarity)	Weights	Transformed (%)	Weights	Protected (%)	Weights
<1.7	1	>50	1	<10	1
1.7–5	0.75	34–50	0.75	10–25	0.66
5–7.6	0.5	18–34	0.50	>25	0.33
>7.6	0.25	<18	0.25		

3. Results

3.1. Landscape classification

Median minimum rainfall for driest and wettest quarters, growth temperature, mean annual temperature, mean maximum temperature for January, and mean minimum temperature for July were highly correlated ($p<0.05$) with elevation (Table 3) and were dropped from further analysis. Elevation alone is a good predictor of orographic precipitation and temperature gradients. Similarly, median annual precipitation was highly correlated with growth days ($p<0.05$) and was also dropped from further analysis (Table 3). Growth days has been found to be a better predictor of water balance for determining the effectiveness of rainfall for biomass production in southern Africa (Ellery et al., 1992).

Table 4

Factor weights, Eigenvalues, and total variance explained derived by the PCA analysis on the chosen topographic and climatic variables[a]

Variables[b]	Axis 1	Axis 2	Axis 3
DEMSD	0.7715	−0.1490	0.3013
DEM	**0.8405**	0.2516	0.0612
GD	0.2079	0.0429	**0.9663**
TLI	0.0637	**0.9747**	0.0324
Eigenvalue	1.34	1.03	1.02
Total variance explained (%)	43.46	25.28	16.63

[a] Values in bold denote the significant variable identified for each axis.

[b] Variable names: topographic heterogeneity (DEMSD); elevation (DEM); topographic landform index (TLI); growth days (GD).

The PCA results (Table 4) showed that the elevation model accounted for most of the variation and, therefore, the primary gradient for the region, on Axis 1 (0.8405), similarly for the topographical landform index on Axis 2 (0.9747) and growth days on Axis 3 (0.9663). These three variables were, therefore, used for construction of the landscapes and the topographic heterogeneity variable was dropped from any further analysis (Fig. 4). By using local a priori knowledge, visual interpretation and examination of the ordering of the factor scores on each axis with the clustering technique we determined elevation could be meaningfully classified into two hierarchical levels of 10 detailed and four coarse classes (Table 5). The topographic landform index was retained at seven classes and lumped to two classes at a coarser level (Table 5). The growth days index was reclassified into 30 and 60-day ranges to produce a six and three-level hierarchical classification (Table 5).

The first data combination involved the overlaying of the detailed Level I elevation classification with the Level I topographical landform index classification producing 20 unique combinatorial classes from the input data. All combinations of classes potentially could have yielded 70 unique classes, but in this case only 20 unique elevation-landform types were

Table 3

Pearson correlation matrix for environmental variables used in landscape classification for KwaZulu-Natal (n=4675)[a]

	DEMSD[b]	DEM	TLI	DM	WM	MDP	GD	GT	MAT	MAXJ	MINJ
DEMSD	1.0	0.37	0.03	−0.13	**0.50**	0.35	0.36	−0.43	−0.39	−0.43	−0.26
DEM		1.0	0.19	**−0.52**	**0.70**	0.22	0.31	**−0.94**	**−0.98**	**−0.84**	**−0.92**
TLI			1.0	0.01	0.05	0.06	0.05	−0.08	−0.05	−0.10	0.05
DM				1.0	−0.04	**0.53**	0.49	0.28	0.43	0.17	**0.63**
WM					1.0	**0.79**	**0.78**	**−0.74**	**−0.72**	**−0.73**	**−0.55**
MDP						1.0	**0.91**	−0.38	−0.27	−0.45	−0.02
GD							1.0	**−0.56**	−0.43	**−0.67**	−0.12
GT								1.0	**0.98**	**0.97**	**0.82**
MAT									1.0	**0.91**	**0.91**
MAXJ										1.0	**0.67**
MINJ											1.0

[a] Correlations highlighted in bold violate the $r>0.50$ multicolinearity limit defined for this study.

[b] Variable names: topographic heterogeneity (DEMSD); elevation (DEM); topographic landform index (TLI); driest quarter precipitation (DM); wettest quarter precipitation (WM); median annual precipitation (MDP); growth days (GD); growth temperature (GT); mean annual temperature (MAT); mean maximum temperature January (MAXJ); mean minimum temperature July (MINJ).

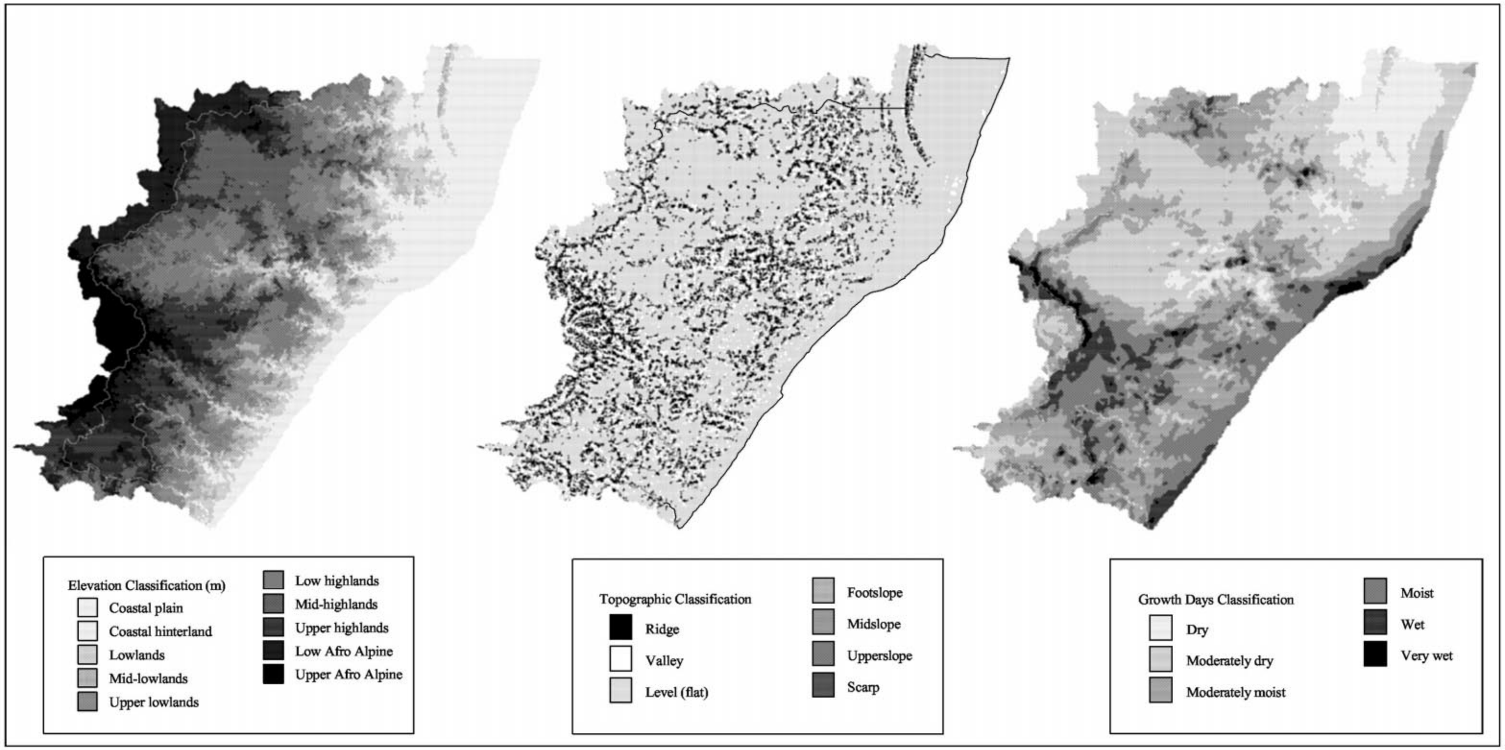

Fig. 4. Environmental data layers chosen to develop the landscape classification model: (a) elevation, (b) growth days, and (c) topographic landform index.

Table 5
Elevation, topographic landform index and growth days index classification hierarchies

Elevation ranges from PCA Axis 1 (m)	Level I	Level II
0–162	Coastal plain	Coastal
162–352	Coastal hinterland	Coastal
352–558	Lowlands	Lowlands
558–754	Mid-lowlands	Lowlands
754–948	Upper lowlands	Lowlands
948–1138	Low highlands	Highlands
1138–1353	Mid-highlands	Highlands
1353–1610	Upper highlands	Highlands
1610–1986	Low Afromontane/Escarpment plateau	Afromontane
1986–3484	Upper Afromontane/Lesotho alpine	Afromontane
Topographic landform index		
	Level/flat	Undulating/flat
	Valley	Mountainous/hilly
	Footslope	Mountainous/hilly
	Mid-slope	Mountainous/hilly
	Upper slope	Mountainous/hilly
	Scarp	Mountainous/hilly
	Ridge/crest	Mountainous/hilly
Growth days ranges (days)		
60–90	Dry	Dry
90–120	Moderately dry	Dry
120–150	Moderately moist	Moist
150–180	Moist	Moist
180–210	Wet	Wet
210–247	Very wet	Wet

derived. This combination was then overlaid with the Level I growth days index. The combined data set derived 104 classes out of a potential 120, but several classes were shown to be small and spurious in nature ($\leq$3 grid cells). The majority class filter was processed over the data surface and a final 97 class landscape map was produced. These 97 classes represent the landscapes of KwaZulu-Natal at the highest level of detail by being derived from the Level I classification hierarchies of the input data. The 97 classes were then hierarchically collapsed to the coarser 24 class landscape Level II classification for ease of use and illustration (Fig. 5).

3.2. Validation

The coarser Level II landscape classification was analysed using conventional error matrices for predicted versus actual class membership at field checked locations. Three summary statistics, percent correctly classified (PCC), 95% confidence limits and the Kappa statistic were generated from the matrix for comparing the performance of the landscape model. The PCC provides an intuitive measure of classification accuracy. The Kappa statistic is a measure of overall agreement based on discrete multivariate analysis described by Bishop et al. (1975) which has been promoted for use in the remote sensing community (Congalton et al., 1983).

Overall the Level II landscape classification accuracy is good at 86.8% PCC (83.8–89.7% at 95% confidence), considering the coarse data resolution, with predictable confusions along landscape borders and within areas where the coarse data were not able to describe local structural anomalies. The Kappa statistic implies that our classification is 85.3% better than the accuracy that would result from a random class assignment. This means that a high repeatability of the

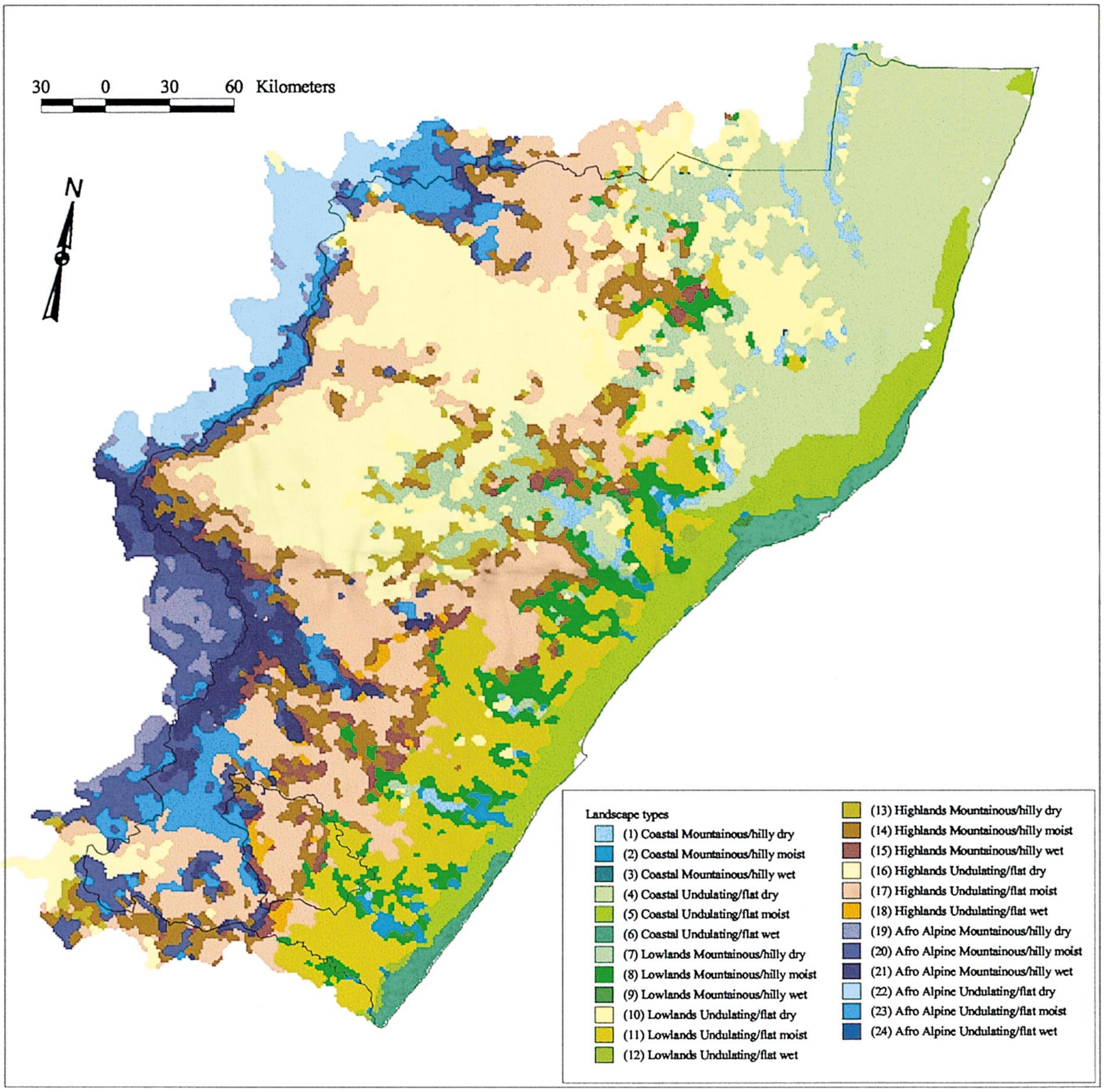

Fig. 5. Landscape classification (24 classes) of KwaZulu-Natal province, South Africa.

same classification results could be acquired by another knowledgeable analyst using our methodology and having local a priori knowledge.

3.3. Landscape conservation analysis

Landscape rarity, current transformation status, and current protection provided by conservation authorities are presented in Table 6. Fig. 6 illustrates the current human-induced transformation status on the Level II landscapes. The majority of the transformation has taken place in the coastal and highland regions. In Fig. 7 we demonstrate the bias that the provincial protected area network, managed by KZNNCS, has in its protection of landscapes versus the landscape vulnerability status. In this case, the

Table 6
Calculations of percent rarity, current transformation percentage and percent protected in managed nature reserves[a]

Level II	Total (%)	Transformed (%)	Protected (%)
1	1.2	24.2	4.2
2	0.6	0.2	1.0
3	0.01	25.2	0.0
4	12.7	29.9	13.3
5	5.9	62.5	13.9
6	1.7	50.0	5.8
7	4.1	21.2	6.3
8	4.0	30.0	0.5
9	0.1	39.3	1.4
10	6.2	34.2	1.5
11	7.6	52.9	1.5
12	0.2	66.1	0.0
13	1.4	18.6	0.7
14	6.7	25.1	2.0
15	1.6	33.1	10.9
16	13.9	30.8	0.8
17	15.0	40.3	0.9
18	0.4	56.2	1.9
19	1.6	34.6	14.8
20	5.1	12.5	20.2
21	3.0	2.5	51.7
22	3.3	11.9	2.6
23	3.7	12.5	4.1
24	0.2	8.2	7.8

[a] The legend for the landscape numbers is given in Fig. 5.

Maputaland coastal region and the Drakensberg Escarpment are well conserved (areas with Malaria and high rocky areas), but the landscapes denoting the lowlands and highlands (highly valued agricultural lands) are severely under protection. This illustrates a much noted paradox in conservation's history: pieces of land have been put aside in an ad hoc manner, often on economically marginal land or to conserve a few charismatic species (Pressey et al., 1994a,b).

Irreplaceability and vulnerability (Fig. 8) reveal the landscapes with high values for both as areas of high priority for conservation action. The majority of these areas have undulating/flat terrain with moist-wet climates in the coastal, lowland, and highland regions (e.g. 5, 6, 12, 17, and 18). These priority landscapes are dominated by mixed woodland and upland grassland ecosystems (Table 7), which are habitats considered in serious threat to development throughout South Africa (Fairbanks et al., 2000). By using the modest IUCN protection rule of 10% minimum area and a hypothetical division of vulnerability status at 50% (see Fig. 7), only three landscape types (4, 5, and 15) are minimally protected with greater than 50% vulnerability (Fig. 9). In the case of landscape type five, which lies along a north–south coastal gradient, only the far northern section receives adequate protection. By using a combination of analytical graphs and spatially plotting, these results landscapes like type five can be identified by their skewed representation and critical contribution to a provincial conservation goal.

Landscape types (6, 8, 10, 11, 12, 14, 16, 17, 18, and 22) represent the bulk of the province and have been historically ignored by the conservation authorities and targeted for development. They primarily contain fertile habitats of mixed woodland and upland and highland grasslands (Table 7). The almost total transfer of land in the formerly white areas of South Africa, from government to private ownership, is possibly unique in the annals of European colonisation. The state by the mid-1930s had lost control over resources which in countries such as Australia or the USA were retained by the authorities because of their unsuitability for agriculture (Christopher, 1982). The strong tradition of land ownership rather than leasehold in South Africa and the absence of state interest in land through a leasehold system has developed a strong demand for land and an attempt to make a living in areas often highly unsuitable for the purposes of farming (Christopher, 1982). Demand for land has further driven land prices to levels far in excess of its value as an agricultural commodity, and thus confounded past and present conservation efforts.

Clearly the goal of conservation is not only to ensure minimum landscape, habitat and species protection, but also to represent geographic gradients and to enable longer-term ecological and evolutionary processes to persist. This is not in conflict with the importance of habitat loss for the immediate persistence of biodiversity, but long-term persistence goals also need to be considered in designing and implementing reserve systems, especially in response to global change.

4. Discussion

This is the first time, to our knowledge, that a landscape or ecoregion classification has been

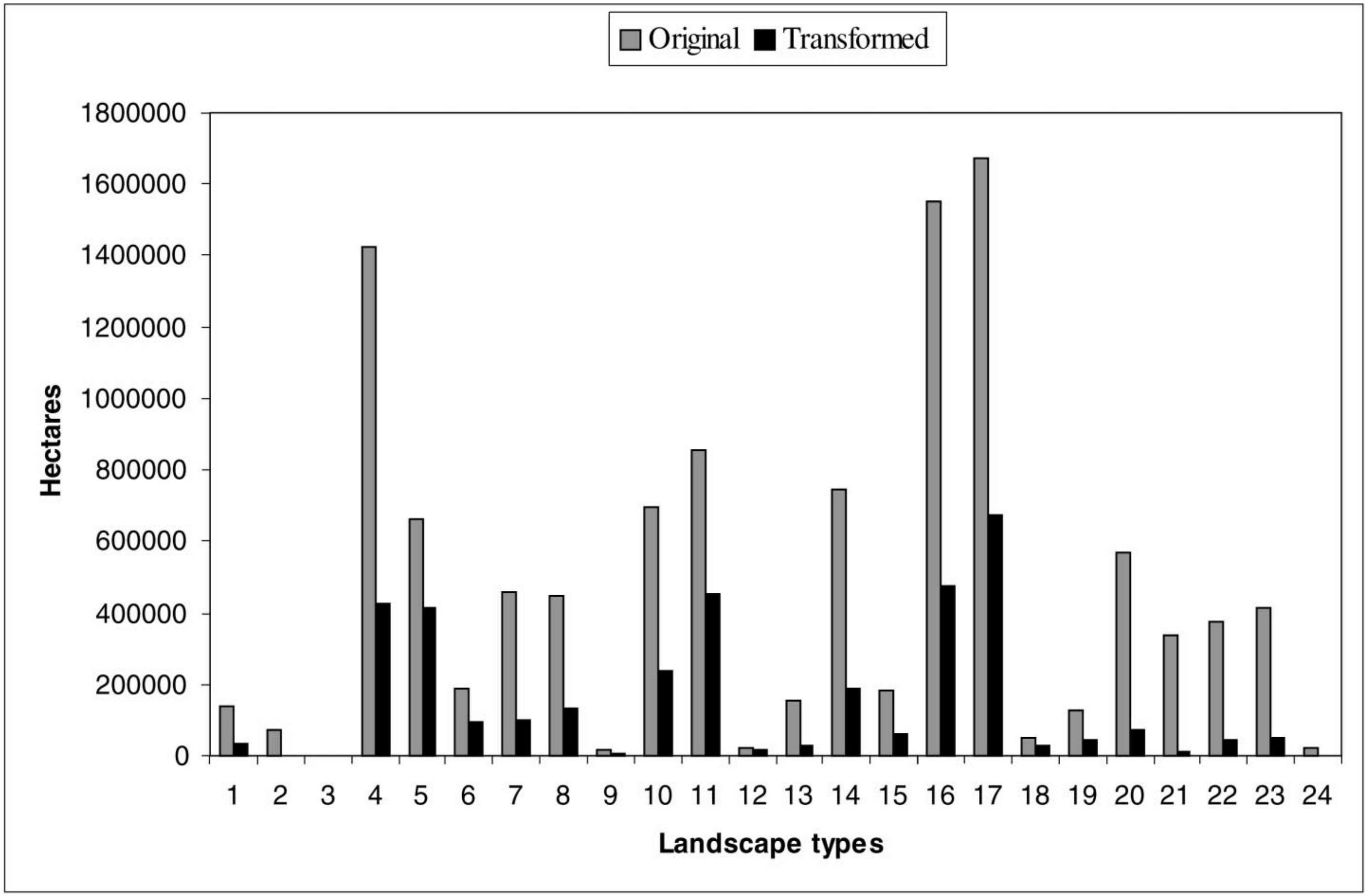

Fig. 6. Preliminary assessment of the level of transformation within the second level landscapes relative to their areal coverage. See Fig. 5 for number code descriptions.

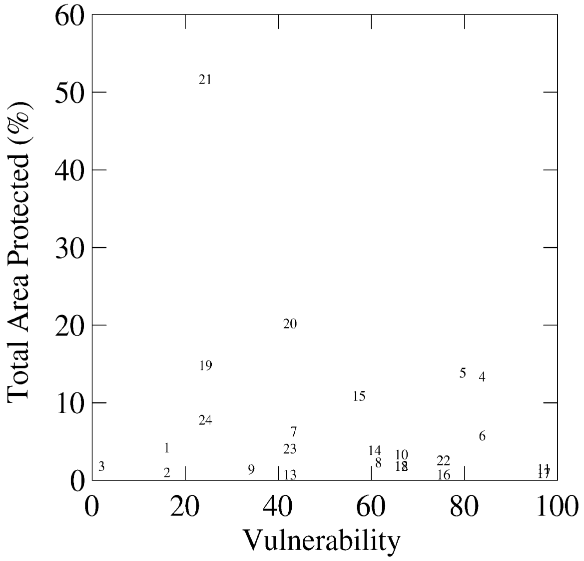

Fig. 7. Scatter plot of current protection status vs. vulnerability for each landscape type. See Fig. 5 for number code descriptions.

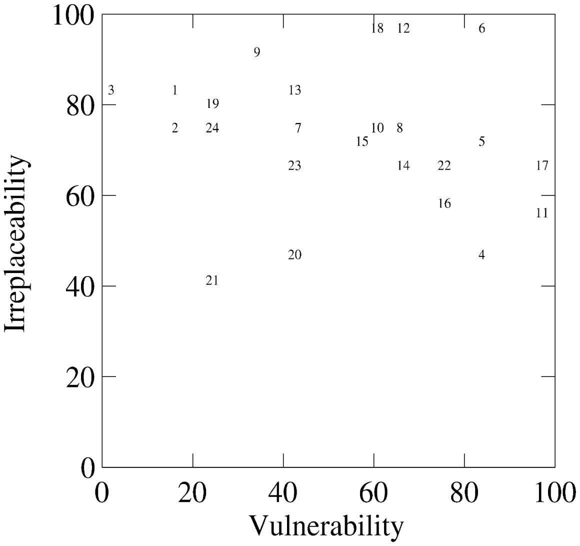

Fig. 8. Preliminary scores for irreplaceability (conservation value) and vulnerability to threatening processes for the landscapes. Landscape types in the upper right-hand corner are conservation priorities. See Fig. 5 for number code descriptions.

Table 7
The values represent the percentage of each Level II landscape type that is comprised of each functional vegetation type[a]

Level II	Forest[b]	Arid woodland	Moist woodland	Mixed woodland	Thicket	Upland grassland	Highland grassland
1	0.5	**47.3**	0.3	**26.9**	**24.2**	0.0	0.8
2	1.7	0.0	**31.7**	**37.0**	**25.6**	3.9	0.0
3	**12.5**	0.0	0.0	0.0	0.0	**87.5**	0.0
4	0.9	**62.7**	**26.2**	7.2	2.8	0.0	0.1
5	1.9	0.0	**76.9**	**10.3**	**10.6**	0.2	0.0
6	3.6	0.0	**88.0**	1.0	2.7	4.7	0.0
7	0.2	**32.0**	0.0	**26.9**	**23.5**	4.6	**12.8**
8	1.2	5.5	5.4	**43.6**	**28.9**	**12.0**	3.4
9	**27.6**	0.0	5.3	**37.6**	8.8	**20.6**	0.0
10	0.0	**33.3**	0.0	**38.4**	**11.2**	2.7	**14.3**
11	0.7	1.7	5.3	**44.6**	**20.6**	**22.5**	4.5
12	3.3	0.0	9.5	**49.2**	4.1	**33.9**	0.0
13	0.0	2.1	0.0	**41.7**	**21.7**	**17.6**	**16.8**
14	1.1	2.2	0.0	**22.4**	4.6	**36.4**	**33.4**
15	8.0	1.3	0.0	7.9	2.8	**61.1**	**18.9**
16	0.1	1.3	0.0	**66.1**	4.9	8.5	**19.1**
17	0.4	1.2	0.0	**13.9**	1.1	**46.2**	**37.2**
18	2.4	2.6	0.0	1.0	1.8	**86.9**	5.4
19	0.1	0.0	0.0	0.0	0.0	0.8	**99.1**
20	0.4	0.1	0.0	1.5	0.0	**28.2**	**69.7**
21	2.2	0.7	0.0	0.0	0.0	**34.6**	**62.5**
22	0.1	0.0	0.0	0.0	0.0	0.1	**99.8**
23	0.8	0.0	0.0	0.9	0.0	**45.0**	**53.3**
24	1.8	0.0	0.0	0.0	0.0	**79.3**	**18.9**

[a] Values in bold represent vegetation types with >10% affiliated area with Level II landscape types.

[b] Forest is a combination of Montane and Coastal forests.

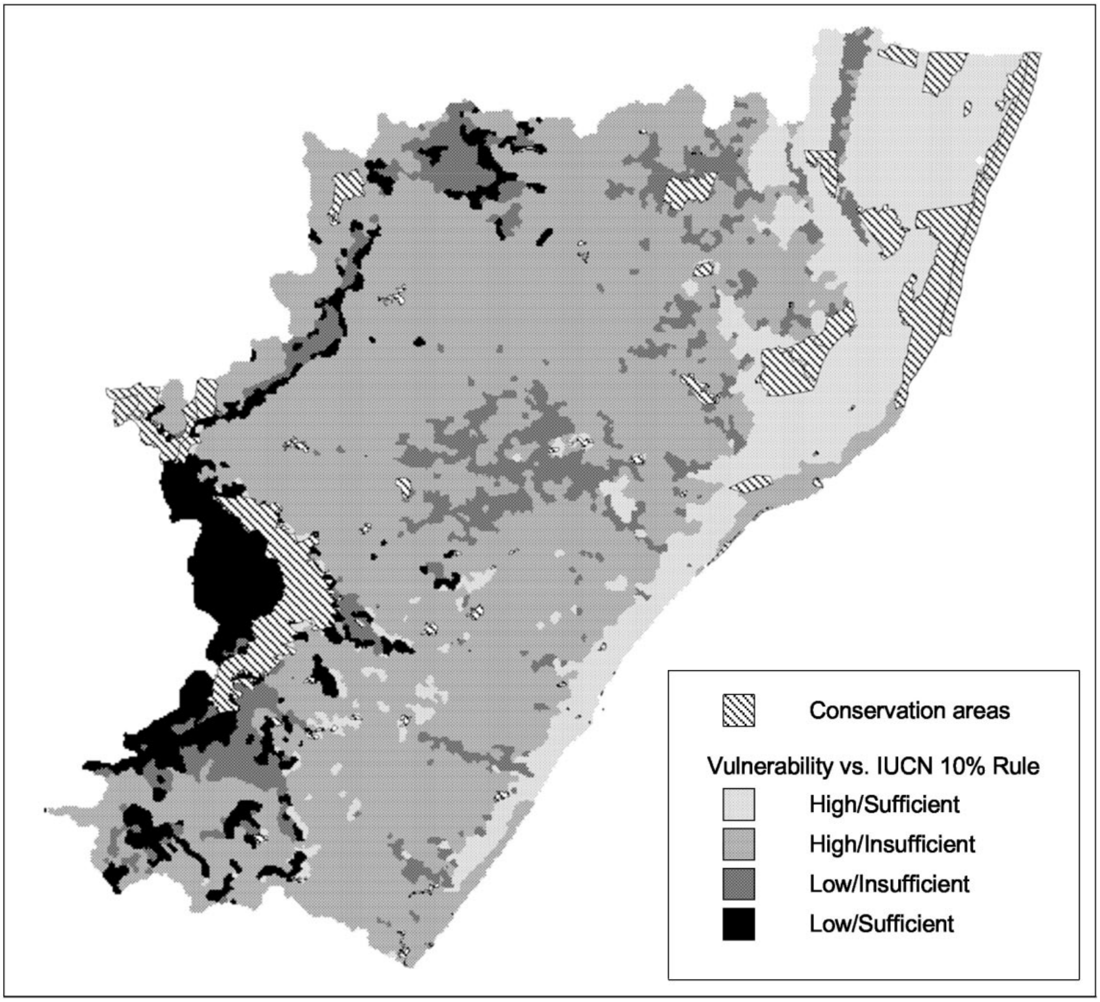

Fig. 9. Landscape types classified by a 50% vulnerability status boundary and using the proposed IUCN 10% target for minimum protection of habitats.

properly assessed for accuracy and fitness for use in the field, and thus evaluated for use in systematic conservation planning. Using more indirect methods Wright et al. (1994) and Host et al. (1996) also assessed the value of larger ecoregional units (e.g. Omernik, 1987) and a machine driven ecosystem classification with mixed success. The use of ecoregion classifications for conservation planning is questionable given the very coarse scale of the units, the mixing of ‘potential’ and actual data sets (e.g. potential vegetation, climate zones, land-use pattern, soils, etc.), and the reliance on boundaries drawn by a consensus of experts, which may not provide a repeatable methodology. Rather, a data driven and parsimonious approach based on ecologically important structural and climatic variables derived at a larger landscape scale may allow for a better understanding of the pattern and processes required for biodiversity preservation. This type of landscape model can then be independently assessed with potential vegetation and edaphic factors as the landscape attributes.

While chosen data layers and analytical methods are relatively objective, there are a number of decisions that require some a priori understanding of the landscapes under study. There are also data processing questions, such as determining a statistically appropriate number of classification levels, selecting important variables or generalizing boundaries that require subjective, yet defendable decisions. It is unrealistic to expect that the process of landscape classification can be accomplished entirely by spatial and numeric analysis; human understanding is also an important component (Host et al., 1996). However, by defining a computationally repeatable methodology, the knowledge of experts may be captured for future refinements within a data driven model.

4.1. Landscape scale and structure

Terrain analysis is the quantitative analysis of topographic surfaces with the aim of studying surface and near-surface processes. In short, terrain analysis provides the basis for a wide range of landscape-scale environmental models which are used to address both research and management issues and objectives. It is widely recognised that landscape pattern analysis is sensitive to the resolution (spatial scale) of the source data (Turner et al., 1989). As the distance between neighbouring elevation samples increases, fine-scale features are lost and the surface becomes more generalised. However, when identifying landscapes there is a tendency to focus on specific finer detailed terrain or ecosystem elements within a landscape rather than the broad scale structures which truly define a landscape. For this study, a landscape was not defined traditionally as a mosaic where the mix of local ecosystems is repeated in similar pattern over a kilometers-wide area (Forman, 1995), but rather where the physical systems integrate together to define identifiable patterns over a kilometers-wide area. Therefore, our database of environmental layers defined at a resolution of 1 km^2 was considered appropriate for striking a balance between regional and local ecosystem heterogeneity.

4.2. Landscapes as an element of biodiversity for use in prioritisation procedures

The present study has shown that it is possible to produce an ecologically inclusive inventory of regional landscapes, notwithstanding the extensive areas they occupy and their inherent spatial complexity. Noss (1990) described landscapes as an upper level in a hierarchical framework which extends upwards from genes–species–ecosystems to describe the range of biological diversity. The analytical framework presented here is an appropriate model for elucidating the landscape level biodiversity dilemmas faced by conservation practitioners. By proposing a top-down, constraint based modelling and conservation assessment an approximation of the main processes and structure maintaining long-term biodiversity pattern can be used in more specific species protection and recovery plans. Biophysically defined landscapes containing elements of vegetation types with edaphic drivers determine and drive co-evolution with other species of mammal, reptile, bird and insect. The products of interacting organisms in a hierarchically defined landscape environment are ecosystems.

Majority of the work on preserving biodiversity and selecting priority areas for conservation has concentrated on the lower level of the biodiversity hierarchy, namely species (Pressey and Nicholls, 1989; Rebelo and Siegfried, 1990; Lombard, 1995; Pressey et al., 1996a,b), populations (Lamberson et al., 1992; Breininger et al., 1995; Doak, 1995) and communities (especially vegetation assemblages: Scott et al., 1993; Barbault, 1995; Strittholt and Boerner, 1995) patterns. Recently, criticism has been levelled at especially the species based approaches to identifying priority conservation areas (Noss, 1983; Franklin, 1993; Scott et al., 1993; Barbault, 1995; Maddock and du Plessis, 1999). However, due to the hierarchical nature of biodiversity any approach, which only concentrates on one of the levels, is flawed. There has been virtually no research on designing reserve systems intended for long-term persistence of biodiversity in the face of global change. Such a strategy must embody the representation and retention of both biodiversity patterns as well as the processes that maintain and generate these patterns. Thus, more comprehensive and inclusive biodiversity protection can be obtained by focussing on as many levels as possible. Landscape areas representing high irreplaceability and vulnerability are focus areas for follow-up species and ecosystem representation analysis, and identification of key processes that are responsible for the maintenance and genesis of biodiversity. If the information is available, important constituent ecosystems within these priority landscapes can be identified using the classification procedure developed here. The dominance of mixed woodland and upland grassland vegetation functional types within the priority landscapes identified in the preliminary analysis suggests the ecosystems needing consideration, and gives significant insight into what conservation actions are needed on the ground.

Hierarchy theory (O'Neill et al., 1986) suggests that constraints operate downward in complex hierarchies such as ecosystems (i.e. from the more aggregated levels to the less aggregated levels). Recognising this, it has been suggested that using higher levels of biodiversity alone to select priority areas for conservation is preferable, especially in areas with inadequate region-wide biological data (Margules and Redhead, 1995). This is based on the assumption that diversity and spatial heterogeneity are intrinsically linked (Diamond, 1988; Hunter et al., 1988; Samways, 1990; Forman, 1995). If for instance landscapes were to be used in this manner, it assumes that a predictable relationship (surrogacy) between diversity at the landscape level and lower levels exist. Unfortunately, little research has tested these assumptions, but some do suggest (see Harner and Harper, 1976; Burnett et al., 1998; Nichols et al., 1998) that the upper levels of biodiversity (e.g. Noss, 1990) may act as effective surrogates for biodiversity as a whole. Though this will vary between ecosystems and depend on levels of disturbance. Until such relationships are adequately explained, the best practice for selecting priority areas and preserving biodiversity will involve multiple levels of biodiversity (i.e. broader classification such as landscapes, vegetation, geology in conjunction with species data and human development induced threats) guided by the principles of retention of pattern and process.

A final issue that must be addressed is the robustness of the derived landscape classification system over time and space. The landscape classification system developed was based on both structural and climatic components. The structural data layers are expected to be robust over time and space due to their slow geological evolution, but climate may present resiliency problems for the current classification. Under a predicted climate change scenario for precipitation in southern Africa (Joubert and Hewitson, 1997) the growth days index can be expected to change over space and in magnitude. Re-defining the classification when newer climatic data sets become available can, therefore, retain the relevance of the landscape classification system. This is not in conflict with the objective of providing a classification system for a functional landscape, which is also expected to undergo evolutionary change over time. However, there is a trade-off between too much data resolution versus the expected resilience of the classification system, which can be tested through sensitivity analysis.

5. Conclusions

The use of regional ecological classification systems is increasing (Bailey, 1996; Host et al., 1996; Pressey, 1997). This is a result of efforts by resource and nature conservation managers to replace political boundaries with ecologically based management units that better reflect the spatial distributions of natural features. This is particularly true in water resource and nature conservation planning sectors, where landscape and regional ecology can be used to spatially combine natural processes and human activities to promote sustainable land management (Davis and Stoms, 1996). Developing a landscape classification allows for this often ignored level of biodiversity to be inventoried and considered in conjunction with species-based conservation prioritisation exercises.

The classification methodology proposed here is not totally objective in that data themes were chosen, and required some a priori knowledge of the focus region's landscapes. However, the method is systematic and extensible to other areas. Furthermore, the method provides approaches for quantitatively classifying data, allows for quantitative understanding of the data heterogeneity among the themes, and can be updated as better data becomes available or environmental changes are documented.

By developing data layers for all the levels of biodiversity we can then provide a protocol for developing a reserve system that will enable biodiversity to persist into the next millennium. Rather than maximizing conservation of contemporary biodiversity patterns, a system should conserve ecological and evolutionary processes essential for sustaining biodiversity. Use of the landscapes-species hierarchy and the identification and role of processes in maintaining biodiversity patterns will help conservation planners to formulate clear representation goals in balance with human induced threat.

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