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A methodology for analyzing rare species distribution patterns utilizing GIS technology: The rare birds of Tanzania

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Abstract

A simple, straightforward, cartographic modelling technique is presented for measuring relations between environmental characteristics and rare species distribution patterns. This approach is corroborated by digitizing rare bird distribution data for Tanzania and statistically analyzing these patterns in relation to geographic and environmental variables. Of the available natural resource data for Africa, only the vegetation and soils data appeared accurate enough to represent regional natural resource distribution patterns. Available data for Tanzania at the regional scale is not currently precise or comprehensive enough to analyze ongoing dynamic ecological processes.

Statistical relations, associated with a study quadrangle within Tanzania, are documented for these parameters. Final confirmation of the accuracy of predictions about rare species diversity patterns will ensue from future field observations. When confirmed, this methodology can be used for setting conservation priorities in biologically little known regions of the world.

Introduction

Regional biotic diversity patterns can be predicted from an analysis of patterns in the spatial distribution of environmental variation. Recent studies have shown strong predictive relationships between regional plant distribution patterns and environmental variables (Miller 1986; Richerson and Lum 1980; Feoli and Orloci 1985). This analytical approach provides a possible method for identifying important areas for the conservation of both floral and faunal diversity (Miller *et al.* 1987). This broad-scale perspective facilitates regional resource inventory, interpretation and management/conservation planning (Bailey and Hogg 1986).

This study focused upon the development of a practical method for the identification of areas of high rare species diversity in need of conservation attention. An additional goal was to determine if a realistic relation could be documented, on the regional scale, between environmental and rare avifaunal diversity patterns.

The precursor of the analysis approach developed in this study originated from research conducted in the southern Appalachians region of the United States (Miller 1986). The original methodology was improved and extended with respect to the rare avifauna of Tanzania. This avifauna is relatively well-known and provided an excellent opportunity to test the predictive validity of the analysis approach. If environmental diversity patterns could be used to predict occurrences of rare species

Table 1. Data acquired and input into the GIS system at the University of Zurich-Irchel to create a database for the Tanzanian landscape analysis.

Acquired data	*Description*	*Type*	*Source*
World Data Bank II	Digital representation of the continents and national boundaries of the world	1:3,000,000; 6,000,000 coordinates	National Technical Information Service, Reston, Virginia, USA
World Digital Elevation Data	Digital values for elevations throughout the world	10 minute scale	United States Department of the Navy
Maps of Tanzania	Maps of roads and cities; topographic maps in scale series; aeronautical charts	Road maps used for determination of location	Kenya, Tanzania, Uganda. Freytag-Bendt Autokarte, Wien. 1:2,000,000
			Shell map of Tanzania. Shell & BP Tanzania Ltd., Dar Es Salaam. 1:2,000,000
			Tanzania: Land of Kilimanjaro. Tanzania Tourist Corp., Dar es Salaam. 1:2,000,000
			Tanzania in Maps. Berry 1971
		Topographic maps at various scales 1:50,000– 1:5,000,000	
		Aeronautical chart	USAF 1969. 1:1,000,000
		Landscape feature maps (*e.g.*, national parks, vegetation associations)	East Africa, BP Kenya Ltd., Nairobi. UNESCO/AETFAT/UNSO 1:5,000,000.
Soil Data	Digital representation of soil classes	1:5,000,000 109 classes	FAO/UNESCO Data Bank (UNEP/GRID)
Precipitation Data	Digital representation of rainfall classes	1:5,000,000 32 classes	FAO/UNESCO Data Bank (UNEP/GRID)
Wet Days Data	Digital representation of annual wet days	1:5,000,000 11 classes	FAO/UNESCO Data Bank (UNEP/GRID)
Wind Speed Data	Digital representation of average wind speed	1:5,000,000 13 classes	FAO/UNESCO Data Bank (UNEP/GRID)
Vegetation Data	Digital representation of vegetation classes	1:5,000,000 17 classes	FAO/UNESCO Data Bank (UNEP/GRID)
Species Data	Identification of geographical site locations	Gazetteers Field surveys	Tanzania Surveys and Mapping Division (1967, 1969). Swynnerton and Hayman 1951; Swynnerton 1945
	Avifaunal distribution, vulnerability, and endemism status		Collar and Stuart 1985; Britton 1980; S. Stuart, personal records; K. Howell, personal records

in Tanzania, this methodology would provide a useful approach for identifying probable areas inhabited by rare species in countries with poorly documented species' distribution patterns. This technique would consequently facilitate the reserve selection and design process.

The requirements of two priorities involve preserve selection and design criteria:

1. The need for functional, regional guidelines for the selection, placement and design of reserves, especially in rapidly developing areas of the world and;
2. The need for ecologically sound predictions of species and habitat changes on the temporal scale, which result from reserve truncation from surrounding natural habitat.

The second priority requires long-term ecological research (Miller and White 1986) which cannot satisfy the more immediate goals of priority I. Our research was oriented towards the formulation of a simple, useful, and rigorous analysis methodology for the identification of sites in need of conservation attention.

Methodology

Data compilation

Digital data for Tanzania were compiled from many different sources. These included published and unpublished maps of many varieties, field data collected by scientists, literature reviews, information from governmental agencies and data from the Global Resources Information Database of the United Nations Environment Programme (UNEP/GRID). Geographic, topographic, geologic, climatic and biotic data were compiled, transformed, and processed within a Geographical Information System (GIS) at the University of Zurich-Irchel (Table 1).

The analysis approach

A grid cell system identified the data pertaining to the Tanzanian landscape (Table 1) with single cells of standard size (*i.e.*, 30" latitude by 30" longitude). Each pixel was georeferenced onto a geographic coordinate system which served as the baseline reference map for both the Tanzanian environmental data and the rare species data. The environmental data were stored as many individual layers of grid cells. For each layer, the grid cells contained single values representing each variable class. The series of environmental variable grids conformed to the same geographic coordinate system as the grids representing rare avifaunal species distribution patterns.

Environmental data were obtained from the United Nations Environmental Program in Geneva, Switzerland (UNEP/GRID). These data included classifications of the following five environmental variables in the East African region: precipitation, soil characteristics, wind speeds, vegetation types, and annual wet days. Each of these variable layers was obtained at the 1:5,000,000 map scale as referenced to the topographic map series of the American Geographical Society.

The only available elevation data for Tanzania was a 10 minute Digital Terrain Model (DTM). The 10 minute elevation data available for the Tanzanian region was at too small a geographic scale to be of use analytically and complete digitization of topographic maps at a larger scale was beyond the limits of this study. Therefore the predictive importance of the elevation parameter was not analyzed.

Incomplete and inconsistent data coverage limited the scope of this study. The mapped precipitation, wet days, and wind speed data appeared upon first inspection to be complete coverages of the Tanzanian landscape. However, when these data were compared with areas of known precipitation patterns, the data were found to be invalid at several locations. These appeared to have been produced from algorithms which generalized known data points into a data representation for the entire continent of Africa. Only the soil and vegetation data adequately and accurately represented environmental elements across the Tanzanian landscape and only these two parameters were analyzed during this study. The annual precipitation and annual number of wet days parameters were thought to have predictive importance to the avifaunal dis-

Table 2. Frequency occurrence information for the recorded soil types within Tanzania, the study quadrangle, and areas within the study quadrangle which included rare bird distribution records. The numbers represent the percentage of land within an Area category characterized by each vegetation type (trace < 0.3%).

Soil type	*Area category*		
	Within Tanzania	*Within study quadrangle*	*Within study quadrangle, with recorded rare bird species*
Ferric acrisols	30	8.0	0.5
Orthic acrisols	2.8	10.4	–
Chromic cambisols	12.3	26.2	84.2
Calcic cambisols	3.2	9.8	2.6
Renzinas	trace	–	–
Orthic ferrasols	3.8	9.6	–
Eutric gleysols	trace	–	–
Humic gleysols	1.2	–	
Plinthic gleysols	1.2	3.9	
Lithosols	2.6	–	–
Eutric fluvisols	2.5	6.3	12.7
Thionic fluvisols	trace	–	
Ferric fluvisols	13.2	–	–
Dystric nitosols	2.6	–	
Eutric nitosols	3.9	–	
Humic nitosols	0.7	–	
Cambic arenosols	0.9	–	–
Ferralic arenosols	3.0	3.1	–
Dystric regosols	1.3	–	–
Mollic andosols	0.6	–	–
Ochric andosols	0.5	–	–
Pellic vertisols	4.8	1.6	–
Eutric planosols	2.5	15.1	–
Water	6.4	–	–

tribution patterns from field studies. Soil and vegetation parameters were hypothesized to be of less predictive importance. Yet, if statistically valid relations could be documented and verified for these less predictive parameters, this would support the usefulness of this methodological approach in areas where the more important digitized environmental data is available.

The environmental data were transferred onto an **IBM** 3033 computer at the University of Zurich-Irchel and were reformatted to be compatible with the GRID software system (ESRI, 1983). For the Tanzanian grid model, each data cell represented an area on the ground of 925m*925m (0.86 km^2) and therefore each 0.86 km^2 within Tanzania was documented by a single data value. The complete data set (*i.e.*, a square which included Tanzania) was contained within a quadrangle of 1,719,526 grid cells, while the area restricted to the boundaries of Tanzania was represented by 1,107,675 grid cells. This was the most accurate digital African data available for any of these variables.

Study areas

A study quadrangle within Tanzania was chosen for analysis (it was not necessary to analyze the entire Tanzanian landscape to obtain statistically and biologically significant results). This quadrangle included a diversity of Tanzanian vegetation and soil types, and it included both areas homogeneous for single soil and vegetation types and areas which contained many different types. This quadrangle was 200 by 200 grid cells in dimension and represented 34,400 km^2 as compared to the total area of Tanzania which is 947,754 km^2. The geographical position of this study quadrangle was defined by the following coordinates:

SW Corner:	*NE Corner:*
7"57'00"S	6° 17'00"S
36"49'00"E	38°29'00"E

The relative representation of the soil (Table 2) and vegetation (Table 3) types within Tanzania and within the study quadrangle was surveyed. Tables 2 and 3 also include results from a survey of these landscape classifications for the 2284 areas in the study quadrangle which contained rare bird species distribution records.

Map registration and transformation procedures

The original soils and vegetation data were referenced to geographical map projections (*i.e.*, longitude-latitude (degrees-minutes-seconds)). The validity of the original soils (FAO/UNESCO 1977) and vegetation (White 1983) data was verified. This

Table 3. Frequency occurrence information for the vegetation types within Tanzania, the study quadrangle, and areas within the study quadrangle which included rare bird distribution records. The numbers represent the percentage of land within an Area category characterized by each vegetation type (trace < 0.3%).

Vegetation type	*Area category*		
	Within Tanzania	*Within study quadrangle*	*Within study quadrangle, with recorded rare bird species*
Swamp forest	< 1		
Lowland rainforest	2.5	–	–
Dry woodland/thorn scrub	9.3	38.0	trace
Cultivation and secondary grassland	< 1	–	–
Undifferentiated montane vegetation	5.4	6.0	22.7
Zambesian miombo woodland-wet and dry	46.8	56.0	77.2
Undifferentiated woodland	< 1	–	–
Undifferentiated woodland transition to Acacia deciduous bushland	1.1	–	–
Deciduous thicket	< 1	1	
Acacia-Commiphora deciduous bushland and thicket	21.7	–	
East African evergreen bushland/secondary Acacia grassland	2.0	–	–
Semi-desert grassland and shrubland	< 1	–	–
Edaphic grassland-volcanic soils	2.0	–	–
Edaphic grassland-semi-aquatic	1.0	–	–
Altimontane vegetation-tropical	< 1	–	–
Halophytic vegetation	< 1	–	–
Mangrove	< 1	–	–
Water	5.6	–	–

was accomplished by comparing the classification for a sample of areas with recent information about the soils and vegetation in these areas.

Rare bird species distribution patterns were mapped using an aeronautical chart with a polyconic projection at the 1:1,000,000 scale (United States Air Force 1969). Geographical locations in Tanzania were precisely identified from a survey of gazeteers, type-locality publications, and various maps of the country (*e.g.*, Surveys and Mapping Division 1967, 1969; Swynnerton 1945). Well documented spatial distribution records of the rare and endemic birds of Tanzania were taken from recent publications (Britton 1980; Collar and Stuart 1985). These maps were then digitized with an ARC/INFO Geographical Information System. Ornithological expertise was obtained to precisely define the rare bird distribution boundaries and to confirm the validity of the final distribution maps. Avifaunal species considered during this study were either listed as 'threatened' in the Red Data **Book** or as endemics in Tanzania with considerably restricted ranges (Table **4)**. The rare bird species information in Table 4 were compiled and used to produce range maps for each of the rare species (Fig. 1). The avifaunal distribution maps were then converted to raster format so they could be analyzed utilizing the GRID software system (*i.e.*, vector to raster data conversion on ARC/INFO(ESRI 1985)). The GRID system was used to identify the number of rare species located within each analyzed area within the study quadrangle.

Table **4.** Bird species in need of conservation attention considered in this study based on their rarity and/or limited distributions. Status categories were determined from the IUCN/ICBP Red Data Book and from a review **of** pertinent avifaunal literature. Common species which were nonetheless endemic to Tanzania were not included in this compilation.

Species	Distribution	Status
Balaeniceps rex Gould 1850.* Shoebill	Swamplands – Western Tanzania, west of Lake Victoria. Also the swamps Nkilandagoga, Moyowosi, and Malagarasi	Of special concern
Bugeramus carunculatus (Smelin 1789) Wattled crane	– Between and including Ufipa plateau and Iringa Highlands – Kalo (on the Ugalla river) – Ugalla river – North of Lake Sagara between Moyowosi, Nikonga and Kigosi rivers	Of special concern
Bubo vosseleri Reichenow 1908. Usambara eagle owl	– East and West Usambara mountains between 900 and 1500 meters – Only known from the eastern side of the West Usambaras	Rare
Anthus sokokensis van Someren 1921. Sokoke pipit	– Pugu Hills – Moa	Vulnerable
Malaconotus slius Friedmann 1927. Uluguru bush-shrike	– Uluguru mountains, in forests above 1300 meters	Rare, endemic
Swynnertonia swynnertoni (Shelley 1906) (S.s. rodgersi) Swynnerton' forest robin	Uzungwa mountains, southern and eastern escarpment above 1000 meters	Rare
Sheppardia gunningi Haagner 1909. East coast skalat	Pugu Hills	Rare
Modulatrix orostruthus (Vincent 1933). (M.o. amani) (M.o. sanjei) Dappled mountain robin	– East Usambara mountains between 800 and 1100 meters (M.o. amani) – Uzungwa mountains, southern and eastern escarpments (M.o. sanjei)	Rare, endemic
Dryocichloides montanus (Reichenow 1907) Usambara ground robin	– West Usambara mountains above 1500 meters	Rare, endemic
Dryocichloides lowei (Grant and Mackworth-Praed 1941) Iringa ground robin	– Two areas, delimited by observations from nine localities: southern Highlands, Uwemba, Mdando forest, Uzungwa mountains, Njombe forest, Dabaga forest, Mufundi, Kigogo forest, Chita	
Turdus fischeri Hellmayer 1901 Spotted ground thrush	– Pangani – Pugu Hills – Ufipa (unconfirmed record) – Mbeya (unconfirmed record)	Rare
Apalis Karamojae (van Someren 1921) Karamoja apalis	– Itumba – Ngongoro – Between Nzega and Igunga, south to Ndala	Insufficiently known
Apalis argentea Moreau 1941 Kungwa spalis	– Mahale (or Kungwe) mountain between 1800 and 2200 meters – Lukolansala river at 1300 meters – Katuma river at 1200 meters	Rare

* The digitization of the distribution records for this single species were estimated rather than precisely located due to insufficient data.

Table 4. Continued.

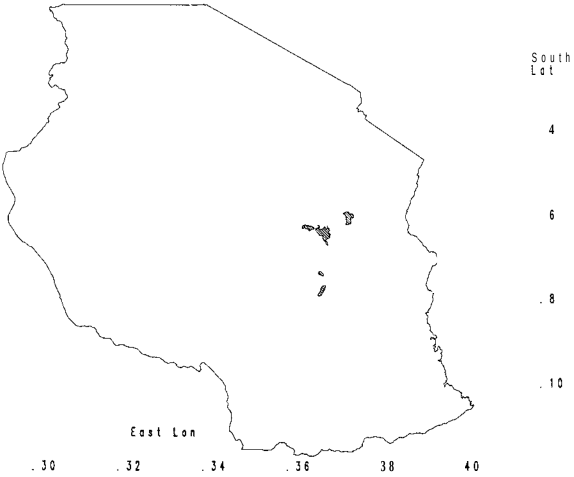
Species	Distribution	Status
Apalis moreaui Sclater 1931 Long-billed apalis	– East Usambara mountains between 900 and 1050 meters	Rare, endemic
Bathmocercus winifredae (Moreau 1938) Mrs. Moreau's warbler	– Uluguru mountains between 1350 and 2350 meters – Ukaguru mountains between 1500 and 1650 meters – Eastern escarpment of the Uzungwa mountains between 1300 and 1700 meters (at Mwanihana Forest)	Rare, endemic
Anthreptes pallidigaster Sclater and Moreau 1935 Amani sunbird	– East Usambara mountains below 900 meters	Rare
Anthreptes rubritorques Reichenow 1905 Banded green sunbird	– Usambara mountains between 750 and 1500 meters – Nguru mountains below 1600 meters – Uluguru mountains between 900 and 1600 meters – Eastern escarpment of the Uzungwa mountains between 850 and 1500 meters (Mwanihana Forest)	Rare, endemic
Nectarinia rufipennis Jensen 1983 Rufous-winged sunbird	Eastern escarpment of the Uzungwa mountains between 600 and 1700 meters (Mwanihana Forest)	Rare, endemic
Ploceus nicolli Sclater 1931 (P.n. andersoni) Tanzanian mountain weaver	– Usambara mountains above 1350 meters – Uluguru mountains between 800 and 1800 meters – Eastern and southern escarpment of the Uzungwa mountains	Rare
Nectarinia loveridgei (Hartert) Loveridge's sunbird	Uluguru mountains between 800 and 2000 meters	Threatened, endemic
Nectarinia moreaui (Sclater) Moreau's sunbird	All areas above 1300 meters: – Nguru mountains – Ukaguru mountains including Kiboriani – Uvidunda mountains – Eastern escarpment of th Uzungwa mountains (Mwanihana Forest)	Threatened, endemic

Two sets of digitized information were compared in this study. The digitized bird distribution maps, taken from a polyconic map series projection, were analyzed in the context of the soil and vegetation maps, taken from geographic projections. Precise identification of the relative position of the study quadrangle on each of the two map projections permitted accurate location information using the grid-cell storage format. It was therefore unnecessary to convert one map set to the projection of the other.

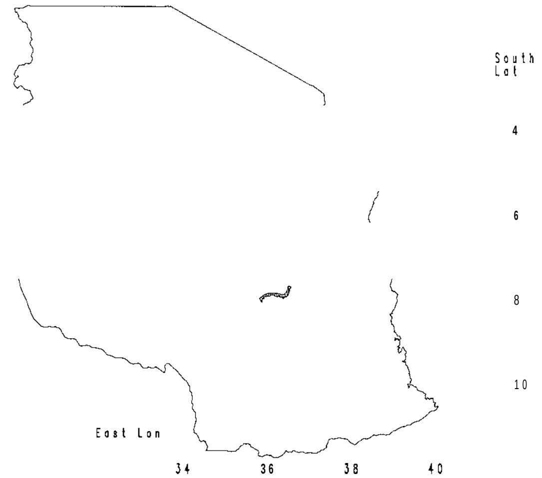
Analysis approach

To measure the influence of small and large area size, each grid cell became identified with an area of 69 km^2 and an area of 607 km^2 (*i.e.*, using the SEARCH subroutine within the GRID software system – ESRI 1983) (Fig. **2).** Subsequent statistical analyses were performed on two data sets: (1) areas of 69 km^2; and **(2)** areas of 607 km^2. These will be referred to below as the small and large area data sets.

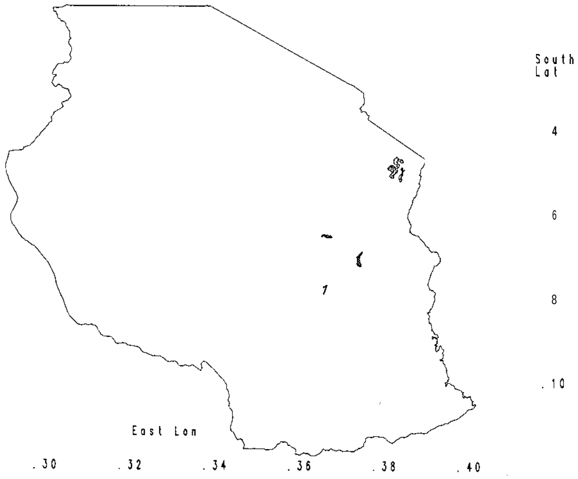
Each area became identified with the number of



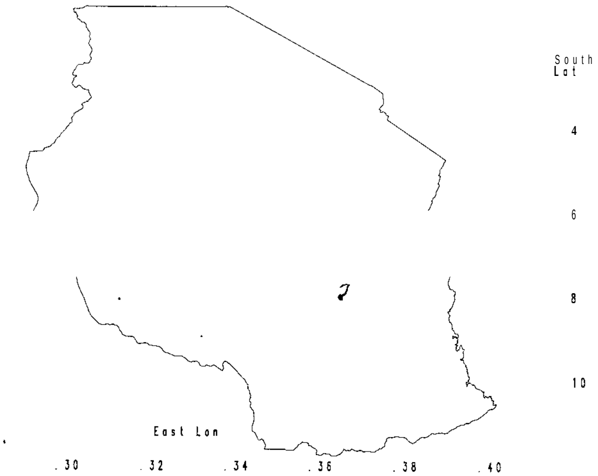
▨ Nectarinia moreaui



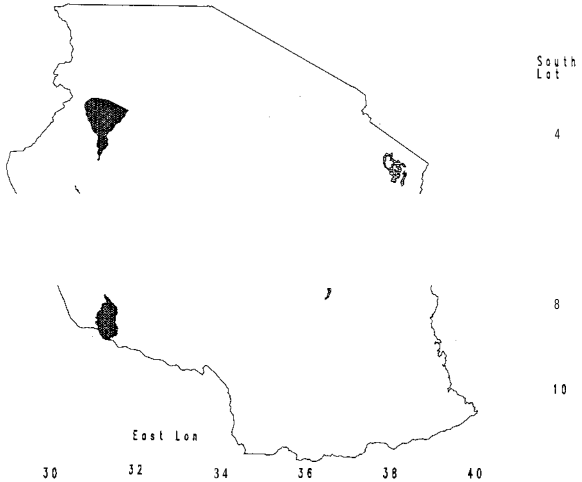
▥ Ploceus nicolli



▩ Bathmocercus winifredae
▒ Bubo vosseleri

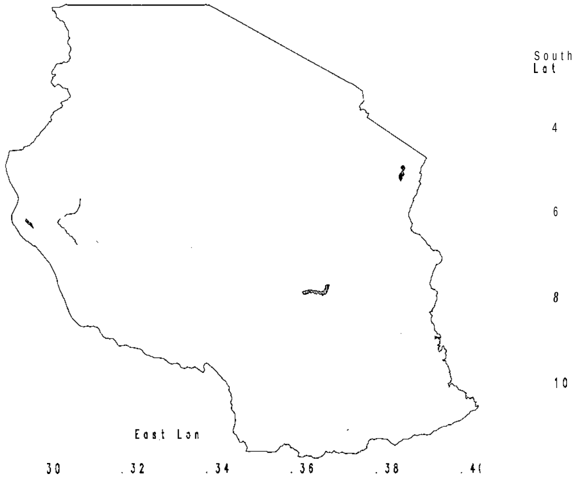


▤ Nectarinia rufipennis
■ Turdus fischeri



▧ Bugeramus carynculatus

▤ Anthreptes rubritcrques
▩ Bugeramus caruncalatus



▧ Apal s argentea

▥ Modu atrix orostruthus
▦ Apol s argentea

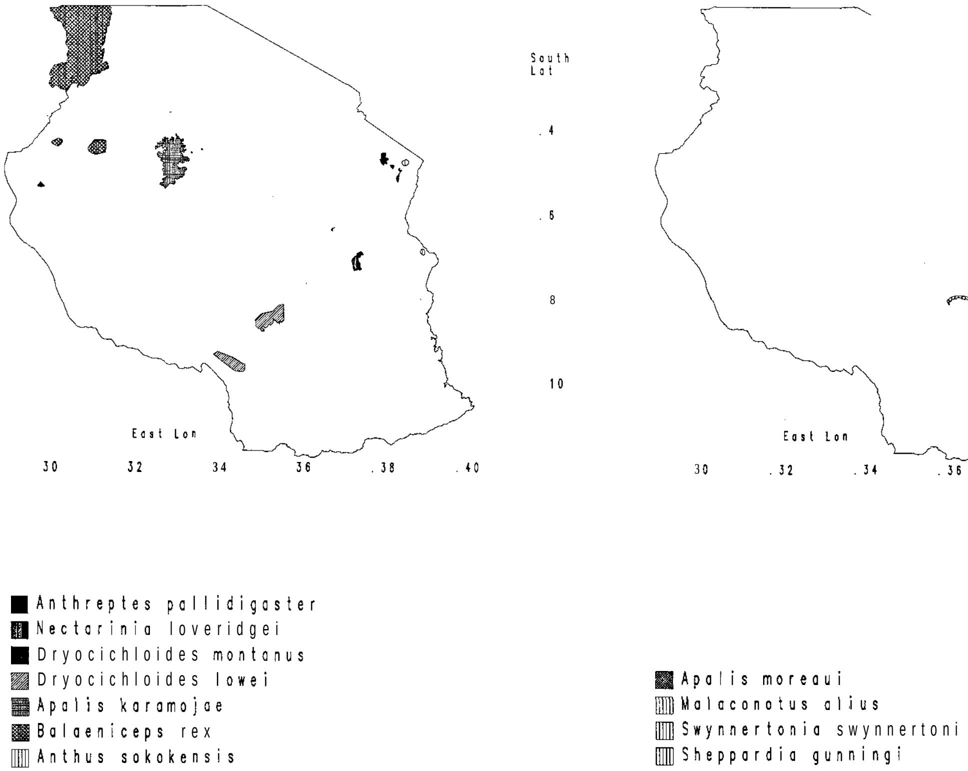


***Fig.** 1*. Eight rare bird species distribution maps digitized during this study. Compiled data in Table **4** were identified by elevation contours on a topographic map. Locations were then more precisely demarcated from ornithological field knowledge.

rare bird species with ranges occurring within the area. Since the lack of species observations in an area does not imply the existence or lack of a relation between species diversity and environmental diversity (Green 1979), the use of only areas containing rare bird species distribution records was justified. As a result, 2284 out of the 40,000 areas created within the study quadrangle (200*200 grid cells) contained rare bird species distribution records. The small and large area data sets now each contained 2284 areas. The rare bird species number associated with each area was transformed into a Shannon-Weaver species diversity index. Since six was the maximum number of species recorded in any area, the use of the diversity index permitted a more sensitive measure of relative species richness than using the number of rare bird species. It was previously determined that both measurements are equally effective representations of the variability of species richness (Miller 1986).

Only areas within the study quadrangle containing more than a single rare bird species distribution record were statistically analyzed (*i.e.*, 1004 of the 2284 areas). Areas with only a single rare bird species record were clumped at Shannon-Weaver diversity values = 0. These values detracted from attempts to distinguish relationships between magnitudes of avifaunal diversity and environmental diversity. Areas with observations for only a single rare bird species were most likely areas containing resources specifically important to the single observed species. Therefore these areas were not characteristic of higher (> 1 rare species) rare avifaunal diversity and were eliminated from consideration in the regression analysis.

Areas created around the boundary of the quadrangle were smaller and included data from a smaller number of grid cells than the standard sized areas in each of the data sets (limitation imposed by the GRID (ESRI 1983) sampling algorithm). The

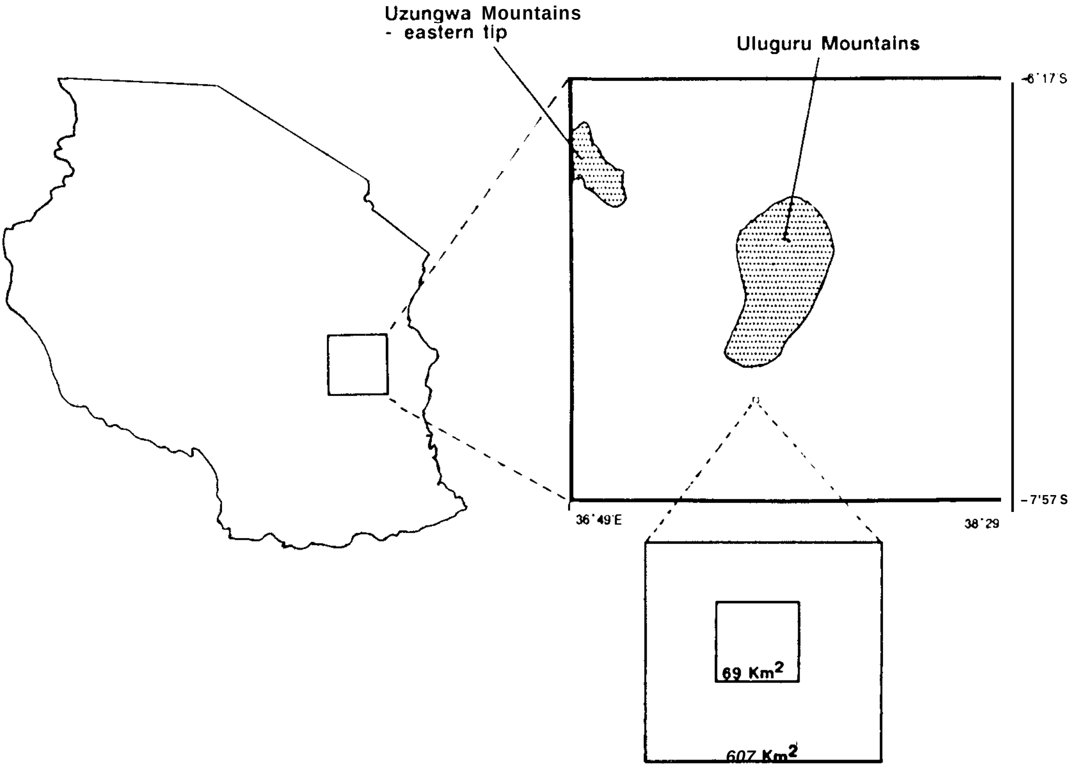


Fig. 2. **A** pictorial representation of the spatial analysis approach used with each of the grid cells analyzed during this study. The position of the study quadrangle within Tanzania is represented by the map on the left. The rectangle on the upper right represents the study quadrangle, its longitude-latitude coordinates, and the position of several mountain ranges within the quadrangle. The quadrangle was divided into 40,000 grid cells, and 1004 grid cells containing more than a single rare bird species were analyzed. Each analyzed grid cell was expanded to represent areas of **69** and 607 **km',** and these two areas associated with each grid cell are represented by the rectangles on the lower right.

influence of area size on bird species diversity was therefore also analyzed within each of the two data sets.

The number and relative abundance of the soils and vegetation classes were used to produce a Shannon-Weaver index of diversity for each environmental variable (see Miller **1986** for a description of this methodology). Areas became associated with indices of diversity for each type of environmental parameter. Statistical correlation and regression analyses were performed on both the small and large area data sets. Rare bird species diversity was the dependent variable and the environmental parameters (*i.e.*, longitude, latitude, soil diversity, vegetation diversity and area) were the independent variables in the correlation analyses. A standard statistical analysis approach for normalizing both the variates and variances was utilized in the regression analyses (Miller **1986;** Miller and White **1986).** The untransformed diversity values for both the dependent and independent variables were most appropriate. The statistical significance of each environmental parameter for predicting the variability of rare bird species diversity within the study quadrangle was thereby determined. Consequently, the predictive importance of the documented environmental factors was identified in relation to the rare Tanzanian avifauna.

Results

Nine rare bird species were recorded within the study quadrangle. All were characteristic of strata within the montane forest (Table ***5).*** The relative

Table **5.** The rare bird species recorded within the study quadrangle and their associated habitats.

Species	Habitat and ecology
Bathmocerus winifredae	Montane forest understory; wet and dry forests; food – insects and other invertebrates
Nectarinia rufipennis	Forest interior; food – nectar
Anthreptes rubitorques	Middle altitude rainforest canopy; food – nectar and small berries
Malaconotus alius	Montane forest canopy; food – insects?
Nectarinia loveridgei	All strata of the montane forest; food – insects and nectar
Nectarinia moreaui	All strata of the montane forest
Swynnertonia swynnertoni	Ground strata of middle altitude and evergreen montane forest; food – insects and small fruits
Modulatrix orusfruthus	Middle altitude evergreen montane forest; food – insects
Ploceus nicolli	Montane evergreen forest; also along the forest edge; food – insects

Table **6.** Mean and maximum parameter values which characterized the small and large data sets. Rare birds, soils and vegetation were represented by Shannon-Weaver diversity index values. Areas containing a single rare bird species, a single soil type or a single vegetation type were represented by Shannon-Weaver diversity values = 0.0. Only areas containing rare bird species records were analyzed (2284 areas).

Parameter	Value	Small areas	Large areas
Area	Mean	61.5	545
(Km^2)	Maximum	69.4	606.9
Soils	Mean	0.18	0.54
diversity	Maximum	1.00	1.89
Vegetation	Mean	0.22	0.57
diversity	Maximum	1.00	1.18
Rare bird	Mean	0.68	0.65
diversity	Maximum	2.56	2.58

diversities for these rare bird species in the small and large areas were very similar (Table **6**).

Pearson correlation coefficients were obtained for all the biogeographic variables identified with both the small and large area data sets (Table **7**). Several correlations between variables in Table 7 were artifacts of the analysis schema. For example, correlations between area size and other variables resulted from inclusion of areas of non-standard size. Smaller areas with rare bird distribution records were at the eastern tip of the Uzungwa mountains located at the far western portion of the study quadrangle. The inclusion of these areas produced the correlation between area size, soil diversity and vegetation diversity. In another example, the two mountain ranges included in the quadrangle occurred at increasingly southern latitudes in the quadrangle. Soil diversity significantly increases in these montane areas and this accounted for a significant portion of the correlation between latitude and soil diversity. The correlation between vegetation diversity and longitude was not explainable by the schema and appeared to represent a realistic trend.

The high correlation coefficient between soils and vegetation diversity in Table **7** ($r = -0.75$) provided strong evidence for the ecological validity of these data. The data used to construct the vegetation and soils maps were collected and compiled independently for each of the UNESCO maps. Therefore, the appearance of the expected strong relation between edaphic and vegetation factors (a tenet of modern ecology) supported the veracity of these maps.

The negative sign associated with the soils-vegetation correlation was at first more difficult to understand. However, when the representation of the **17** major vegetation categories and the **23** soil categories located within Tanzania were considered the reason for this negative sign became clear. Within the study quadrangle, the data depicting the soil distribution patterns represented a significantly more detailed picture (**10** soil categories) than did the data representing the vegetation distribution patterns (three vegetation categories). The more

Table 7. Pearson correlation coefficients ($p > 0.0001$) were calculated for the analyzed independent variables in the study quadrangle. Two data sets, comprised of small areas (S = 69 km^2) and large areas (L = 607 km^2), were analyzed. Correlation statistics between these two data sets were not considered (–). Soil and vegetation diversities were quantified with the Shannon-Weaver diversity index. The latitude and longitude coordinates were represented by the grid cell coordinate position in the study quadrangle. Statistically non-significant coefficients ($p > 0.05$) are indicated by NS. Only areas containing rare bird species records were analyzed (2284 areas).

Vegetation		Soil diversity		Vegetation diversity		Area size		Latitude		Longitude	
		S	L	S	L	S	L	S	L	S	L
Soil diversity	S	1.0	–	−0.34	–	<0.15	–	0.64	–	<0.15	–
	L		1.0	–	−0.75	–	−0.19	–	0.84	–	NS
Vegetation diversity	S			1.0	–	0.15	–	−0.31	–	NS	
	L				1.0	–	0.26	–	−0.62		
Area size	S					1.0	–	<0.15	–	0.33	–
	L						1.0	–	−0.15	–	0.63
Latitude	S							1.0	–	<0.15	–
	L								1.0	–	<0.15
Longitude	S									1.0	–
	L										1.0

specialized vegetation types associated with the additional soil types were not represented in White's vegetation categories. In each biogeocenose (Walter 1973), these vegetation categories were identified with a few specific soil types, but not with the less widely distributed soil types. Most of the vegetation categories represented on White's map were associated with the most fertile soil categories within the biogeocenose. Therefore, the high soils-vegetation correlation coefficient demonstrates the relation between the vegetation categories and this subset of the soil types. Most importantly, the statistical relation is between the *diversity* of soil types and the *diversity* of vegetation types. The negative sign on the coefficient points out the inverse relation between a high diversity of the represented vegetation types found on the few most fertile soil categories.

All areas in the small and large area data sets were not of equal size because of limitations of the software. In the small area data set, 85.5% of the areas covered 69 km^2 while 99.7% of the areas were larger than 39 km^2. In the large area data set, 55.6% of the areas covered 607 km^2 while 88.6% of the areas were larger than 392 km^2. The mean and maximum area values in each of these data sets further define the range of this variability (Table 6).

To determine the importance of this size variation, regression analyses were performed between rare bird species diversity and area size for the 1004 areas in both the small and large area data sets. There was a lack of a statistically significant species-area relation in both data sets ($p > F$ was > 0.05 for both data sets) and it was concluded that the area size variability contained in these data sets did not influence the observed rare bird species diversity patterns. However, when only areas characterized by the highest (? 2.00) diversity values were considered, area did explain a percentage (19%) of the variability in rare bird species diversity (Table 8).

Regression models representing the relationships between rare avifaunal species diversity and area, latitude, longitude, soils diversity and vegetation diversity demonstrated the expected predictive importance of these parameters (Table 8). Graphical analysis determined that untransformed versions of the dependent and independent variables best

Table 8. Areas with the highest Shannon-Weaver rare bird diversity values (≥ 2.00) were analyzed. Regression values for the small areas were not significant ($p > 0.05$), and values are reported from only the large areas data set analysis (105 areas within the study quadrangle). The dependent variable in all models was Shannon-Weaver species diversity.

Model	Dependent variable	Independent variable	F value	R^2 adj.	P > F
$S = c + mA$	Species diversity	Area	25	.19	.0001
$S = c + m(LONG)$	Species diversity	Longitude	79	.43	.0001
$S = c - m(LAT)$	Species diversity	Latitude	106	.50	.0001
$S = c - m(SOILS)$	Species diversity	Soils diversity	124	.54	.0001
$S = c + m\ (VEG)$	Species diversity	Vegetation diversity	172	.62	.0001

Table 9. Observed changes in landscape composition along the gradient of increasing rare bird species richness within the study quadrangle. These data are from an analysis of all areas in the study quadrangle containing rare bird distribution records. All the areas analyzed here were 4.3 km^2 (5 grid cells).

Parameter	Increasing rare bird species diversity >>>					
Recorded rare bird species richness	–0	>1	>2	>3	>4	>5
Mean number of species in all areas	**2**	3.2	4.2	4.3	5.1	6
Number of study areas	2284	1004	580	498	151	15
Soil types(%):						
Ferric acrisols	0.5	0.9	0.7	0.8	–	–
Chromic cambisols	84.2	70.6	62.6	58.6	44.4	–
Calcic cambisols	2.6	3.1	–	–	–	–
Eutric fluvisols	12.7	25.4	36.7	40.6	55.6	100.0
Vegetation types (%):						
Dry woodland/ thorn scrub	0.1	–	–	–	–	–
undifferentiated montane vegetation	22.7	11.4	9.1	8.4	9.3	–
Zambesian miombo woodland	77.2	88.6	90.9	91.6	90.7	100.0

represented these variables in the statistical models. Soils and vegetation diversity respectively were most important in predicting the highest avifaunal species diversity values.

A large percentage of areas inhabited by at least one rare bird were characterized by chromic cambisol soils (84.2%), while a much smaller percentage of these areas contained eutric fluvisols (12.7%) (Table 9). However, the opposite pattern occurred as rare bird species diversity increased. All areas containing the maximum number of rare bird species (six species) were characterized by eutric fluvisols.

According to the analysis of the vegetation map tesselations, the highest diversities of rare birds in the study quadrangle were most likely to be found in the Zambesian miombo woodland vegetation category (Table 9). This contradicted field data which placed the highest rare bird diversities in the montane forest type. Undifferentiated montane vegetation represented 22.7% of the areas containing at least one rare bird species. However, this vegetation category represented smaller percentages of areas with higher rare bird species diversities.

Discussion

Methodology and data considerations

Multivariate analysis was of no predictive or interpretive value because a finer resolution was required to determine the relative or cumulative ecological influence of multiple environmental variables. Analysis of most ecological phenomena required digitized environmental data on a scale significantly finer than the data available for this study. The grid cell size (0.86 km^2) limited the possibility of accurately modeling many autecological, synecological, or habitat phenomena which required a finer scale of resolution. These ecological phenomena were therefore not able to be analyzed at this regional data scale. Only the predictive importance of environmental factors considered independently from one another was meaningful.

This research highlighted several issues which should be considered in the analysis of regional landscape classification data:

1. The authenticity of the regional data layers need to be confirmed. Often small scale data coverages are useful primarily for visual demonstration purposes but are worthless for scientific analysis. Precipitation, wet days and wind speed data for Tanzania were determined to be invalid. The soils (FAO/UNESCO **1974,1977)** and vegetation (White **1983)** map tesselations were validated by comparison with known Tanzanian vegetation and soils information from other sources. These map tesselations generally appeared accurate, but the precision of the boundaries for each of the landscape categories was not determined.

2. Differences in accuracy on natural resource maps occur due to scaling factors (Meentemeyer and Box **1987).** For example, the difficulty in distinguishing between montane and miombo vegetation on the maps does not occur when these two habitat types are observed in the field. We concluded that the vegetation map was accurate on the regional scale but the tesselations were not reliable at finer scales of resolution.

3. This analysis methodology requires environmental data at a scale consistent with the scale of precision necessary for the recorded biological data. If topography is an important parameter influencing the distribution of a species, the topographic data used in the analysis must be of a large enough scale to represent topographic diversity in relation to the species distribution patterns. In this study, the ten minute elevation data was too coarse to be of use in the analysis of the bird distribution patterns.

4. Ecological phenomena are not currently able to be modeled or documented at small scales because of the difficulty in accurately representing underlying ecological processes. In this study, categorical data at the .86 km^2 grid cell dimension was too coarse to document population or even community dynamics for the rare birds. As more precise remotely sensed data becomes available for this region, modeling and analysis of ecological processes may be possible.

Abiotic variables may represent emergent properties which are the result of the synergism of ecological properties at a higher level of system integration (Meentemeyer and Box **1987).** However, comparisons between the predictive significance of abiotic environmental variables were not useful because of our inability to analyze the ensemble of ecological properties contributing to the importance of each of these variables at this scale. A multivariate statistical analysis approach would have obscured the predictive significance of each of the environmental variables. The multivariate approach would be more useful in explaining the influence of different ecological processes, *vis-à-vis* abiotic variables, on the geographical distribution of species diversity. We believe that simple regression statistics, which documented species and environmental diversity relations in this study, could be used to identify specific areas of high species diversity.

The most difficult problem in applying this methodology to areas in the developing world is the apparent lack of quality environmental data. The scale of the African environmental data was adequate for conducting the statistical analysis presented here and these results can be useful for a realistic conservation plan for Tanzania. However, a thorough analysis of the ecological factors influencing rare bird distribution patterns in Tanzania must await the availability of complete, validated, and more precise environmental data for this region.

Applicability to the Tanzanian region

Rare birds in Tanzania are most common at higher elevation ranges characterized by moist montane forest. Since the only available digital data documenting elevation and moisture patterns in Tanzania were inadequate, the focus of the study shifted to a determination of whether documented rare bird distributions could be statistically related to the available validated environmental parameters using this methodology.

The great variability of topography, climate and soils in Tanzania make landscape classification analysis techniques particularly useful. Vegetation types may occur over a wide range of physical conditions in East Africa (Bell and McShane 1984) and landscape classifications refine the meaning of vegetation categories (Bell and Mphande 1980). A landscape classification utilized in conjunction with the vegetation map (White 1983) would have improved the realism of the Tanzanian soils and vegetation data. However, accurate landscape classifications for Tanzania were not available for this analysis.

This study was conducted at a regional scale and White's Vegetation Map of Africa provided a useful and valid vegetation classification at this scale of analysis. However, the generalized vegetation categories in this map limited its usefulness in Tanzania because of the small scale variation and diversity of forest types (Lovett 1986). For example, White may not have clearly distinguished between wet and dry miombo forest vegetation when he created his vegetation type categories.

The results of the vegetation map analysis indicated that the highest rare bird species diversity occurred in the Zambesian miombo woodland vegetation type (Table 9). Yet Tanzanian ornithologists have observed rare birds most frequently in areas associated with the montane vegetation category. This discrepancy may have occurred for several reasons:

- Uncommon land cover data is easily lost at coarse scales of resolution (Turner *et al.*, in review).
- An uncommon land cover type with a patchy arrangement across the landscape will be rapidly lost at coarser scales of resolution (*ibid.*).
- Montane habitat in Africa in general is extremely disjunct.
- The coarseness of the scale of White's vegetation map probably precluded accuracy for the montane land cover type in Tanzania.

Regional patterns of rare avifaunal diversity appear to be predictable from regional patterns of environmental diversity (Table 8) when sufficient and accurate data is available. The species patterns require validation either from field survey or from consultation with biologists with experience in the region.

Future prospects

The accuracy of predictions about the location of areas with high species diversity or endemism will be improved by more precise vegetation and landscape categorical data. These data can be used to produce diversity indices. Environmental and species diversity relationships, documented by regression statistics, can be used to identify areas more likely characterized by high species diversity. These areas will be recognizable only on the regional scale, and field observations will be required for precise boundary determination.

The results of this landscape analysis will benefit from the further development of standardization techniques in landscape ecology (Gardner *et al.* 1987). The significance of relations between species diversity patterns (*e.g.*, rare avifaunal diversity in this study) and landscape cover (*e.g.*, soil and vegetation diversity in this study) will become clearer when these patterns can be compared to quantitative standards.

The importance of identifying centers of species richness and endemism in Africa has recently been emphasized at a Forum on Biodiversity in the **U.S.** (Huntley 1988). The analysis approach developed in this study can produce a procedure, based upon the most accurate available scientific criteria, for identifying these areas in developing countries. These areas can then become the foundation of a conservation which can then be integrated into the prevailing economic, political, and social milieu of a region. This would be accomplished through cooperation between governmental representatives and regional conservationists. By founding the politically and economically motivated decision making process on a firm scientific analysis approach, the goals of conservation will become optimized and integrated with human needs in the final product.

Conclusions

The methodological approach first developed in the southern Appalachian region of the U.S. (Miller 1986) and extended in this Tanzanian study can be used to predict the distribution of rare and endemic plant and animal species on a small scale. The regional perspective requires the sacrifice of ecological precision for the sake of the generality and usefulness of the statistical predictions.

Environmental data availability, validity, comprehensiveness, and scale must be carefully considered before this methodology can be successfully applied. As more detailed landscape classification data becomes available for areas in Latin America, Africa and Asia, more precise location information will be obtainable from predictions derived from this methodology. Currently obtainable predictions will be useful for identifying areas in biologically undocumented regions in need of immediate study and of potential conservation concern.

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