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A new predictive tool for identifying areas of desertification that combines Principal Components Analysis and Geographical Information Systems: a case study from Namibia

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Abstract

Identifying the sources of potential desertification has become a major field of scientific endeavor. Mapping the different causes of desertification allows quick localization of the major causes of desertification of a region. As a consequence of the identification of these causes, priorities can be established for dealing with desertification by regional planning. In this study, we provide a technique to assist in the identification of areas of potential desertification. To achieve this, we mapped a variety of abiotic and biotic variables that may affect the process of desertification using a Geographical Information System. We then used Principal Components Analysis as a non-arbitrary, statistical system for weighting these variables relative to one another. With these weighted variables, we were able to produce an overall, composite map of priority areas for combating desertification. We used Namibia as a case study because it is the driest country in Africa, with a host of environmental problems that may be linked to desertification. Using the above-mentioned technique, we were able to identify priority areas that may suffer or be suffering desertification. Most of these areas are in the north and northeastern parts of Namibia.

Introduction

Arid, semi-arid and sub-humid zones cover one third of the earth and two-thirds of Africa. Desertification of these regions has become a major cause for concern, with about 170 million people affected by land degradation worldwide (Balling 1995). In the last decade, about 25% of the fertile soil in these regions of Africa has been removed through desertification (Glantz and Katz 1987). Desertification is further exacerbated by frequent droughts in one or other arid or semi-arid zone in Africa (Darkoh 1994). With a natural human population increase of 3.3 % per year in East and South Africa, there is great pressure on the land (Glantz and Katz 1987). This large rate of human population increase in Africa makes it vital to identify major problem spots to initiate research and education programs to combat desertification before the process becomes completely irreversible (Chou and Dregne 1993).

Mapping the different causes of desertification allows quick localization of the major causes of desertification of a region, in order to update priorities for dealing with desertification by regional planning. In this study, we provide a technique to assist in the identification of areas of potential desertification in Namibia. To achieve this, we mapped a variety of variables that may affect the process of desertification using a Geographical Information System and then provide a non-arbitrary, statistical system for weighting the importance of these variables relative to one another. With these weighted variables, we were able to produce an overall map of Namibia with a list of priority areas for combating desertification.

The role of Geographical Information Systems in identifying problems

Geographical Information Systems (GIS) have revolutionized the processing of geographical information by allowing researchers to simultaneously overlay maps of various factors affecting an environment to achieve a composite map of the interactions between the factors (Maguire *et al.* 1991). Traditionally, most applications of GIS have concentrated on the non-statistical analysis of the spatial coincidence of factors (Coppock and Rhind 1991). However, in some applications, mathematical techniques such as regression, kriging and universal kriging have been used to determine the behavior of a response variable to several independent variables (reviewed by Ver Hoef 1993).

In any study that seeks to achieve a composite analysis of a variety of factors that may influence a process of interest, it is recognized that it is frequently necessary to weight these factors relative to one another because some factors are more important to that process than others. For example, n the case of factors that might influence desertification, some factors such as annual precipitation and human population densities may be more important than soil type. Principal Components Analysis (PCA) is a statistical ordination technique that is ideally suited to the task of weighting variables in a way that is non-arbitrary and does not introduce the biased perception of the researcher as to the relative importance of the variables into the analysis. PCA effectively reduces a large number of often correlated variables (e.g. precipitation and potential evapotranspiration are often negatively correlated) to a smaller number of variables that are a linear, weighted function of the initial variables (see e.g. Morrison 1976, Flury and Riedwyl 1988, Jongman *et al.* 1995 - for further details of this technique, see *Methods* below). In this study, we use PCA to reduce a number of weighted environmental and biotic variables to a linear weighted function to produce a composite map in a GIS of areas potentially affected by desertification.

Namibia: a case study

Namibia is the most arid country in Africa, and most of its land (93.2% - UNESCO 1994) is a desert or semi-desert with an arid climate (Van der Merwe 1983). Most precipitation falls in the north-east of the country, in which over half the population lives. Rains in Namibia are unreliable, soil quality is poor and the carrying capacity of the land is concomitantly low (Van der Merwe 1983, Davis 1993, Seely and Jacobson

1994). It is considered that 74.6 % of Namibia's land area constitutes a moderate to severe desertification hazard (UNESCO 1994). Annual deforestation is about 50 000 ha (UNESCO 1994), while overgrazing has caused thorn bush encroachment in large areas of the wetter, northern part of the country and land denudation in much of the dry, southern part of the country (Quan *et al.* 1994). Moreover, if the forecasted global climatic warming does occur, the most significant effects of this will likely be seen at the edges of deserts because they are already subjected to substantial climatic fluctuations and may be suffering from desertification (Warren and Agnew 1988). Hence, much of Namibia may be in danger of desertification.

The desertification process in Namibia is a subject of major concern (see e.g. Kambatuku 1994, Quan *et al.* 1994, Seely and Jacobson 1994). The process of desertification in Namibia is currently being researched by a number of research groups (see e.g. Strohbach 1992, Quan 1994, Shanyengana 1994) and is being financed by large aid packages from countries such as Germany (Namibian National Program to Combat Desertification, NAPCOD) and Sweden (Environmental Education, ENVIROTEACH), both run by the Desert Research Foundation of Namibia. The purpose of much of this research is to identify potential causes of desertification in Namibia, to find information and data on those potential causes from different sources, and to provide management guidelines to combat desertification in Namibia.

Methods

Information on soils, vegetation, climate (specifically mean annual precipitation and potential evaporation) was obtained from Van der Merwe (1983). We also represent climatic regions according to the ratio P/PE, where P = mean annual precipitation and PE = potential evapotranspiration, as a conventional measure of the effectiveness of precipitation (Lettau 1969). Soil data were converted to categories indicating low, medium and high water-holding capacity (Klute 1986). Vegetation was categorized into 20% classes of canopy cover.

Human population data were obtained from the most recently published national population census in Namibia (1991). Domestic livestock data were obtained from the 1994 annual livestock census conducted by the Namibian department of veterinary services. In order to create a single scale for animals of different masses, we weighted the different types of animals according to their body masses raised to the power of 0.75 to account for the relationship between energy consumption and body mass (Schmidt-Nielsen 1990). For sheep, we used a mean mass of 50 kg, for goats 40 kg and cattle 500 kg. For both human and livestock data, data were entered according to the smallest spatial scale for which data were available. This usually meant that the spatial scale was the administrative regions delineated prior to independence from South Africa.

All data mentioned above were either digitized from maps in Van der Merwe (1983)(soils, vegetation and climate) or entered directly (human and livestock data) into a geographic information system (GIS), using ARC/INFO version 6.0 software. Human and livestock population data were entered as numbers per km^2 in this analysis.

In order to achieve an unbiased weighting of the variables in this analysis in a composite map showing potential areas of desertification, we used Principal Components Analysis (PCA). PCA searches for the most appropriate weighting of the variables in the study by first finding that combination of weightings (called component loadings) of the initial variables that explains most of the variance between data points in the dataset. This first combination is called the first principal component axis. Thereafter, second, third and more principal component axes are found that explain progressively less of the variance in the data in directions that are orthogonal to each of the preceding axes. By definition, the first axis explains most of the variance in the dataset. Thus, using the component loadings of the variables in the first principal component axis as a new composite variable will explain most of the variance in the data by weighting the variables in a non-arbitrary fashion that does not introduce observer bias as to the relative importance of these variables. Once this new composite variable was derived, the data were entered into the GIS and divided into three equalsized categories of potential desertification, indicating low (< 33.33 % of the maximum value on the first principal component axis), medium (33.33-66.66 % of the maximum value) and high (>66.66 % of the maximum value) potential. A composite map of potential desertification was thus obtained.

Results

Abiotic variables

Precipitation in Namibia gradually increases from southwest to northeast (Fig. 1), while potential evaporation is highest in the southeast and gradually decreases towards the northeast (Fig. 2). These two patterns lead to an overall climatic pattern of semi-arid in the northeast, hyper-arid in the west and south and arid in between (Fig. 3). The hyper-aridity along the coast is caused by the cold Benguela current (Lindesay and Tyson 1990).

In terms of the water-holding capacity of the soil, soils of high capacity are found in the northeast, with soils of moderate capacity in the west and east, with soils of the lowest capacity in a strip that runs from north to south down the center of the country (Fig. 4).

Biotic variables

Highest vegetation cover is found in the northeast of the country with gradual declines towards the west (Fig. 5). Thus, vegetation cover roughly mirrors the precipitation pattern (Fig. 1).

Trends in human population densities are best viewed within the perspective of administrative areas (Fig. 6) Highest human population densities are in Owamboland, followed by the area around Windhoek, the capital city (Fig. 7). Moderately high human populations occur in Kavango and Caprivi, with low population densities elsewhere (Fig. 7).

The highest livestock populations occur in Owamboland, concomitant with the largest human populations (Fig. 8). Lowest livestock population densities are found along the coast, most of which is a national park. Other areas in the north and east present a patchwork of intermediate livestock densities.

Principal Components Analysis (PCA)

The first principal components axis explained 44.22 % of the variance in the data. We used the component loadings on this axis only (Table 1) to weight the variables for the composite map. The composite map (Fig. 9) of potential desertification shows high values in Owamboland where the largest human and livestock populations occur, together with Caprivi, Okahandja, Hereroland, Hereroland West and Gobabis. Intermediate values were obtained for Grootfontein, Otjiwarongo, Omaruru, Windhoek, Rehoboth and Hereroland East and Kaokoland. Also noteworthy in this map are the western and southern regions of Namibia, which are considered to be in low danger of desertification; these areas are already deserts and therefore can not "desertify".

Discussion

This new technique of combining Principal Components Analysis and GIS provides an unbiased means of making predictions about areas that are likely to suffer desertification. This technique therefore avoids the pitfalls involved in arbitrary weighting of variables where *apriori* assumptions about the importance of a variable are inevitably supported by the conclusions.

In applying this technique to Namibia, desertification appears most likely in the northern part of the country, particularly in the north-east. Districts of especial importance are Gobabis, Okahandja, Hereroland, Owamboland and Caprivi. The map analyses show that the predominant factors are the large populations of animals and humans, the kind of soil and vegetation cover of the land. Although there is relatively high precipitation and low rate of evaporation in these areas, they are nonetheless most in danger of desertification. Thus, the quantity of precipitation does not bear directly on the carrying capacity of the environment. Indirectly, however, people may initially be attracted to the higher rainfall areas. Social, economic and political factors may lead people to remain in such areas even after the population exceeds the carrying capacity of the environment (reviewed by Quan *et al.* 1994, Seely and Jacobson 1994).

Testing the model

We stress that this technique presents an hypothesis of areas of greatest risk of desertification, in this case in Namibia. The technique in no way confirms that these areas are suffering desertification. Thus, it is now necessary to follow up this work with field studies that specifically examine the potential for desertification. In Namibia, we recommend starting with a comparison of the eastern areas of Gobabis and Hereroland with the adjoining area of Mariental because these areas are similar in climate and vegetation but differ in other variables. These other variables, such as livestock population sizes, lead to the prediction of desertification in Gobabis but not in Mariental. Interestingly, human population sizes do not differ between these areas (Fig. 7). A similar comparison could be made between Kavango and Caprivi which are similar in environmental but not population variables. The technique can be verified by showing that Caprivi and Gobabis/Hereroland suffer more from desertification and degradation than Kavango and Mariental, respectively.

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Table 1. Component loadings on the first principal component axis for the variables included in the overall analyses.

VARIABLE	COMPONENT LOADINGS
Mean Annual Precipitation	-0.840
Potential Evapotranspiration	0.667
Soil Water-holding Capacity	0.447
Vegetation Cover	0.618
Livestock Population/km^2	-0.741
Human Population/km^2	-0.587

FIGURE CAPTIONS

Figure. 1. Mean annual precipitation in Namibia. Data from Van der Merwe (1983).

Figure 2. Mean annual potential evaporation in Namibia. Data from Van der Merwe (1983).

Figure 3. Climatic regions of Namibia, according to the ratio P/PE (see Methods for explanation).

Figure 4. Soil types grouped according to their water-holding capacity. Data from Van der Merwe (1983).

Figure 5. Natural vegetation of Namibia grouped according to 20 % increments in total vegetation cover. Data from Van der Merwe (1983).

Figure 6. Old administrative regions of Namibia. We were unable to use the new regional delineations because most data were available according to the old regional delineations and therefore were most readily entered in this form.

Figure 7. Total human population per region of Namibia in 1991. Data are from the national census of Namibia of 1991.

Figure 8. Total sheep, goat and cattle populations per region in Namibia. The three species were weighted according to their average biomass in order to put them in the same units. Thus, the numbers represent large stock units. Data from the national census of livestock in 1994 from the department of veterinary services of Namibia.

Figure 9. Composite map of potential desertification derived from the first principal component axis weightings (Table 1) of the variables in Figures 1-7 (excluding Figure 3, which is a function of the variables in Figures 1 and 2).

PRECIPITATION

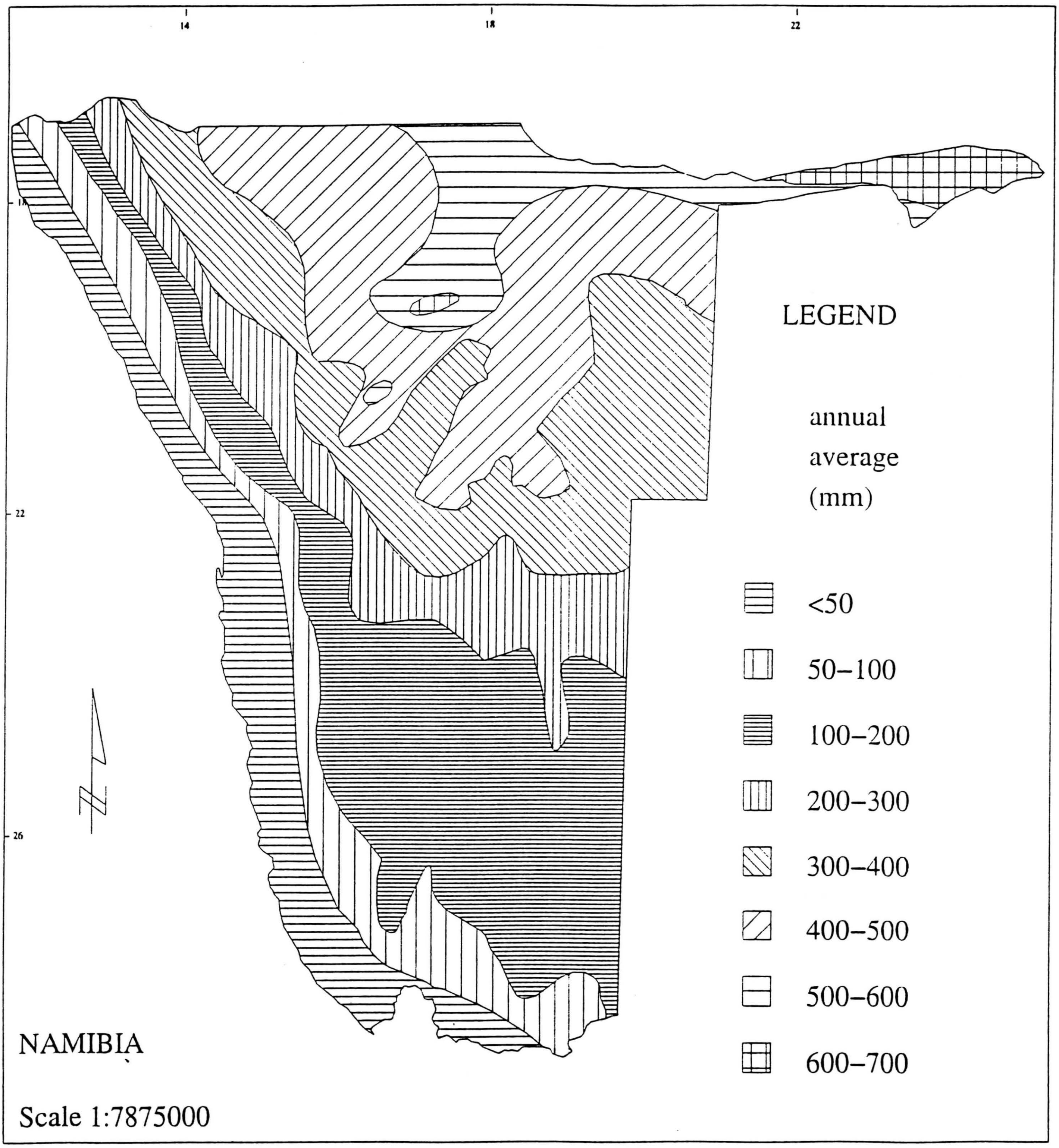

Fig. 1
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POTENTIAL EVAPORATION

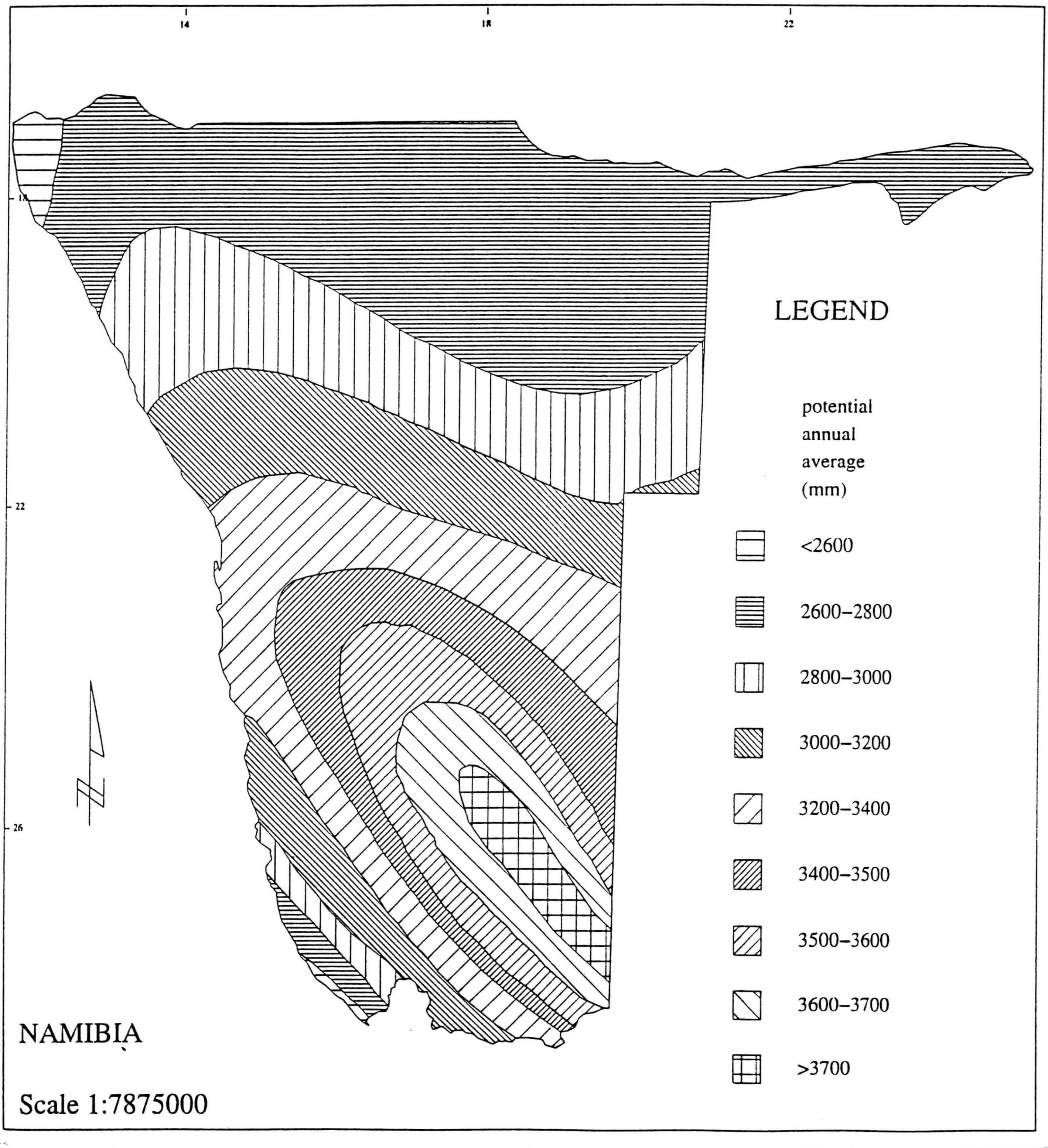

Fig. 2
Aharoni & Ward

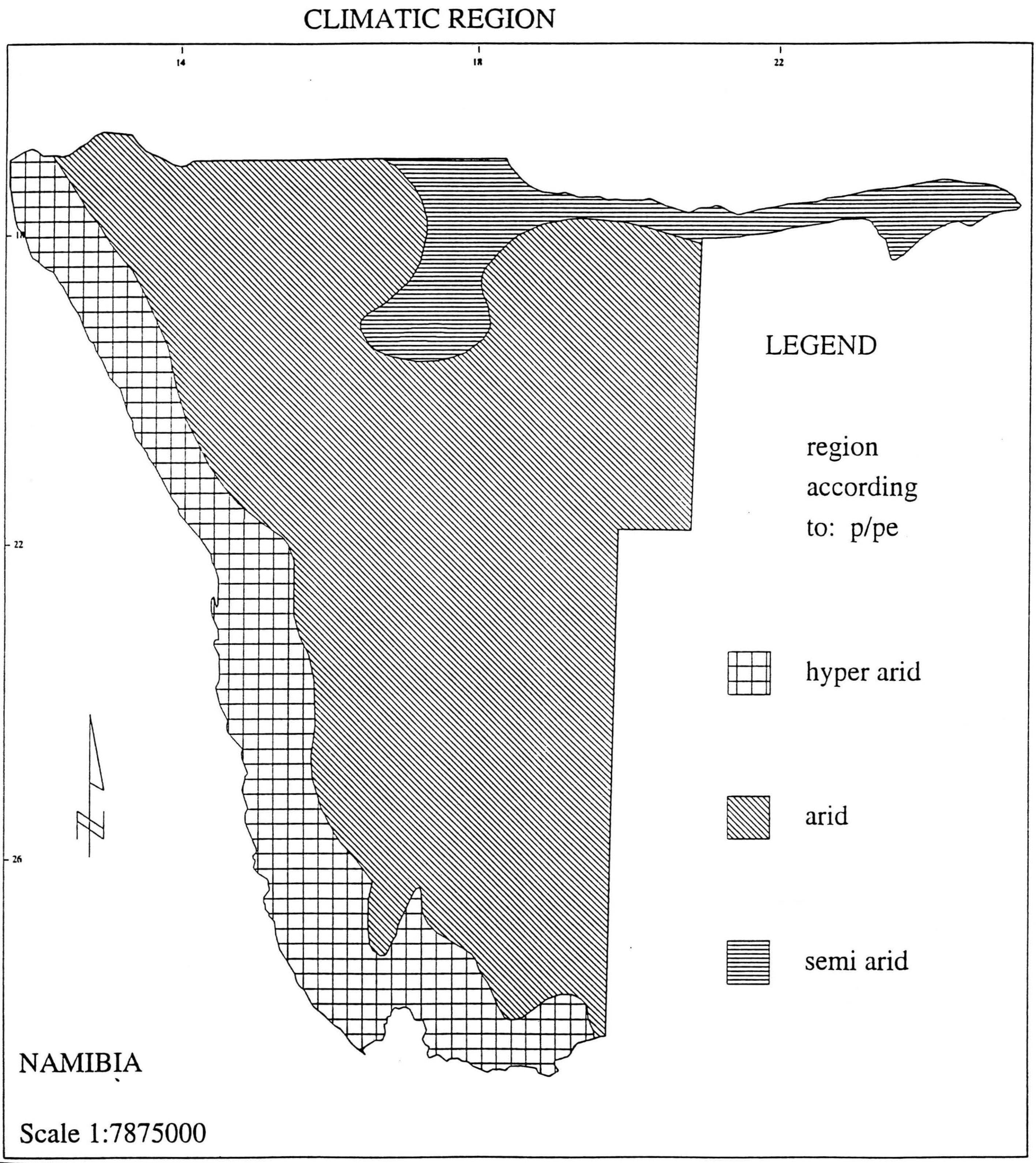

Fig. 3
Aharoni & Ward

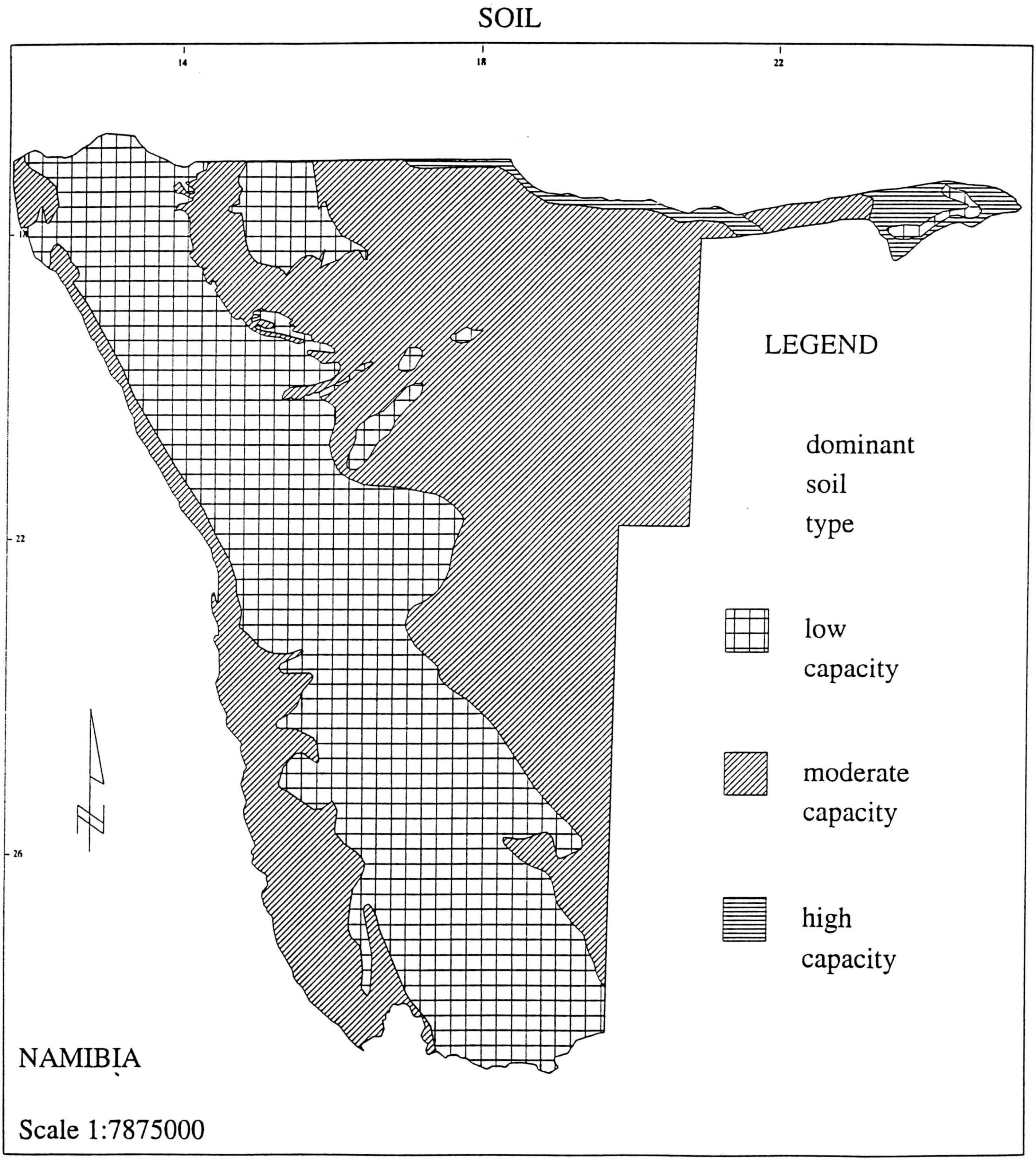

Fig. 4
Aharoni & Ward

NATURAL VEGETATION

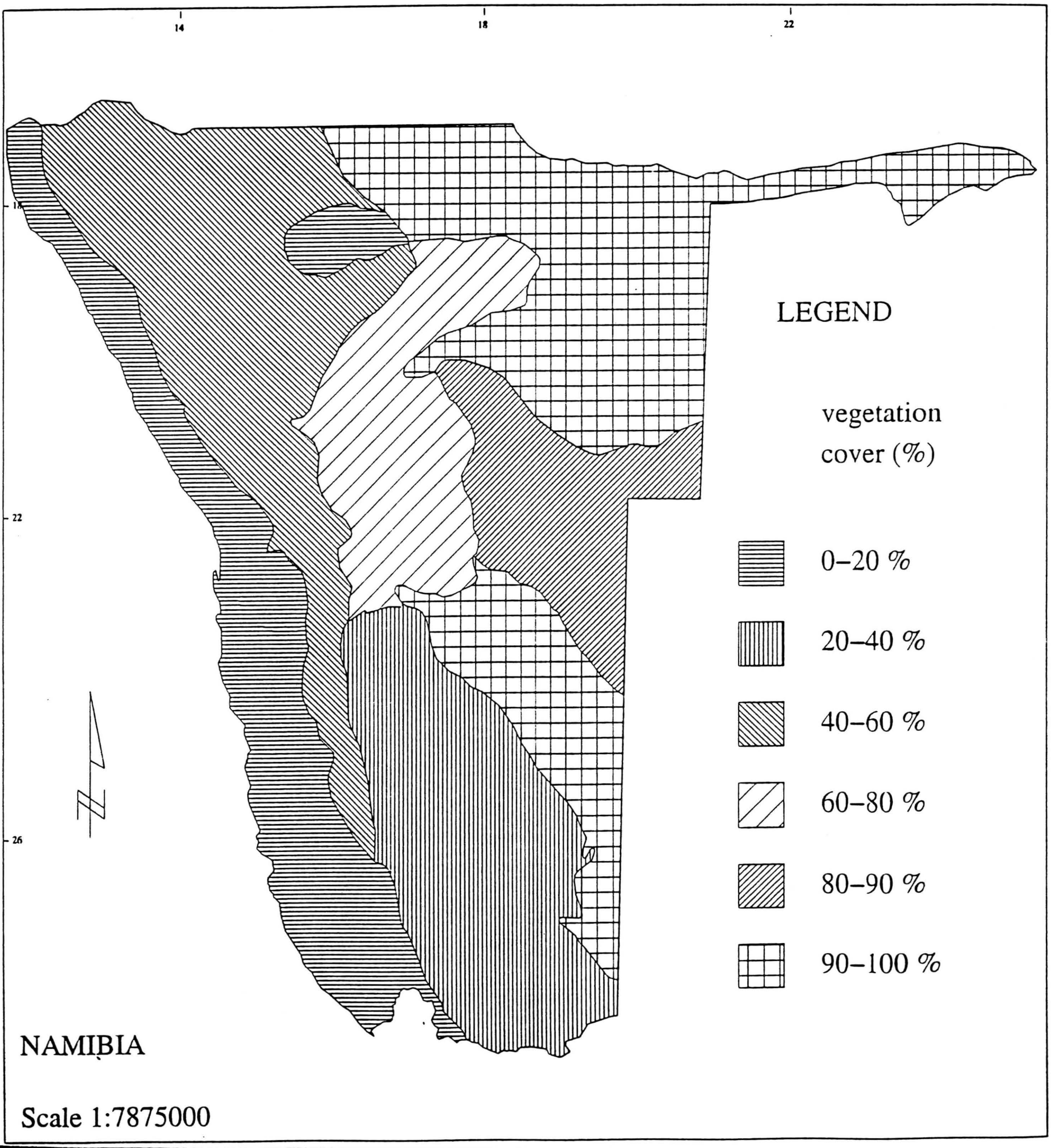

Fig. 5
Aharoni & Ward

HUMAN POPULATION

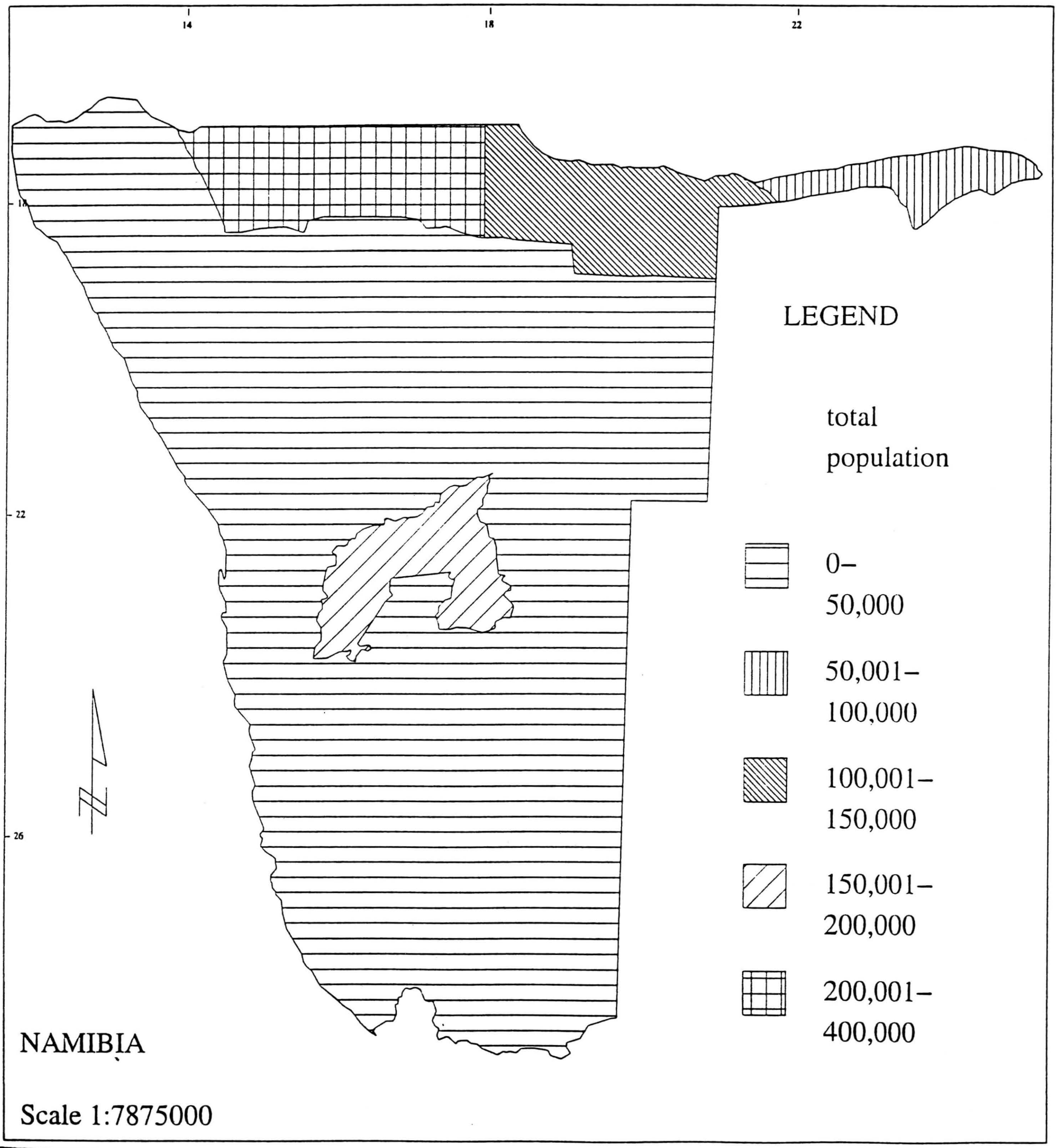

Fig. 7
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SHEEP & CATTLE POPULATION

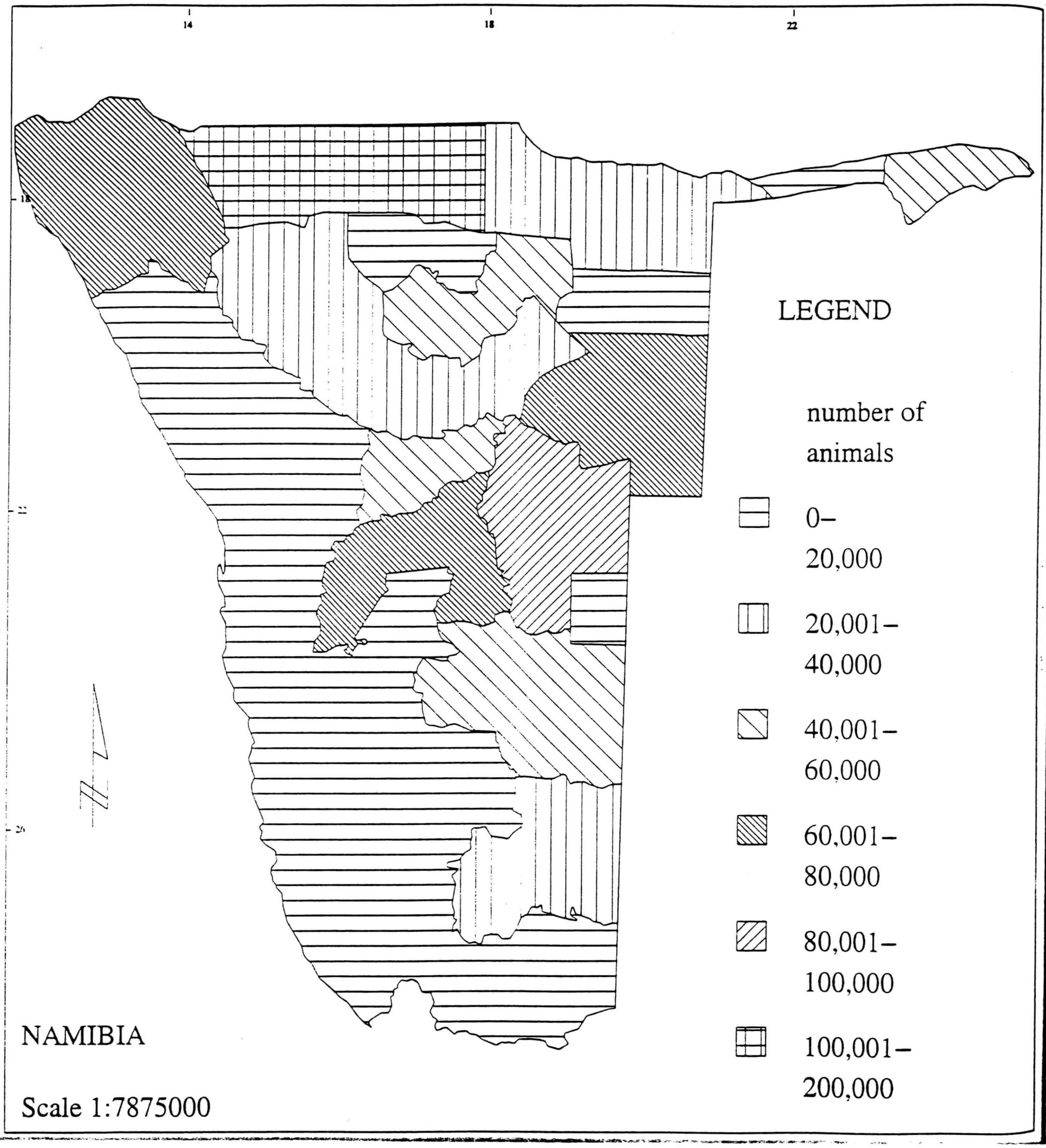

Fig. 8
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ADMINISTRATION

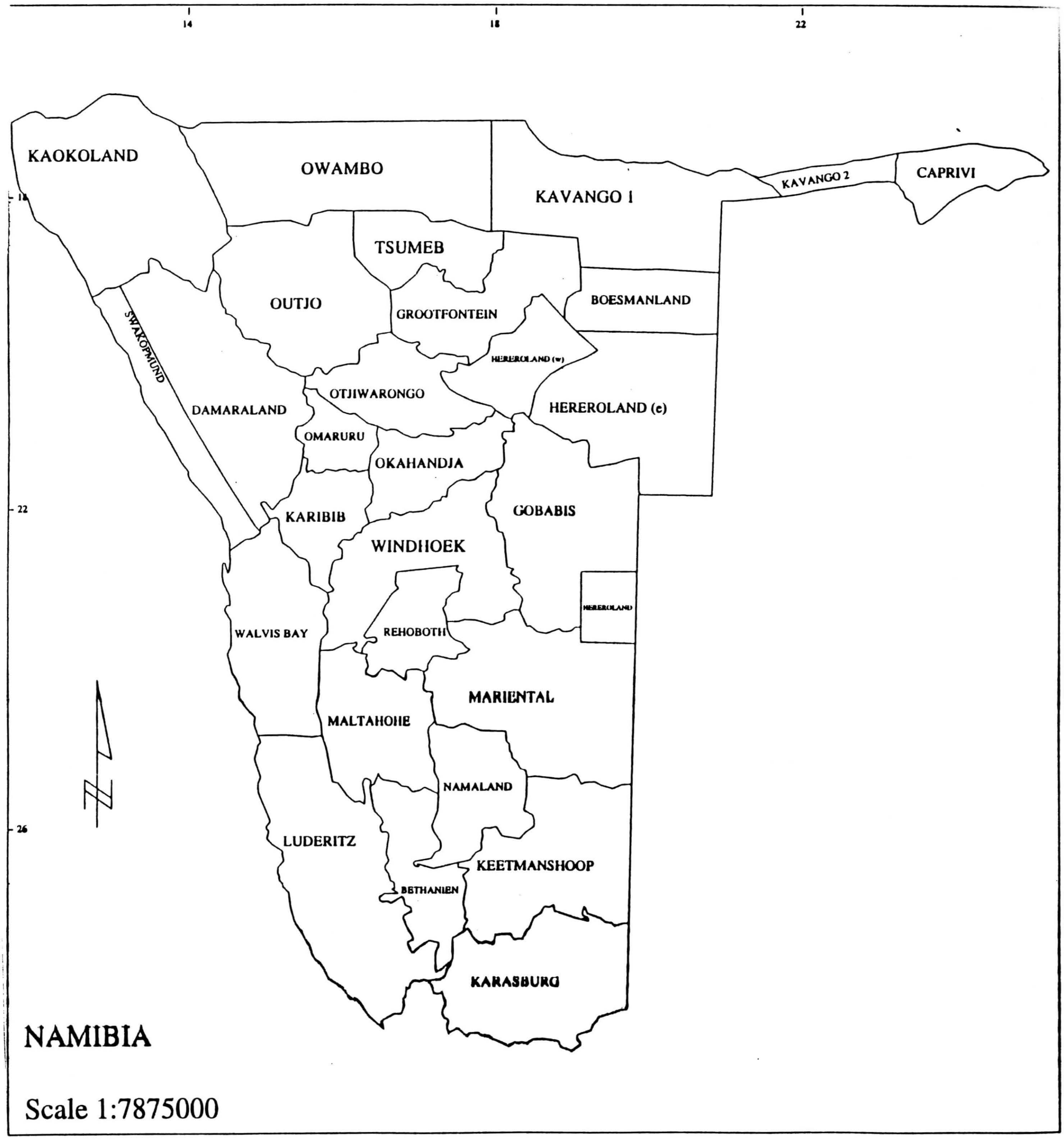

Fig. 6
Aharoni & Ward

DESERTIFICATION

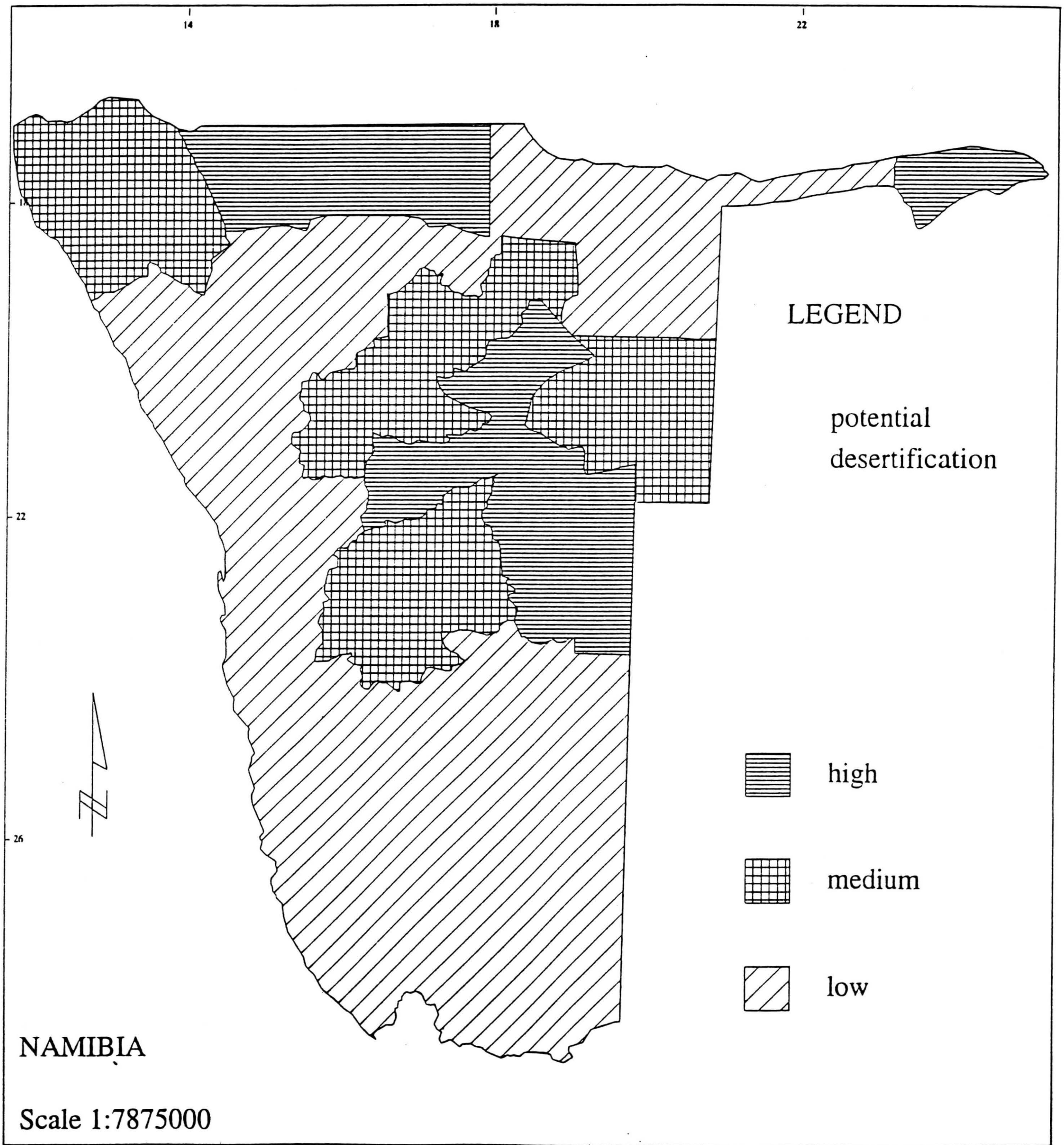

Fig. 9
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