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Geographic Modeling of Human Carrying Capacity from Rainfed Agriculture:

Senegal Case Study

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GEOGRAPHIC MODELING OF HUMAN CARRYING CAPACITY FROM RAINFED AGRICULTURE: SENEGAL CASE STUDY

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EXECUTIVE SUMMARY

GEOGRAPHIC MODELING OF HUMAN CARRYING CAPACITY FROM RAINFED AGRICULTURE: SENEGAL CASE STUDY

Statement of the Problem:

The United States Agency for International Development's Mission in Senegal (USAID/Dakar) needed to evaluate the agricultural potentials of Senegal by crop and by region to support their Agricultural Sector Analysis (ASA), as part of their Country Program Strategic Plan (CPSP). The analysis was limited to rainfed cereal and cash crops. The development alternatives considered for increasing rainfed agricultural production were to increase the cropped area, to increase technology (and thereby crop yields), and a combination of both.

The alternatives were evaluated as forecasts of agricultural production in terms of human carrying capacity (HCC) and gross domestic product (GDP). The resulting information was to be reproduced as national and subnational statistics, and thematic maps showing national distributions. The results were to provide information appropriate at the national planning level.

Specific questions included:

- What are the potentials for cereal and cash crop production?
- How are these potentials currently being used?
- What production increases could result from investments in different development alternatives?
- What is the relationship between projected production and population increases?
- How are these potentials distributed within the country?

Approach:

The Office of Technical Resources (TR) of the Bureau for Africa in Washington (AID/W) responded to the USAID/Dakar request for analytical support. Existing arrangements with the U.S. Geological Survey's EROS Data Center (EDC) and U.S. Bureau of Census (BUCEN) facilitated a timely response. A meeting of experts from USAID/Dakar, TR, and EDC was held at EDC to clarify the specific assumptions and products, outline the analytical framework for deriving the information, and specify the data necessary to support the model.

Data were acquired from a variety of sources. Many data existed in map-registered digital files obtained from AGRHYMET, FEWS, BUCEN, and USGS. Interception of these data bases was crucial to the timely completion of the analysis. Other data available from a variety of AID-sponsored investigations were provided by USAID/Dakar.

The EDC completed the geographic information system (GIS) analyses according to a prescribed analytical framework. This required frequent interaction with USAID/Dakar and TR to address a variety of assumptions and decisions throughout the process.

Products:

Initial products were available to USAID/Dakar within 3 months after the project was initiated. Page-sized maps to support the CPSP, larger scale national maps, and statistical tables were delivered. A computerized data base was provided for use in Dakar. The data, in electronic form and the computer model, were provided to the Mission in Dakar. The data included aggregate statistics and map boundaries which permitted the Mission to continue to adjust key parameters within the context of the interpretation models in order to obtain new results under a variety of development alternatives.

Some of the basic resource maps display the occurrence and extent of natural resources and socio-economic data of Senegal. These maps and associated tabular information served as basic inputs to the analytic model. They also will be a useful guide during implementation of an agricultural development program, in that they provide information on biodiversity, environmental constraints, and co-occurrence of resources. The maps presented in this report were reduced from their original 1:1,000,000 scale.

The HCC and GDP estimates were computed for various development alternatives. The HCC from rainfed cereal production ranged from 3.9 million people under current production to 17.4 million under a scenario that would use all possible lands for production. Likewise, the GDP from cash crops ranged from zero to 128 billion FCFA. The HCC of two development alternatives of particular interest were: (1) increasing the area under cultivation to support 5.6 million people and (2) improving the yields of the current cultivation to support 5.4 million people. Selected HCC potentials to current and projected populations (2010) are presented.

Thematic map information are represented in statistical tables with aggregations to the arrondissement, departmental, regional, and national levels. These tabulations are necessary for further quantitative economic and impact analyses. The tables were delivered to USAID/Dakar in electronic and hardcopy form. Only national aggregate statistics are included in this report.

The analytical framework was deliberately constructed for use as a starting point by USAID/Dakar and Senegalese Ministries for future analyses. Summaries of the data base and many of the linear programming models used for the products displayed in this report were delivered to USAID/Dakar. The data are in a form that USAID could easily develop new models to work on the data. These provide a capacity for additional on-site analytical work and refinement of the applications model. These techniques serve as a mechanism for continuing on-going policy dialogue with the Government of Senegal and other donors.

Significance of the Study:

USAID/Dakar asked for and received information and an analytical framework to support decision making on their 1992-1997 economic assistance program. The effort provided the best possible information from available data on a timely basis. The approach integrated field knowledge of Mission staff with experts in AID/W and key U.S. Federal Government agencies. This interagency cooperation was crucial to obtaining credible results which were responsive to specific Mission needs.

The long-term importance for AID lies outside the actual numeric and cartographic country-specific results. The approach was a significant departure from past analytical work of AID, and points towards a new path to support the Development Fund for Africa's (DFA) program directions. AID is moving away from an individual project approach to a broader "program focus". The GIS approach to evaluating diverse sectoral and cross-sectoral issues provides the base for prioritizing and shaping AID investment programs, and for monitoring their field impact. Many AID-sponsored projects, such as the Famine Early Warning System (FEWS) and AGRHYMET, are currently developing and evaluating GIS approaches for accomplishing AID needs for information management and analysis. These will assist in determining appropriate approaches for implementing GIS technology.

The GIS is an efficient method to link knowledge and data bases, and to provide for their institutional memory. The system provides an effective line of communication between resource technicians and decision makers. Application of the technological advances should serve to encourage a broader use of data in the decision making process influencing wise and sustainable use of a country's resources.

GEOGRAPHIC MODELING OF HUMAN CARRYING CAPACITY FROM RAINFED AGRICULTURE: SENEGAL CASE STUDY

1.0 Introduction

The long-term objective of the U.S. Agency for International Development (USAID) in Senegal is to increase private incomes from natural resources. The Mission's portfolio includes projects to diversify and increase the production of cereal crops.

Programs such as these are helping increase Senegal's food production in absolute terms. Yet Senegal, like most sub-Saharan African countries, is facing a long-term decline in per capita food production as population growth outpaces agricultural growth. This is the current trend despite some expansion of land under cultivation over the past several decades. If Senegal is to make significant strides towards food self-reliance, it must take a hard look at its physical resource and socio-economic management options, and act quickly to overcome the major obstacles. If one is to look at options for narrowing the food gap between food production and the demands of an increasing population, one must assess the potential of Senegal's resource base to determine the realistic upper limits of the land's carrying capacity, and to identify those interventions which will provide the best return.

Estimates of agricultural potential and national carrying capacity from a land resource perspective have often been based on very general, small scale (typically 1:5,000,000) maps of soils, vegetation, land use, and rainfall. In most cases, these general data are all that are available for synoptic, national coverage. Analyses and conclusions drawn from such maps represent crude generalizations. The United Nations Economic Commission for Africa commented that data on national resources and the environment are, if available, in a very rudimentary state (World Bank, 1989a). Where possible, resource management and planning should be based on a strong data base with accurate assessments of the location and quality of individual resources (AAAS, 1983).

The baseline resource information for Senegal increased substantially in 1986 when the results of a 3-year USAID-sponsored integrated resource inventory were published (Stancioff, Staljanssens, and Tappan, 1986). The national level, detailed resource maps were produced for Senegal's National Plan for Land Use and Development and included inventories on the geology, hydrology, soils, vegetation, and land use. The resource data base for Senegal is one of the more detailed, comprehensive ones in sub-Saharan Africa. Despite this, Senegalese resource managers, development planners, and policy makers have made little progress in capitalizing on this wealth of information. The major constraint has been the lack of knowledge and experience in linking resource information to resource management, the form and format of the available data, in translating these data into economic terms, and in tying together multisectoral spatial information into meaningful interpretations.

USAID/Senegal took a major step recently by incorporating natural resource information into its Strategic Plan and project assessment efforts. As part of its efforts to prepare its Country Program Strategic Plan (CPSP), the Mission initiated a study to determine the impact of various development options on human carrying capacity from rainfed agricultural production. The Mission requested technical assistance from the U.S. Geological Survey's EROS Data Center (EDC), and the USAID Bureau for Africa Office of Technical Resources, to help interpret and integrate the multisectoral geographic data and to help construct a model using a Geographic Information System (GIS) approach.

The goal of the present study was to conduct a planning level country study on the current and projected relationship of human carrying capacity from rainfed agriculture. This includes relating current and potential rainfed agricultural development alternatives to current and projected population. The model is resource-based, relying heavily upon the detailed integrated resource inventory of Senegal. The study strives to provide some answers and guidelines for the mission's Agriculture Sector Analysis (ASA), part of the overall CPSP.

Some of the basic agriculture development questions include: should the mission continue to provide major support to the agriculture sector; what is the potential for increasing agricultural production in Senegal; what is the human carrying capacity based on rainfed agriculture; how much arable land remains in Senegal; can Senegal significantly narrow the food gap within the context of an expanding population base; what is the potential for sustainable agricultural development through improved management of natural resources; what are the consequences of doing nothing to increase the diffusion of sustainable agricultural practices; what are the projected trends (to the year 2010) and relationships between various food production options and the food requirements of an increasing population; what are the limits of agricultural expansion given the need to preserve the biodiversity of Senegal's natural ecosystems?

2.0 The Physical, Demographic and Agricultural Setting

2.1 Climate

Although Senegal is a relatively small country of 196,722 square kilometers (NGS, 1990), it spans three distinct ecological zones - the Sahelian, the Sudanian, and the Guinean. These bioclimatic regions are the result of extreme annual rainfall differences between the semi-arid north (with 200 mm of average annual rainfall from 1950-1979), and the well-watered south (1500 mm). The Gambia forms an enclave of 11,295 square kilometers situated along the Gambia River in the Sudanian zone. The annual rainfall is almost entirely limited to the summer wet season, which lasts up to six months in the south and decreases to three months in the north. Like many of its Sahelian neighbors, Senegal suffers from extremely variable rainfall. While the quantity of rainfall for a certain year may approach the norm, it can also vary greatly in its time of onset, periodicity and termination, especially in

central and northern Senegal. Such variations play havoc with agricultural practices and may result in disastrously low crop production.

2.2 Physiography

Senegal's topography is relatively flat except for moderate relief in the southeast. Most of the country is a Tertiary sedimentary subsidence basin. There are four major rivers which flow west into the Atlantic - the Senegal, Saloum, Gambia, and Casamance. They are wide and meandering with broad estuaries at their mouths.

Geologically, Senegal is composed of two primary relief features. The first is a dissected, elevated region of Paleozoic and Precambrian folded and faulted rocks in the southeast. These are rocks of the "African Shield." They are primarily quartzite, granite, and granitized schists. The second is a sedimentary basin of Tertiary and Quaternary rocks and sediments occupying the western and northeastern part of the country. This is the "Continental Terminal" formation, which occupies by far the largest part of the country. This sedimentary layer is composed of heterogeneous clay sandstones of varying thickness. It consists of a low plateau and plains overlain by wind-blown sediments, alluvial deposits, and intermittent laterite hardcap (Stancioff, Staljanssens, and Tappan, 1986).

2.3 Population

The population of Senegal is estimated (1988) at 6.88 million with an annual growth rate of 2.7 percent (République du Sénégal, 1988). The growth rate has been relatively stable since the first national census in 1976. About 61 percent of the population is rural with about 70 percent of the population employed in agriculture.

While the overall population growth rate is stable, there is a large difference in rates for the urban and rural populations. The urban growth rate has averaged 3.83 percent in the 12 years between the 1976 and 1988 censuses, while the rural population has averaged 2.07 percent. This suggests that there is considerable continuing migration from the rural areas to the towns and cities (République du Sénégal, 1988). As a result, the distribution of the Senegalese national population is becoming increasingly unbalanced. The west central regions are growing at the expense of the rest of the country. This is occurring despite efforts by the Government of Senegal (GOS) to decentralize industry from the Dakar Region to other Regions.

As the overall population increases, so does the population density. In 1976, there were an average of 25 persons per square kilometer. In 1988, the figure had increased to 35 persons per square kilometer. The uneven distribution of population has resulted in six administrative departments having over 100 persons per square kilometer in 1988 (République du Sénégal, 1988).

The Senegalese population is made up of at least 12 ethnic groups of which the major ones are: Wolof, Serer, Toucouleur, Manding, Diola, and Peul. The Wolof make up a considerable majority of the population, more than a third of the total. Despite the diversity of Senegalese peoples, there is relative harmony among the groups and is well know for its politically stable democratic nation (Arid Lands Information Center, 1980).

2.4 Agriculture

Agriculture is the dominant economic activity in Senegal, providing employment for about 70 percent of the labor force. It is dominated by rainfed cultivation whose vegetative cycle coincides with the short wet season. The distribution and kinds of crops are closely tied to the amount, distribution, and timing of rainfall. Crops in the northern half of the country are particularly prone to the effects of erratic rainfall and drought. In addition to rainfed cultivation, two other types of traditional agriculture are practiced. One depends on flooding of low-lying areas from runoff. This type is found in the humid south and is associated with paddy rice cultivation. The second is the flood recessional agriculture associated mainly with the Senegal River. A non-traditional form of cultivation is irrigated agriculture. It is found mainly along the Senegal River where water is available year-round (Pelissier, 1983).

Agriculture plays an essential role in both the national food supply and in the national economy. Rainfed (dryland) cultivation consists of cash crops dominated by groundnuts (peanuts), and subsistence crops dominated by millet and sorghum. Groundnuts are the main cash crop grown in Senegal and, althoug its share of total export value has fallen drastically in recent years, it is still a major source of rural income and critical to one of Senegal's major industries - the groundnut oil mills - which produce groundjut oil for the domestic market and for export. Climatic conditions and the world price for groundnuts are dominant in determining Senegal's balance of trade. There is a chronic shortage of foodstuffs in the country, and much of it must be imported to cover domestic food requirements.

The performance of the agriculture sector and thus the economic health of Senegal has been poor since independence in 1960. According to The World Bank (1989b), the performance can be attributed to poor agricultural policies, a poor natural resource base, adverse climatic conditions, the energy price shocks of the 1970's, a high population growth rate, and falling terms of trade. Rapidly increasing population, exacerbated by internal migration, has accelerated deforestation, decreasing use of fallow periods, and led to soil degradation.

3.0 Geographic Information System Approach to Resource-Based Analysis of Carrying Capacity

An analysis of the human carrying capacity from various agricultural development options requires the integration and linkage of multi-sector physical and socio-economic data. On the physical side, an evaluation of

national resource assets and limitations must be made, including soils, vegetation, and climate resources. On the socio-economic side, demographic data, farming and land use practices, infrastructure, commodity pricing data, and nutritional requirements are among the key inputs. These disparate data types all have a common feature that link them together: they can all be geographically referenced and thus lend themselves to geographic analysis.

The approach was to take advantage of automated techniques to enter, store, manipulate, analyze, and display geographically referenced information. The GIS is a computer-based system including hardware, software, and graphics that can integrate and analyze multiple data layers. A GIS was used to assemble and analyze the detailed spatial data gathered for this study. The processing system selected for this study was ARC/INFO and PC-ARC/dBASE, both general purpose geographic information software systems.

An added benefit of using a GIS is its ability to support the planning, modeling, and policy-making processes of an organization. It is particularly appropriate for evaluating various "what if" questions that cannot be readily visualized by other means. By changing some of the basic assumptions that contribute to the model, one can immediately see the consequences. This flexibility may become particularly useful in supporting the findings of this study during discussions with the GOS.

Administratively, a GIS can provide a single location for an organization's resource information. This can extend an organization's institutional memory that survives staff changes.

4.0 The Model: Estimating Human Carrying Capacity

The model for computing human carrying capacity was developed jointly by technical staff from USAID/Senegal, the USAID Africa Bureau Office of Technical Resources, and the U.S. Geological Survey. The tentative model was extensively reviewed and modified by those most knowledgeable of agriculture, development, and the Senegal resource base.

The goal of this study was to develop and apply a model which estimates human carrying capacity from rainfed cereal grain production. The model needed to be national in scope, yet capable of incorporating detailed map and statistical data. It should be stressed that the model estimates carrying capacity only from rainfed cereal grain production. This excludes other important types of agricultural production, including irrigated, flood recessional, and market garden. Also excluded are the food producing livestock and fishing activities.

Rainfed (dryland) agriculture is, currently, the most important form of agricultural activity in Senegal, both from an economic and food production standpoint. It is estimated that 80 percent of the caloric needs of the Senegalese diet, taken nationally, are satisfied from cereal grains (Cogill et al., 1989).

Human carrying capacity is defined as the total annual caloric production of a given agricultural area divided by the annual human caloric consumptive needs. The minimum daily consumption requirement of 2300 calories per person (Cogill et al., 1989), with 80 percent (1840 calories) from cereal grains, was used for this study. This is based on a regional estimate; these figures can be adjusted in future analyses as more specific data become available.

In order to evaluate the current and potential carrying capacity from rainfed agriculture, it was necessary to consider the current situation, and potential options for food production in Senegal. There are essentially two approaches to increasing production: a) increase crop yields through improved technology and b) expand the area under cultivation onto arable soils. Both approaches were investigated, singly and in combination, and both required a number of qualifying assumptions for constructing the analytical framework.

Estimating human carrying capacity from current production levels required such data inputs as current locations and cropland areas, by crop type, milling rates and post harvest losses, crop yields and production figures, caloric value of the major food crops, agricultural fallowing practices, and human consumptive needs. Predictions of carrying capacity from increased production scenarios draw heavily on soils and climate interpretations about where crops can and cannot feasibly grow. Thus, it was necessary to rely upon and integrate multiple data sources. Figure 1 presents an overview of the data sources, the processes used to integrate and analyze the data, and the resulting products.

5.0 Data Sources

The data required for the model fall into six distinctive groupings: natural resources data, demographic data, political division data, agricultural data, health data, and other data. This section describes the sources and characteristics of each of these geographic data types.

5.1 Natural Resources Data

5.1.1 Soils

Soils data are one of the key types of natural resource data because of their importance for making agricultural interpretations. There have been two national soil surveys of Senegal, one conducted by ORSTOM (Office de la Recherche Scientifique et Technique Outre-Mer) (Maignien, 1965) at a reconnaissance scale of 1:1,000,000, and one completed in 1986 by South Dakota State University (SDSU) at the more detailed scale of 1:500,000 (Stancioff, Staljanssens, and Tappan, 1986). Both use the French/ORSTOM soil classification system. The present study used results of the USAID/Senegal-sponsored detailed SDSU survey.

The SDSU soil map (Carte Morpho-pédologique du Sénégal) was prepared from manual interpretation of Landsat images of Senegal. Multi-date Landsat Multispectral Scanner (MSS) images acquired in the 1970's and early 1980's were used to delineate physiographic types; these were further subdivided into soil associations. Physical and chemical characteristics of each soil

association were collected during extensive ground surveys conducted throughout the country in 1982-1985. The soil delineations were confirmed or adjusted using conventional survey techniques.

The result was a spatially detailed national soil inventory with a considerable set of supporting soil attribute data. The attribute data consist of 11 first order soil parameters (examples are slope, soil depth, texture), and 10 second order parameters (these include permeability, water-holding capacity, wind erosion susceptibility, chemical fertility). These files form the basis for making agricultural (and other) interpretations. The minimum size of a soil polygon is approximately 4 square kilometers.

In order to use the soils data in a GIS, the maps and their soils attributes were digitized by the EROS Data Center using ARC/INFO. Figure 2 shows the spatial density of the soils coverage following digitization.

5.1.2 Vegetation

Discussions of agricultural development must take into consideration the impact of cultivation (particularly expanding cultivation) on natural vegetation. Indeed, agricultural development plans must be carefully weighed against the obvious need to preserve the natural environment and maintain the biodiversity of the region. The Government of Senegal has made significant efforts since independence to set aside major tracts of land as natural preserves. The present study takes the current extent and condition of natural vegetation formations into consideration.

Prior to the SDSU survey (Stancioff, Staljanssens, and Tappan, 1986), national maps of the vegetation of Senegal were both outdated and spatially very general. The best of the early inventories was published in 1962 as part of a vegetation map series on tropical West Africa (Roberty, 1962). Later surveys, also supported by France, provided detailed maps of some of the regions of Senegal, but did not result in national coverage.

The SDSU survey published a detailed map of vegetation cover: Carte du Couvert Végétal at 1:500,000 scale (Stancioff, Staljanssens, and Tappan, 1986). The mapping approach was the same as that for the SDSU soil map described above. The vegetation map is based upon a physiognomic classification of vegetation types, using the "Yangambi" convention for nomenclature of tropical African vegetation (Trochain, 1957; Monod, 1963). In addition, the vegetation map provides floristic information, subdividing vegetation formations into communities. Thus, the map is based on a combined physiognomic-floristic system.

The vegetation map is already somewhat dated, since it is based upon Landsat imagery collected no later than 1982, and extensive field surveys conducted from 1982 to 1985. Nevertheless, it is one of the best available spatial references on vegetation cover. It is estimated that the vegetation cover has changed slightly in some of the regions of high agricultural pressure. However, these changes are not expected to have a significant impact on the findings of this study conducted at the national level.

Like the soils map, the vegetation map was digitized at EDC for use in a GIS. A generalized map output of the vegetation coverage is presented in Figure 3.

The SDSU vegetation map shows official forest and rangeland preserves. This information was provided by the GOS. These boundaries were digitized by EDC as a separate layer for use in the present model. A generalized map was produced from the vegetation data base for the present study. The resulting map is entitled "Range and Forest Resources of Senegal." The map is presented in Figure 4.

5.1.3 Land Use and Land Cover

The SDSU survey produced a map of land use and land cover of Senegal at 1:500,000 scale (Carte de l'Occupation et l'Utilisation du Sol). The map delineations are essentially the same as those presented on the vegetation map with different polygon attribute information. The attributes refer to the various types of cultivation, and to crop mixtures found during the early 1980's.

The land use and land cover information is an essential layer of the present model. This type of spatial information is often missing from national resource surveys of African countries. For the present study, it provides the key to the location and extent of rainfed agriculture. We did not use the crop mixture information from the SDSU survey, preferring to use the more recent (1986-1989) data from the GOS crop reporting statistics. The land use and land cover attribute data were encoded by EDC and tagged to the vegetation polygon coverage.

5.1.4 Climate

Rainfall, producing available soil moisture, is a very important limiting factor to natural and agricultural vegetation growth in the West African environment. An understanding of the climatic regimes of the region, particularly rainfall, is essential for considering current and potential crop production alternatives. Rainfall plays a primary role in determining "which crops can grow where."

The model used rainfall data provided by the regional AGRHYMET (Agriculture-Hydrology-Meteorology) Program. Ten-day rainfall summaries from each synoptic weather station in Senegal were used to compute statistics on average annual rainfall for Senegal. This study examined rainfall data from the period 1930 to 1987. Computations and interpretations from these data are discussed later.

5.2 Demographic Data

Demographic data were brought into the analytical framework in order to compare current and projected population with estimated human carrying capacity. The demographic data were based on preliminary results from the 1988 census (République du Sénégal, 1988). Preliminary growth rates, current and projected, were provided by U.S. Bureau of the Census (BUCEN) from comparisons of the first national census of 1976 to the preliminary 1988

census. Population figures and growth rates were reported on the basis of an arrondissement, a fourth order administrative unit. Population statistics were further broken out into rural and urban. For this study, we used the total population (rural and urban) reported by arrondissement. Computations and projections made from these data are discussed later.

5.3 Political Division Data

Senegal is divided into a hierarchy of political divisions, a result of internal reorganization at the time of independence. The following outlines the administrative hierarchy, using the official French terms. Within the national borders (limites d'état) (first order boundaries), the country is divided into ten régions (second order); regions are divided into departments (third order); the next finer subdivision is the arrondissement (fourth order); arrondissements are subdivided into the communauté rural (fifth order); the communaute rural is composed of lands administered by villages (sixth order).

Many of the data collected for this study were reported at the arrondissement level. The official administrative map (Carte Administrative) of Senegal was provided by a joint GOS - United Nations Development Programme study (UNDP-DAT, 1984). Boundaries were digitized to the arrondissement level (there are 93 arrondissements in Senegal).

5.4 Agricultural Data

The agricultural data used here fall into two groups: agricultural statistics and price data. The agricultural statistics were one of the primary sources for determining current and projected human carrying capacity. HCC was computed by relating crop production amounts to human consumption requirements. The agricultural data used here were provided by the GOS Ministry of Agriculture (République du Sénégal, 1987, 1988, 1990). The data consisted of crop reporting statistics by arrondissement for the years 1986, 1987, and 1989. Statistics on specific cash and food crops included yields, areas under cultivation, and production. Crop mixture ratios were derived from the basic data. Post harvest losses for all crops were estimated at 15 percent (Cogill et al., 1989). The milling rates were determined and reported by region (Martin, 1988).

Areas devoted to fallow in a given year, an indicator of crop use intensity, were not reported. The fallow factor was estimated from aerial photographs of the major agricultural regions in Senegal, and from GOS crop reporting statistics (additional discussion below).

Agricultural price data are those used by USAID/Senegal; the original source are the CSA Monthly Price Reports. The present study used producer prices in FCFA (CFA Francs) per kilogram, representing an average over the October 1989 to July 1990 period. The data are crop specific, reported on a per region basis.

5.5 Health Data

The only facet of health data required by this analysis was human consumption requirements. These data result from a USAID Food Needs Analysis (Cogill, 1989). The analysis reports on the minimum food consumption requirements for Senegal (2300 calories per person per day), and the percentage of calories, taken as a national average, provided by cereal grains (estimated at 80 percent).

5.6 Other Data

Several types of polygonal, linear, and point data were integrated into the final map products to serve as geographic references to the thematic maps. These include roads, cities and towns, rivers, lakes, and geographic tic marks. Most of these locational features were digitized from Operational Navigation Charts (ONC), and from the map: Senegal: Carte au 1:1,000,000 (IGN, 1980), a general purpose road map.

6.0 Methodology and Analysis

This section describes the steps taken to derive the final human carrying capacity estimates from rainfed cereal grain production (refer to Figure 1). It presents the approach used to integrate the various data sources defined above. Qualifying assumptions made about the data, and about operations on the data are specified.

Intermediate map and tabular products are described. These intermediate products build upon one another to achieve the final results. The discussion will not delve into the sequence of ARC/INFO commands and processes used to produce the maps and tables. In some cases, however, key geographic analysis terms are mentioned in describing the map compilation process.

6.1 Location of Current Rainfed Agriculture Lands

One of the first tasks after data collection and digitization of source map was to answer the question: Where does rainfed agriculture currently occur in Senegal? This involved identifying and delineating all areas that were labeled as "rainfed agriculture". Descriptive or statistical information describing a map unit will be subsequently called "attributes". This information was tagged to the vegetation cover map (see Section 5.1.2), originally an attribute of the land use and land cover map (Section 5.1.3). Using ARC/INFO, the approach was to search through the polygonal vegetation coverage to identify the rainfed agriculture polygons. All polygons which matched the desired attribute were assigned a color code, (yellow, on original color maps). All remaining polygons with non-matching attributes were assigned a second color code, grey.

The result was a new map entitled "Current Rainfed Agriculture Lands of Senegal" (Figure 5). Locational features were added to the map to extend its usefulness. These included nature preserves, administrative boundaries to the arrondissement level, roads, and cities.

Several assumptions were made about the data and the resulting map. First, the agricultural polygons represent delineations based on data collected no later than 1982. Thus, "current" refers to the latest available information. It is assumed that the extent and location of agriculture has not changed greatly at this map scale between 1982 and 1988, the year designated as the current baseline.

The map excludes irrigated, flood recessional, and market garden forms of cultivation, falling into the grey background class. Rainfed agriculture includes both cash crops and food crops. Individual fields and fallow lands were not mapped in the original survey and cannot be shown here. Fallow lands are considered part of a rainfed agriculture polygon.

6.2 Determining Average Annual Rainfall

Climate has much to do with crop distribution. In tropical Africa, rainfall is a primary limiting factor. Seasonal distribution and amount of rainfall are critical for producing agricultural crops. Both are highly variable from year to year.

The approach used in this study was to produce a series of maps (Figure 6) that summarize average annual rainfall amounts for Senegal for the six decades from 1930 to 1987. Additional maps were made showing annual rainfall averages over the 30 year period of 1950 to 1979 (Figure 7).

The rainfall data were provided by the regional AGRHYMET Program. First, decadal (10-year) averages were computed from 10-day rainfall summaries from each weather station using RAINMAN, a rainfall database management system developed for the AID-sponsored Famine Early Warning System Project (FEWS). A 3-dimensional surface of values was then computed through automated interpolation of the geographically referenced point rainfall data using SURFER surface generation and plotting software. Interpolation was based on an inverse distance squared approach which creates a full raster of values. Grid cell size was set at one tenth of a degree of latitude and longitude. The final process was to produce isohyets of average annual precipitation in 100 mm increments by converting the precipitation values to lines or contours of equal value.

For simplicity, only a subset of the 100 mm isohyets are shown on the maps. Criteria for selecting them was based on crop specific rainfall requirements (e.g., the 400 mm is commonly accepted as the minimum for short season millet and groundnuts). The decadal maps show the weather stations which provided the point data for producing a each map. The series of decadal average rainfall maps (Figure 6) show the dramatic southward shift of isohyets over time.

In order to show a longer term average, the maps in Figure 7 represent the 1950-1979 average rainfall period. This time frame has been used by other investigators in Senegal and was adopted for the present human carrying capacity model. It incorporates the relatively wet 1950's and 60's with the dry 70's. The present study focuses on the 400 mm and 500 mm isohyets. The 400 mm isohyet (bold red line) was adopted for the present study to delimit

the minimum threshold for rainfed agriculture in Senegal. The 500 mm isohyet is shown for comparison, as requested by USAID/Senegal Mission, becuase of its close correlation with a concept of "reliable rainfall" (400 mm, 80 percent of the years). Finally, the positions of the 400 mm and 500 mm isohyets from the individual decades are shown for comparison.

6.3 Determining Potential Rainfed Agriculture Lands

Rainfall and soils are the dominant factors which determine if lands are arable. Rainfall amounts are adequate over much of Senegal to support crops, but in many areas the soils are too poor or insufficiently developed. This section describes a parametric approach taken to determine soil potential for rainfed cultivation.

6.3.1 Potential Based Upon Soils

The original study by Stancioff, Staljanssens, and Tappan (1986) evaluated all the soils for their agricultural suitability. This suitability was determined by evaluating soil parameters in conjunction with the climatic regime in which the soil was found. First order soil parameters are those that are observed or measured. They include slope, texture, depth, stoniness, rockiness, coarse fragments, soil drainage, pH, salinity, sodicity, and actual soil erosion. First order parameters are combined to produce second order parameters. These include permeability, wind and water erosion susceptibility, chemical fertility, water holding capacity, potential irrigability, workability, seeding establishment, and potential mechanization. Interval classes were prepared for each parameter during the original survey.

The procedure was to examine all parameters of each soil association in conjuntion with known data on climatic/rainfall regimes in Senegal and rate each soil for its suitability to support general rainfed cultivation. If any one parameter posed a major limitation to crop development, the soil was classified as less than moderately suited. For example, soil association Oa6 is a hydromorphic, weakly developed, deposited soil on gravelly material in east central Senegal. It was judged as having low suitability because the soil depth falls into depth class 4, too shallow to support acceptable crop yields. Furthermore, the organic matter content and chemical fertility are low. Polygons representing soil association Oa6 are therefore excluded from consideration for potential agricultural expansion.

The food crops considered in the model were millet, sorghum, corn, cowpeas, and rainfed paddy rice. The cash crops considered were peanuts and cotton. Although there is some local consumption of peanuts, this model treats them as strictly a cash crop. Clearly, there are some differences in the soil requirements of these rainfed crops (for example, peanuts do better in coarser soils than in finer textured soils). For the most part, the soil requirements are similar. All do well on soils that are nearly level or gently rolling, deep, medium textured, and supplied with fertilizer elements (Westin, 1990).

Only the characteristics of the major component of a soils association were considered in the soil suitability ratings. Ironstone is a small but extremely important component of many mapping units since it is unsuitable for

any kind of cultivation. The unmapped minor soil inclusions (with low suitability) were taken into consideration in the agriculture expansion options discussed later.

The judgement as to which soil associations are "moderately suited" versus "less than moderately suited" is not entirely objective. The classification represents an interpretation made from parameters by soil scientists with considerable field experience in Senegal, and with extensive experience in soil taxonomy and soil interpretations.

6.3.2 Potential Based Upon Climate

Known climatic/rainfall regimes in Senegal were considered when evaluating each soil for its agricultural potential. To be considered moderately suited for agricultural, a soil must receive approximately 400 mm of rainfall. The northern extent of rainfed cultivation corresponds approximately to the 400 mm average annual rainfall isonyet (using the 1950-1979 period; Figure 7). While there are many suitable soils, the northern quarter of Senegal is excluded from consideration for potential rainfed cultivation due to moisture limitations. The map of Potential Rainfed Agriculture Lands (Figure 8) represents an integration of the soils and rainfall characteristics.

6.3.3 Map of Potential Rainfed Agricultural Lands

The map of Potential Rainfed Agriculture Lands (Figure 8) was generated by simply selecting from the soils database all soils that were identified in the SDSU study as having moderate potential for agriculture. These were shaded green while the others were shaded grey.

6.4 Current and Potential Agricultural Land Use

It was convenient to compare the above two interpretation maps to show the relation between current areas of rainfed agriculture and potential areas of expansion. To facilitate comparison, the coverages were combined to produce the map "Current and Potential Rainfed Agriculture Lands" (Figure 9). The map shows four land use situations: a) lands currently cultivated; b) lands of potential cultivation; c) lands currently cultivated on soils of less than moderate potential; and d) lands not cultivated with little potential for cultivation.

The map indicates that some areas are presently cultivated on soils that are marginal for that use (orange areas). Most of these areas are in the northwest, where cultivation occurs in a zone of less than the 400 mm average annual rainfall requirement established for this model. Some of the soil associations in the area have major limitations for cultivation, including steep slopes, a relic of an ancient erg. Certainly, cultivation in these areas is possible in "good" years, but the risk of crop failure is very high. The carrying capacity analyses based on "current area," define "current area" as all lands presently under rainfed cultivation, including the farming of these marginal production areas.

As a management tool, the map should be used only as a general indicator of suitable (or unsuitable) land uses, not as a definitive implementation document.

6.5 Soil Susceptibility to Wind Erosion

Many arable (and non-arable) soils are highly prone to wind erosion. If not properly protected, the top soil is blown away, causing a decline in soil productivity. Many areas of the "Peanut Basin," a region of intensive cultivation in west-central Senegal, have suffered irreversible damage from wind erosion. As new lands are cleared for agriculture, soils with high erosion potential must be carefully managed.

While not a direct input to the present carrying capacity study, a map of Soil Susceptibility to Wind Erosion (Figure 10) was compiled from the soil texture parameter of the soils data base. Each soil association was grouped into one of eight classes of wind erosion potential. The ratings are based on conditions that occur when vegetation cover is removed. This map was not used to further exclude lands from potential cultivation. Rather, it was designed as a soil conservation and management planning input. Where soils are highly erodible, practices to maintain windbreaks, intercropping, or maintaining vegetation cover as long as possible must be adopted for sustainable development.

6.6 Current and Potential Distribution of Specific Crops

One of the final analyses required before computing human carrying capacity from rainfed agriculture was to determine the current and potential geographic distribution of specific food and cash crops. For example: Where is sorghum presently grown and what is its production? Where can sorghum potentially be grown on the basis of rainfall and soils? Such questions needed to be answered for all crops considered by the model. Rainfed sorghum is an important subsistence crop in Senegal, and was chosen to illustrate the approach taken for determining current and potential crop distributions.

Sorghum does well on a variety of soil textures and is relatively tolerant to periodic waterlogging. The main West African varieties (gros mil) require at least 700 mm of rainfall in the growing period for acceptable yields (Traore, 1983).

The first task was to determine the current sorghum producing areas. The determination was based on averages computed from the 1986, 1987, and 1989 GOS crop reporting statistics (République du Sénégal, 1987, 1988, 1990). All arrondissements reporting the production of sorghum were flagged. A polygon attribute table was created, listing arrondissements with and without sorghum production. If the reported area of sorghum cultivation within an arrondissement was less than 5 percent of the total reported area (of all crops) under cultivation, the area was deemed insignificant and sorghum was not considered to occur in that arrondissement. Each agricultural polygon (from the vegetation coverage) was then tagged as sorghum producing areas for those arrondissements reporting sorghum.

The second part of the process was to determine potential sorghum producing areas. The procedure was essentially the same as that for determining potential rainfed agriculture discussed in Section 6.3. Potential areas for production were defined by favorable soil and climatic regions. Soils were limited to those having at least moderate agricultural potential. The distribution was further limited to the north by the 700 mm isohyet (from the 1950 to 1979 period). Finally, the range and forest preserves were intersected with the preceding coverages in order to exclude those areas from production.

The final step was to merge the current and potential sorghum map coverages into a final map: "Current and Potential Sorghum Producting Areas of Senegal" (Figure 11).

The procedures followed for sorghum were repeated for the other crops addressed in the model. The distributions of these crops were not shown in map form, but polygon attribute tables tagged crops to agricultural polygons by arrondissements.

Geographic limitations of the other crops were defined by the soil suitability interpretations (Section 6.3.1) and average annual rainfall. The rainfall limitations used for the other crops were: peanuts and millet were restricted to areas of greater than 400 mm; corn was restricted to 800 mm or greater; rice was set at 1000 mm or more; cowpeas were limited to the 400 to 700 mm zone. The isohyet positions were based on the 1950 to 1979 period of average annual rainfall. The rainfall thresholds adopted for each crop were based on comparing general crop distribution maps from the UNDP-DAT (1984) study to the average annual rainfall maps prepared for the present effort.

Due to current production trends, areas of cotton and rainfed rice cultivation and production were held constant in all projections. Areas, yields, and production figures were based on the GOS 1986, 1987, and 1989 averaged arrondissement crop statistics. Official range and forest preserves were excluded from all crop production.

6.7 Range and Forest Resources

Options for increasing agricultural production through expanding the area of cultivation must take into account impacts on the natural environment. Throughout Africa, agricultural expansion is impinging upon natural habitat, in quantitative and qualitative terms.

In order to provide project managers with a national picture of the vegetation resources, we compiled the "Range and Forest Resources of Senegal" map (Figure 4) from the vegetation data base (refer to Section 5.1.2). The map represents a spatial and thematic generalization of the extensive original data base. Vegetation units were generalized by grouping vegetation community (floristic) units into the more general vegetation formation (physiognomic) units. The reduced number of map units resulted in a reduced number of polygons (spatial generalization). The range and forest preserve boundaries also shown. The purpose of the map was to capture the natural vegetation patterns and to determine where and what natural vegetation would be consumed

by agricultural expansion. It should be noted that the charcoal industry has (and continues to) cut large forest areas so some of the reserve areas and vegetative coverage information are no longer precisely accurate.

The map distinguishes between rangeland and woodland (forest) formations. The division between these is somewhat arbitrary, although rangeland formations are relatively open grasslands with scattered shrubs and trees, and woodlands have denser woody cover. A concrete boundary does not usually exist between these since the natural vegetation forms a gradual transition from open savanna to dense woodlands and forests as one proceeds south into higher rainfall regimes. The present study defined rangeland formations as having less than 20 percent woody cover, and forest formations at over 20 percent. The division was based on data from the original survey (Stancioff, Staljanssens, and Tappan, 1986). Under this definition, rangeland formations may possess considerable woody resources, and woodlands offer valuable forage (woodlands are used for grazing throughout Senegal).

6.8 Human Carrying Capacity from Rainfed Agriculture

At this point, we addressed the questions: What is the estimated human carrying capacity from current rainfed agriculture? What is the potential human carrying capacity from increased production alternatives? What is the estimated geographic distribution of human carrying capacity from current and projected rainfed production?

The first task was to compute carrying capacity from a baseline of current rainfed agriculture. The current baseline was 1988, established as an average of 1986, 1987, and 1989 agricultural conditions, and from the 1988 Senegal census. Subsequent tasks involved estimating potential carrying capacity from three basic development alternatives. One alternative is to limit cultivation to the current area while increasing yield through improved technology. The second is to expand the area under cultivation fully utilizing Senegal's potential, while maintaining current levels of technological input. The third option is to combine the two: increase yields and the area under cultivation to estimate a maximum carrying capacity.

6.8.1 Baseline Data and Assumptions

Computations of carrying capacity from the baseline situation and from agricultural production options required making a number of assumptions about the data and its geographic distribution. Before examining the specific options, it is necessary to discuss the assumptions made on the baseline data. The assumptions made can be grouped into the following headings: crop production, crop yields, cropped area, crop mixtures, and crop production values.

6.8.1.1 Crop Production

Current crop production was derived from averaged crop reporting statistics (Section 5.4). Production figures were averaged for the five food crops and two cash crops, at the arrondissement level. National production was aggregated by summing arrondissement level figures.

Projected production (for expanded area options) is the yield times the cropped area, computed by agricultural polygon and aggregated to administrative subdivisions.

The food crops, contributing directly to carrying capacity, are millet, sorghum, maize, rice, and cowpeas (locally known as niébé). The cash crops are groundnuts and cotton.

Production figures are adjusted using post harvest loss, milling rates, and retained seed amounts. The model assumes a post harvest loss factor of 15 percent per food crop. Milling rates of 0.82 for millet and sorghum, 0.72 for maize, 0.67 for paddy rice, and 1.00 for cowpeas were used (Martin, 1988). Retained amounts for seed in kg/ha were: 8 for millet and sorghum, 16 for maize, 100 for paddy rice, 18 for cowpeas, 120 for groundnuts, and 50 for cotton.

Caloric yields by crop, after milling rate adjustments, were 3300 calories per kg for millet and sorghum, 3680 for maize, 3530 for whole grain paddy rice, and 3420 for cowpeas (Cogill et al., 1989).

6.8.1.2 Crop Yields

Crop yields were also derived from averaged 1987-1989 GOS arrondissement crop statistics. For the expanded area of cultivation options, yield figures were taken from the 1987-1989 averages of adjacent arrondissements having similar rainfall.

The 1987-1989 averaged crop yields were considered as attained under medium levels of farm technology. For increased yield options under high technology, yields were computed on the basis of a percentage increase from current (1987-1989) yields. The high yield figures were based on data from ISRA, which shows yields for high, medium, and low levels of technology applications for an average rainfall year (Martin, 1988).

6.8.1.3 Cropped Area

Cropped area is based on averaged crop reporting statistics at the arrondissement level. Thus, current production figures are based on these.

Rainfed agriculture is not permitted in range and forest preserves in either current or projected situations.

Cropped area for the expanded area option was computed in two steps:
(1) Current area: the locations of cropped area was determined by lands currently used for agriculture. A fallow factor of 50 percent of an agricultural polygon was used. The assumption was that in a given year, 50 percent of the land area is actually cultivated in crops, the remainder left in fallow. This level of fallow is found commonly in western Senegal. It represents intensive use of the land. Cropped area was not adjusted for the area required for human needs (e.g., living space, infrastructure), or for unfarmed poor soil inclusions. These were considered part of the fallow area;
(2) Expanded area: the locations of the expansion of cropped area was

determined by the moderate potential soils for rainfed agriculture (from Section 6.3). In order to maintain some of the local habitat and biodiversity, 50 percent (by area) of the natural vegetation was retained. The resulting landscape would be a mosaic of natural and agricultural areas. The natural areas contain unfarmed poor soil inclusions. Within the cropped 8areas, 50 percent of the area was assumed to be fallow, and includes areas for human needs.

A third scenario of agricultural expansion onto moderate potential soils was investigated: maximum area. In this scenario, only 15 percent of the natural habitat (rangelands, woodlands, etc.) is retained. Hence, natural vegetation is left only on the poor soil inclusions. A 50 percent fallow factor is maintained for the cultivated area.

6.8.1.4 Crop Mixtures

Current crop mixtures were derived from the GOS averaged crop statistics. The mixtures were extended into the expanded and maximum area options. They were determined by crop, by arrondissement, as a percentage area of the total area reported under cultivation.

Projected crop mixtures (referred to below as allocated mixture) were based on several assumptions and operations (their order is significant). Three variations of the allocated mixture theme were implemented:

Allocated Mixture #1) This scenario is based on the allocation of both cereal crops and cash crops. First, 50 percent of the land area is left in fallow in a given growing season. Second, if cotton or rice are currently reported in an arrondissement, they are allocated to the cropped areas at the current levels. The area (and production) of cotton and rice remains constant over time, again using current figures on an arrondissement basis. Third, 50 percent of the remaining area is planted in groundnuts (they may be grown on all moderate potential soils). Fourth, the remaining land is devoted to rainfed cereal crops on the basis of optimizing caloric production. The crop with the highest caloric value is assigned to 75 percent of the remaining area, if the crop can be grown in the particular rainfall zone. The crop with the second highest caloric value is assigned to the remaining 25 percent area, if the rainfall regime can support that crop. For crop distribution limitations by rainfall, refer to Section 6.6.

Allocated Mixture #2) This option allocates only cereal crops (no cash crops are grown). As above, 50 percent of the land is left in fallow. Second, if rice is currently reported in an arrondissement, it is allocated at current levels, and its area is kept constant over time. Third, the remainder is devoted to rainfed cereal crops on the basis of optimizing caloric production using the 75/25 percent proportions described above.

Allocated Mixture #3) This option allocates only cereal crops, while cash crops are retained in their original areas. The first operation is to set 50 percent of the farmable area aside for fallow. Second, groundnuts and cotton are allocated to arrondissements at their current reported levels.

Remaining land is assigned to rainfed cereal crops using the 75/25 percent approach described above.

6.8.1.5 Crop Production Values

Crop production values were computed for both food and cash crops for current and projected situations. These were based on crop producer prices in FCFA per kilogram (see Section 5.4). Price figures used in production projections were based on the 1989-1990 FCFA. Prices were held constant for all projections.

6.8.2 Carrying Capacity from Current Yield, Current Area, Current Mixture

The current (1988 baseline) human carrying capacity was computed using current yields, current areas, and current mixtures, as defined in Section 6.8.1. At the national level, the computed (estimated) human carrying capacity was 3,879,600 people.

The basic approach was, first, to compute crop production (in total kilograms, by crop, by arrondissement) using the averaged yields times the reported areas. Second, the arrondissement yield data of the five food crops were converted to their caloric equivalents. For example, for millet, the caloric value per hectare was computed as follows:

millet calories/hectare = ((yield * 0.85) - 8) * 3300
where, 0.85 is the post-harvest loss factor, 8 is the retained seed amount per hectare, and 3300 is the caloric value/kg after milling. The computation was repeated for the other four food crops using the quantities presented in Section 6.8.1.1.

Third, the total calories produced per hectare were computed by summing the calories per hectare of the food crops that occur in a given arrondissement.

Fourth, the human carrying capacity (HCC) per hectare per arrondissement was calculated using equation (see Section 4.0):

HCC = (Kcal / 671.6 Kcal per person-year)
where, Kcal is the total kilocalories produced per hectare, per arrondissement, and 671.6 Kcal per person-year are the human needs per annum from cereal grains. This value was precomputed using:

$$= \frac{2300 \text{ cal}}{\text{person day}} * \frac{365 \text{ day}}{\text{year}} * \frac{\text{Kcal}}{1000 \text{ cal}} * \frac{0.8 \text{ cal from grains}}{1 \text{ cal required}}$$

Finally, it was more convenient to express HCC in terms of people per square kilometer. The HCC per hectare was multiplied by 100 to convert the units to square kilometers.

The results were summarized in map form (Figures 12a and 12b). The range of HCC per square kilometer was divided into 7 classes. Current agricultural areas were also shown for reference.

Although the main thrust of the study was to estimate human carrying capacity from rainfed agriculture, a series of parallel calculations were undertaken to estimate the production value from rainfed agriculture, using the same current and projected agricultural options. Under the current yield, current area, current mixture situation, the production value was computed by multiplying the producer value (FCFA/kg) of each crop times the total production (kg) per crop per arrondissement. This was first done for the food crops, then for the cash crops. The production values were summed for the crops reported in each arrondissement. The figures were aggregated to the national level. The result was a report on the producer value of rainfed cereals, estimated at 65.9 billion FCFA, the producer value of cash crops: 62.6 billion FCFA, and the total producer value: 128.5 billion FCFA.

6.8.3 Projections from Improved Yield, Current Area, Current Mixture

The second agricultural option investigated was human carrying capacity from improved yield, current area, and current mixture. The improved yields were derived from ISRA research as presented by Martin, 1988. Their reports indicated that higher yields could be obtained using high technology. The national carrying capacity under the improved yield option was estimated at 5,425,200 people. The total producer value was computed at 161.8 billion FCFA. Refer to Figure 12a.

The approach to computing human carrying capacity mirrored the approach described above (Section 6.8.2). The sole difference was the substitution of higher yields by factoring in percentage increases from current yields. A high technology management regime to increasing yields assumes that soil fertility, structure, and moisture conservation properties can be improved and sustained. Without considerable inputs and conservation practices, this approach may prove difficult to sustain over large areas in the long-term. The ferruginous and ferralitic soils, which are the dominant types in Senegal, are susceptible to degradation when natural vegetation is cleared for new cultivation. ORSTOM studies have shown that these soils experience nutrient loss and loss of structure resulting in loss of available soil moisture capacity. Charreau (1974) reported that the clearing of perennial vegetation results in the loss of soil organic matter quantity and quality. This results in the overall loss of soil productivity, with yields falling off. Soil organic matter appears to be a critical parameter for gaging soil productivity.

The present model did not consider scenarios of declining soil productivity associated with agricultural practices. Future work building upon this study should consider scenarios of declining yields associated with soil degradation, drawing upon the extensive Sahelian literature. The intent here was to point out the pressing need for increased soil management to sustain agricultural development and to obtain higher yields. This will not occur unless smallholders adopt practices that have short-, medium-, and long-term impacts on soil fertility, soil and moisture conservations, and management of the vegetative cover (McGahey, 1990).

Refer to Table 1 for a summary of this and subsequent development scenarios.

6.8.4 Projections from Current Yield, Expanded Area, and Current Mixture

The third option was to estimate carrying capacity from current yield, expanded area, and current mixture. The national carrying capacity was estimated at 5,563,000 people; total producer value of food and cash crops was 182.3 billion FCFA.

The approach to expanding the area of cultivation was presented in Section 6.8.1.3. Human carrying capacity was computed in the manner described above, converting current yield levels from current and expanded areas to caloric value, and dividing these by the human yearly consumption needs from cereal grains.

6.8.5 Projections from Improved Yield, Expanded Area, Current Mixture

The fourth alternative was to examine carrying capacity from improved yield, expanded area, current mixture. The national carrying capacity was 7,785,000 people; total producer value was 231.3 billion FCFA. This agricultural alternative is summarized in map form (Figure 12b). The areas of agricultural expansion are shown as a shaded overlay to the carrying capacity information. The reader is reminded that the expanded area option maintains 50 percent of the natural vegetation cover.

The approach parallels the one used in the preceding scenario, substituting percentage increases in yields as discussed in Section 6.8.3.

6.8.6 Projections from Improved Yield, Expanded Area, Allocated Mixture #1

The fifth scenario is based upon improved yield, expanded area, allocated mixture #1. This development option endeavored to increase carrying capacity by optimizing the caloric food value of cereal crops using improved crop mixtures. It also placed considerable importance on continued cultivation of groundnuts as a cash crop. The national carrying capacity from this option was estimated at 7,191,000 people; the total producer value was 246.4 billion FCFA.

The approach to allocating crops to current and expanded areas of cultivation for the allocated mixture was presented in Section 6.8.1.4.

6.8.7 Projections from Current Yield, Maximum Area, Allocated Mixture #3

The sixth scenario is computed from current yields, maximum area, and allocated mixture #3. The maximum area option uses virtually all land that can be farmed, reducing natural habitat to 15 percent of the area of moderate potential soils. Natural habitat also remains on poor soils, on preserves, and in areas of less than 400 mm average annual rainfall. Under allocated mixture #3 (Section 6.8.1.4), only cereal crops are allocated (optimizing caloric production), with cash crops retained in original areas.

The national carrying capacity was calculated at 10,341,000 people; the total producer value is 236.4 billion FCFA.

6.8.8 Projections from Current Yield, Maximum Area, Allocated Mixture #2

The seventh scenario is derived from current yields, maximum area, and allocated mixture #2. The sole difference between this scenario and the previous one is the allocation of cereal crops to all areas (and the absence of cash crops). This produces a jump in the HCC to 13,084,000 people; the total producer value is computed at 214.3 billion FCFA.

6.8.9 Projections from Improved Yield, Expanded Area, Allocate Mixture #3

The eighth scenario is based on improved yields, expanded area, and allocated mixture #3. It represents a variation of scenarios 2 and 4. Cash crops retain the same areas as in current area of scenario 2 (see 6.8.3), but the cereal crops are allocated to the expanded area of scenario 4 (see 6.8.5). It is important to note that cash crops remain in their current (from 1986, 1987, and 1989 averages) areas, and do not expand into new areas. The HCC was computed at 10,213,000 people; total producer value is 241.4 FCFA.

6.8.10 Projections from Increased Yield, Maximum Area, Allocated Mixture #2

In the ninth scenario, all parameters are maximized in order to extend HCC to the limits of the resource base. The approach is based on improved yields, maximum area, and allocated mixture #2. This is a variant of the seventh scenario, the difference being improved yields. HCC jumps to 17,140,000, and total producer value is 284.6 FCFA (producer value of cash crops is 0.).

Note that the scenarios based on maximum area exclude the fundamental need to preserve the natural habitat, and leave little room for activities of such other sectors as the livestock/pastoral sector, forestry and wood production, etc.

6.9 Population Density

The final phase of the model examines the question: What is the relation of the estimates of human carrying capacity to the current and projected population of Senegal? This is the fundamental issue - relating human carrying capacity from rainfed agriculture to the realities of today and tomorrow. The comparison is critical to measuring the food gap between production and demand from a growing population. Ultimately, it is one measure of Senegal's progress towards the goal of achieving food security and self-reliance.

Factoring in population data required processing it into a form that could be related to human carrying capacity (people per square kilometer). The solution was to generate a current and projected population density map, by arrondissement, from summed urban and rural population figures from the preliminary 1988 census data.

6.9.1 Current Population Density

The current map of "Population Density of Senegal," Figure 13a, was based on the total population figures reported by arrondissement. The model made two simplifying assumptions with regard to population distribution within an arrondissement: 1) Population is distributed uniformly within an arrondissement, irrespective of the land use, and 2) Population does not occur in the range and forest preserves. The first operation was to overlay the administrative boundary coverage onto the protected (preserve) areas coverage. The area of each arrondissement was adjusted by subtracting the areas of the preserves. Population density, reported in people per square kilometer, was then computed for each arrondissement:

$$\text{Population Density} = \frac{\text{Arrondissement Population}}{\text{Adjusted Arrondissement Area}}$$

The range of population density values was divided into 7 classes to produce a choropleth map.

6.9.2 Projected Population Density

USAID/Senegal requested that projected carrying capacity options be related to population projected to the year 2010. The map of projected population density (Figure 13b) used the same approach and assumptions outlined above. However, a series of precalculations were carried out to project population to 2010 by arrondissement.

First, population was projected to the year 2001 by BUCEN, using the 1976 and preliminary 1988 census data (1990). Their approach was to use a standard methodology for projecting the rural residual population of the various regions of a country. The method is based on the extrapolation of the change in the proportion of a given region to the country's total population. For example, if a region or an arrondissement had 10 percent of a country's population in 1976 and 11 percent in 1988, it would be projected to have 12 percent in the year 2000. Likewise, if it had 12 percent in 1976 and 11 percent in 1988, it would have 10 percent by 2000. A problem arises when a region loses population at a significantly faster rate; for example, a region with 4 percent in 1976, falling to 2 percent in 1988, would be reduced mathematically to zero by the year 2000. Therefore, extreme negative growth rates are held at the actual intercensal rate during the projection period, which produces a small surplus of population. This is compensated for by applying a factor to the increments in all regions that gained population that proportionally reduces the sum of the increments to equal the total growth for the country.

For Senegal, each arrondissement was assigned a code and then treated as if it had been a separate region. The proportion of each arrondissement to the total population of Senegal at the April 1976 and preliminary May 1988 census data was calculated, and the average annual change was extrapolated to 1990 and then for each year in the period 1991 through 2001. The few negative growth rates were adjusted, the increments were raked to compensate for the

adjustments, and all the results were then rounded to the nearest hundred. The final computer program calculates the adjustments needed to make the sums of the individual urban and rural projections add up to the national projected totals.

Projections to the year 2010 were computed at the EDC by applying a linear extrapolation of growth rates, by arrondissement, determined by comparing population changes between the preliminary 1988 census data and the 2001 projections. The projected 2010 population data were converted into population density as defined above.

6.10 Human Carrying Capacity Related to Population

The above process converted current (1988) and projected (2010) population statistics into population density. At this point, the final comparison became possible: relating the 9 human carrying capacity scenarios (Section 6.8) to population. The comparison was achieved by computing the difference between human carrying capacity and current and projected population, on an arrondissement basis. The basic operation was:

HCC - Population

where positive numbers (people per arrondissement) indicate arrondissements where the human carrying capacity exceeds population (surplus production), and negative values indicate arrondissements where population exceeds human carrying capacity (deficit production). This is an indicator of the ability of rainfed agriculture to support the population. The range of results were grouped into 8 classes and presented in map form in Figures 13a and 13b.

The relation was established for the 9 agricultural development options. The reader must be cautious when interpreting the results. First, the reader is reminded that carrying capacity is restricted to the cereal grains production sector, and does not represent the total carrying capacity from all food producing sources. Certainly, there are other important food producing activities, including animal husbandry, fishing, market gardening, irrigated agriculture, etc. Secondly, revenues from the rainfed cash crops are used to purchase food, both from local sources and from imports.

Population projection figures do not account for the migration of population into rural areas associated with expanding areas of cultivation. Under the expanded and maximum area situations, rural populations will likely be higher than those given in the projections, but the national population figures are not expected to change significantly.

6.10.1 Current Yield, Current Area, Current Mixture Related to 1988 Population

The current yield, current area, current mixture option (see Section 6.8.2) was related to current (1988) population. The resulting map (Figure 14a) shows that human carrying capacity generally exceeds the current population in the central and southeastern areas of Senegal, where population is predominantly rural and the density is relatively low. In the rest of the

country, population generally exceeds current carrying capacity. At the national level, the difference between carrying capacity (3,879,600) and 1988 population (6,869,232) indicates that the population exceeds the carrying capacity by 2,989,632 people. This is an indication of the current situation in Senegal.

6.10.2 Improved Yield, Current Area, Current Mixture Related to 2010 Population

The improved yield, current are, current mixture option was related to the projected 2010 population. This assumes that yields can be improved by the amounts indicated above in the next 20 years. Despite the improvement in yields, population growth outpaces the increase in carrying capacity, resulting in arrondissement populations that exceed production capacity over most of the country (Figure 14a). The national summary indicates that the 2010 population (14,680,412) exceeds carrying capacity (5,425,200) by 9,255,212 people. The food gap widens from the current situation.

6.10.3 Current Yield, Expanded Area, Current Mixture Related to 2010 Population

The third agriculture development option, current yield, expanded area, current mixture was related to the 2010 projected population. The national summary indicates that the carrying capacity is exceeded by 9,117,000 people.

6.10.4 Improved Yield, Expanded Area, Current Mixture Related to 2010 Population

The fourth option, improved yield, expanded area, current mixture was related to the 2010 population. Food surplus areas are concentrated in the southeast and central parts of Senegal, but these are more than offset by deficit areas in most of the rest of the country (Figure 14b). Nevertheless, the national summary indicates that the food gap was significantly lessened by this option. The projected population exceeded HCC by 6,895,000 people.

6.10.5 Improved Yield, Expanded Area, Allocated Mixture #1 Related to 2010 Population

A fifth comparison was to relate HCC from improved yield, expanded area, and allocated mixture #1 to 2010 population (Figure 14b). The carrying capacity dropped somewhat from the previous situation, resulting in a greater gap (population exceeded HCC by 7,490,000). This occurred because of the importance given to growing groundnuts as a cash crop, reducing the area devoted to food crops.

6.10.6 Current Yield, Maximum Area, Allocated Mixture #3 Related to 2010 Population

The sixth comparison measures current yield, maximum area, and allocated mixture #3 to 2010 population. The difference dropped significantly (population exceeded HCC by 4,339,000 people) due to the restriction of cash crops to current areas, and the maximum expansion of food crops.

6.10.7 Current Yield, Maximum Area, Allocated Mixture #2 Related to 2010 Population

The seventh scenario compares current yield, maximum area, and allocated mixture #2 to 2010 population. The gap between HCC and projected population is significantly reduced (population exceeds HCC by only 1,596,000 people). This is largely a result of the replacement of all cash crops with food crops.

6.8.10 Improved Yield, Expanded Area, Allocated Mixture #3 Related to Population

The eighth scenario relates improved yield, expanded area, and allocated mixture #3 to 2010 population. The difference between population and HCC is 4,467,000, similar to the result from the sixth scenario. Note that only the cereal crops grow into the expanded area, while cash crops remain at the baseline level. As usual, a 50 percent fallow factor is used on all cultivated lands.

6.10.9 Increased Yield, Maximum Area, Allocated Mixture #2 Related to 2010 Population

In the ninth scenario, all parameters are maximized to boost HCC: increased yields, maximum area, and allocated mixture #2. This is the only scenario in which HCC exceeds the projected 2010 population (a surplus of 2,760,000). The nine scenarios are summarized in Table 1.

7.0 References

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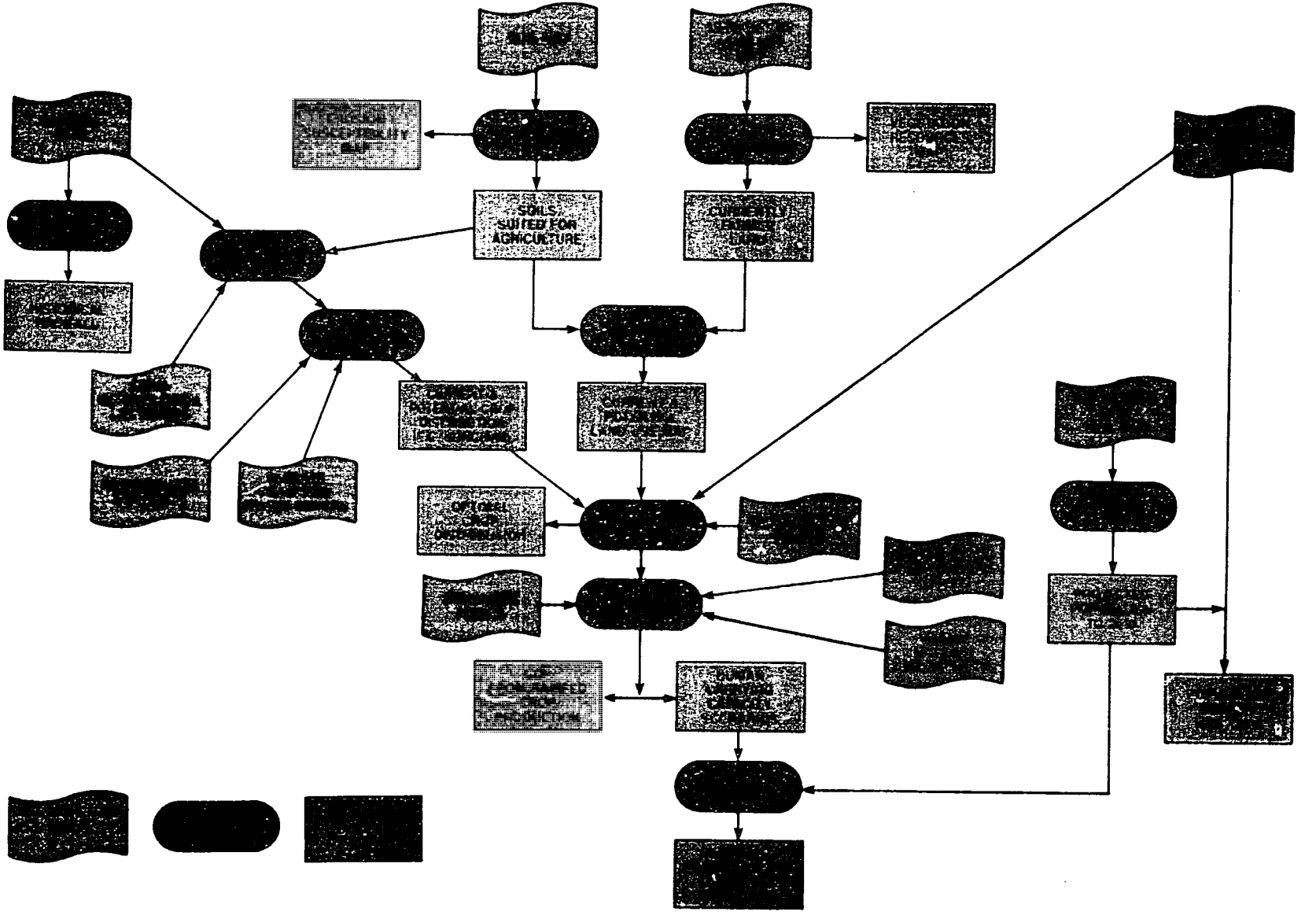
APPENDIX - Figures/Tables

HCC PROCESSING ALGORITHM



IPS3-6-91

USGS/EDC TIO

Figure 1

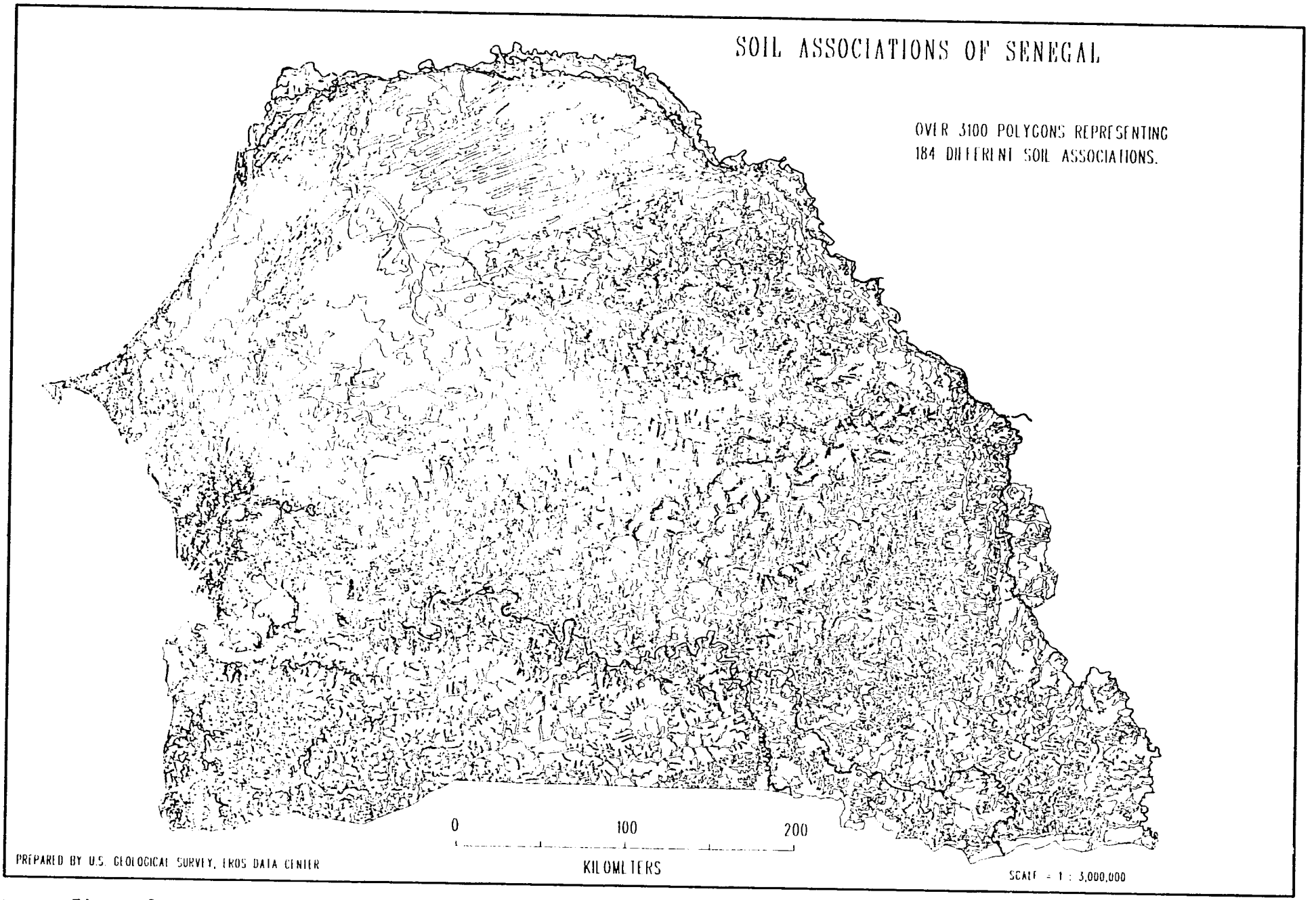

SOIL ASSOCIATIONS OF SENEGAL
OVER 3100 POLYGONS REPRESENTING
184 DIFFERENT SOIL ASSOCIATIONS.
0
100
200
KILOMETERS
PREPARED BY U.S. GEOLOGICAL SURVEY, EROS DATA CENTER
SCALE = 1 : 3,000,000

Figure 2

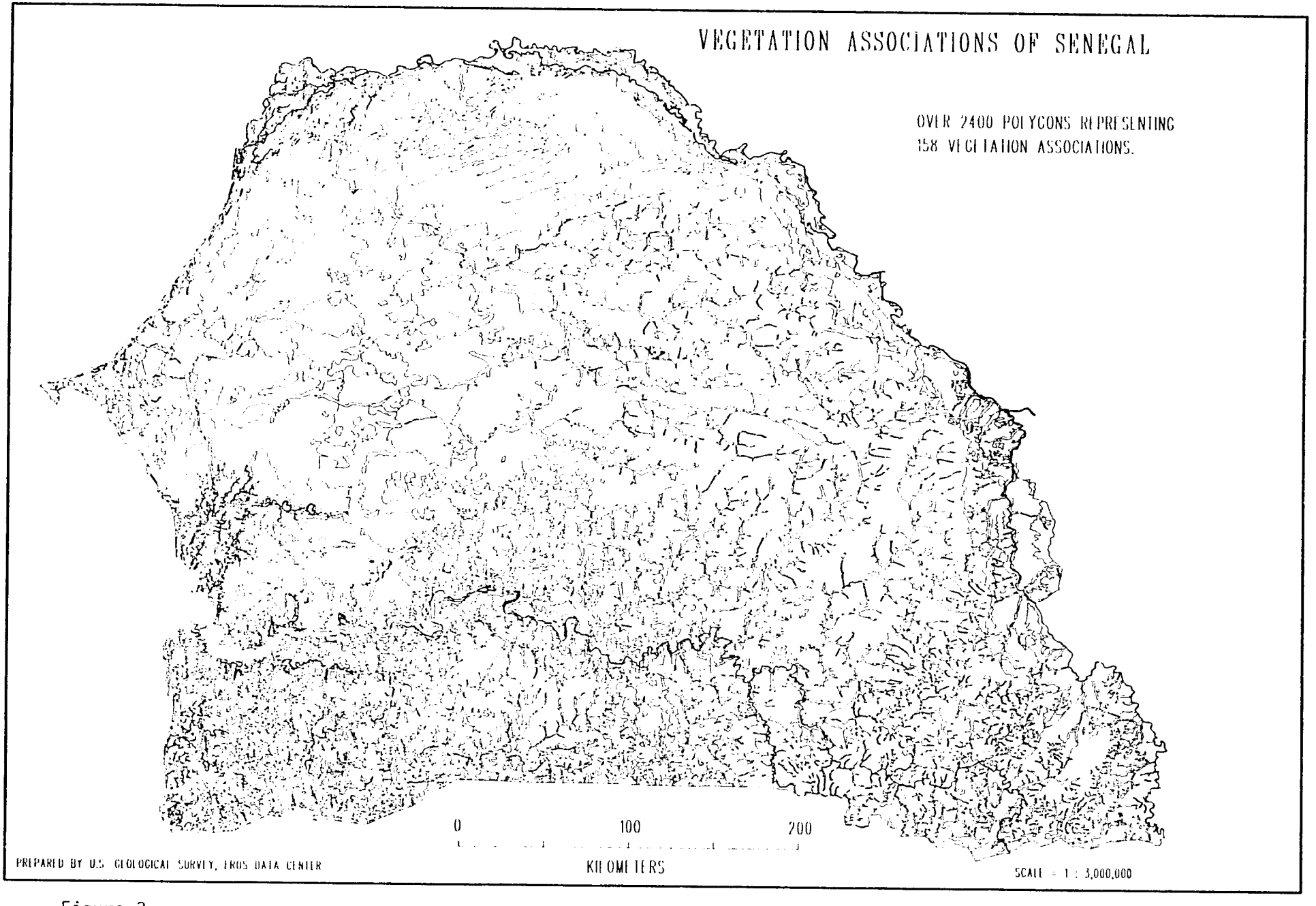

VEGETATION ASSOCIATIONS OF SENEGAL
OVER 2400 POLYGONS REPRESENTING
158 VEGETATION ASSOCIATIONS.
0
100
200
KILOMETERS
PREPARED BY U.S. GEOLOGICAL SURVEY, EROS DATA CENTER
SCALE = 1 : 3,000,000

Figure 3

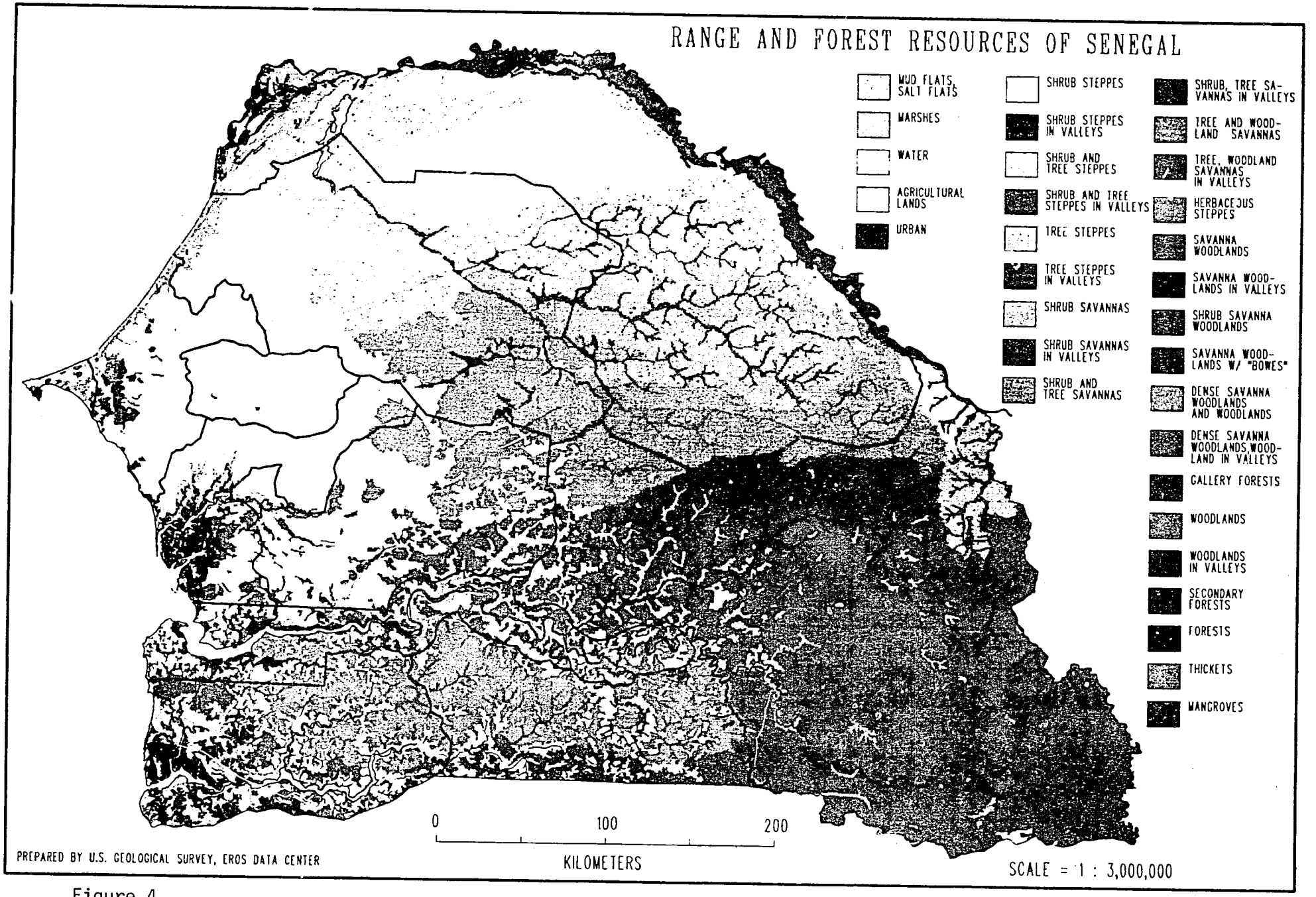

RANGE AND FOREST RESOURCES OF SENEGAL
MUD FLATS, SALT FLATS
MARSHES
WATER
AGRICULTURAL LANDS
URBAN
SHRUB STEPPES
SHRUB STEPPES IN VALLEYS
SHRUB AND TREE STEPPES
SHRUB AND TREE STEPPES IN VALLEYS
TREE STEPPES
TREE STEPPES IN VALLEYS
SHRUB SAVANNAS
SHRUB SAVANNAS IN VALLEYS
SHRUB AND TREE SAVANNAS
SHRUB, TREE SAVANNAS IN VALLEYS
TREE AND WOODLAND SAVANNAS
TREE, WOODLAND SAVANNAS IN VALLEYS
HERBACEOUS STEPPES
SAVANNA WOODLANDS
SAVANNA WOODLANDS IN VALLEYS
SHRUB SAVANNA WOODLANDS
SAVANNA WOODLANDS W/ "BOWES"
DENSE SAVANNA WOODLANDS AND WOODLANDS
DENSE SAVANNA WOODLANDS, WOODLAND IN VALLEYS
GALLERY FORESTS
WOODLANDS
WOODLANDS IN VALLEYS
SECONDARY FORESTS
FORESTS
THICKETS
MANGROVES
0
100
200
KILOMETERS
PREPARED BY U.S. GEOLOGICAL SURVEY, EROS DATA CENTER
SCALE = 1 : 3,000,000

Figure 4

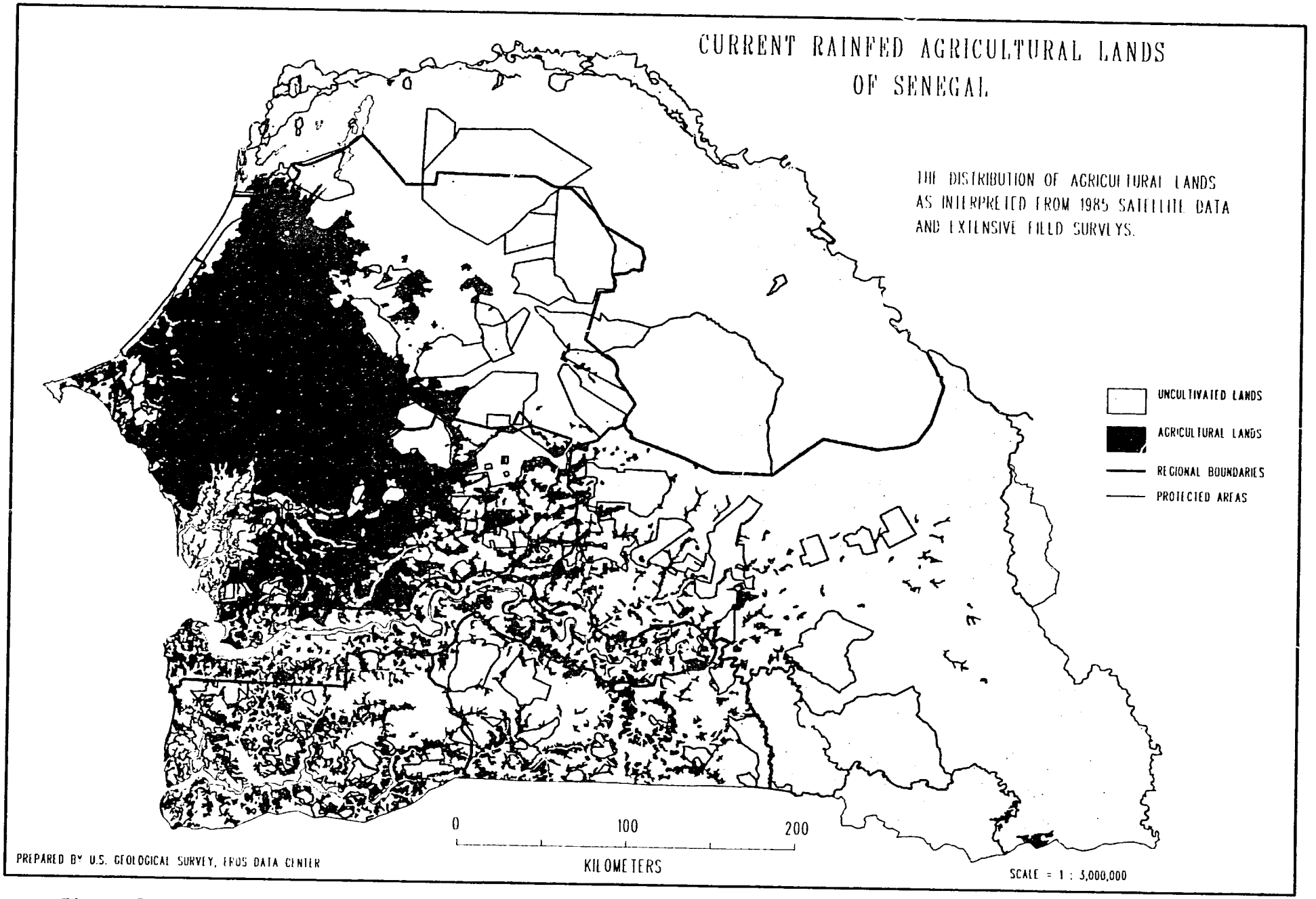

CURRENT RAINFED AGRICULTURAL LANDS
OF SENEGAL
THE DISTRIBUTION OF AGRICULTURAL LANDS
AS INTERPRETED FROM 1985 SATELLITE DATA
AND EXTENSIVE FIELD SURVEYS.
UNCULTIVATED LANDS
AGRICULTURAL LANDS
REGIONAL BOUNDARIES
PROTECTED AREAS
0
100
200
KILOMETERS
PREPARED BY U.S. GEOLOGICAL SURVEY, EROS DATA CENTER
SCALE = 1 : 3,000,000

Figure 5

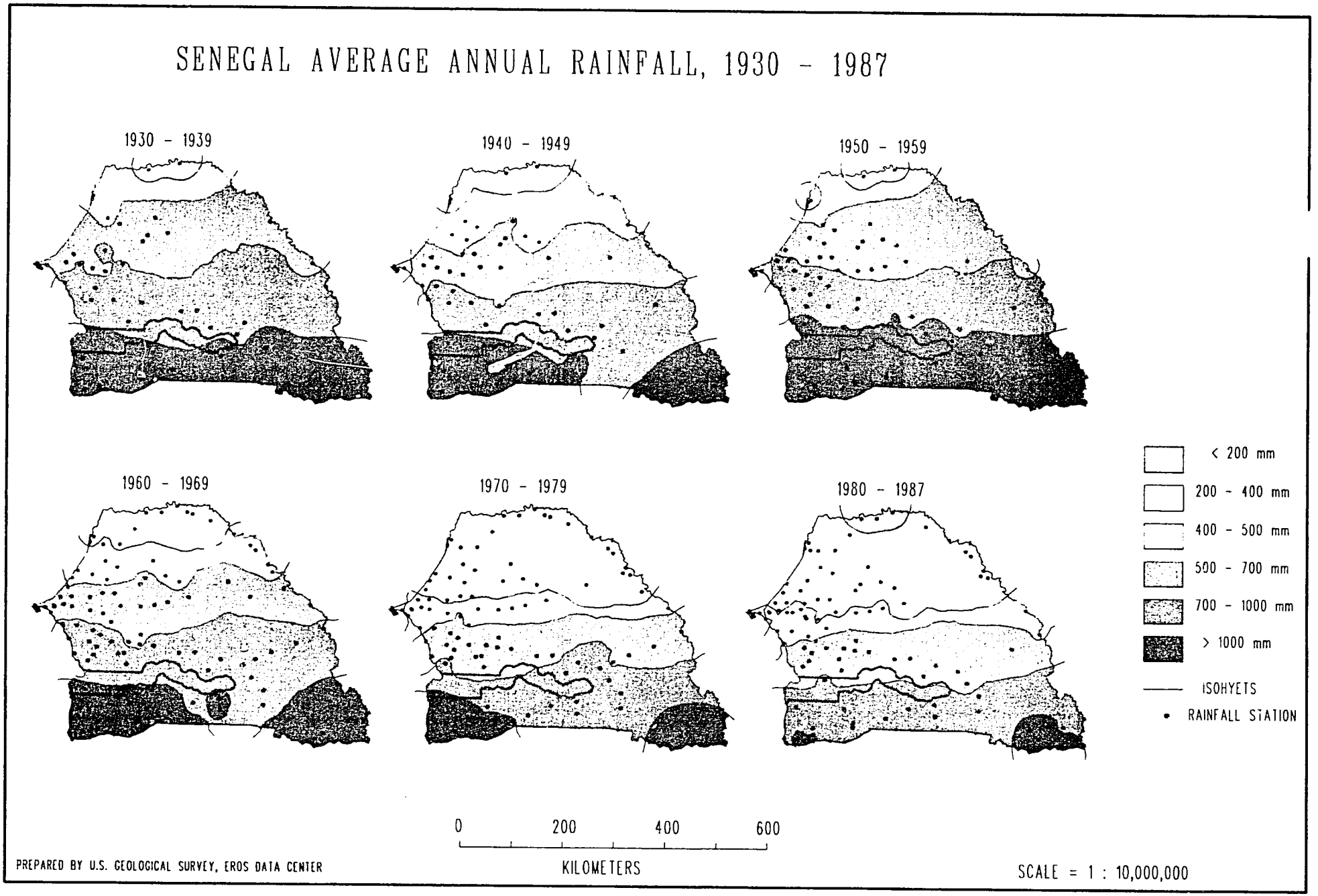

SENEGAL AVERAGE ANNUAL RAINFALL, 1930 - 1987
1930 - 1939
1940 - 1949
1950 - 1959
1960 - 1969
1970 - 1979
1980 - 1987
< 200 mm
200 - 400 mm
400 - 500 mm
500 - 700 mm
700 - 1000 mm
> 1000 mm
ISOHYETS
RAINFALL STATION
0
200
400
600
KILOMETERS
PREPARED BY U.S. GEOLOGICAL SURVEY, EROS DATA CENTER
SCALE = 1 : 10,000,000

Figure 6

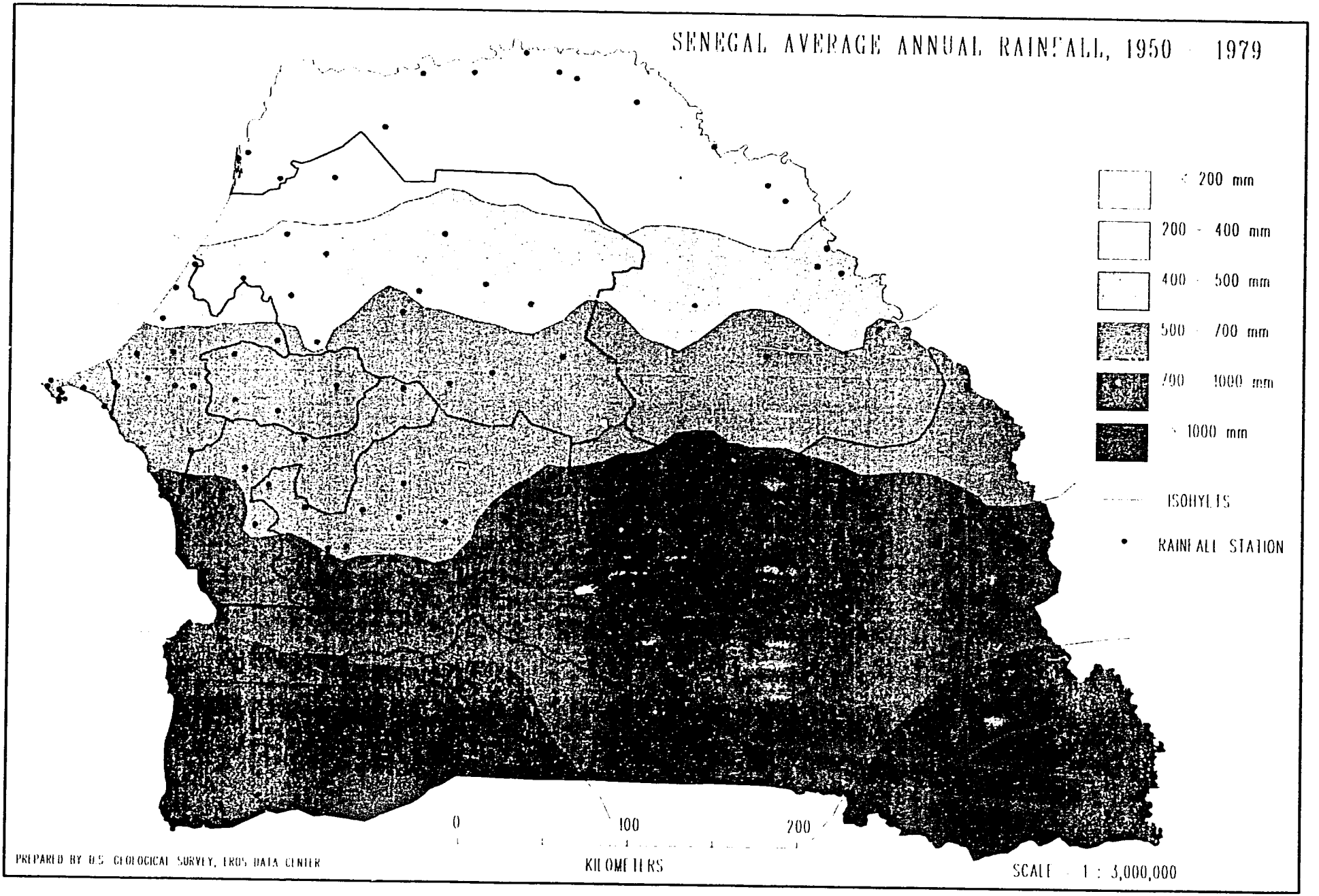

SENEGAL AVERAGE ANNUAL RAINFALL, 1950 - 1979
< 200 mm
200 - 400 mm
400 - 500 mm
500 - 700 mm
700 - 1000 mm
> 1000 mm
ISOHYETS
RAINFALL STATION
0
100
200
KILOMETERS
PREPARED BY U.S. GEOLOGICAL SURVEY, EROS DATA CENTER
SCALE 1 : 3,000,000

Figure 7

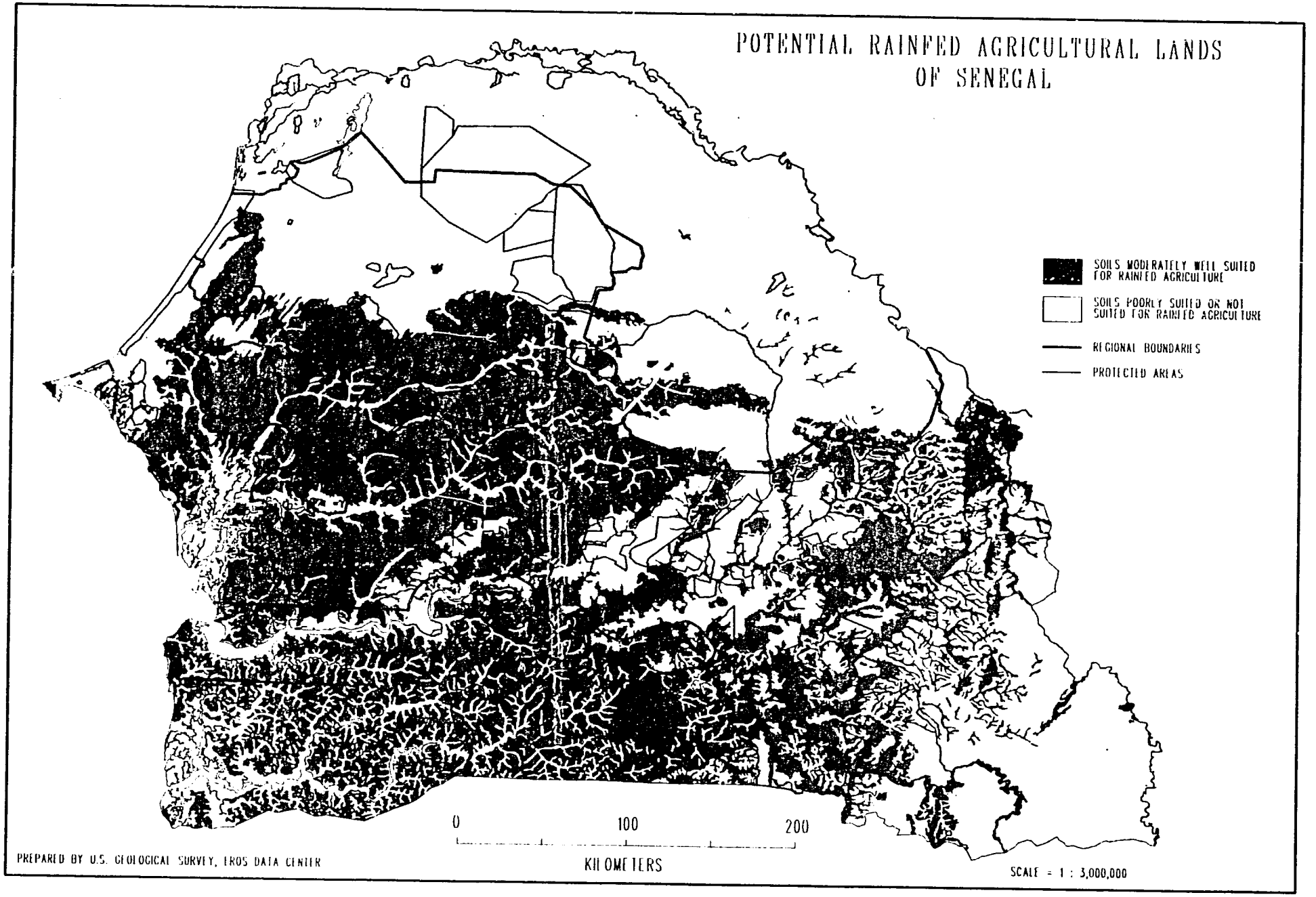

POTENTIAL RAINFED AGRICULTURAL LANDS
OF SENEGAL
SOILS MODERATELY WELL SUITED FOR RAINFED AGRICULTURE
SOILS POORLY SUITED OR NOT SUITED FOR RAINFED AGRICULTURE
REGIONAL BOUNDARIES
PROTECTED AREAS
0
100
200
KILOMETERS
PREPARED BY U.S. GEOLOGICAL SURVEY, EROS DATA CENTER
SCALE = 1 : 3,000,000

Figure 8

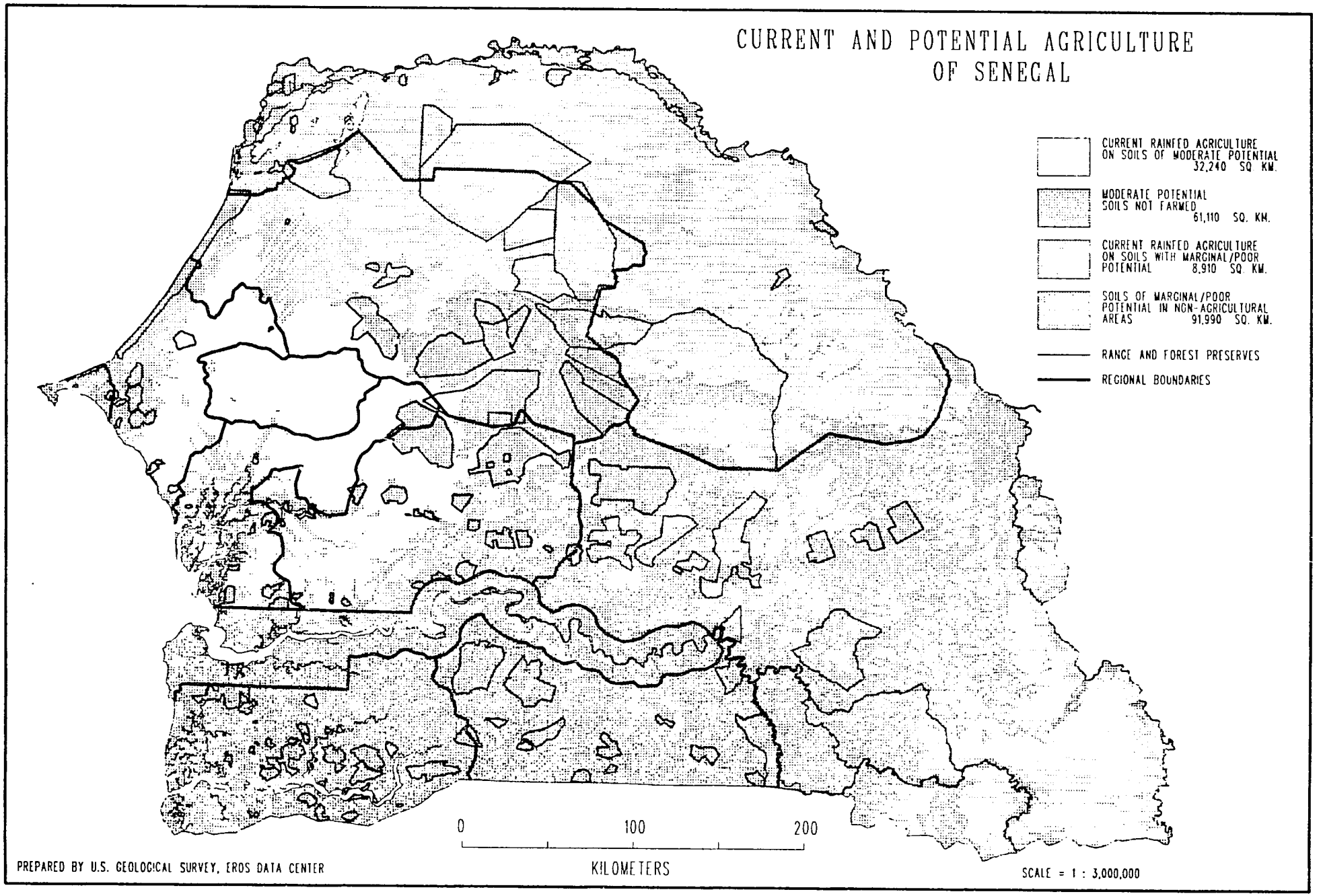

CURRENT AND POTENTIAL AGRICULTURE
OF SENEGAL
CURRENT RAINFED AGRICULTURE ON SOILS OF MODERATE POTENTIAL 32,240 SQ KM.
MODERATE POTENTIAL SOILS NOT FARMED 61,110 SQ. KM.
CURRENT RAINFED AGRICULTURE ON SOILS WITH MARGINAL/POOR POTENTIAL 8,910 SQ KM.
SOILS OF MARGINAL/POOR POTENTIAL IN NON-AGRICULTURAL AREAS 91,990 SQ. KM.
RANGE AND FOREST PRESERVES
REGIONAL BOUNDARIES
0
100
200
KILOMETERS
PREPARED BY U.S. GEOLOGICAL SURVEY, EROS DATA CENTER
SCALE = 1 : 3,000,000

Figure 9

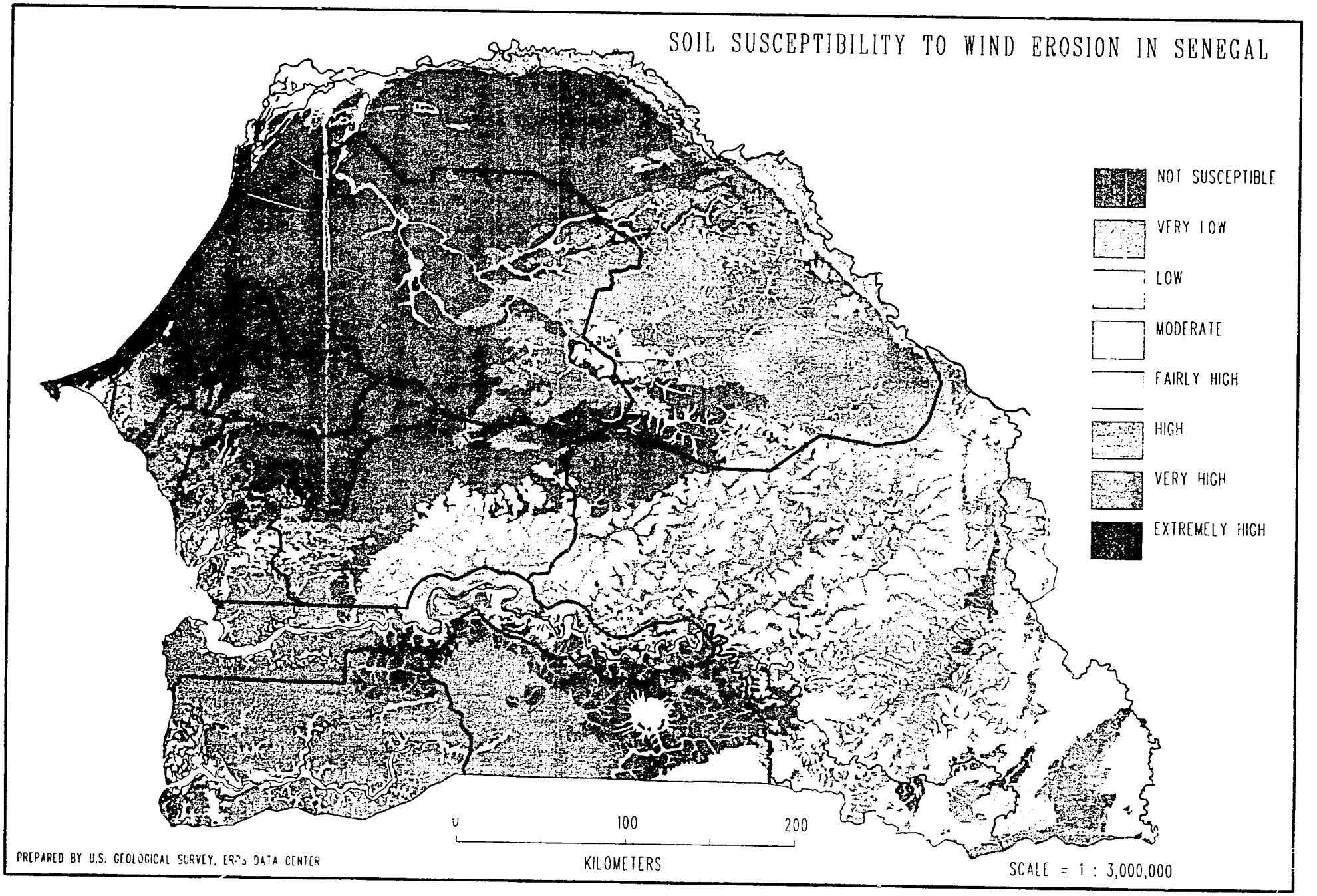

SOIL SUSCEPTIBILITY TO WIND EROSION IN SENEGAL
NOT SUSCEPTIBLE
VERY LOW
LOW
MODERATE
FAIRLY HIGH
HIGH
VERY HIGH
EXTREMELY HIGH
0
100
200
KILOMETERS
SCALE = 1 : 3,000,000
PREPARED BY U.S. GEOLOGICAL SURVEY, ERDS DATA CENTER

Figure 10

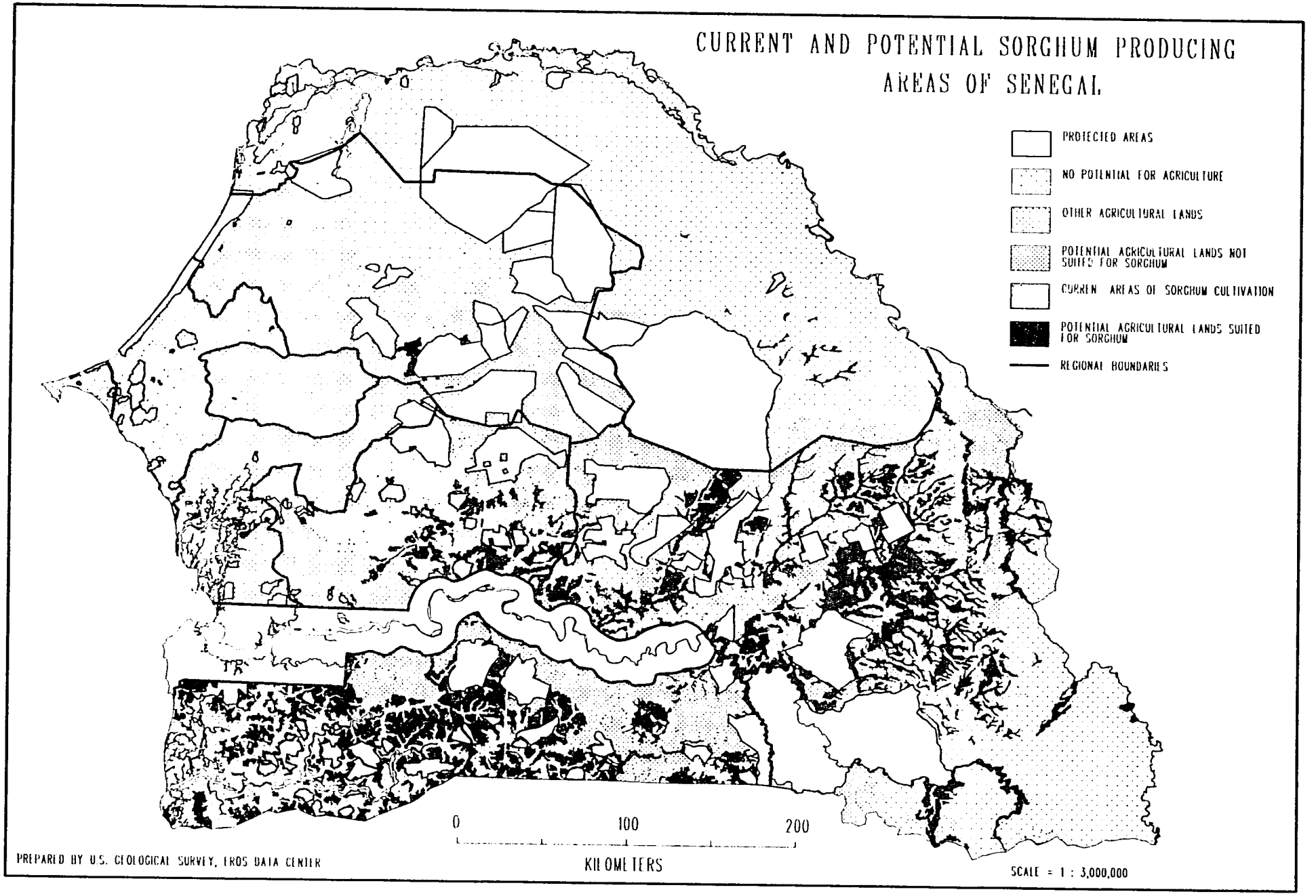

CURRENT AND POTENTIAL SORGHUM PRODUCING
AREAS OF SENEGAL
PROTECTED AREAS
NO POTENTIAL FOR AGRICULTURE
OTHER AGRICULTURAL LANDS
POTENTIAL AGRICULTURAL LANDS NOT SUITED FOR SORGHUM
CURREN AREAS OF SORGHUM CULTIVATION
POTENTIAL AGRICULTURAL LANDS SUITED FOR SORGHUM
REGIONAL BOUNDARIES
0
100
200
KILOMETERS
PREPARED BY U.S. GEOLOGICAL SURVEY, EROS DATA CENTER
SCALE = 1 : 3,000,000

Figure 11

HUMAN CARRYING CAPACITY BY RAINFED CEREAL GRAIN PRODUCTION IN SENEGAL

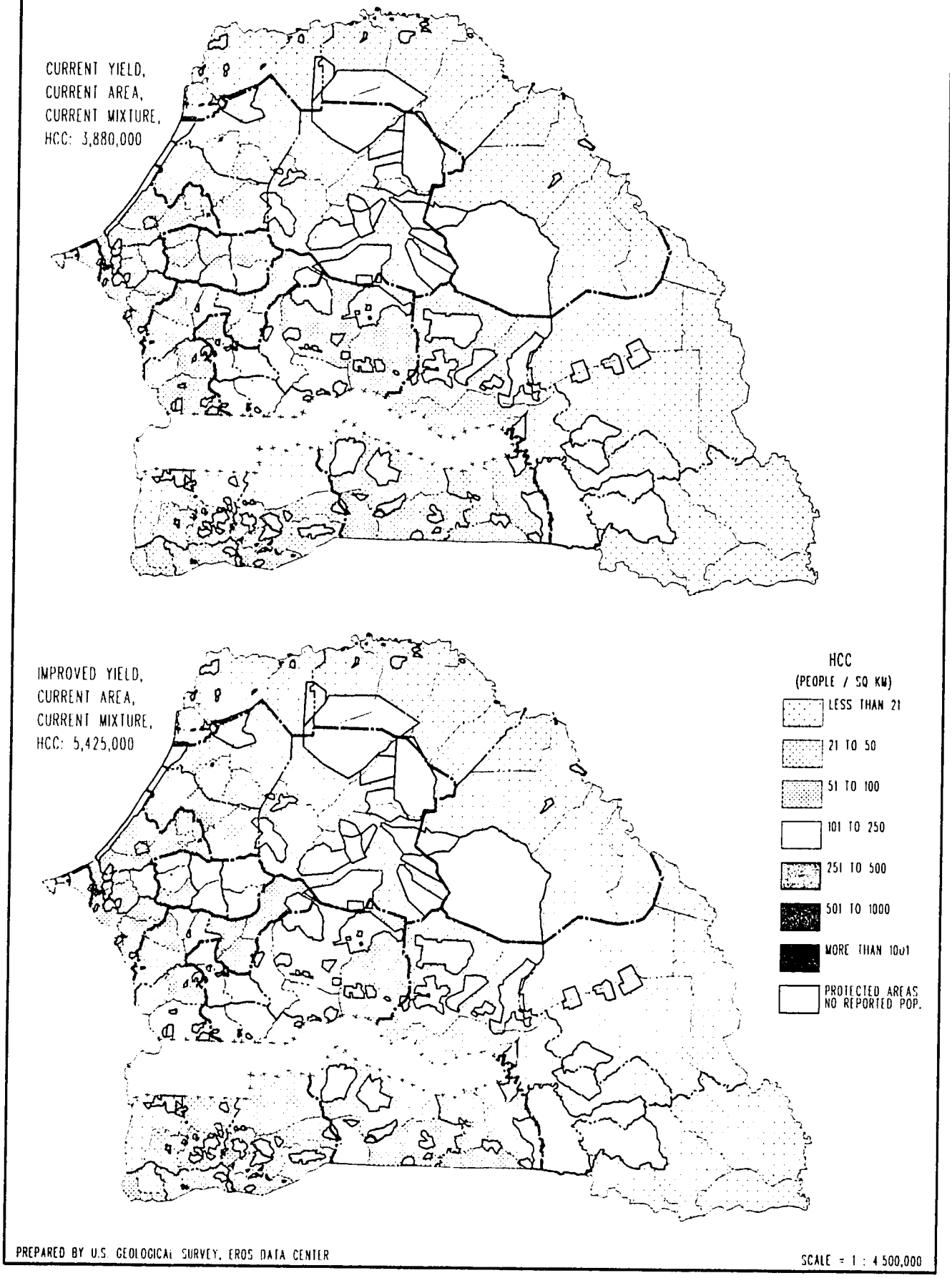


Figure 12a

HUMAN CARRYING CAPACITY BY RAINFED CEREAL GRAIN PRODUCTION IN SENEGAL

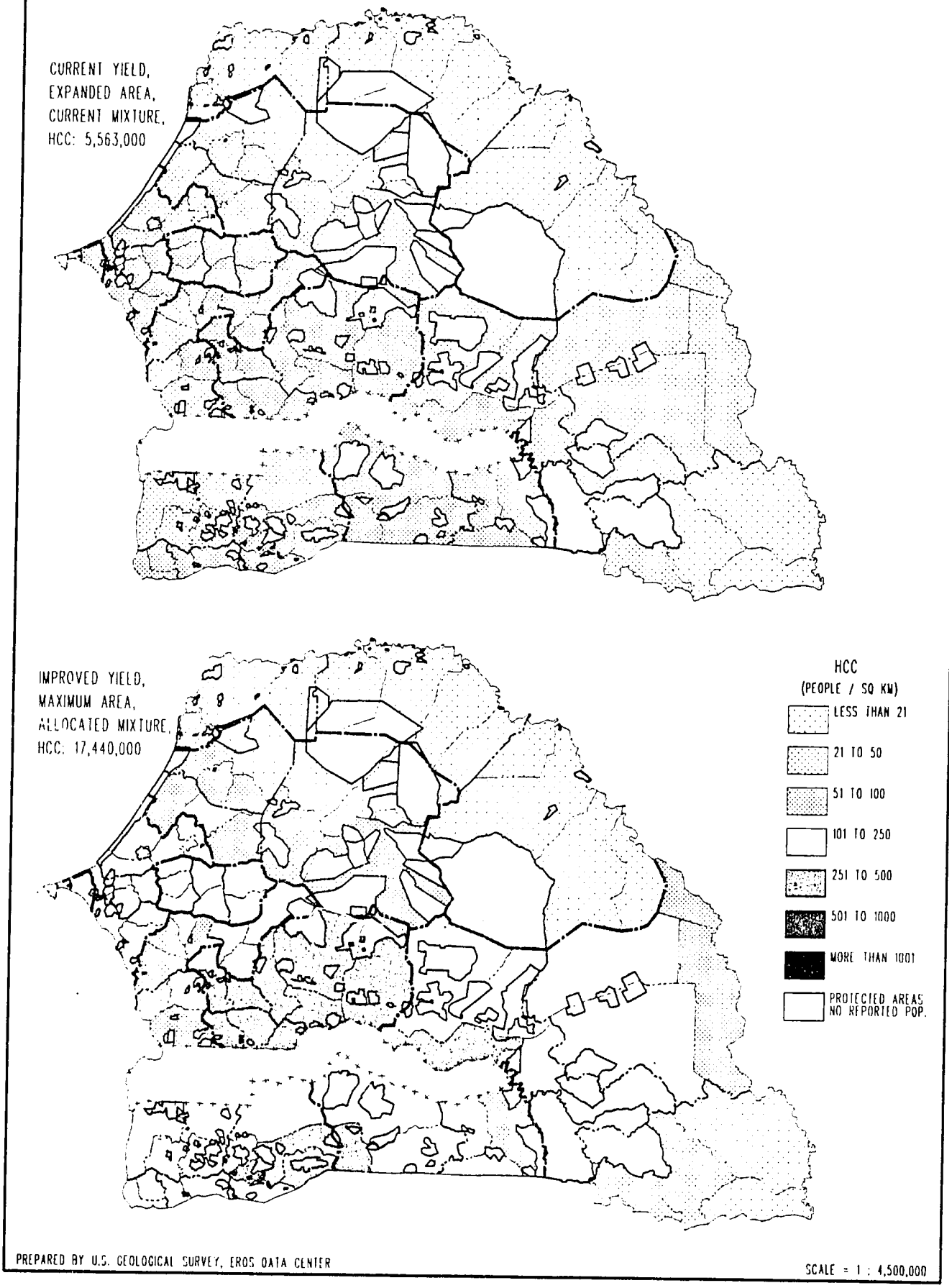


Figure 12b

4.2

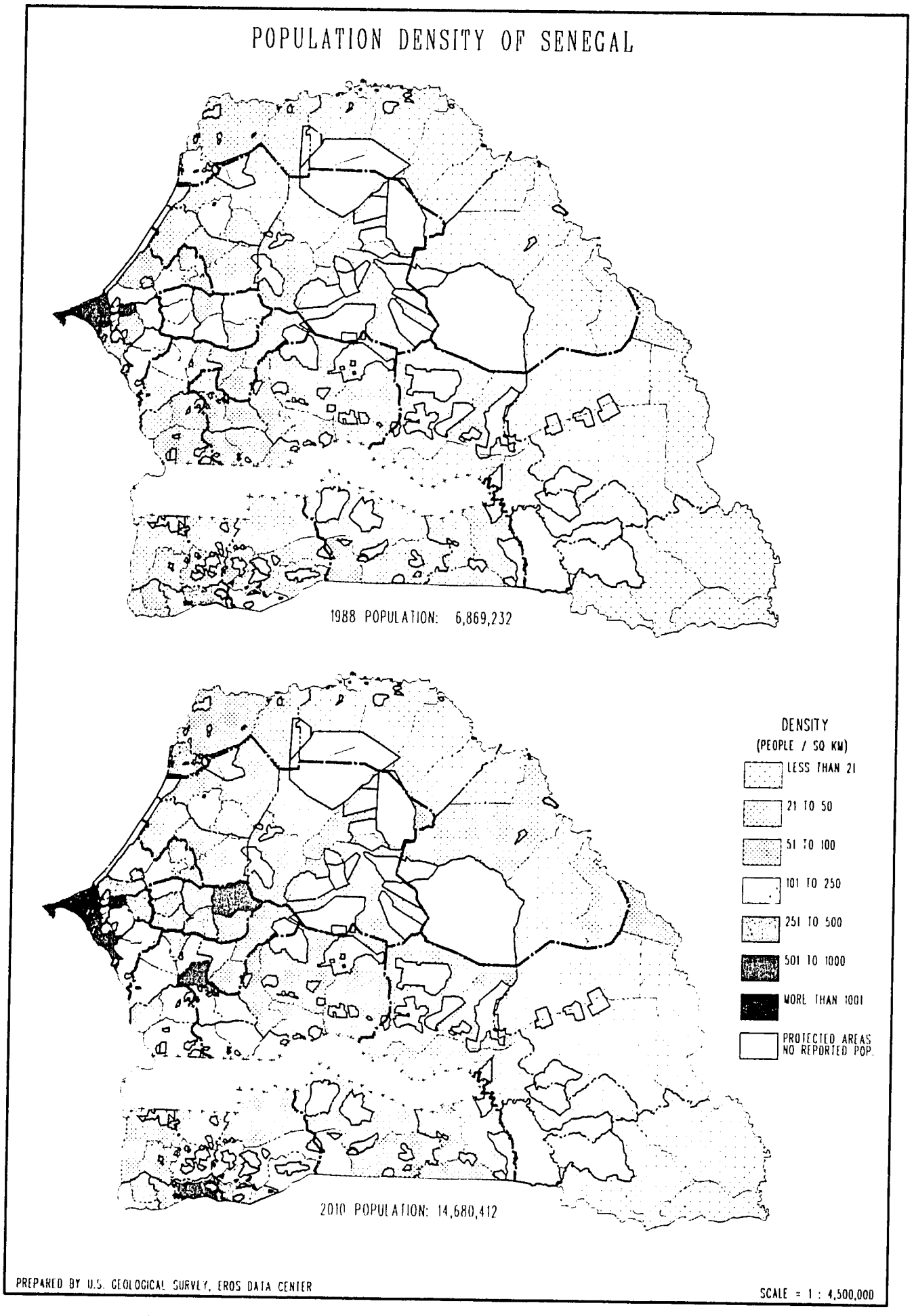


Figure 13a (top); 13b (bottom)

HUMAN CARRYING CAPACITY FROM RAINFED CEREAL GRAIN PRODUCTION RELATED TO POPULATION

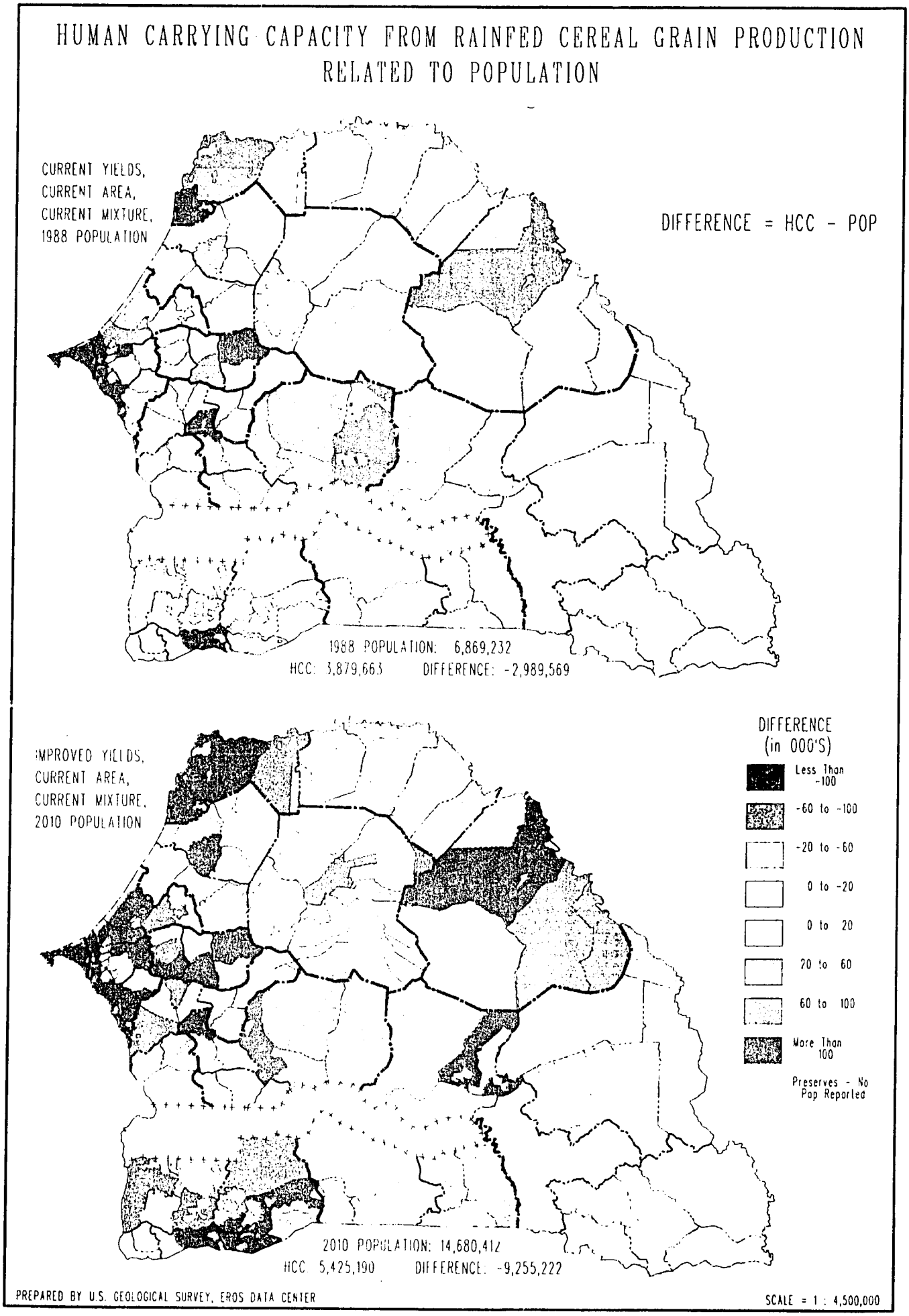


Figure 14a

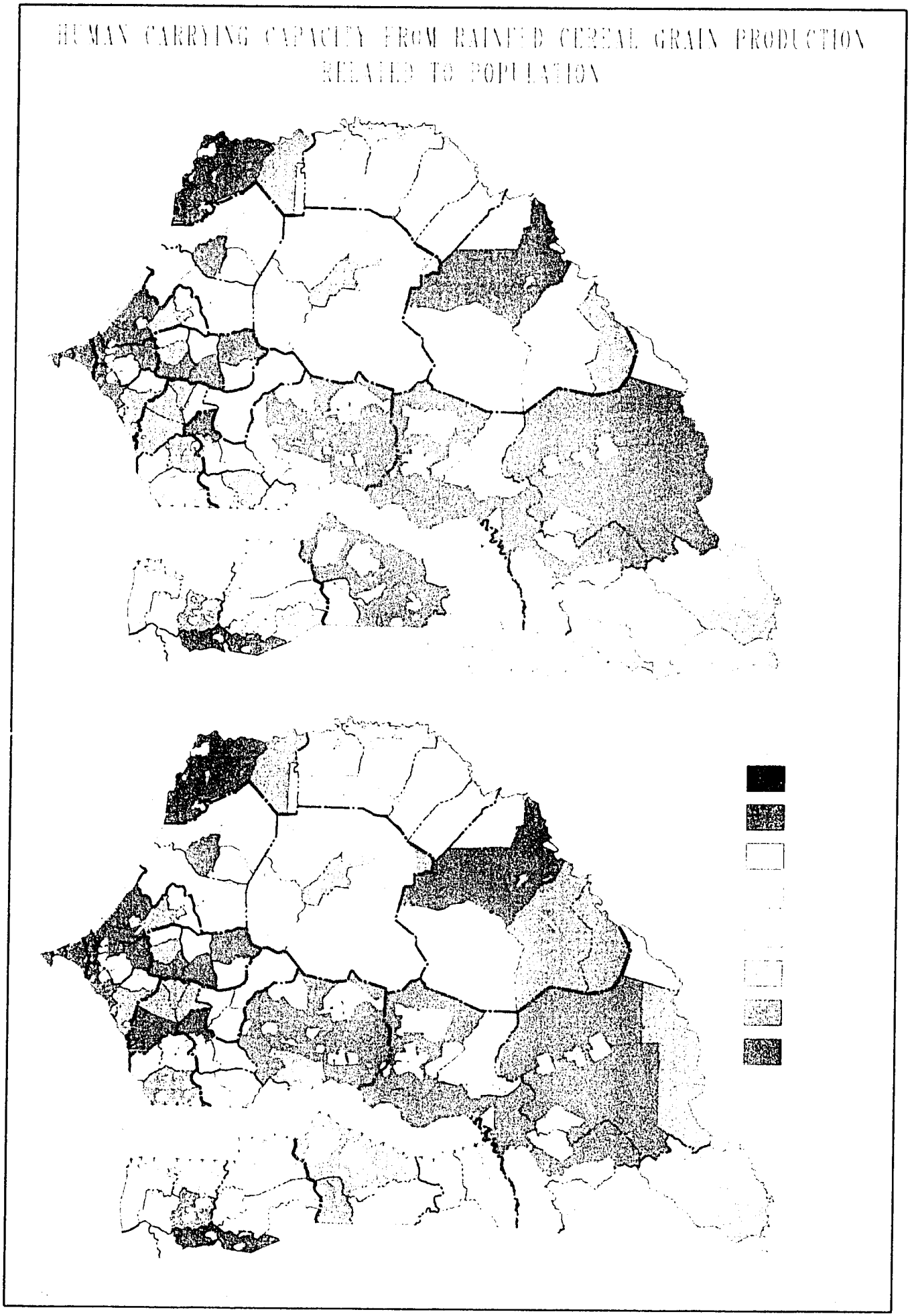

HUMAN CARRYING CAPACITY FROM RAINFED CEREAL GRAIN PRODUCTION
RELATED TO POPULATION

Figure 14b

Table 1. Summary of Development Alternatives and Resulting Human Carrying Capacities

Scenario	GDP-FCFA (000,000's) Cash	Cereal	Total	HCC(a)	DIFF(a,b) (HCC-POP)
1 (cy-ca-cm)	62,589	65,940	128,529	3,880	-2,989
2 (iy-ca-cm)	70,392	91,372	161,764	5,425	-9,255
3 (cy-ea-cm)	85,113	97,233	182,346	5,563	-9,117
4 (iy-ea-cm)	96,293	134,997	231,290	7,785	-6,895
8 (iy-ea-am3)	70,483	170,903	241,386	10,213	-4,467
5 (iy-ea-am1)	127,677	118,724	246,401	7,191	-7,489
6 (cy-ma-am3)	62,671	173,749	236,420	10,341	-4,339
7 (cy-ma-am2)	0	214,317	214,317	13,084	-1,596
9 (iy-ma-am2)	0	284,585	284,585	17,440	2,760

NOTES: Pop 1988 = 6,869; Pop 2000 = 10,540; Pop 2010 = 14,680

(a) all HCC, POP, and DIFF figures in 000's
(b) POP @ 1988 for Diff #1 and @ 2010 for Diff's #2-9

Description of the scenarios:

1 (cy-ca-cm) : Current Yield, Current Area, Current Crop Mixture
2 (iy-ca-cm) : Improved Yield, Current Area, Current Crop Mixture
3 (cy-ea-cm) : Current Yield, Expanded Area, Current Crop Mixture
4 (iy-ea-cm) : Improved Yield, Expanded Area, Current Crop Mixture
8 (iy-ea-am3): Improved Yield, Expanded Area, Allocated Mixture #3
5 (iy-ea-am1): Improved Yield, Expanded Area, Allocated Mixture #1
6 (cy-ma-am3): Current Yield, Maximum Area, Allocated Mixture #3
7 (cy-ma-am2): Current Yield, Maximum Area, Allocated Mixture #2
9 (iy-ma-am2): Improved Yield, Maximum Area, Allocated Mixture #2

where: ea => expansion to non-farmed ag land retains 50% in natural vegetation
ma => expansion to non-farmed ag land retains 15% in natural vegetation
am1 => allocation of both cereal crops and cash crops
am2 => allocation of cereal crops only, NO cash crops grown
am3 => allocation of cereal crops only, with cash crops retaining original areas