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GEOGRAPHIC MODELING OF RAINFED AGRICULTURAL PRODUCTION: SENEGAL CASE STUDY

Paper submitted by the United States of America

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1 Abstract

One objective of the U.S. Agency for International Development (USAID) in Senegal is to support development that will increase private income from natural resources. USAID's portfolio includes projects to diversify and increase rainfed agricultural production (USAID, 1991). Programs such as these are helping increase Senegal's production. Yet Senegal, like most sub-Saharan African countries, is facing a long-term decline in per capita production as population growth surpasses the increase in agricultural production, despite expansion of cultivated land over the past several decades.

The goal of the present study was to conduct a planning-level analysis of the current and potential agricultural production from rainfed agriculture. This study estimated the number of people that could be fed from rainfed production of cereal crops and the value of cash crops produced under a variety of development alternatives. The food production was further related to food need requirements of the current and projected population. The model relies on combining the detailed integrated resource inventory of Senegal and various socioeconomic data.

1/ U.S. Geological Survey.

2/ Hughes STX Corporation. Work performed under U.S. Geological Survey contract 1434-92-C-40004.

3/ Bureau for Africa, Agency for International Development.

4/ USAID/Senegal, Agency for International Development.

2 The Physical, Demographic, and Agricultural Setting

Senegal's topography is relatively flat except for moderate relief in the southeast. Most of the country is geologically a Tertiary sedimentary subsidence basin. Senegal encompasses 196,722 km^2 (NGS, 1990), and 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 semiarid north (with 200 mm of average annual rainfall from 1950-79) and the well-watered south (1,500 mm).

The annual rainfall is almost entirely limited to the summer wet season, which lasts up to 6 months in the south and decreases to 3 months in the north. Like many of its Sahelian neighbors, Senegal suffers from variable rainfall. Although the quantity of rainfall for a certain year may be normal, it can also vary greatly in its time of onset, periodicity, and termination, especially in central and northern Senegal.

The 1988 population of Senegal was estimated 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.

Agriculture is the dominant economic activity, providing employment for about 70 percent of the labor force. It is dominated by rainfed agriculture 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: flood recessional and irrigated agriculture. These are restricted to localized areas (Pélissier, 1983).

Agriculture plays an essential role both in the national food supply and in the national economy. Rainfed agriculture consists of cash crops dominated by groundnuts (peanuts) and subsistence crops dominated by millet and sorghum. Cotton is an additional cash crop, as are maize, rainfed paddy rice, and cowpeas (locally known as <u>niébé</u>) additional food crops, but all grown in lesser quantities.

3 Using a GIS to Analyze Production by Resource Type

Analyses of rainfed agricultural production from various development options requires the integration of physical land and socioeconomic data. Physical land data are used to evaluate the national resource assets and limitations; including soils, vegetation, and climate resources. Socioeconomic data are used to determine the human use of the resource assets and include demographic, farming and land use practices, infrastructure, commodity pricing information, composition of diet, and nutritional requirements. These disparate data types all have a common feature that link them -- they can all be spatially referenced and, thus, can lend themselves to geographic analysis.

A benefit of using a geographic information system (GIS) is that it can be used 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 observe the consequences in both quantity and geographic distribution of the agricultural product.

4 The Model: Estimating Production Outputs

The goal of this study was to develop and apply a model that estimates rainfed agricultural production. Production from rainfed cereal crops is reported as the number of people that could be fed (human carrying capacity) and from cash crops as the value of production at local markets (gross domestic product). The study did not consider the cost of production inputs to complete a cost-benefit analysis. The first step of the analysis was to determine what potentials existed within the country under sustainable agricultural practices. Additional steps beyond this study will be required to determine which alternatives would be financially feasible and cost effective.

Human carrying capacity (HCC) was defined as the total annual caloric production of a given agricultural area divided by the annual human caloric consumptive needs. The minimum per capita daily consumption requirement of 2,300 calories per person (Cogill, Marzilli, and McNabb, 1989), with 80 percent (1,840 calories) from cereal grains, was used for this study.

Gross domestic product (GDP) was defined as the value of cash crops in a given geographic area as sold at the local markets.

There are essentially three approaches to increasing production: (a) increase crop yields through improved technology, (b) expand or intensify the area under cultivation onto arable soils, and (c) change the crop species composition to maximize the production of calories and/or cash. Many approaches were investigated, singly and in combination, with all requiring a number of qualifying assumptions for constructing the analytical framework.

5 Data Sources

Figure 1 presents an overview of the data sources, the processes used to integrate and analyze the data, and the resulting products. The primary data include:

1. Soils data were essential because of their importance in determining any limitations to crop growth. The study used results of a soil survey (Carte Morpho-Pédologique du Sénégal) at a scale of 1:500,000 (Stancioff, Staljanssens, and Tappan, 1986). The data included supporting soil attribute data (examples are slope, soil depth, and texture). Figure 2a shows the spatial complexity of the soils map coverage. Approximately 184 different soil associations were mapped, represented by 3100 map polygons.

2. The study considered the current extent and condition of natural and cultivated vegetation, based on the Carte du Couvert Végétal, at 1:500,000 scale (Stancioff, Staljanssens, and Tappan, 1986). The vegetation map represents a physiognomic classification of vegetation types, using the "Yangambi" convention for nomenclature of tropical African vegetation (Trochain, 1957; Monod, 1963). The map also delineated official forest and rangeland preserves. The land use data defined the location and extent of lands currently used for rainfed agriculture. The vegetation map has a polygon density similar to the soils map in fig. 2a.

3. Rainfall is a primary factor for supporting vegetation growth in the West African environment. Rainfall also plays a primary role in determining which crops can grow where. The rainfall data were provided by the regional AGRHYMET (Agriculture-Hydrology-Meteorology) Program. An averaged baseline period of 1950-1979 was used (fig. 2b).

4. Demographic data were based on preliminary results from the 1988 census (République du Sénégal, 1988). These data were used to estimate current and projected populations.

5. Senegal is divided into a hierarchy of political divisions. This study incorporated data reported at the fourth level in the hierarchy: the arrondissement. Many of the final results were presented at this relatively detailed level. Administrative boundaries were digitized from the official Government of Senegal (GOS) map.

6. The agricultural data included crop production statistics, commodity prices, milling rates, and postharvest losses. These 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.

7. Health data required by this analysis were limited to human consumption caloric requirements and dietary composition. These data result from a USAID Food Needs Analysis (Cogill, Marzilli, and McNabb, 1989).

8. Several types of polygonal, linear, and point data were integrated into the final maps to serve as geographic references to the thematic maps. These included roads, cities and towns, rivers, lakes, and geographic tic marks.

6 Methodology and Analysis

Intermediate steps were taken to derive the final production estimates.

6.1 Location of Current Rainfed Agriculture Lands

One of the first tasks was to answer the question: Where does rainfed agriculture currently occur in Senegal? The approach was to search through the polygonal vegetation coverage to identify the rainfed agriculture polygons. Polygons that included agriculture were assigned one color code. All remaining polygons were assigned a second color code. The result was a new map that shows the current rainfed agriculture lands in Senegal (fig. 3).

6.2 Determination of Average Annual Rainfall

A long-term average of annual rainfall, from 1950 to 1979, was used (fig. 2b). It incorporates the relatively wet 1950's and 1960's with the dry 1970's. The present study focuses on the 400 mm and 500 mm isohyets. The 400 mm isohyet was adopted for the present study to delimit the minimum threshold for rainfed agriculture in Senegal.

6.3 Potential of Rainfed Agriculture Based on Soils

The next step was to determine soil potential for supporting rainfed crops. All parameters of each soil association were examined in conjunction with known data on climatic and rainfall regimes in Senegal. Each soil was rated for its suitability to support general rainfed cultivation. In general, all crops do well on soils that are nearly level or gently rolling, deep, medium textured, and supplied with nutrients (Westin, 1990). If any one parameter posed a major limitation to crop development, the soil was classified as less than moderately suited. The interpretation was then tailored to the specific differences of the five food crops and two cash crops. If the soil had a particular limitation for any specific crop, it was noted.

6.4 Potential of Rainfed Agriculture Based on a Combination of Soils and Climate

An evaluation was made regarding the geographic distribution of specific crops based on rainfall requirements. To be considered moderately suited for agriculture, a soil must receive at least an average of 400 mm of rainfall. The northern extent of rainfed cultivation in Senegal (and throughout the Sahel) generally corresponds to the 400 mm average annual rainfall isohyet (see fig. 2b). While there are many suitable soils in the northern quarter of Senegal, they are excluded from consideration for potential rainfed cultivation because of moisture limitations. The map of potential rainfed agricultural lands (fig. 4) represents an integration of the soils and rainfall characteristics.

Crop specific rainfall limitations used by the model were: 400 mm as the lower limit for groundnuts and millet, 700 mm for sorghum, 800 mm for maize, 1000 mm for rice, and a range of 400 to 700 mm for cowpeas. Certainly these lower limits can be exceeded in certain circumstances, but in general they represent the bounds of crop adaptability.

6.5 Current and Potential Agricultural Land Use

A comparison was made of the previous two 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 a map showing the current and potential rainfed agriculture lands (fig. 5). The map shows four land use situations: (1) lands currently cultivated; (2) lands of potential cultivation; (3) lands currently cultivated on soils of less than moderate potential; and (4) lands not cultivated with little potential for cultivation.

6.6 Current and Potential Distribution of Specific Crops

One of the final analyses required before computing potential production 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 in 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 (Traoré, 1983).

The first task was to determine the current sorghum producing areas 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 noted, thereby identifying current production areas. 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. Potential areas for production were defined by favorable soil and climatic regions. Soils were limited to those having at least a moderate agricultural potential. The distribution was further limited to the north by the 700 mm isohyet. Finally, the range and forest preserves were intersected with the preceding coverages to exclude those areas from potential production.

The final step was to merge the current and potential sorghum map coverages into a final map showing the current and potential sorghum producing areas (fig. 6). The procedures followed for sorghum were repeated for the other crops addressed in the model.

6.7 Computing Production from Rainfed Agriculture

At this point, the following questions needed to be answered. What is the estimated production from current rainfed agriculture? What is the potential production under different production alternatives? What is the geographic distribution of both? Each analysis of production needed to be estimated as HCC for cereal crops, and GDP for cash crops.

6.7.1 Crop Production

Current crop production was derived from averaged crop reporting statistics. 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) was determined as the yield times the cropped area, computed by agricultural polygon and aggregated to administrative subdivisions.

Production figures for each crop were adjusted using postharvest loss, milling rates, and retained seed amounts. The model assumes a postharvest loss factor of 15 percent per food crop. Milling rates of 0.82 (times the production) 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 per hectare 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 3,300 calories per kg for millet and sorghum, 3,680 for maize, 3,530 for whole grain paddy rice, and 3,420 for cowpeas (Cogill, Marzilli, and McNabb, 1989). The cash value of each crop was determined by multiplying producer prices (local market selling price in CFA Francs (FCFA) per kilogram times the production in kilograms. The prices used were average prices of all reporting markets for the period October 1989 through July 1990.

6.7.2 Crop Yields

Crop yields were derived from averaged 1986-89 arrondissement crop statistics (République du Sénégal, 1987, 1988, 1990). For the expanded area of cultivation options, yield figures were taken from the 1986-89 averages of adjacent arrondissements having similar rainfall.

The 1986-89 averaged crop yields were 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 yields (1986-89). The high yield figures were based on data from the Institut Sénégalais de Recherche Agricole (ISRA), which provided yields for high, medium, and low levels of technology applications for an average rainfall year (Martin, 1988).

6.7.3 Cropped Area

The current cropped area is based on the averaged area reported in their crop reporting statistics at the arrondissement level. Cropped area for the expanded area option was computed in three steps. (1) Determination of the total area of polygons suitable for crop production. (2) Retention of 50 percent of the land in natural vegetation and local infrastructure to preserve biodiversity. (3) Computation of the actual area that can be cultivated by applying a fallow factor of 50 percent by area in each polygon. The result is that only one quarter of the area of the polygon would actually be cultivated in any given year (one-half saved for biodiversity and one-half of the remainder under cultivation). This fallow factor was determined from aerial photography and by relating current crop statistics to amounts of arable land. The 50 percent factor is common throughout Sahelian Africa.

6.7.4 Crop Mixtures

Current crop mixtures were determined using the reported crop statistics. Projected crop mixtures (referred to as allocated mixture) were varied in different options. One allocated the mixture to growth of only cereal crops. Another optimized the mixtures for caloric production, where the highest caloric production crop that could be grown was allowed to be 75% of the crop, with the remaining 25% of the crop the second highest caloric producer.

6.7.5 Population Projections

The 1988 GOS census reported a population of 6,869,232. Since development of the agricultural potential would take many years, a future population projection was also used in comparison. A projection for the year 2010 was conducted by the U.S. Bureau of Census as 14,680,000 total population (BUCEN, 1990). Density of population was computed by dividing the area's population by area of land less any protected areas.

7 Results

Nine different model estimates were prepared. Table 1 reports these according to development alternative.

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: Population in 1988 = 6,869; Population in 2010 = 14,680

(a) all HCC, Population, and Difference figures in 000's
(b) Population at 1988 for Diff #1 and at 2010 for Diff nos. 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-ma-am1) : improved yield, maximum 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 nonfarmed ag land retains 50% in natural vegetation
ma => expansion to nonfarmed 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

8 Population Density Related to Human Carrying Capacity

The final phase of the model examined the question: What is the relation of the estimates of HCC to the current and projected population of Senegal? This is the fundamental issue - relating HCC from rainfed agriculture to the realities of today and tomorrow.

The model computed the distribution of HCC for each development alternative (fig 7). It 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 final step compared the current (1988) population (national total estimated at 6,869,232) and the projected (2010) population (national total projected to be 14,680,412) with the human carrying capacity scenarios. The comparison was achieved by computing the difference between human carrying capacity and current and projected population, by arrondissement. Maps were prepared (not shown here) illustrating where the human carrying capacity exceeds population (surplus production) and, conversely, where population exceeds human carrying capacity (deficit production).

9 Conclusions

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. Despite scenarios for improving yields, or significantly increasing the area cultivated, population growth quickly outpaces the respective increases in carrying capacity, resulting in arrondissement populations that exceed production capacity over most of the country. According to the projections, at the national level, the 2010 population (14,680,412) will exceed the improved yield and expanded area carrying capacity scenarios (5,563,00 and 5,425,200) by over 9,000,000 people. The food gap widens greatly from the current situation. Only in the unrealistic scenario of improved yield, maximum area, and allocated mixture does food production keep ahead of the 2010 projected population.

Results of this study point to a serious situation if the present population growth rate continues. The statistics show population growth rapidly outstripping the country's ability to produce enough food. Carrying capacity figures are restricted to the cereal grains production sector and do 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, and so on. Secondly, revenues from the rainfed cash crops must be used to purchase food.

The study highlighted two important facts: (1) unused arable land still exists in Senegal in significant quantities (largely in the more humid southern half of the country), and (2) improved farming technologies exist that could be applied to increasing food production.

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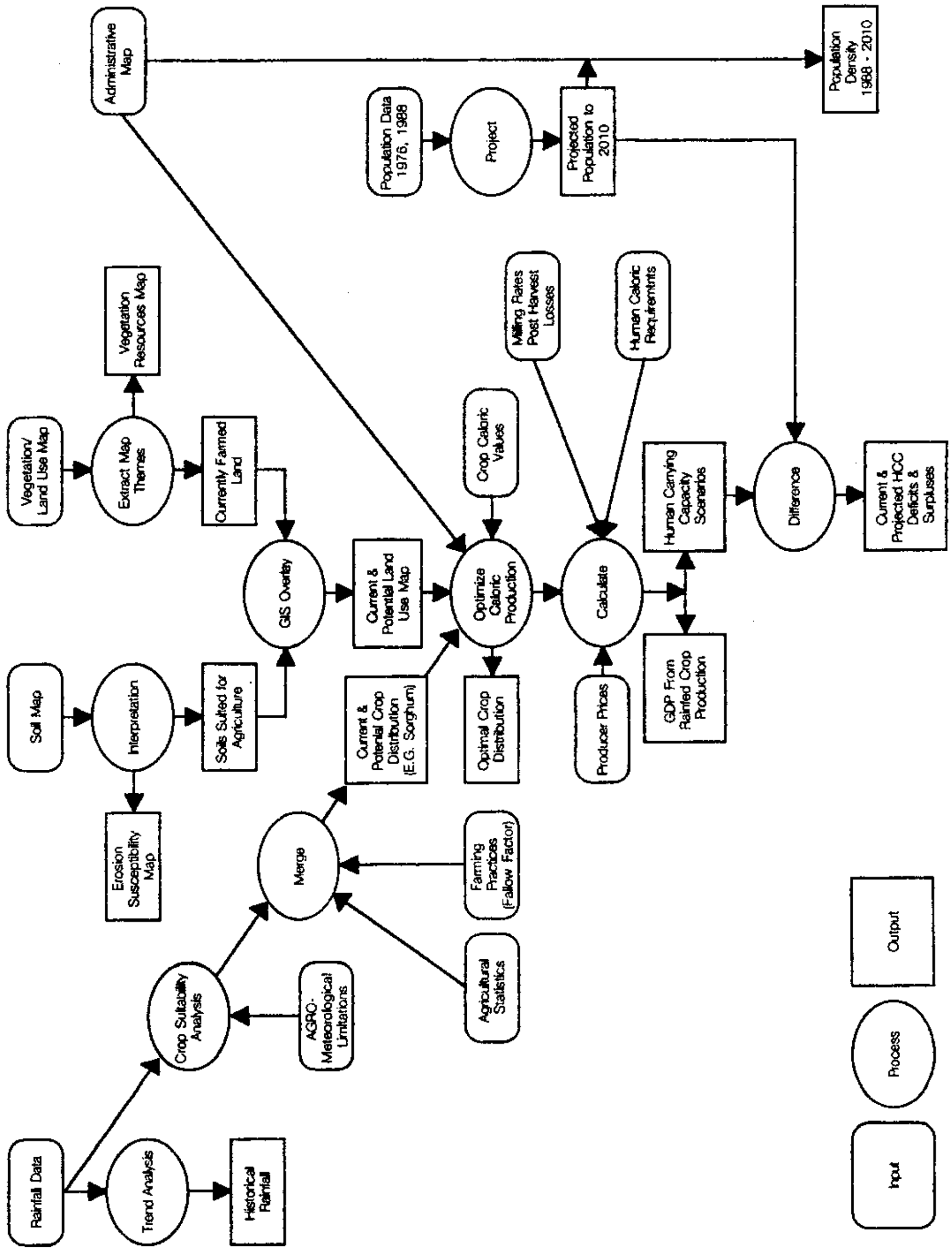
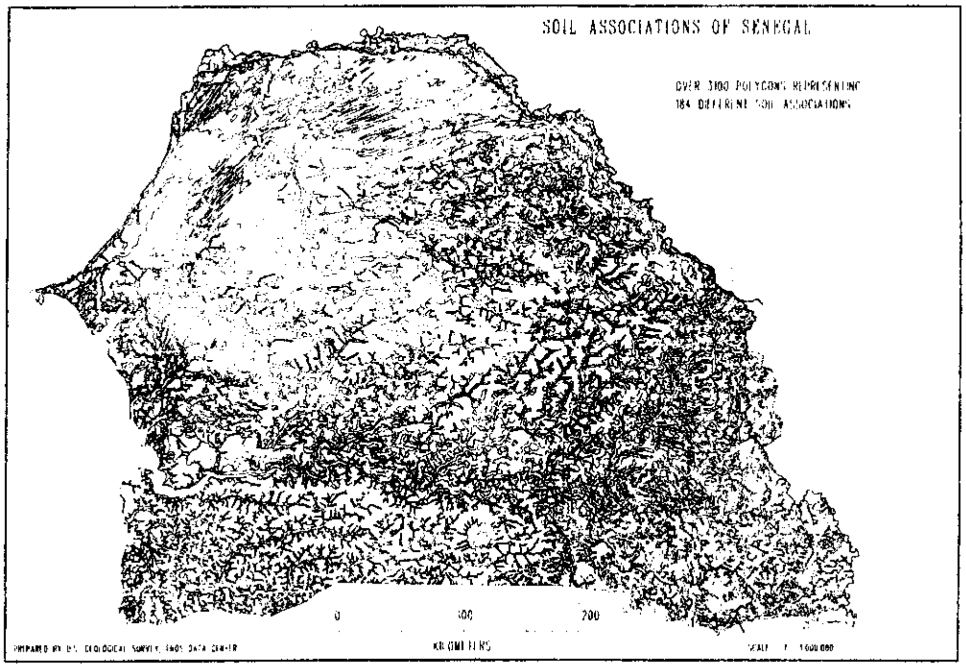


Figure 1.- Human carrying capacity processing algorithm.



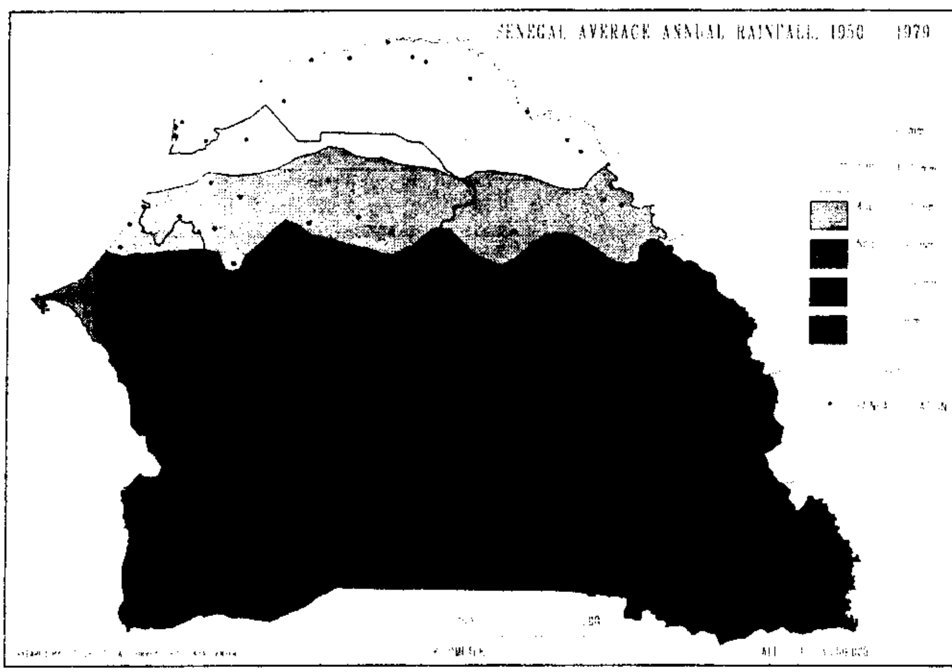
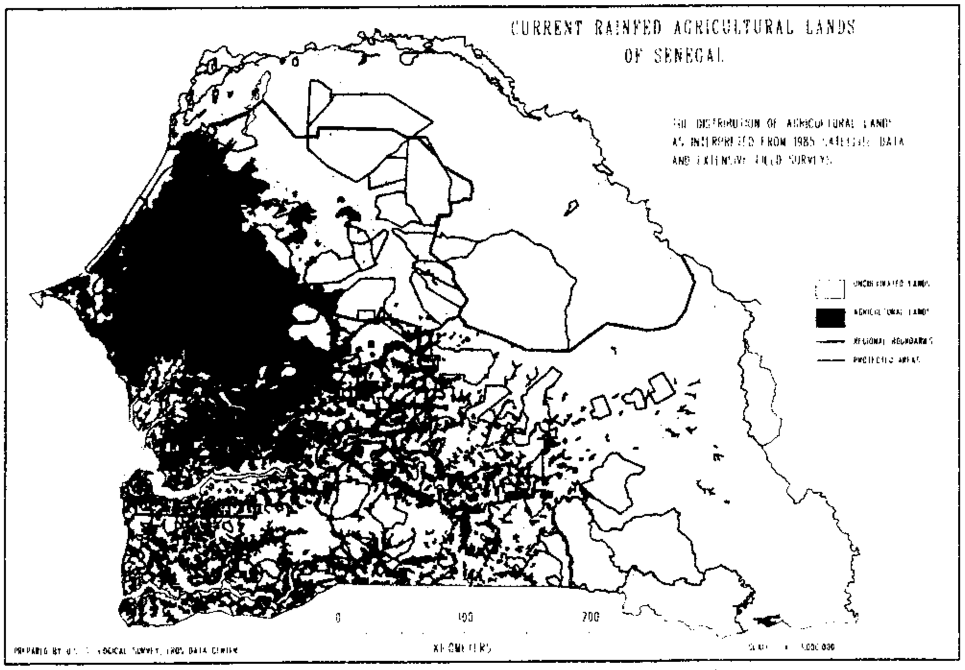


Figure 2a.--Digital soil map of Sengal

Figure 2b.--Average annual rainfall for the period 1950-1979



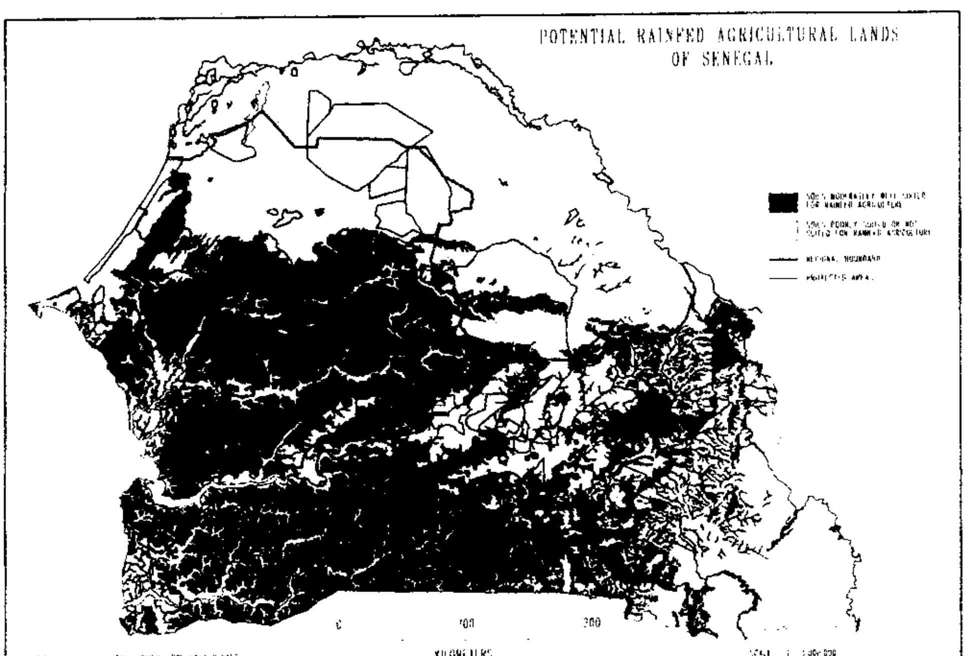
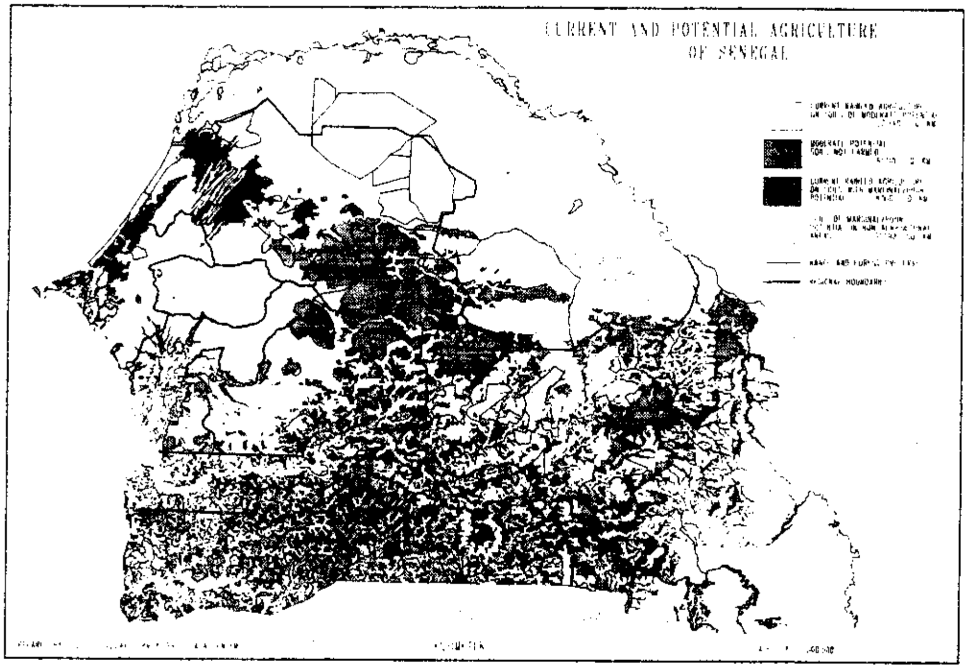


Figure 3.--Current rainfed agricultural lands of Senegal

Figure 4.--Potential rainfed agricultural lands of Senegal



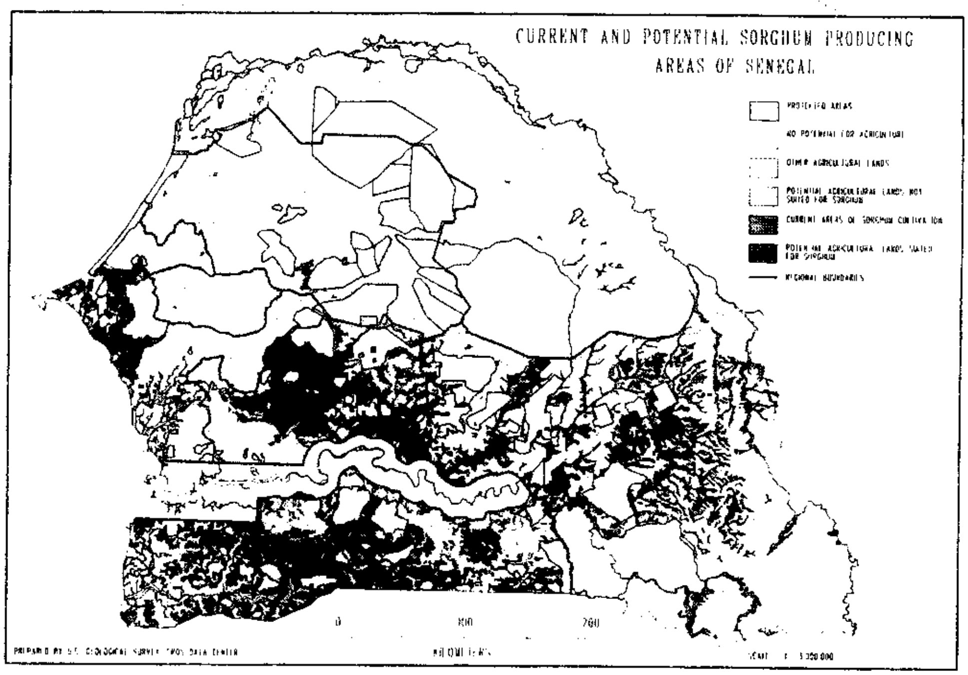


Figure 5.--The current and potential agriculture of Senegal

Figure 6.--Current and potential sorghum producing areas of Senegal

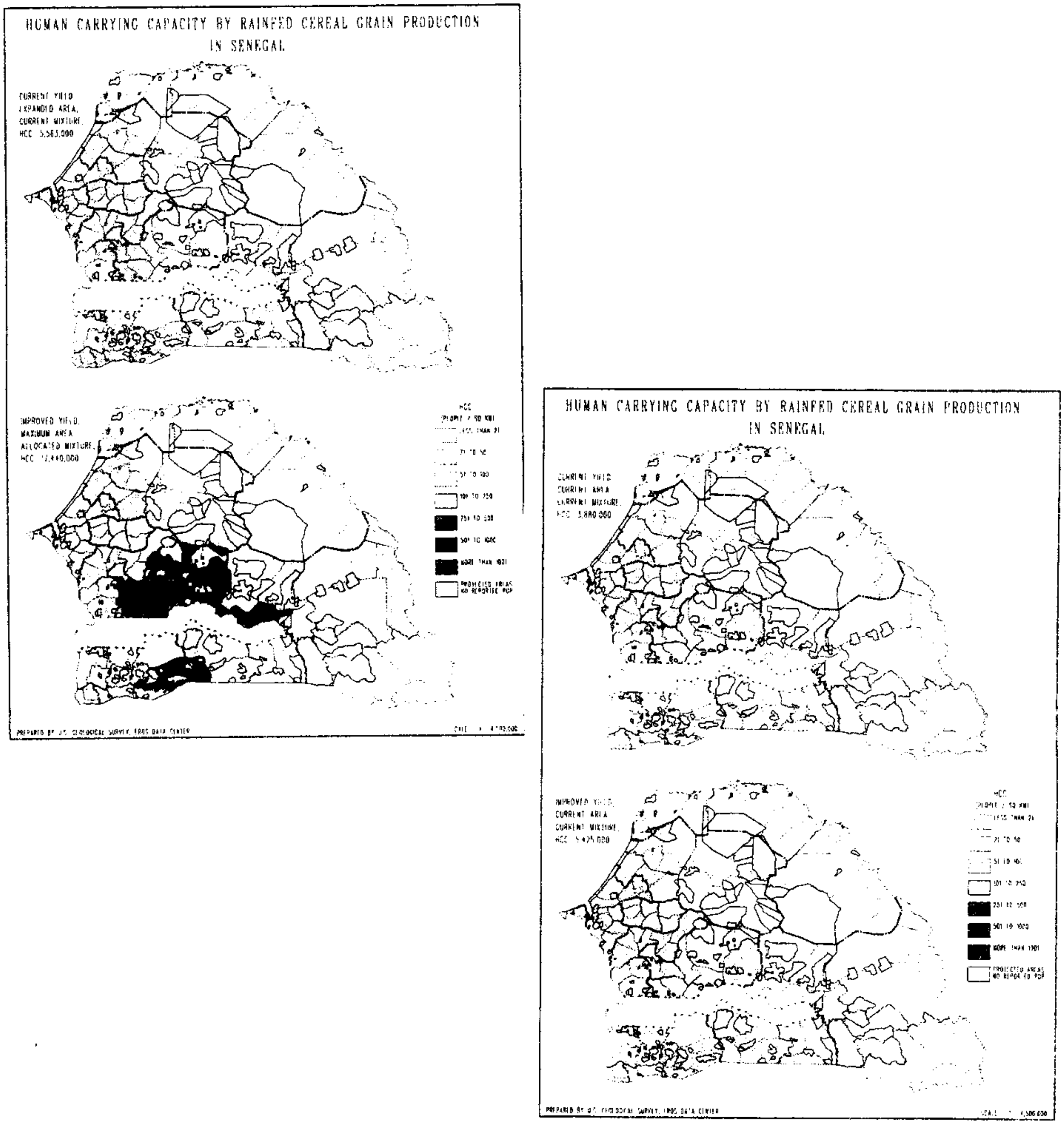


Figure 7.--Human carrying capacity geographic distribution resulting from various development alternatives