Modelling the Land Production Potential for Maize in North-West Cameroon Using GIS

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Abstract

A crop growth model is integrated with a geographical information system (GIS) in order to predict the rainfed maize production potentials in the North-West Province of Cameroon at three hierarchically ordered production levels. The modelling is designed to use generalised crop phenology, statistical climatic averages, and soil information made available by a detailed reconnaissance soil survey. Calculation of the production potential is performed at the level of individual raster cells and the results can be displayed on a digital elevation model (DEM), permitting a visual interpretation of the relations between physiography and maize performance. A combined application of a crop growth model and GIS can be a very useful tool in resource mapping and agricultural planning at regional scale.

Résumé

Un modèle de croissance de culture est intégré à un Système d'Informations Géographiques (SIG) dans le but de prédire les productions potentielles d'une culture pluviale de maïs dans la province du Nord-Ouest Cameroun, à trois niveaux de production hiérarchisés. Le modèle est conçu de manière à utiliser les caractéristiques phénologiques générales de la culture, les moyennes statistiques des données climatiques, et des informations relatives aux sols, acquises au cours des travaux détaillés de reconnaissance et d'inventaire des ressources en sol. Le calcul de la production potentielle est fait individuellement au niveau de chaque cellule raster et les

résultats pourront être présentés sous forme d'un modèle numérique de terrain (MNT), permettant une interpolation des relations entre la physiographie et les performances du maïs. Une application combinée d'un modèle de croissance et du SIG peut constituer un outil très utile en inventaire des ressources et en planification agricole à l'échelle régionale.

Introduction

In developing countries, land evaluation as a basis for land-use planning is often undertaken for fairly large areas. Unfortunately, in these countries, the climate and soil data required to estimate land productivity for selected crops are not always available. Land evaluation involves the process of deriving suitability maps to meet users' requests for special purpose information. The strong moves towards quantifying the land evaluation process in recent years have concurred with the development of Geographical Information Systems (GIS). This quantification consists of linking the climatic and soil information databases to crop models simulating production potentials.

Different empirical modelling approaches to predict land productivity for crops under a wide range of weather and soil conditions have been described (e.g. FAO, 1978; DE WIT and VAN KEULEN, 1987; THOMASSON and JONES, 1991; TANG *et al.*, 1992; DAROUSSIN *et al.*, 1993). Most of these models are designed to use available climatic and soil information as statistical averages and generalised crop phenology. Several hierarchically ordered production situations are distinguished in such a way that the results of simulations on one hierarchical situation are used as input for the calculations of another. A production situation is a hypothetical land-use system, with one or only a few relevant land characteristics and/or land qualities. Land characteristics and/or qualities not considered in the definition of a production situation are assumed not to constrain the performance of the system, and the production calculated is not the actual production but the production potential.

Handling the variability in climatic conditions and in soils can be approached through the use of GIS. GIS are a set of computer tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world (BURROUGH, 1986). Using the GIS technique, it is possible to produce thematic maps, as an output, with information on the impact of differences in climate and soils on land productivity for a specific crop.

Climatic and soil profile data are often stored in relational databases, whereas the spatial distribution of soil mapping units (polygons) is often stored in topological vector form or raster form, depending on the applied software. GIS software, with its ability to classify soil polygons or pixels according to the attributes held, can perform many functions in the land evaluation process (BURROUGH, 1991).

This paper describes the use of the GIS technology in a study on the variation of potential crop production at a regional scale, using information made available by a detailed-reconnaissance soil survey. This is exemplified by the integration of a GIS and a crop growth model, which is used for estimation of maize production potential under varying climatic and soil conditions.

Physiography of the study area

The study area is situated in the North-West Province of Cameroon, just south the Nigerian border and covers the large central part (10,750 km²) or 60% of the Province (Fig. 1). Geomorphologically, the area has a staircase configuration dominated by high lava plateaus (several compartments with altitudes between 1,500 and 2,200 m) around the central volcano, Mount Oku (3,011 m). These high plateaus are surrounded by steep mountains, hills and more or less dissected planation surfaces, generally at lower levels (between 250 and 1,400 m altitude), on basement rock. Locally, recent volcanic ash deposits are present on top of the residual weathered materials. In many places, impressive escarpments separate the plateaus and the planation surfaces.

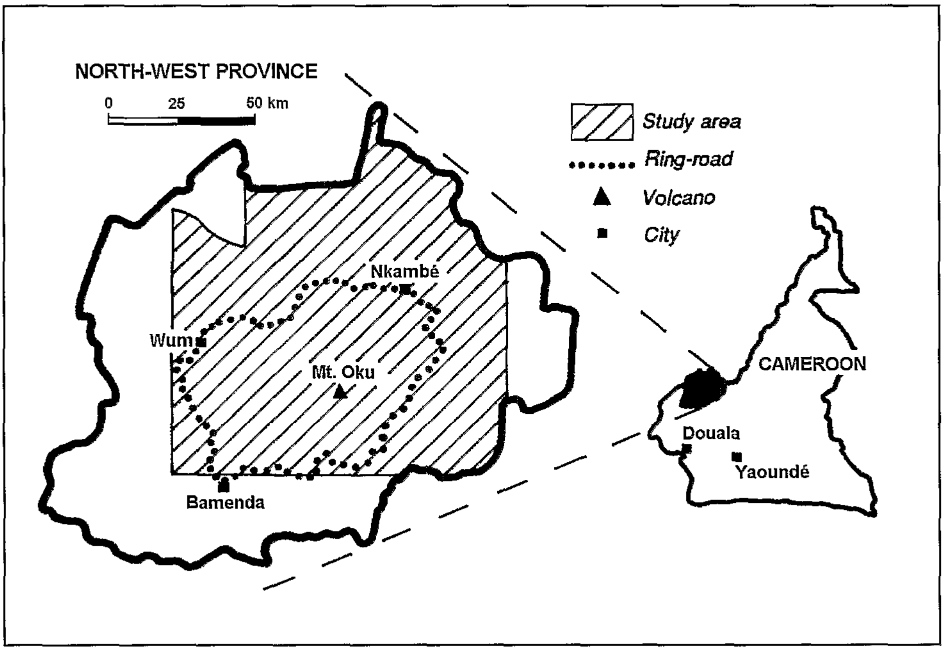

Figure 1. Location of the study area.

The overall mountainous nature of the terrain and the variety of soil parent materials (basalt, trachyte, migmatite, granite, pyroclastic, colluvial, and alluvial deposits) resulted in complex soil patterns. Even over short distances soils may differ considerably in such characteristics as texture, effective depth and gravel content. Most of the soils classify as Cambisols, Andisols, Acrisols and Ferralsols (FAO, 1990).

Annual rainfall varies from less than 1,700 mm in the lowlands to over 3,000 mm in the west-exposed highlands. The dates of the onset and end of the rainy season vary slightly over the area. The rainy season starts in early or mid-March and ends in early or late November. The temperature is fairly constant over the year and mean annual temperatures are closely related to altitude (> 24 EC below 500 m and < 17 EC above 2,000 m), with some anomalies linked to topographic position. Data on relative humidity are scarce, but mean annual values are around 65%.

The lands are used intensively for subsistence-farming with maize as major crop. Rainfed agriculture is mainly concentrated on the volcanic plateaus because of the overall favourable soil conditions, and on the colluvial soils, enriched with volcanic ash, in the lowlands. Burning of savannah grass takes place in January and February to promote vigorous regrowth when the rains start in March. The high mountain peaks are under a primary forest cover.

Crop modelling approach

The production potentials for rainfed maize have been determined using a model that considers three hierarchically ordered production situations.

Radiation-thermal Production Potential (RPP)

As temperature and radiation regimes during the crop cycle cannot normally be manipulated, these factors determine, within the physiological capacity of the crop, the potential production level in a specific area. The RPP of a crop is then only determined (within limits set by the crop's physiological properties) by the irradiance of photosynthetically active radiation that the crop can intercept, and the temperature regime of the production environment.

Calculation of the RPP is based on the crop growth model of the Agro-Ecological Zones project (FAO, 1978), and is derived using the following equation :

$$RPP = \frac{0.36 \cdot b_{gma} \cdot L \cdot KLAI \cdot H_i}{1 + 0.36 \cdot C_t \cdot L} \qquad (1)$$

where RPP is the radiation-thermal production potential ($kg_{dry\ matter}.ha^{-1}$); *0.36,* half the conversion efficiency; b_{gma} the overall gross rate of assimilate production ($kg.ha^{-1}.d^{-1}$); L the length of growing cycle (d); $KLAI$ the correction factor for incomplete ground cover (dimensionless); H_i the harvest index and C_t the rate of loss of b_{gma} by maintenance respiration at actual temperature (kg $kg^{-1}d^{-1}$). A detailed description of the variables, their values, as well as the calculation procedures, are given in DRIESSEN and KONIJN (1992).

Water-limited Production Potential (WPP)

For the second hierarchical production situation, the influence of moisture availability on transpiration and crop production is taken into account. The influence of water availability on the crop production potential can be quantified through the yield response factor *(ky)*. This factor relates the relative production decrease *(1-WPP/RPP)* to the relative evapotranspiration deficit *(1-ET_a/ET_c)* as follows:

$$(1 - WPP/RPP) = ky \cdot (1 - ET_a/ET_c)$$

$$WPP = RPP \cdot [1 - ky \cdot (1 - ET_a/ET_c)]$$

where *WPP* is the water-limited production potential ($kg_{dry\ matter}.ha^{-1}$); *ky* the yield response factor; ET_a and ET_c the actual and maximum crop evapotranspiration (mm/crop cycle), respectively. The above relationship is valid for both individual crop growth periods and for the entire crop cycle. The average *ky* value for the total maize cycle is 1.25, indicating maize is sensitive to water shortage (DOORENBOS and KASSAM, 1979).

Actual crop evapotranspiration has been calculated from rainfall data taking into account the soil water storage. If crop water requirements are fully met, $ET_a = ET_c$, and maximum production is obtained. When available soil moisture decreases, ET_a remains equal to ET_c until a critical moisture content *(p)* is attained. Below this critical value $ET_a < ET_c$ and production is reduced. The degree of reduction depends on the crop species, the crop growing cycle and the soil type. A maximum water storage of 210 mm/m has been taken for all soils in the study area. RIJTEMA and ABOUKHALED (1975) formulated this relationship as follows:

$$ET_a = [(S_t \cdot D)/(1 - p) \cdot S_a \cdot D] \cdot ET_c$$

$$ET_a = [-d(S_t \cdot D)]/dt$$

where $S_t.D$ is the available soil moisture (mm) at time *t* over the rooting depth (*D* in m), $S_a.D$ the maximum available soil moisture (mm) over the rooting depth (*D*) and *p* the fraction of easily available soil water.

Land Production Potential (LPP)

The land production potential has been calculated using an equation in which the effects of climate, water availability and selected soil characteristics on crop production have been combined :

$$LPP = WPP \cdot S_i$$

where S_i is a soil suitability index, obtained by multiplying a physical soil index (P_i) with a chemical soil index (C_i). Determination of both indices implies matching of soil characteristics with the maize soil requirements (Table 1) and attribution of a numerical rating value to each characteristic.

All physical soil characteristics are represented only by one rating, calculated after subdividing the soil profiles in equal sections; to each of these sections a "depth correction index" (weighting factor) is attributed starting with a minimum value at depth and increasing towards the surface section (SYS *et al.*, 1991). The numerical rating values attributed to the three chemical soil characteristics (Table 1) are combined into one single value (C_i), using the square root method (KHIDDIR, 1986):

$$C_i = R_{\min} \cdot \sqrt{R_a + R_b}$$

where R_{min} is the lowest rating value, R_a and R_b the other two rating values.

Table 1. Soil requirements considered in the calculation of a soil suitability index for maize production (SYS *et al.*, 1993).

Soil characteristics	Rating scale 1.00	0.95	0.85	0.60	0.40	0.25
Physical Texture structure*	C-s, Co, CL, SiCs, SiCL, SiL, Si	C+s, SC, SCL, L	SL, LS	LcS, fS		Cm, S
Chemical (0-25 cm)						
Sum basic exchangeable cations (cmol(+).kg^{-1} soil)	> 6	5.6	4.9	2.0	1.5	
pH H_2O (1:2.5)	5-8-6.5	6-8	7.5	9.1	9.7	
		5.7	5.5	5.0	< 4.6	
Organic carbon (%)						
Kaolinitic soils	> 2.0	1.9	1.6	< 1.0		
Other soils	> 1.2	1.1	1.0	< 0.6		

* C-s : clay (< 60%), blocky structure; Co : clay, oxisol structure; CL : clay loam; SiCs : silty clay, blocky structure; SiCL : silty clay loam; SiL : silt loam; Si : silt; C+s : clay (> 60%), blocky structure; SC : sandy clay; SCL : sandy clay loam; L : loam; SL : sandy loam; LS : loamy sand; LcS : loamy coarse sand; fS : fine sand; Cm: massive clay; S : sand

** The content of coarse fragments and effective soil depth are evaluated together with texture/structure. In the parametric approach, this is achieved by a downgrading of the texture/structure rating for coarse fragments and by attributing a rating of 0 to a limiting impermeable layer at a depth of less than 100 cm (SYS *et al.*, 1991)

Geographical analysis

In this study, a vector GIS (PC ARC/INFO 3.4D) has been used to digitize map information from the topographic map (IGN, 1972), the soil map (KIPS *et al.*, 1987) and a rainfall distribution map (HAWKINS and BRUNT, 1965). The contour lines of the topographic map were digitized with an interval of 500 m elevation difference. An additional introduction of 62 points with known elevation in the study area allowed the creation of a digital elevation model (DEM) with the aid of the SEM (Structured Elevation Model) module of PC ARC/INFO. The small scale of the base map, the large height interval between the contour lines and the strongly dissected landscape in the study area resulted in a strongly simplified DEM (Fig. 2). This information was imported into IDRISI for further processing.

The DEM generated is unsuitable for further geographical analysis of slope gradient or orientation, but provides an ideal basis for a graphical display of the relationship between the physiographic position and the crop production potential. It can be used as a template upon which to drape thematic data such as land suitability values.

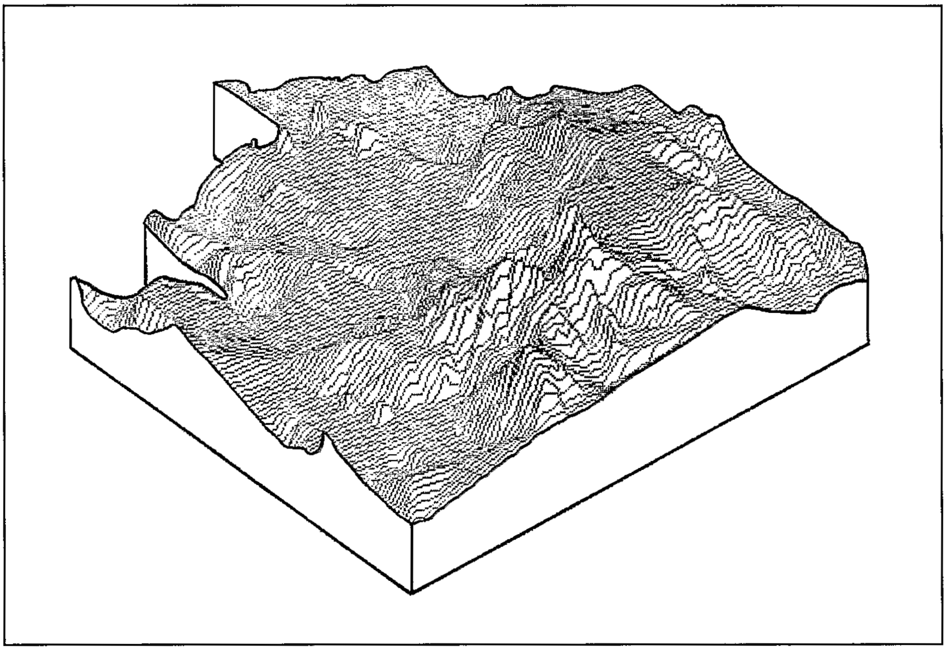

Figure 2. Three-dimensional surface response curve of the landscape; surface produced from a 500 m DEM by IDRISI.

The soil map of the study area at the scale of 1:200,000 covers 160 different mapping units. Each soil mapping unit is supported by a single set of records containing general information on 4 polygon attributes: parent material (9 classes), FAO classification name (FAO-UNESCO, 1987) of the dominant and associated soils, slope (6 classes), and stoniness (4 classes). Through aggregation of polygons with similar characteristics, the number of unique mapping units was reduced to 71. Because a single mapping unit may consist of many polygons all carrying the same soil information, the relational database will have the form shown in figure 3a.

The data from 79 soil profiles, representing all major soil types present in the study area, were also stored in a series of tables (Fig. 3b).

There are tables for the classification name, physical (texture, soil depth and stoniness) and chemical (sum of basic cations, pH, organic carbon) properties. In order to facilitate the use of profile data to support crop modelling and spatial interpolation of weighted means of soil properties, each profile is cross-linked with the polygon in which it falls. Each soil polygon is characterized by the attributes of a profile with the same classification name as the dominant soil type of the mapping unit.

Like in many areas in developing countries, weather records in the study area are scarce and often unreliable. The methodology used for the determination of the production potential of maize requires a climatological dataset consisting of monthly averages of the following parameters : daily mean, maximum and minimum temperature (EC), rainfall (mm), insolation (hours), relative humidity (%), and wind velocity (m.s^{-1}).

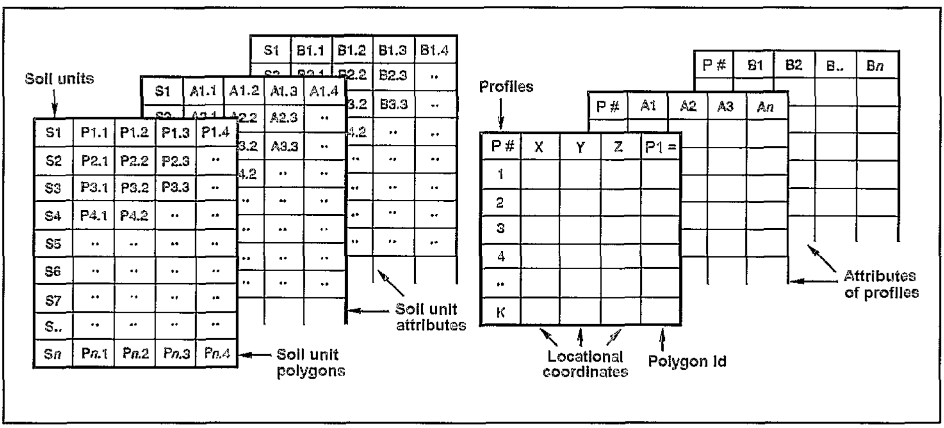

Figure3a. Relational structure of a soil polygon map : S1-Sn refer to the kinds of soil (mapping units) : P1.1... refer to the polygons representing the location of each kind of soil; the property values held by each kind of soil for all polygons are given by the attribute tables A.1....B1.1.... (BURROUGH, 1986).

Figure 3b. Relational structure for the soil profiles. Profiles are identified by a serial number (P); the tables contain data on location (X.Y an Z coordinates), the soil polygon in which they occur and attribute values (A1....An,B1....Bn), (BURROUGH, 1986).

Weather records of 58 stations in or near the study area were analyzed. None of the stations provide complete records for all required parameters. Because the study area is characterized by a considerable climatological variability, it was preferred to infer missing parameters based on relationships between individual parameters, rather than using the records of a selection of climatological stations.

Rainfall and temperature are the major parameters that determine the climatological suitability for maize growth. The spatial variability of these parameters was used to divide the study area into climatological zones. The highly significant correlation between altitude and temperature (correlation coefficients between 0.886 and 0.972, significant at 0.001 level, for mean monthly temperature data of 14 climatological stations) permitted the use of the contour line map to simulate temperature at every location. An overlay of the contour lines map (7 classes, 500 m intervals) and the rainfall distribution map (5 classes; from < 1,700 mm to > 3,000 mm) resulted in a polygon map with 30 climatological zones (12 smaller polygons were integrated in the remaining polygons). A procedure was developed to attribute a representative set of climatological data to each zone:

- <u>Rainfall</u>: rainfall records are, in contrast with other parameters, abundantly available. For several polygons, a selection of the most representative station had to be made based on the principle of Thiessen polygons. However, in zones without a climatological station, the dataset of a neighboring zone with similar physiographic characteristics was used.

- <u>Insolation</u>: for six stations with insolation records a linear relationship with rainfall data was found ($r = 0.861$, significant at 0.001 level):

$$Insolation = 227.197 - 0.346041 \cdot Rainfall$$

This equation permitted the simulation of monthly insolation values based on recorded rainfall data for each climatological zone.

- <u>Mean Temperature</u>: an increment of 100 m in altitude corresponds with a decrease of the monthly mean temperature of about 0.5 EC. This relationship in combination with the average elevation of each climatological zone, inferred from the DEM, provided a reliable estimate of the mean temperature.

- <u>Daily Temperature Difference</u>: the average difference between daily maximum and minimum temperature (ΔT) is well correlated with insolation. Recorded data on insolation and temperature difference of six stations provided the following linear relation ($r = 0.791$, significant at 0.001 level):

$$\Delta T = 0.50642 + 0.05946 \cdot Insolation$$

- <u>Relative Humidity</u>: because no significant correlation with rainfall, temperature or altitude was found, the available relative humidity data were averaged. Two stations located below 1,200 m provided representative records for the zones with a similar altitude. The weighted monthly average relative humidity values of seven stations were assigned to zones with an average elevation above 1,200 m. Four stations located outside the study area received a smaller weighting factor.

- Wind Speed: wind speed data were only available for Bamenda, located south of the study area. Its records were used for the entire study area, because local differences in wind velocity are reported to be relatively small (HAWKINS and BRUNT, 1965).

The soil polygons and climatological zones were converted to a raster form in IDRISI 4.0 (raster GIS) for easier manipulation of the model results. RPP and WPP were determined for each climatological zone. Evaluation of the soil characteristics resulted in soil suitability indices (S_i) for individual soil units. WPP and Si values were retained as pixel attributes in the conversion process of the climatological zones map and the soil map, respectively. An overlay of both raster maps, using the multiply operator of IDRISI, yielded a new map with the LPP results.

Mapping modelling results

The RPP corresponds to the potential maize yield under the current climatic conditions, assuming the absence of soil limitations or water shortage during the crop cycle. RPP values for the study area vary between 5.6 and 7.8 $t.ha^{-1}$ (Fig. 4a). The lowest values are found in the area around Mount Oku (for location: see Fig. 1), where temperature conditions are unfavourable due to high elevation. Optimal temperature conditions (20 EC < T_{mean} < 30 EC) exist in the areas located between 1,000 and 2,000 m. Below 1,000 m an increased respiration results in a lower biomass production. This is the case in the northern part of the study area. Higher insolation on the leeward side of the SW-NE mountain range results in RPP values up to 7.8 $t.ha^{-1}$ in that zone.

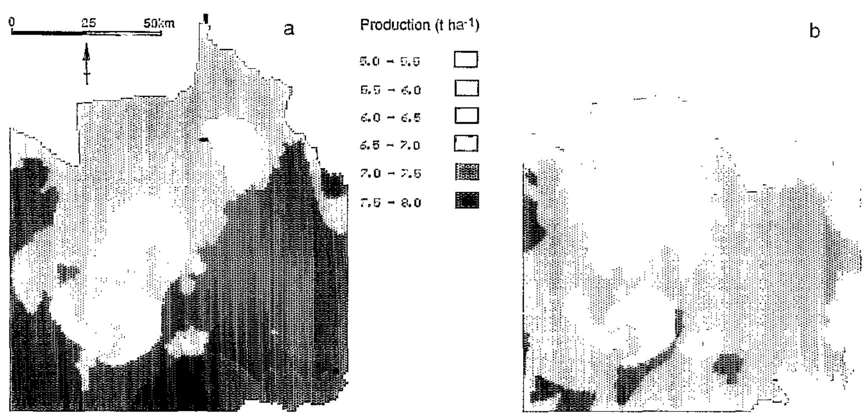

Figure 4. Distribution of estimated (a) radiation-thermal production potential (RPP) and (b) water-limited production potential (WPP) of maize.

Maize is fairly sensitive to moisture deficits during the crop cycle. These water deficits lead to a reduced evapotranspiration and finally result in an estimated yield reduction, amounting to 1.1 t.ha-1 in the dry depressions of the eastern part of the study area. Along the western flank of the mountain range, orographic rains keep the soil moist throughout the crop cycle. In this zone WPP nearly equals RPP. The estimated WPP in the study area range from 4.6 to 7.2 t.ha-1, indicating favourable climatic conditions for maize production (Fig. 4b).

The suitability of the physical soil conditions is expressed by the physical soil index (P_i). The texture of the fine earth fraction is dominantly clayey. Because most soils are deep (> 1 m) and have a favourable structure for root penetration, the physical soil suitability is mainly determined by the amount of coarse fragments in the soil. Gravelly soils, with a reduced water holding capacity, are common in the eroded granitic hills in the northern part of the study area. The physical soil conditions are markedly better on the central high (lava) plateau and in the alluvial plains along the main rivers.

The humid tropical climatic conditions and the maturity of the soils have resulted in a rather poor chemical fertility status. Both pH and amount of basic cations are below the required level for optimal maize growth. If the chemical soil conditions are not improved by adapted management, as is the general rule in tropical subsidence farming systems, maize yields will be seriously affected. Maize productivity in traditional farming systems without fertilizer application will be mainly determined by the low chemical fertility status, expressed by the yield reduction factor C_i. The lowest C_i values are found in soils on granitic parent materials. Slightly higher values were calculated for soils on the lava plateaus, whereas the soils on alluvial and colluvial materials are chemically the most fertile. Combination of P_i and C_i resulted in a soil suitability index (S_i) that is an indication of the suitability of the soil for maize production. Figure 5 shows the distribution of the soil suitability index in the study area and reflects the geographical pattern of soil parent materials. The following sequence in soil suitability can be recognized based on parent material: alluvium > colluvium > basalt/trachyte > granite. Volcanic ash soils have a variable suitability index.

The soil suitability index has a strong impact on the estimated land production potential (Fig. 6). The considerable variability of soil characteristics over short distances will undoubtedly also lead to important local differences in maize productivity. However, integration of this spatial variability is impossible with the soil information made available by a reconnaissance soil survey The generally favourable climatic conditions for maize production are countered by the poor fertility of the soils. This is expressed by the reduction of the WPP to an average LPP of 2.0 $t.ha^{-1}$. About 50% of the study area has an estimated production potential below 1.8 t ha^{-1}, which was the statistical mean maize yield for Cameroon in 1992 (FAO, 1993). Compared to the average farmers' yields of 1.0 $t.ha^{-1}$, the LPP values appear to be overestimated. This production gap could be due to local yield reducing conditions ignored in the current model, such as the use of traditional (low-yielding) varieties, poor management practices, and losses through damage by rainstorms and erosion. On the other hand, yields varying between 2.7 and 3.4 $t.ha^{-1}$ have been recorded in five research stations located in the study area.

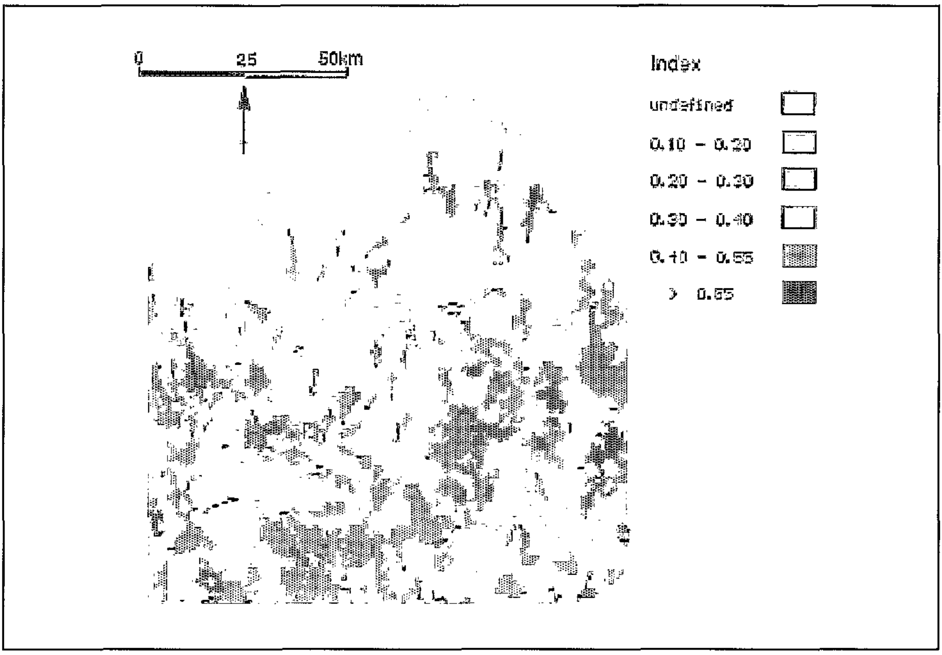

Figure 5. Distribution of soil suitability index for maize production.

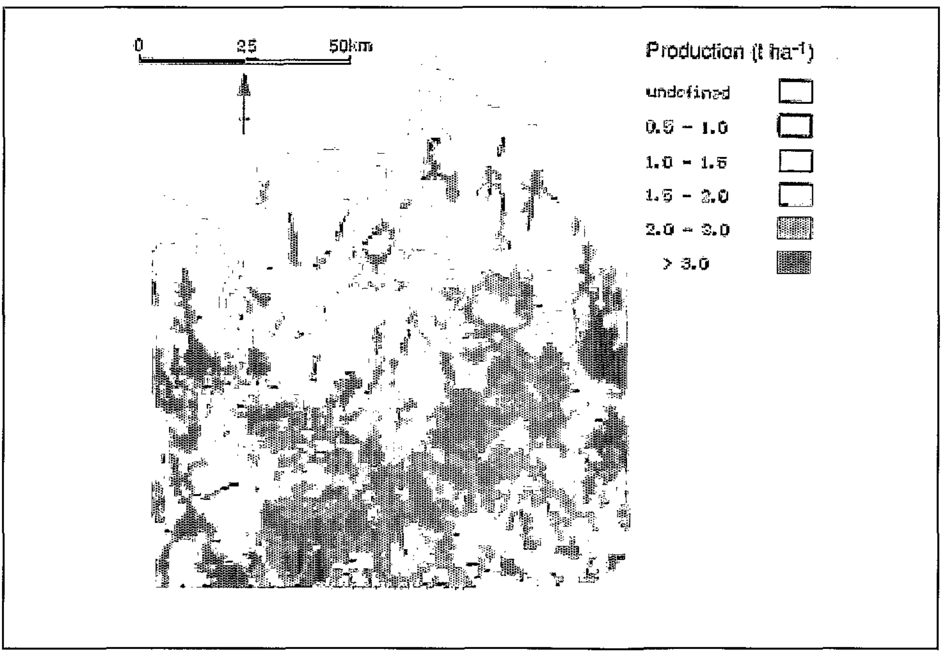

Figure 6. Distribution of estimated land production potential (LPP) of maize.

Conclusions

Integration of a crop growth model with GIS allowed the study of the variability in maize production potentials caused by differences in soils and climatological conditions at a regional scale, using information made available after a reconnaissance survey. Ordinary maps of topography, climate and soils were digitized and used as an input data source for the crop model after manipulation in a GIS. Calculation of three hierarchically ordered maize production situations was performed at the level of individual raster cells. The results could be displayed on a digital elevation model, permitting a visual interpretation of the relationships between physiography and maize performance. This study has shown that such a combined application of a crop growth model and GIS is a very useful tool for land-use planning, especially in developing countries where often limited amounts of easily accessible climate and soil data are available.

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