Report 2004/02

The Impact of Desertification on Food Security in Southern Africa: A Case Study in Zimbabwe

UNEP projects: FP/1300-96-75-22d and
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Abstract

Degradation of the drylands, also known as desertification, of Southern Africa is thought to have a negative impact on the food security of the region. General observations on the degree of the impact have been made over the years but quantification of the process has been lacking. The United Nations Environment Programme, UNEP, requested ISRIC – World Soil Information, to execute a study on Zimbabwe and to quantify the effects of degradation, in particular soil degradation, on the productivity of the country. Zimbabwe has been selected because of its representativeness for the region in respect of natural resources. Also, the country has a long history of research in soil erosion and well-stocked archives of natural resources data.

The study consists of a series of modelling exercises using soil and terrain data (SOTER), climate and land use data. The land use under consideration is rain-fed maize cultivation with low inputs and technology; the dominant land use in Zimbabwe. A mixed qualitative-quantitative approach is used, consisting of an assessment of the suitability of the land for the land use under consideration, a soil loss scenario – 20 years of continuing erosion – and a quantification of the productivity under the current and future soil conditions. Finally a comparison of the two situations is made.

About 53 % of Zimbabwe is suitable for the specified land use. Constraint-free productivity of maize is from 10 to 15 $t.ha^{-1}$ for almost half of the country. Modelled production figures for yields in the suitable area under nutrient limitations are much lower: about 90% of that area has a productivity under 1.5 $t.ha^{-1}$. The actual yields in the Communal Lands, where the land use type is similar, fall within the lower range.

Productivity after 20 years of simulated erosion is lower under the nutrient-limited modelling conditions: slightly less than half of the suitable land units will lose between 25 and 50% of their, already low, productivity. The possible effects of climate change in combination with the scenario of erosion will aggravate the food security situation even more if no counter measures are taken.

Most soils in Zimbabwe have a low inherent fertility. Yields are low; without appropriate management, soils will be further degraded. Sustainable maize production in Zimbabwe requires nutrient amendments; integrated soil fertility management is the key to sustained crop production.

Keywords: natural resources databases, qualitative land evaluation, crop growth modelling, erosion modelling, food security, land degradation

Acknowledgements

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1 Introduction

1.1 Background

The United Nations Environment Programme (UNEP) requested ISRIC to undertake a study, 'The Impact of Desertification on Food Security in Southern Africa: a Case Study in Zimbabwe', in which the impacts of dryland degradation (desertification) on productivity in Southern Africa will be assessed, taking Zimbabwe as a case. This report presents the results of the study.

Zimbabwe has been selected 'because of the challenge to sustainably manage precious land resources in the decades to come, but also because national capabilities and past and present international activities in this country provide a solid foundation to a successful implementation of the proposed activities' (Project document, unpubl.). Almost the entire country falls within the drylands as defined by UNEP (1992) with a ratio P/PET <0.65 except for a small area on the border with Mozambique. Being of limited extent, this wetter zone is incorporated in this study.

Since the start of the project in 1999, the political and economic situation has changed substantially and has had an impact on the project progress.

Land degradation in the dryland areas of Southern Africa and its effect on food security is becoming a major challenge to governments in the region in view of population growth and economic developments. Although the problem is on the agenda, it has been lacking quantification in productivity figures. Data from a global expert assessment on soil degradation from the GLASOD study (Oldeman *et al.* 1991) show that most of Zimbabwe has been affected by moderate to strong water erosion with the highest degree in the southern water-divide area. The major types of land degradation that occur in the Southern African region are water erosion, wind erosion and salinization.

In Zimbabwe, erosion features were observed at a national level by Whitlow (1988) from aerial photographs and mapped by percentage of area affected. With a lower resolution, for example seen from space (Figure 1), the lowest vegetation cover and highest associated degradation occur in the densely occupied Communal Lands of Zimbabwe (bright areas).

Assessments of the impact of land degradation are based on the general assumption that soil and land degradation will have a negative impact on the food security; so far, few studies have succeeded in generating figures at national or regional scales.

Yield decline due to land degradation is often based on extrapolation of field plot data on erosion. Wiebe (2003) identified for the world's croplands 179 published plot-level studies that report changes in yield as a result of erosion. The geographical distribution shows a strong geographical bias to North America. Africa, as a continent, is proportionally well represented but records tend to be concentrated in areas that, although highly productive, are not particularly sensitive to erosion.

There are few long-term time-series exist that compare yields of differentially eroded test plots on similar soils, or involve mechanically removed topsoil or measured topsoil thickness. Overall yield losses per ha vary between 0.01 and 0.04 percent per unit ton soil loss with the highest values in the tropical regions.

Several studies have extrapolated erosion vulnerability in combination with data on land use and natural resources (soils, climate). They are based on broadly available

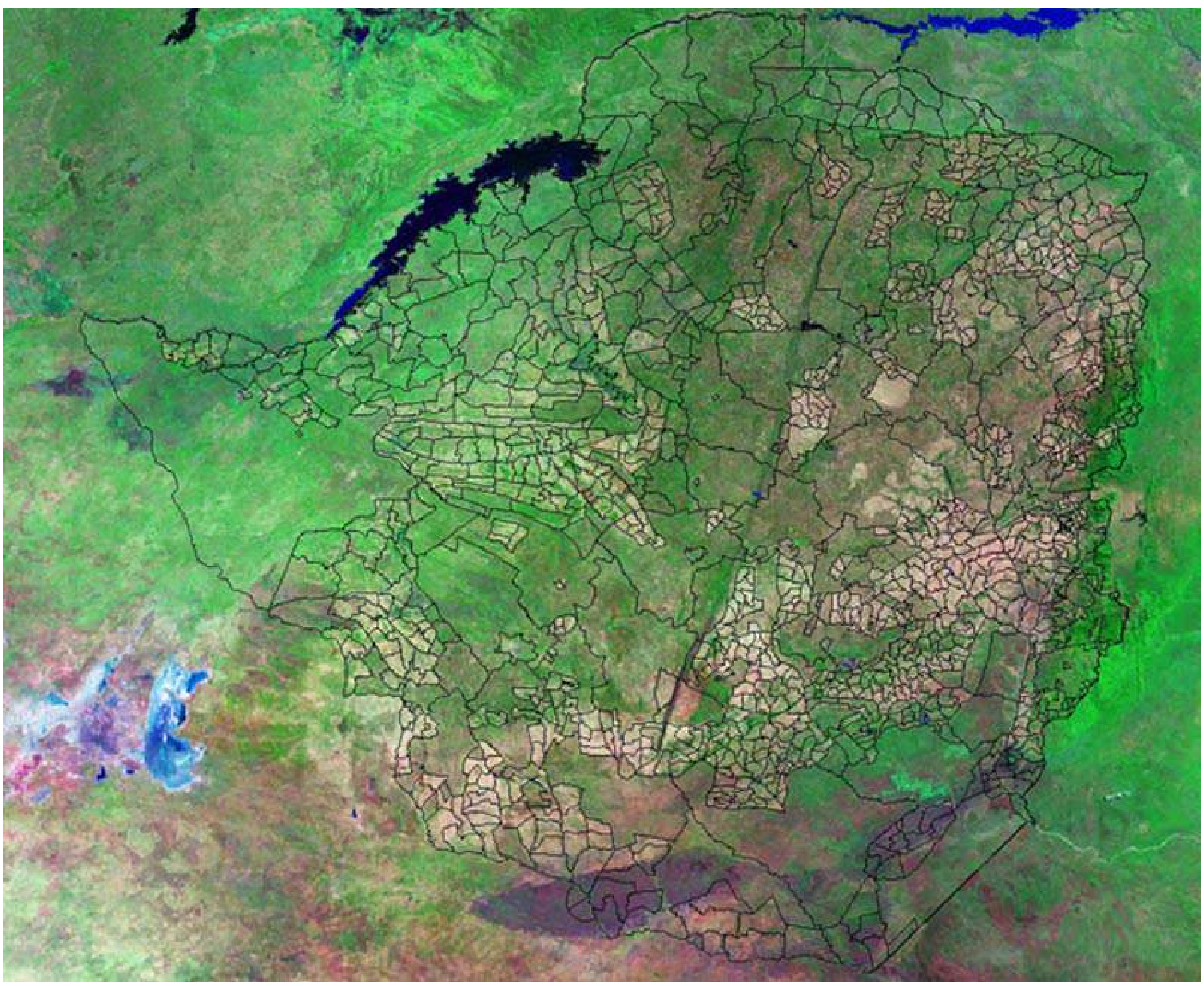

Figure 1. Landsat TM image of Zimbabwe with administrative units. Source: Prince (1999)

data like soil type and climate that lack the precision needed for quantification. Soil data are available for example, at Group level of Soil Taxonomy; the assessment of erosion risk is based on soil characteristics like depth and moisture regime.

Based on the GLASOD study, some authors have tried to convert the qualitative data into productivity loss figures. Crosson (1995) used the productivity loss figures from Dregne and Chou (1992) to estimate productivity loss at global scale at 0.1% annually. Other authors (Oldeman 1998) came to similar figures that, when applied to the drylands of Southern Africa, would imply an annual productivity loss of 0.5 %. Although this figure is a rough estimate, such a decline in productivity has a high impact on countries like Zimbabwe. The population growth in Zimbabwe is 2.9% annually (Central Statistical Office 1991) and the agricultural production is lagging behind with a growth of less than 1% annually. This indicates a worsening food security situation for the region.

1.2 Contents of the study

This report describes a methodology for estimating the impact of land degradation on crop production in the drylands in Southern Africa, as applied to Zimbabwe.

Chapter 1 gives an introduction to the study. In Chapter 2 the natural resources, agriculture and land use, and degradation status are described. The methodology is described in Chapter 3. The data and the models form the first sections of this chapter. Suitability for smallholder maize cultivation is assessed, erosion risk under this land use is estimated and production levels before and after continuing erosion are modelled.

Results of the modelling are presented in Chapter 4, conclusions and a final discussion are presented in Chapter 5.

2 Characterization of Zimbabwe

2.1 Agro-Ecological Zones

The country falls entirely in the tropics although the highlands on the border with Mozambique and the Highveld area in the North have a temperate or subtropical climate due to their altitude. North of the line Bulawayo-Masvingo there is only one rainy season of 4 months that follows the Inter-Tropical Convergence zone. In the South the wet season is marked by brief convectional storms petering out to light rain at the end of the season when cooler moist air masses penetrate occasionally from the South.

The climatic regions of Zimbabwe have been classified in various ways starting with the five natural regions based on rainfall, distribution and elevation (Department of the Surveyor General 1984). Later, moisture availability was used to define Agro-climatic Zones (Bernardi and Madzudzo 1990), based on the ratio of the 80% probability of the mean annual rainfall and the average annual evapotranspiration. The resulting six zones followed largely the natural regions with addition of a drier zone VI in the South. The characteristics of the natural regions have been further refined by Venema (1998) on the basis of moisture storage characteristics of the different soils as shown on the Provisional Soil Map of Zimbabwe (Department of Research and Specialist Services 1979) resulting in five major agro-ecological zones and 16 sub-zones (see Figure 2). When applying the criteria for dryland definition of UNEP (1992) - P/PET <0.65 - only AEZ I with a value of 0.9 falls outside.

Average annual rainfall ranges from 325 mm in Beitbridge in the South to 1127 mm in Chipinge in the Eastern Highlands, with an increasing reliability from the southern Lowveld to the northern Highveld. The reliability, expressed as the coefficient of variability ranges from 40% in the Bulawayo area towards 20% in the Highveld around Harare and the Eastern Highlands (Anderson *et al.* 1993). Indicators of the rainfall probability are used to describe the various Agro-Ecological Zones of Figure 2. Definitions of the characteristics of the AEZ's are given in Appendix 1, Table 9.

Rainfall intensities, an important feature determining the risk of soil erosion, are high as most of the precipitation is associated with thunderstorms. An analysis of rainfall intensities by Anderson *et al.* (1993), shows that more than 50% of the precipitation can be considered as erosive, having an intensity over 13 $mm.h^{-1}$. Not much variation in intensity distribution exists between high and low rainfall areas.

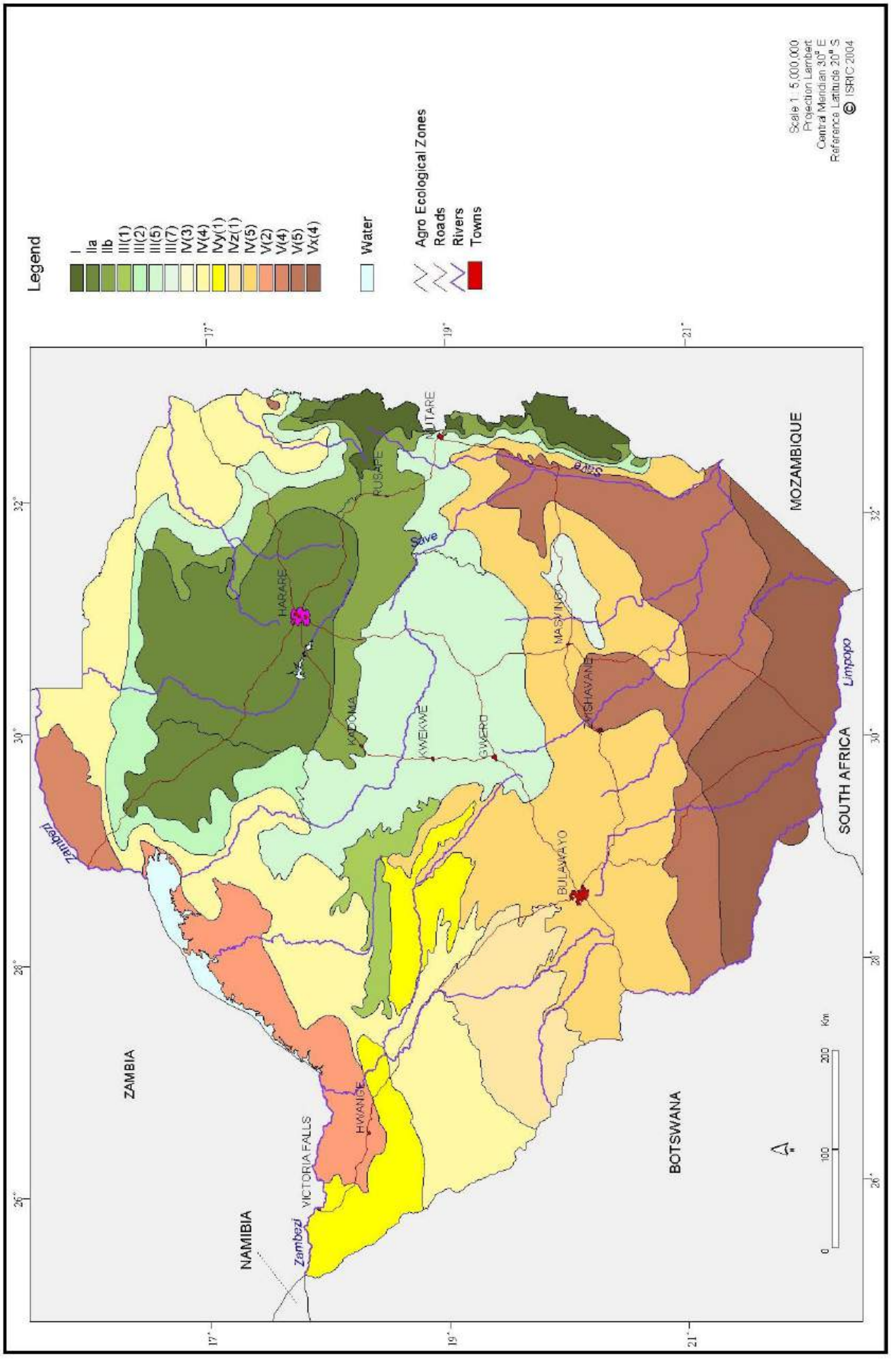

Figure 2. Agro-Ecological Zones (for details see Appendix 1) Source: Venema (1998)

2.2 Soils and terrain

General physical regions have been defined by Anderson *et al.* (1993), based on earlier-defined cycles of weathering, erosion and tectonic movement. Information on soils, landform and lithology in these zones is based on the Soil and Terrain Database of Zimbabwe, compiled by the Pedology and Cartography Section of CSRI (FAO-ISRIC 2003) (see Appendix 2).

The major regions are:

- Eastern Highlands: a narrow strip of high altitude along the border with Mozambique with an elevation between 2000 and 2400 m and mountainous and hilly characteristics. Dominant soil classes as defined by the World Reference Base for soil resources (WRB) (IUSS *et al.* 1998) are Leptosols, Phaeozems, Acrisols and Nitisols
- The Highveld: a gently undulating old erosional surface at an elevation rising from 1400 m in the South to 1700 in the North. Soils are Cambisols, Luvisols, and Ferralsols on most rocks and Arenosols on coarse grained granites in the north; and Lixisols, Acrisols, Luvisols and Gleysols in the more southern areas
- The Middleveld: surrounding the Highveld at an elevation between 800 and 1200 m, with somewhat steeper slopes and some hilly areas in the southeast and the west with many rock outcrops (*koppies*) and characterized by Leptosols, Lixisols and Luvisols
- The Kalahari Sandveld, covering the western part of the older surfaces. Soils in this sandy area are Arenosols, Lixisols and Acrisols
- The Lowveld, Save and Zambezi valleys, young erosional surfaces between which major rivers have laid down terrace and floodplain deposits. They have a wide range of soils: shallow Leptosols, cracking clays (Vertisols), salt-affected soils (Solonetz and Solonchaks) and Luvisols
- The northern Zambezi escarpment with shallow stony soils
- Linear topographic features, like the Great Dyke are dominated by shallow soils (Leptosols and Cambisols)

The major landform units are shown in Figure 3 and the generalized lithology in Figure 4. Figure 5 shows the dominant soils of Zimbabwe at the first level of WRB (IUSS *et al.* 1998), derived from the SOTER database. Second level WRB classifications of the dominant soils are shown in Figure 30 in Appendix 2.

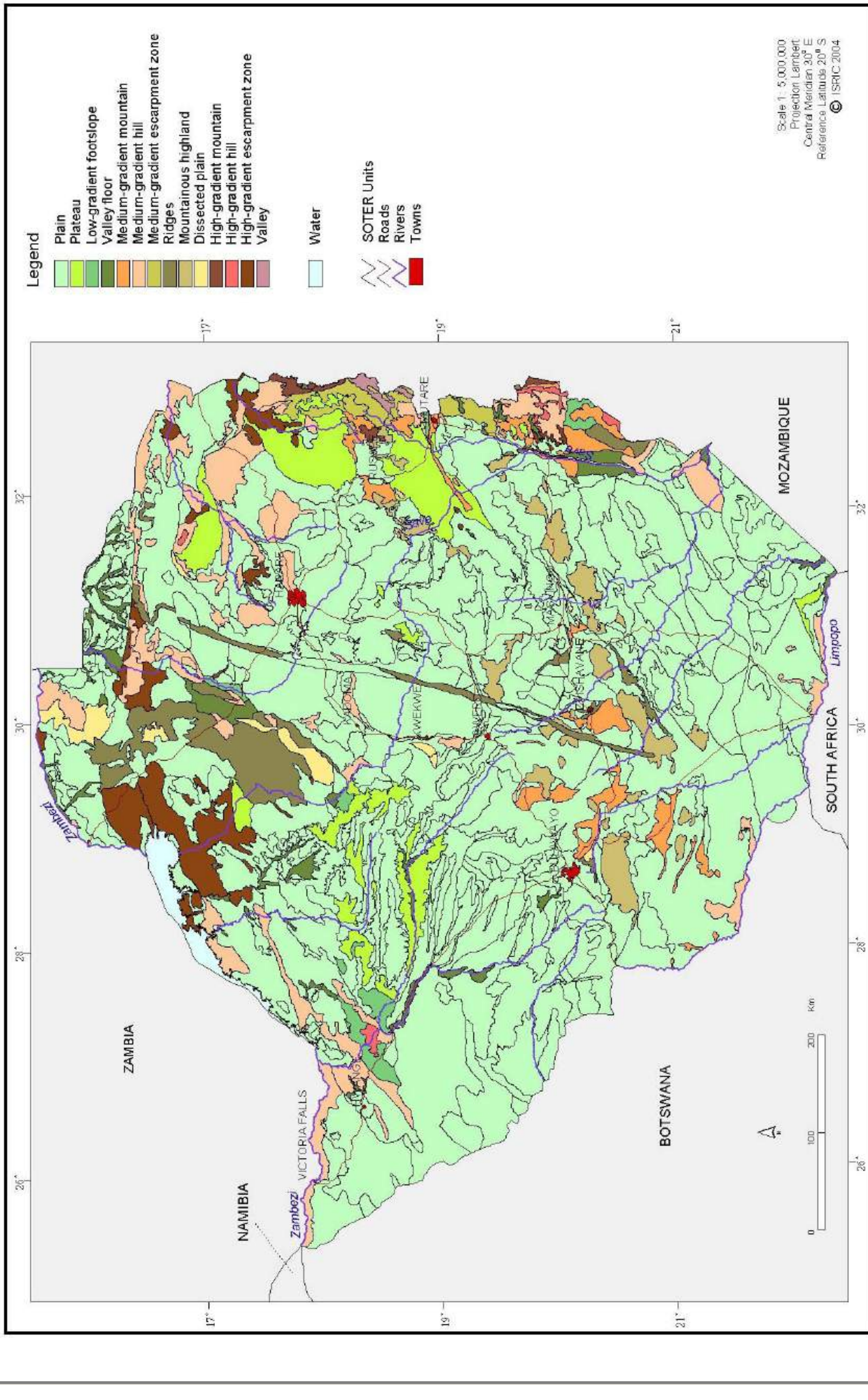

Figure 3. Major landform units

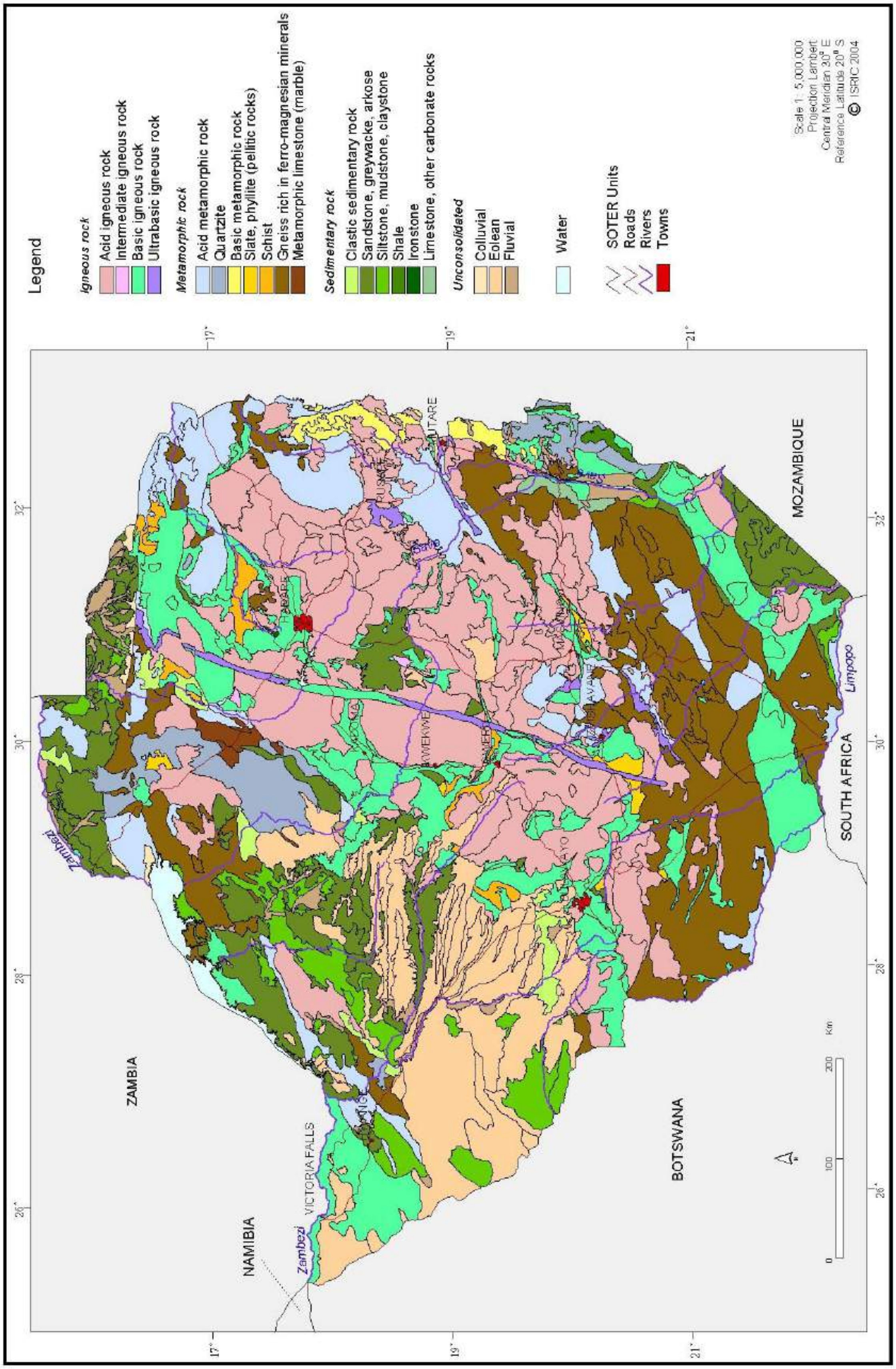

Figure 4. Generalized lithology

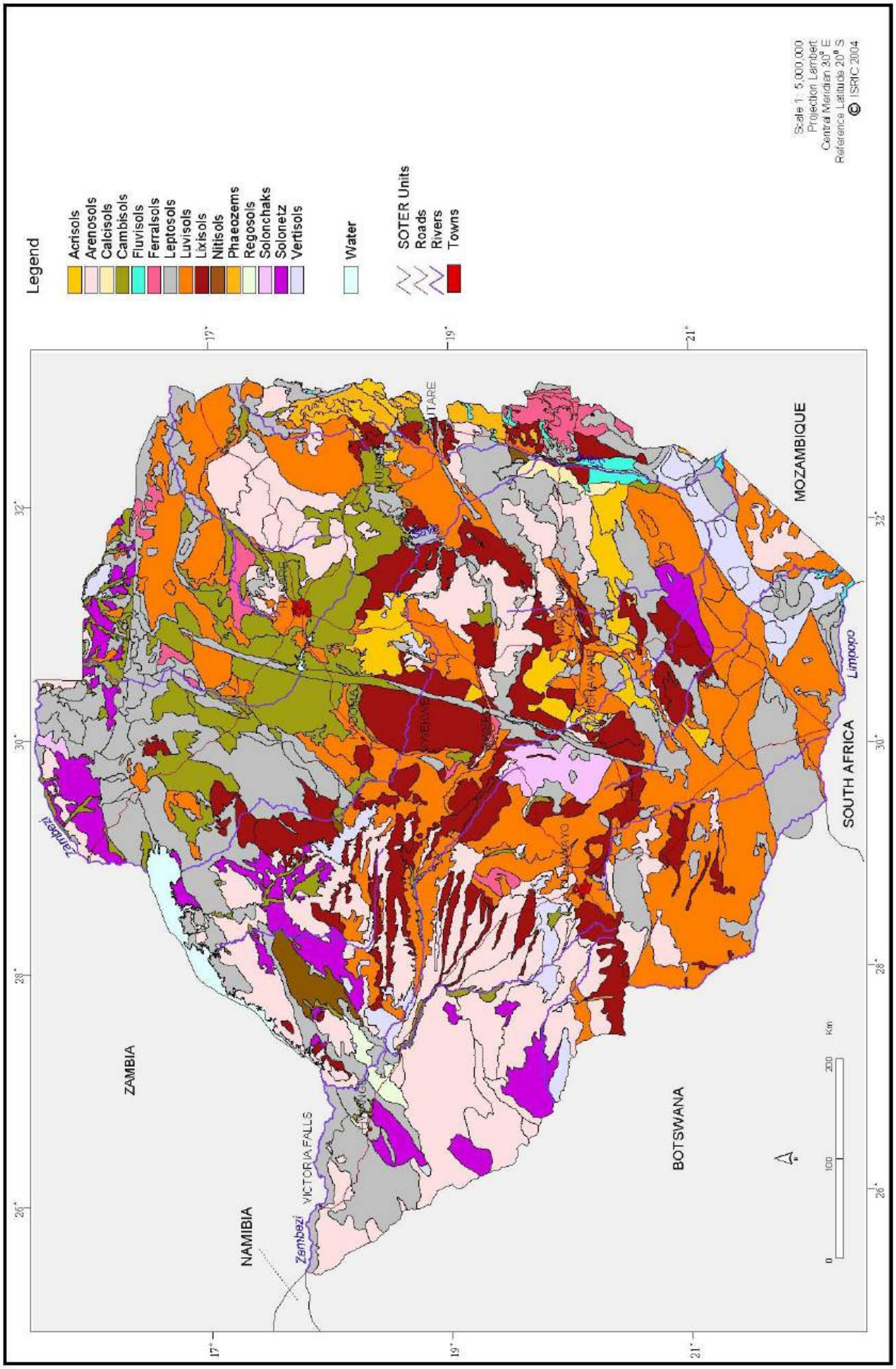

Figure 5. Dominant soils (1st level WRB)

2.3 Population and land use

The total population of Zimbabwe in 2002 was 11.6 million (Central Statistical Office 2002). Distribution of the population over the country is uneven with the highest densities in the wetter Communal Land areas. A map showing the population density in a 25 km^2 grid (UNEP-GRID 2002) is shown in Figure 6.

Land use is to a large extent determined by the colonial past. Commercial large-scale farms, formerly exclusively white farmers, occupied the areas with deep soils and low relief. The black, rural population is concentrated in the Communal Lands. Recent developments, the so-called Fast Track reform program adopted in mid-2000, and accelerated in May 2002, have changed the landownership in the commercial farming areas but their impact on the population distribution is not clear; it is estimated that 13% of the population now lives in the resettlement areas including the former commercial farming areas (Zimbabwe National Vulnerability Assessment Committee 2003).

Figure 7, land use, is based on a generalized version of the SADC Land Cover Dataset (CSIR 2002) which, in turn, is based on the land cover map of the Forestry Commission (1997). Added to his map are Communal Lands taken from the soil map of Anderson *et al.* (1993) and National Park and Nature Reserves from the Department of the Surveyor General (1997). Land use has been defined according to the classes of the SOTER Procedures Manual (van Engelen and Wen 1995) and the original land cover classes were transformed accordingly (see Appendix 4).

It is to be noted that the recent changes in ownership of the majority of commercial farms have not been taken into account in this map: lack of reliable data on the extent of the re-allocation and the area under cultivation by the new occupants made it impossible to adapt this map.

2.4 Agriculture

Maize is the major crop in Zimbabwe, in particular for the Communal Land farmers; as much as 90 % of their area is used for this culture. The commercial sector plants other crops besides maize, for example tobacco, but recent data on area planted and production are unavailable. Statistical data from FAO (FAOSTAT 2003) show the total production of maize of Zimbabwe and some other countries in the region up to 2002 (Figure 8).

There is a clear relation between rainfall and productivity. The rainfall anomalies shown in Figure 9 correspond with the maize production of Zimbabwe until the year 2000 as shown in Figure 8. Variations in regional rainfall can be correlated with the ENSO (El Niño/Southern Oscillation) (Phillips *et al.* 1998). A correlation of 0.78 has been found between maize yield in Zimbabwe and sea surface temperatures in the

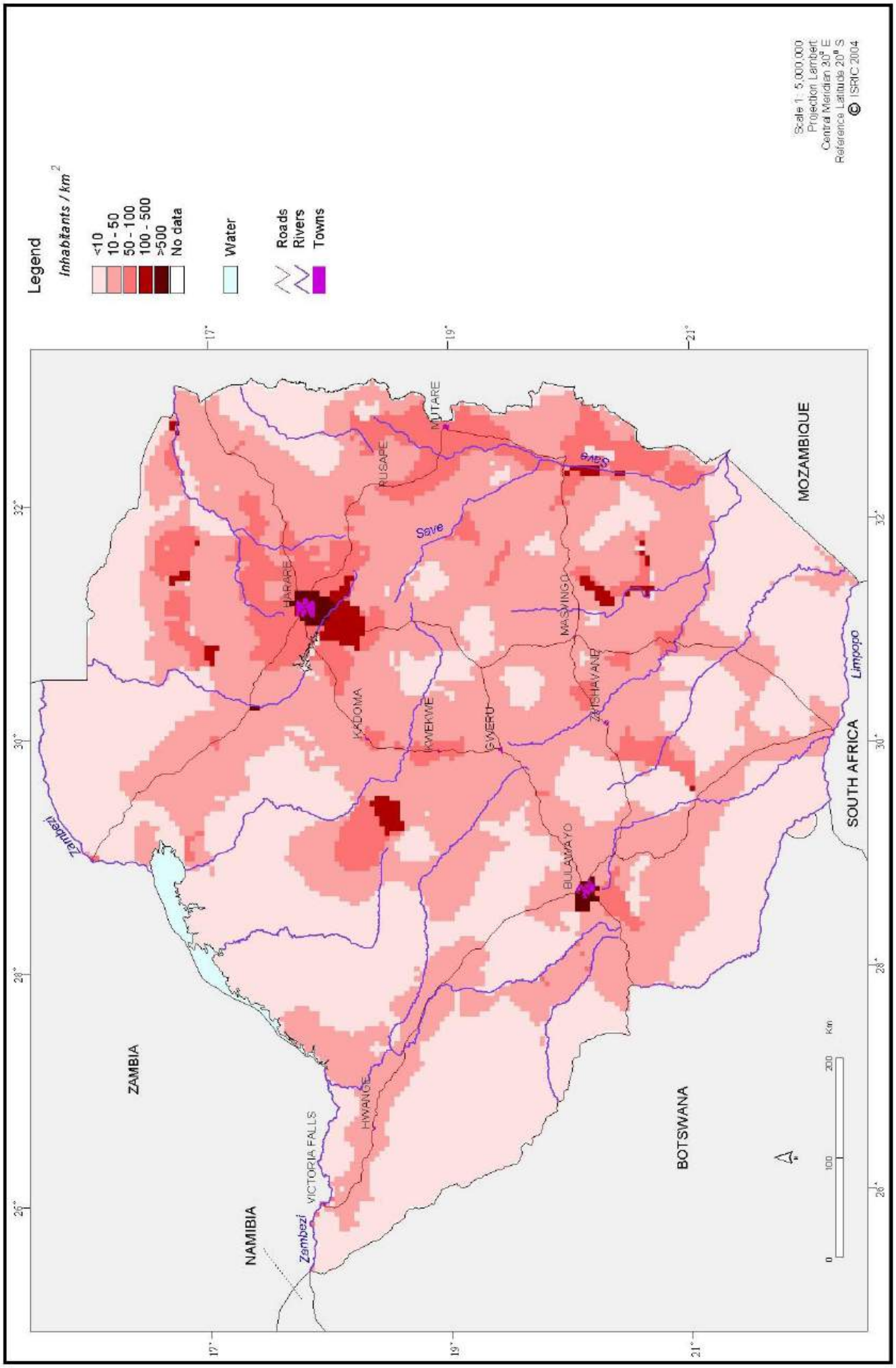

Figure 6. Population density. Source: UNEP-GRID (2002)

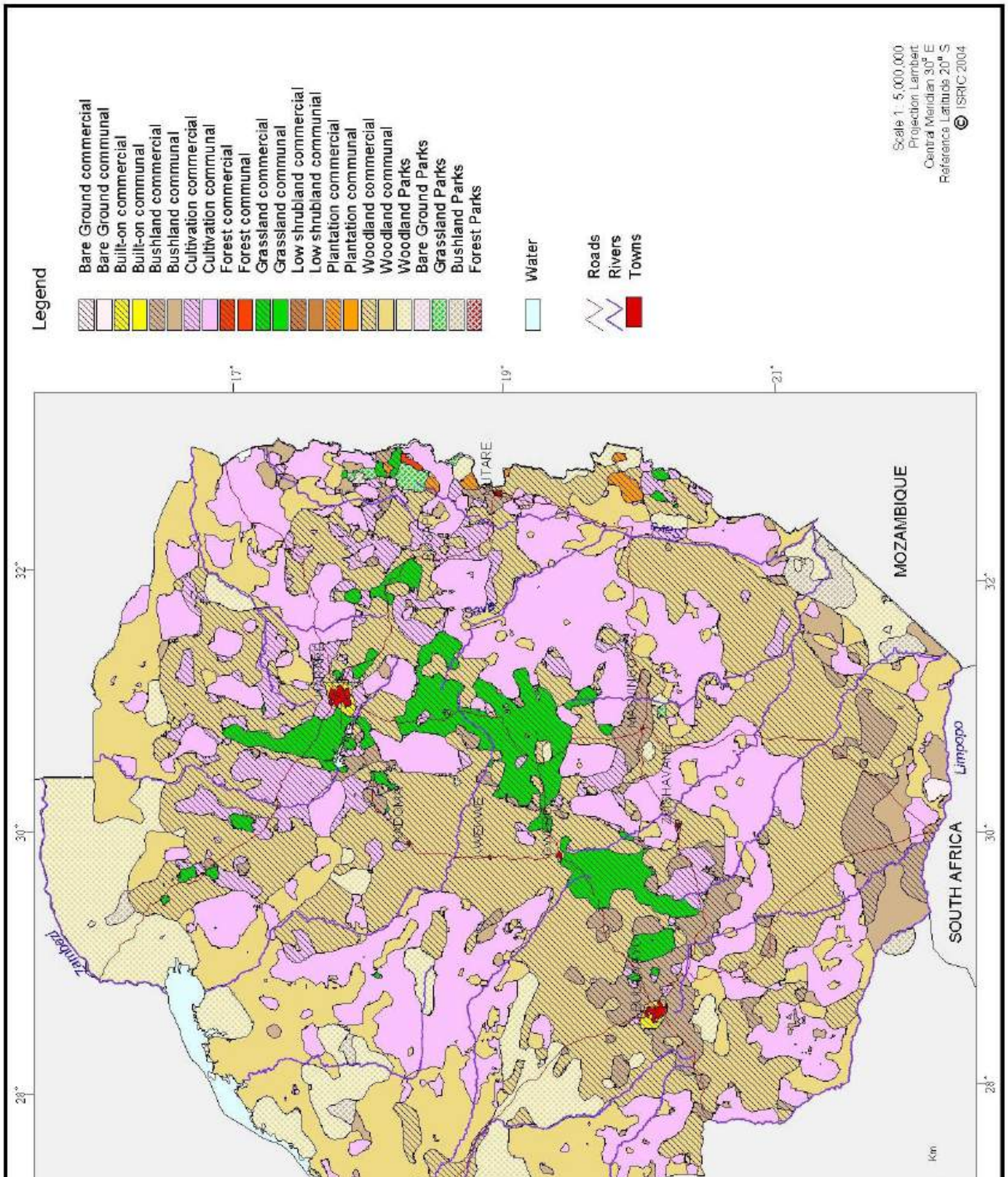

Figure 7. Land use. Sources: Anderson *et al.* (1993), CSIR (2002) and Department of the Surveyor General (1997)

ocean (Cane *et al.* 1994). Besides total rainfall, there are other factors that have an impact on maize yields - such as rainfall distribution and the area planted in anticipation of a forecasted El Niño occurrence. It looks as if the continuing decline in maize production after 2000 in Zimbabwe cannot be attributed to an El Niño occurrence alone as neighbouring countries show a recovery in production. Declining economic conditions in Zimbabwe as a result of political measures play a role as well.

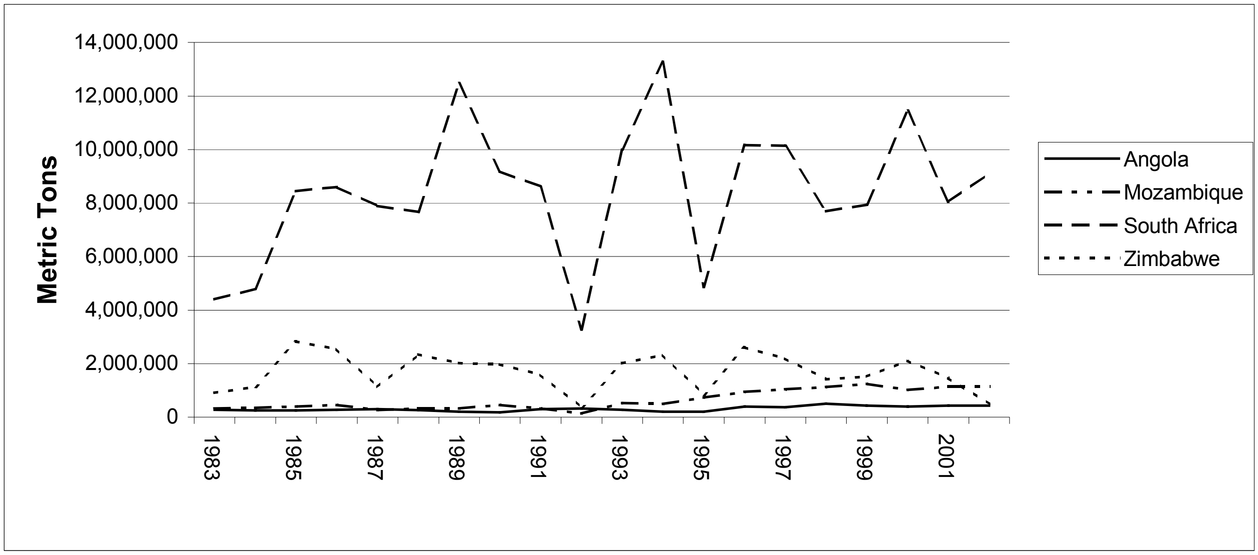

Figure 8. Maize production in major Southern African countries between 1983 and 2002. Source: FAOSTAT (2003)

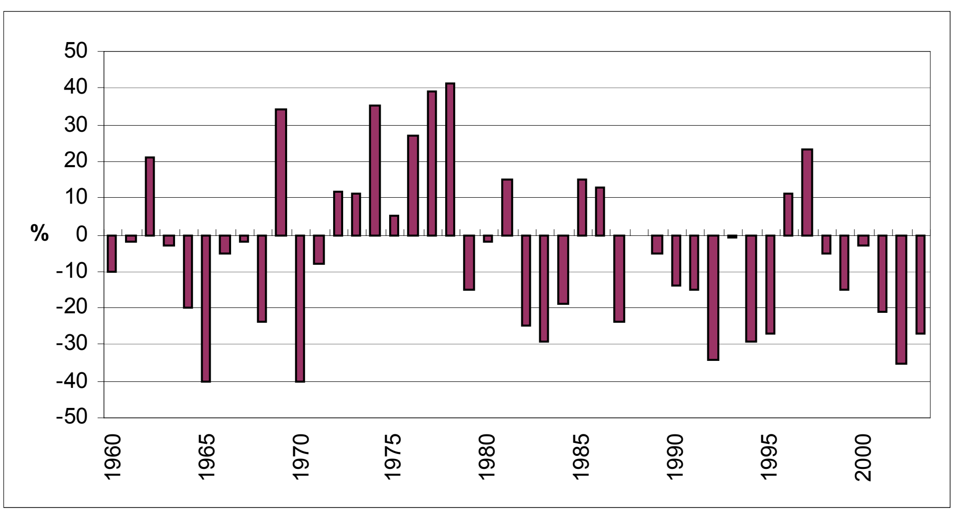

Figure 9. Rainfall anomalies between 1960 and 2003 in Zimbabwe, modified after Hulme and Sheard (1999) and Rekacewicz (2002)

2.5 Soil erosion

Soil erosion is, increasingly, degrading agricultural sustainability in Zimbabwe, particularly in the densely occupied Communal Lands, despite conservation measures that have been introduced since the nineteen-fifties (Whitlow 1988).

2.5.1 Status

No comprehensive survey on the status of soil erosion in Zimbabwe was executed until the nineteen-eighties (Whitlow 1988). The survey method included sampling 1000 one hectare grid squares of the central photograph (scale 1:25,000) in each 1/16 division of a standard 1:50,000 topographic map. The method did not allow for mapping at a national scale of each different kind of recorded soil erosion feature (rills, gullies, sheet erosion under different land uses) but generated actual erosion in terms of total erosion, erosion on cropland and erosion on non-cropland. The resulting map, indicating areas affected by erosion, is shown in Figure 10. About 27% of all Communal Lands are seriously to very seriously eroded. Taking into account the method of aerial photo interpretation, where slight erosion features might be difficult to identify, it is expected that the map underestimates the extent of erosion.

A comparison of this map with the land use map (Figure 7) and the satellite image (Figure 1) shows a strong relation between erosion extent and land use. The highest rates are found in the Communal Land areas, shown as bright areas in the satellite image.

2.5.2 Risk

Erosion processes in Zimbabwe have been studied well, in particular in the late 1950s and early 1960s when experiments have been executed, amongst others, at the Henderson Research Station, at Mazowe Valley about 20 km north of Harare, resulting in the Soil Loss Estimation Model for Southern Africa (SLEMSA) (Elwell 1982). Soil erosion risk for the country has been mapped with this model by Madhini and Manyanza (1989), and by Grohs and Elwell (1993) for the Communal Lands only (Figure 11), using data from the 1:1 M national soil map (Department of Research and Specialist Services 1979). The study by Grohs & Elwell predicts an average annual soil loss from arable fields in the Communal Lands of 43 t ha^{-1}. With an average bulk density of 1.3 kg dm^{-3} this can be translated to a soil loss of 3 mm yr^{-1}. Plot studies, using Caesium-137 radio nuclides, to trace sediment movements and quantities (Quine *et al.* 1993), cited by Vogel (1994), have generated somewhat lower figures than SLEMSA.

Of course, soil is not removed or re-deposited evenly – there are order of magnitude differences across any field. And such values alone are not sufficient to indicate whether there is a problem or not; only when the soil loss is compared with

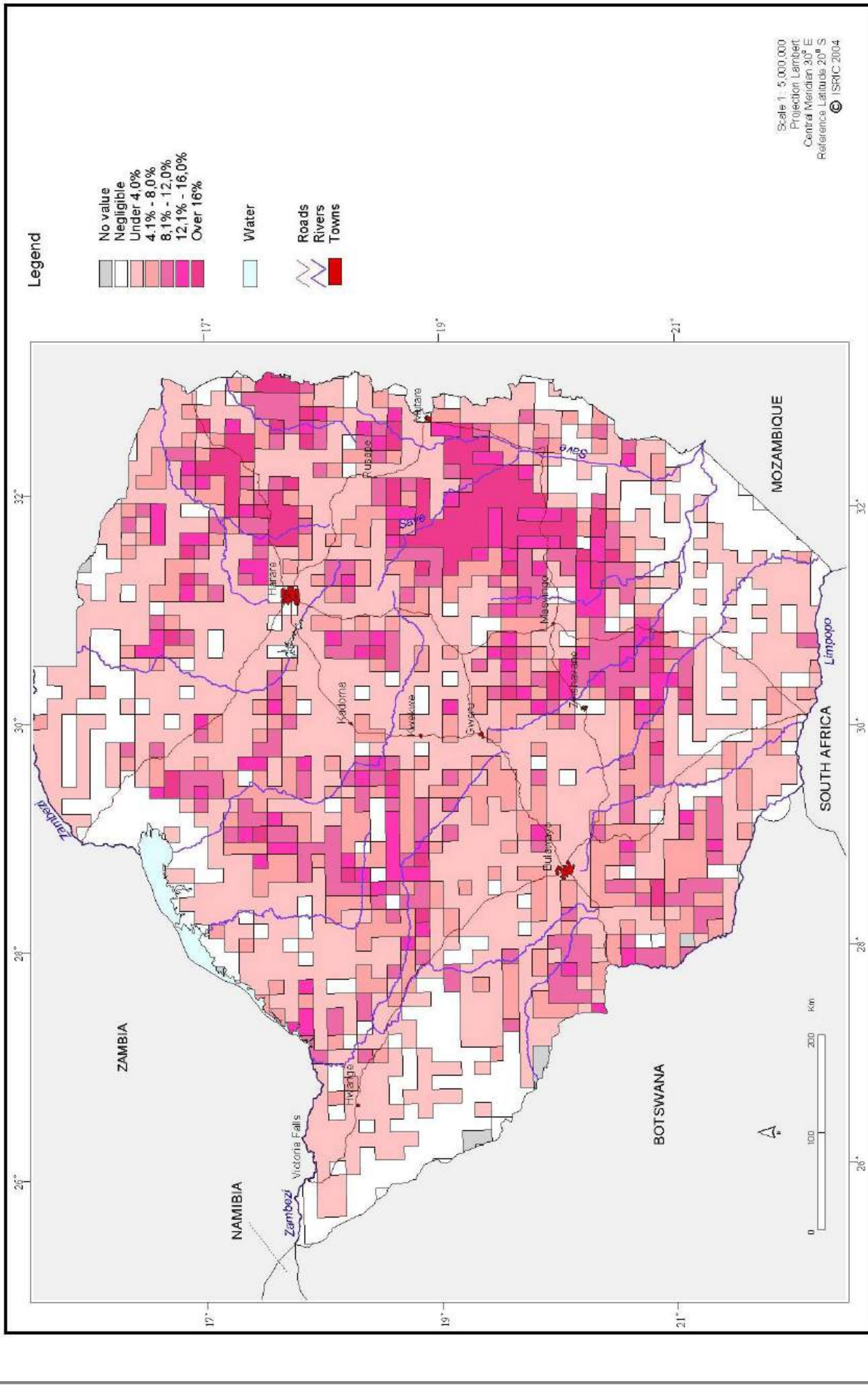

Figure 10. Percentage of eroded land. Source: Whitlow (1988)

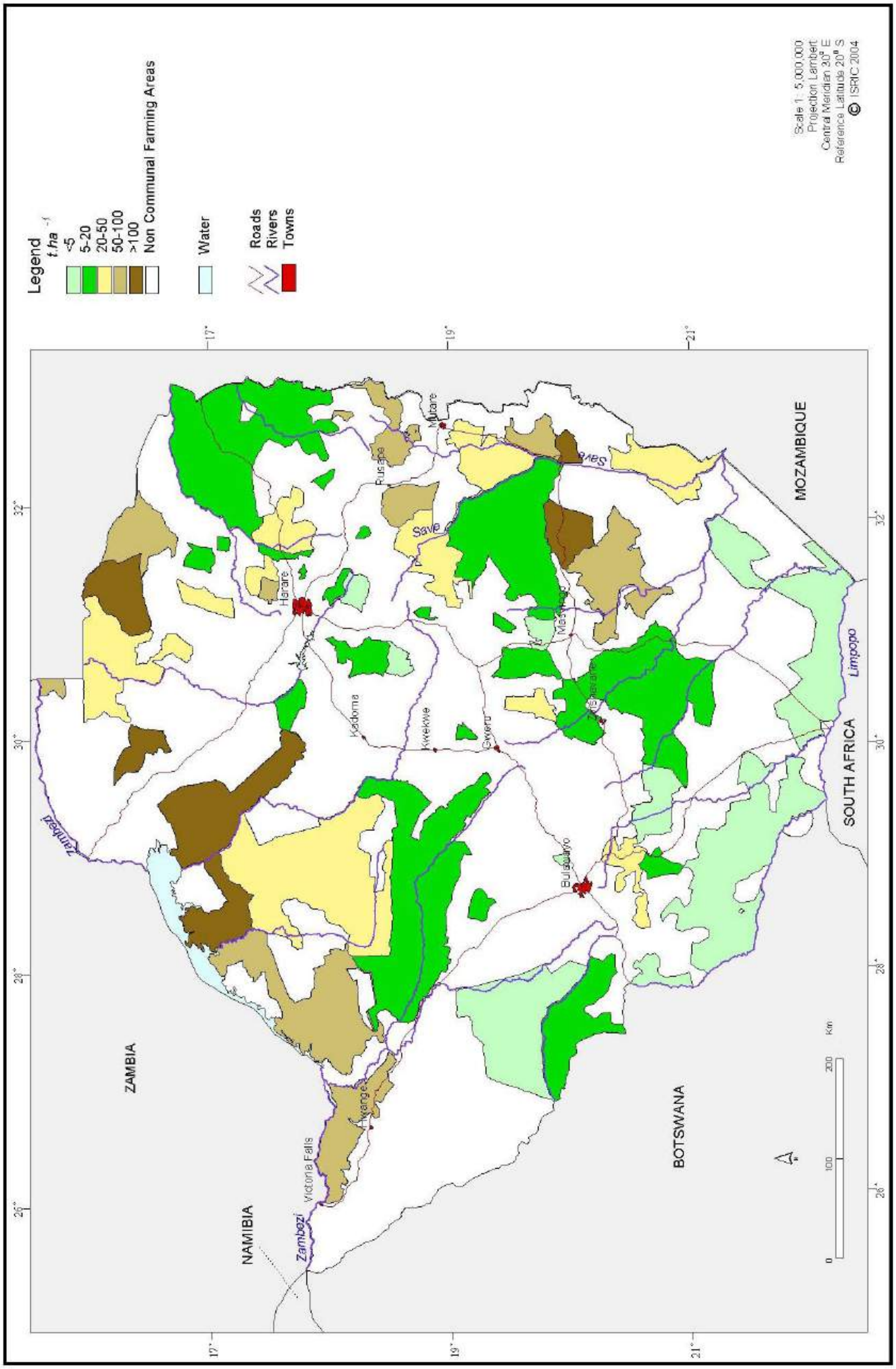

Figure 11. Predicted annual erosion rates from the cropland of the Communal Lands. Source: Grohs and Elwell (1993)

the rate of soil formation may a conclusion be drawn. It is estimated that soil formation on granites, one of the dominant soil parent materials in Zimbabwe, varies between 4 and 11 mm 1000 yr^{-1} (Owens and Watson 1979). These values, put against an annual soil loss of 3 mm yr^{-1} clearly show that the current agricultural practices are not sustainable.

Besides the movement and quantities of material, also their chemical composition is important; most nutrients are concentrated in the topsoil. Data on soil nutrient losses from erosion plots have been analyzed by Stocking (1986). Removed topsoil materials contained as much as 2.5 times the amount of nutrients (mass for mass) as compared with the original topsoil.

3 Methodology

3.1 Data

3.1.1 Soil and terrain data

The terrain and soils attribute data for the Zimbabwean case study were taken from the Soil and Terrain (SOTER) Database for Southern Africa (FAO-ISRIC 2003). This database contains basic terrain and soils information to run the different models applied in this case study. Where data were missing, gaps have been filled through the application of different methods. An explanation of the data completion methods is given in Appendix 3.

3.1.2 Climate data

Climate data are needed, amongst others, to assess the erosivity of the rainfall and to define the growing period of crops (the period during which sufficient moisture is available). Important parameters include the starting date of sowing or planting, and the approximate length of the growing period for a specific land use.

Thirty-five climate stations for Zimbabwe have been selected from the AMDASS climate database, giving monthly averages of eleven climatic parameters (FAO 1992). The rainfall figures cover a time series of 30 years; the other climatic parameters are generally recorded over periods of 10 years (FAO 1984). For this case study the approximate starting date of planting has been taken from the FAO study *Agro-climatological data of Africa* (FAO 1984). The approximation of the starting date of planting is based on the ratio between rainfall and potential evapotranspiration, interpolated over 10-day intervals. A regression formula was made that estimates the number of rainy days (a required input parameter for the crop growth modelling) from the average monthly rainfall. This is explained in Appendix 1, where also other relevant information of all climate stations, including the starting dates of the planting season, is listed. The agro-ecological zones (AEZs) (see Figure 2) have been taken from the revised AEZ map of Venema (1998).

3.1.3 Land cover data

Information on actual land use and vegetation cover is needed to assess the erosion risk and to compare the outcome of the suitability evaluation with the current land use. A land cover data set of Southern Africa was obtained as an individual digital land cover set for Zimbabwe through the SADC Regional Land Cover Database Project (CSIR 2002).

3.2 Models and basic assumptions

Several models have been used to assess actual and future effects and changes in crop production capacity of the land. In particular, models calculate: (1) the suitability of the land for a specified use, (2) the erosion risk under actual and the specified land use, (3) the potential production for this specified land use under the reigning moisture and nutrients limits and (4) production after the calculated erosion that could modify the moisture and nutrients conditions (Figure 12).

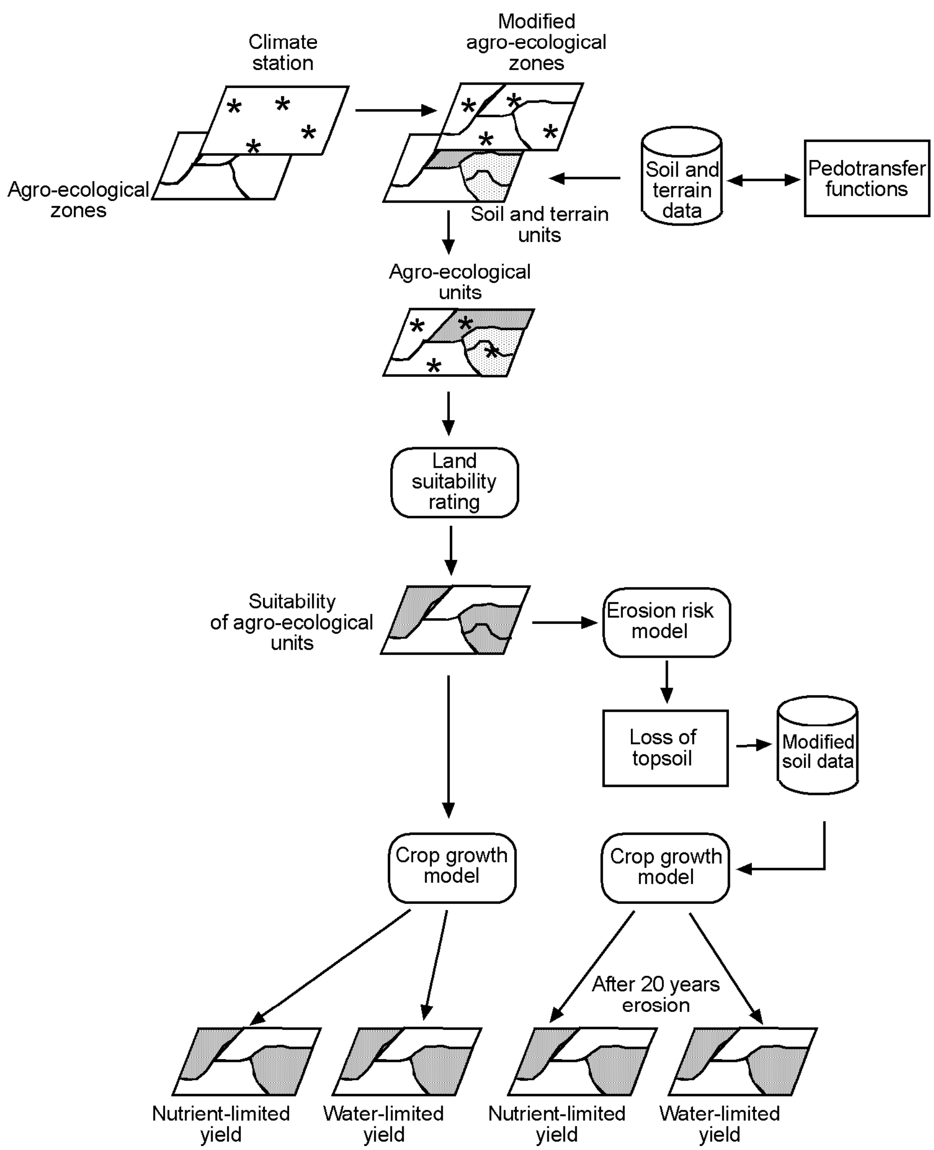

Figure 12. Flow chart of the modelling approach

The approach displayed in Figure 12 uses qualitative and quantitative methods (Mantel and van Engelen 1999; Mantel *et al.* 2000). The applied procedures in these studies can be summarized as follows:

- *Definition of Land Utilization Type* (define the land use under study);

- *Creation of basic evaluation units*, so-called agro-ecological units (aggregations of AEZ, rainfall zones and soil- and terrain units) for assessment of the suitability for low-input, low-technology, rain-fed maize cultivation;

- *Application of pedo-transfer functions* to fill data-gaps for required input parameters;

- *Land suitability assessment* to determine the land area that can support sustained application of the defined land utilization type;

- *Calculation of yield potentials* using a crop growth simulation model (WOFOST 4.3);

- *Assessment of erosion risk* using a parametric model (SWEAP) and, from this;

- *Determination of the potential top soil loss* over a 20 year period, and on the basis of this, *define erosion scenario* topsoil-loss classes;

- *Re-running the crop growth simulation* model based on the topsoil-loss scenario;

- *Comparison of yields before and after erosion* has taken place, and calculation of the yield decline.

3.2.1 Definition of land utilization type

Major kind of land use

An inventory made by the Forestry Commission of Zimbabwe on 1992 Landsat TM imagery of Zimbabwe (CSIR 2002) indicated woodland as dominant with slightly more than 50 percent cover, followed by more than 25 percent cultivated land. For the cultivated area, including both disturbed and fallow lands, no differentiation was made between communal or commercial use of the land.

Cereals are the dominant staple food and account for 62 per cent of the total calorie intake *per caput*: the share of maize is 47 per cent, wheat 8 and sorghum/millet 7 per cent (SADC/FSTAU 2000).

Over 20 years (1970-1990) both planted area and production of maize in the Communal Lands doubled (Anderson *et al.* 1993). For the 1989/90 seasons nearly

83 per cent of the total area planted to maize was in the communal sector, providing 57 per cent of the national production.[1]

Maize is the most important crop for food supply. Therefore, cultivation of maize is chosen as land utilization type. In Zimbabwe, maize is generally grown within a cropping system with a legume crop, e.g. groundnuts. Early maturing hybrid seed is generally available and used by communal farmers in low rainfall areas with short growing season. Most hybrids mature in 110 days (Middleveld) to 130 days (Highveld). Very short-season hybrids with 80-110 days maturity provide better opportunities for areas of low and erratic rainfall.

Land utilization type

A Land Utilisation Type (LUT) (FAO 1976) is a land use for which a set of technical specifications is described in a given physical, economic and social setting. The LUT as defined in this study is mono-cropping, rain-fed cultivation maize with low inputs and low technology. Cultivation practices include the use of hybrid maize. It is assumed that the crop matures in 100 days in the Middle and Lowveld and 120 days in the Highveld (lower temperatures). Farm size is generally small. Cultivation practices include manual tillage as well as animal ploughing. The latter is more important for the drier regions in the South. No, or limited, use is made of chemical fertilizers. After harvest, stubble is left for grazing or incorporated before next sowing. Sowing dates are from the second half of October until early December, and harvest is in March-April. Only one crop is grown under rain-fed conditions. Although land is under pressure from increasing population density, fallowing is still practiced; there is no continuous cropping under low-input farming.

3.2.2 Creating basic evaluation units

Locations of climate stations (FAO 1992) were plotted on the revised AEZ map (Venema 1998), that contains 16 units. Each AEZ polygon was allocated a representative climate station. Subdivisions were made of those AEZ units that had more than one climate station, resulting in more units (22) than the original AEZ map (Appendix 1, Figure 25). This modified AEZ map was combined with the 145 units of the SOTER map, creating a map with 493 new agro-ecological units (AEUs). These AEUs form the basis for the land evaluation and all other assessments.

Essential attribute data missing from the SOTER database have been estimated with pedo-transfer functions and taxo-transfer rules (Batjes 2000, 2003). For satisfying model input requirements, some parameters (such as soil hydraulic characteristics) had to be estimated using pedo-transfer rules (see Appendix 3).

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[1] All these figures are based on data collected and analyzed in the past; they do not necessary reflect the present trends and conditions.

3.2.3 Physical land suitability assessment

Suitability was assessed for maize grown with low inputs and under low-technology cultivation. An expert model (ZIMALES) for physical land evaluation developed in the Automated Land Evaluation System (Rossiter 1990), was used to separate potentially suitable AEUs from unsuitable ones. The ZIMALES model combines for each map unit the physical, chemical and climatic characteristics available in the various databases, and matches the resulting land quality values with the land use requirements of the land utilization type (Mantel 1995).

Preparing input for land evaluation
Linking the databases with the various models involves several phases of data manipulation. The land quality *availability of moisture* in the ZIMALES model was estimated separately using WATSAT, a simple water balance model (Mantel 1995). The WATSAT model is run on the basis of an interpolation of monthly rainfall and evapotranspiration averages into daily moisture gains and losses. Specific soil, crop and climatic parameters are used for the calculation of the water sufficiency over the growing period. Results are given as a ratio between actual and maximum crop transpiration rate and serve as input into the ZIMALES model to assess the sufficiency of moisture availability (see Appendix 5). An extraction program (SOTALES) allows for the transfer of SOTER data into the format suitable for input in the ZIMALES model.

SOTER units often comprise more than one soil component. These cannot be shown together on the map but the various soil components are represented in the database. Each soil component of all AEUs has been assessed for its suitability for the specific land use – maize cultivation with low inputs and low technology.

After running ZIMALES, class ratings (from no limitation to severely limiting) are provided for each land quality. The final suitability class is derived from the land quality ratings using the maximum-limitation method. The results are linked to the AEU map. In the maps shown in this report, the physical suitability of the dominant soil component within each AEU is selected for display.

3.2.4 Yield potential before erosion scenario

The potential maize yield under the prevailing agro-ecological conditions (soil, climate) was calculated using the crop growth simulation model WOFOST, version 4.3 (Pulles *et al.* 1991). WOFOST (van Diepen *et al.* 1991; van Diepen *et al.* 1989; van Keulen and Wolf 1986) calculates crop yields for three principal growth constraints. This results in theoretically defined production situations that are ordered according to increasing analytical complexity. The effect of principle growth constraints are evaluated by making separate calculations of:

1) *Constraint-free yield*, or potential yield, reflecting the bio-physical production ceiling determined by the crop's genetic potential under ambient radiation and temperature regime;
2) *Water-limited yield*, additionally reflecting the influence of limited or excessive water supply;
3) *Nutrient-limited yield,* the constraint-free yield additionally reflecting the influence of limited nutrient supply.

WOFOST has been applied at regional scales, e.g. to calculate potential wheat and sugar-beet yields within the European Community at a scale of 1:1 M (van Lanen *et al.* 1992a; van Lanen *et al.* 1992b), to simulate maize growth in Zambia (Wolf *et al.* 1989) and to calculate scenarios for erosion impact on maize productivity in Kenya (Mantel and van Engelen 1999) and on wheat production capacity in Argentina and Uruguay (Mantel *et al.* 2000).

The theoretical crop growth situations have been discussed in Mantel and van Engelen (1997):

Potential production, i.e. constraint-free yield (CFY), is the biophysical production ceiling determined by solar radiation, temperature, and crop photosynthetic properties. Other factors influencing crop growth are considered optimal at this production level.

Water-limited yield (WLY) refers to the potential crop production as constrained by water availability. Assimilation of atmospheric CO_2 to carbohydrates is the fundamental process in plant growth. With the intake of carbon dioxide through the stomata in plant leaves, water is lost through transpiration. When plants are exposed to drought, they close their stomata, to avoid more water loss, thereby reducing carbon dioxide intake and, consequently assimilation (and thereby growth). Water losses from the system are through transpiration and evaporation; supply is through rainfall. The water-holding capacity of the soil determines the fraction of rainfall that will be available to the plant, so plant production depends only indirectly on rainfall.

When only monthly average data are available, WOFOST 4.3 uses a rainfall simulator to generate daily rainfall patterns. The pattern is simulated on the basis of average monthly rainfall, the number of rainy days, and the value of the Markov constant (a figure between 0 and 1 that determines the degree of clustering of rainy days). A regression formula was derived from 160 data pairs of monthly average rainfall and number of rainy days to estimate the number of rainy days (see Appendix 1). Each run with the crop growth model is repeated 20 times with different generated rainfall patterns so as to simulate stochastic variation in rainfall.

The nutrient-limited yield (NLY) is calculated with a sub-module based on Janssen *et al.* (1990), which is defined as the potential production or yield, limited by availability of soil nutrients. The QUEFTS methodology (Quantitative Evaluation of the Fertility of Tropical Soils) provides a procedure to calculate nutrient-limited yield as a function of the availability of macro-nutrients, for which P-Olsen, exchangeable potassium and soil pH_{H2O} are diagnostic criteria (Janssen *et al.* 1990; Smaling and Janssen 1992). In calculation of the nutrient-limited yield, it is assumed that no other factor, e.g. water deficit, hampers growth.

The crop production levels indicate possibilities and constraints within prevailing biophysical conditions and allow for an estimate of yield decline as a consequence of loss of topsoil due to water erosion. The constraint-free yield is approximated in irrigated, high-input agriculture (most constraints are counterbalanced or neutralized), water-limited production is approximated in rain-fed, high-input agriculture. Although the complexity of the actual farmer's environment is not simulated (e.g. the effects of pests and weeds are not taken into account), the calculated yield gaps may point to management options (irrigation, water conservation, fertilization) when higher yields are profitable or desired. The yield gap analyses and yield decline study are used to quantify the impact on yield of degradation-induced soil changes.

3.2.5 Erosion risk on agricultural land

Erosion risk was estimated by means of a modified Universal Soil Loss Equation (USLE) model (van den Berg and Tempel 1995; Wishmeier and Smith 1979). The erosion hazard risk calculated in t ha^{-1} was transformed into estimated loss of topsoil over a 20-year period (see paragraph 3.2.6).

All agro-ecological units that are considered suitable for rain-fed, low-input, low-technology maize growing have been analyzed for their erosion risk under this land use. For that purpose, the SOTER Water Erosion Assessment Program – SWEAP (van den Berg and Tempel 1995) has been used to calculate erosion risk in qualitative terms. For this study, the USLE sub-module of SWEAP was used. The model has been adapted for use at the scale of the databases. The original slope gradient and slope length factors of the model have been combined into a single one.

Homogeneous units were identified that have similar rainfall characteristics (erosivity), potential evapotranspiration (length of growing period, required for the ground cover factor that is related to the development stage of the crop) and soils and terrain (slope gradient and length, erodibility of the soil).

Before this could be done, the agro-ecological zones were used as a first subdivision of the country into areas with similar rainfall characteristics. When such an area contained more than one climate station, a further subdivision of the AEZ was made (see also paragraph 3.2.2). This was, in particular, the case for AEZ IIa where natural boundaries of the terrain/soil units were used for the subdivision (see also Figure 25 Appendix 1). Overlaying the SOTER units with agro-ecological zones and land use maps creates homogeneous units called agro-ecological units (AEUs).

SWEAP was run for those AEUs with the input data obtained in the first step for those areas that are considered suitable for rain-fed maize cultivation with low inputs and technology.

Land use in the erosion model has been defined as maize grown without soil conservation measures. Management of the crop residue is set as stubble left on the field and ploughed in before planting of a new crop. Planting month is November and harvesting month April.

3.2.6 Definition of erosion scenario

In this scenario, water erosion only occurs in the form of sheet erosion. To estimate the effect of prolonged sheet erosion on low-input and low-technology maize yield, computed water erosion risk was translated into 4 classes of topsoil removal over 20 years (0, 10, 25, 50 cm). With the loss of topsoil in these four scenarios nutrients are lost with the removal of soil particles from the top. The water retention characteristics and nutrient status of the newly exposed subsoil are different from the topsoil that has been removed.

The USLE soil loss estimates, calculated at the soil component level for ach AEU, were multiplied by the number of scenario years (20) and re-calculated to volume per unit area. The values then represent cm of soil lost and these figure were classified to aforementioned classes of topsoil loss.

The following formula was used:

$$L = (E/10^4 \times Y/B) \times 100$$

Where L = topsoil loss (cm), E = soil erosion risk (kg ha^{-1} yr^{-1}), Y = the number of years in the scenario (20 in this case), B = bulk density of the topsoil (kg m^{-3}).

No account is taken of the fact that soil deposition occurs in some units, rather than soil removal. The assumption is that all soil material removed by erosion is lost to the rivers. This simplification is justified when the objective is to study the impact of erosion on crop productivity under different agro-ecological settings. The effect of the process is studied, but not the extent and side effects of the process.

3.2.7 Yield potential after erosion scenario

The impact of change in soil properties induced erosion of topsoil, is analyzed in this study. Soils are decapitated according to the scenario class of loss of topsoil. Scenarios are specific for combinations of soil and terrain components and climate zone. The soil data are averaged over topsoil and subsoil after decapitation and new input files are prepared for the crop growth simulation model, accounting for lost nutrients through topsoil erosion and for altered soil physical conditions. Crop yields are calculated again with the new input files that include changed soil properties after simulated erosion. The new crop yields are compared with the yields assessed for actual conditions and results are linked to the AEU map.

A single land use system was considered. Possible effects of land use between maize-growing cycles were ignored. It was assumed that no change in the land use scenario would occur and that climate conditions would not change significantly.

4 Results

4.1 Land suitability

A major part of the soils of Zimbabwe has moderate to severe limitations in nutrient availability. Therefore a large part of the country is only marginally suitable for growing maize under low inputs (Figure 13). This applies for all regions, Eastern Highlands, the Highveld and Middleveld to the Kalahari Sandveld. The poor fertility is generally due to very low organic carbon content, the moderately acid nature of the soils and the often-sandy texture of the topsoil.

Limitations of soil moisture availability are more severe, but less extensive than nutrient limitations. Soil moisture limitations are a dominant constraint for units that key out as not suitable. In the suitable areas, nutrient limitations are dominant (see Table 1 and Appendix 6, Table 15). The moisture availability limitations occur notably in the Eastern Lowveld, and on all soils with a low rootable soil volume (see Appendix 5, Figures 31 and 32). Deep clay soils with a rootable depth of 120 cm or more seem to effectively buffer soil moisture and they key out as moderately suitable even in the low rainfall areas.

Soil salinity and sodicity are other severe limitations occurring in the drier areas of Zimbabwe e.g. Upper and Mid-Zambezi Valley, the lower parts of the Kalahari Sandveld and in the southeastern Lowveld.

Poor drainage conditions and oxygen shortage in the rooting zone are locally limiting conditions, sometimes combined with sodicity, but more often a specific problem of the Vertisols. Erosion is an important limiting factor for the Eastern Highlands and for some medium gradient mountain areas north and south of Bulawayo. Table 1 gives the evaluation result with the subdivision of the suitability classes and their extents. A further specification of the limitations for each suitability class can be found in Appendix 6.

Table 1. Approximate extent of areas suitable for maize cultivation

Suitability Class	**Major limitation**	**Extent (km^2)**	**Extent (%)**
Highly suitable	No	2585	0.7
Moderately suitable	soil fertility	37978	9.7
Marginally suitable	soil fertility	166945	42.9
Not suitable	soil moisture	177791	45.6
No data	-	1184	0.3

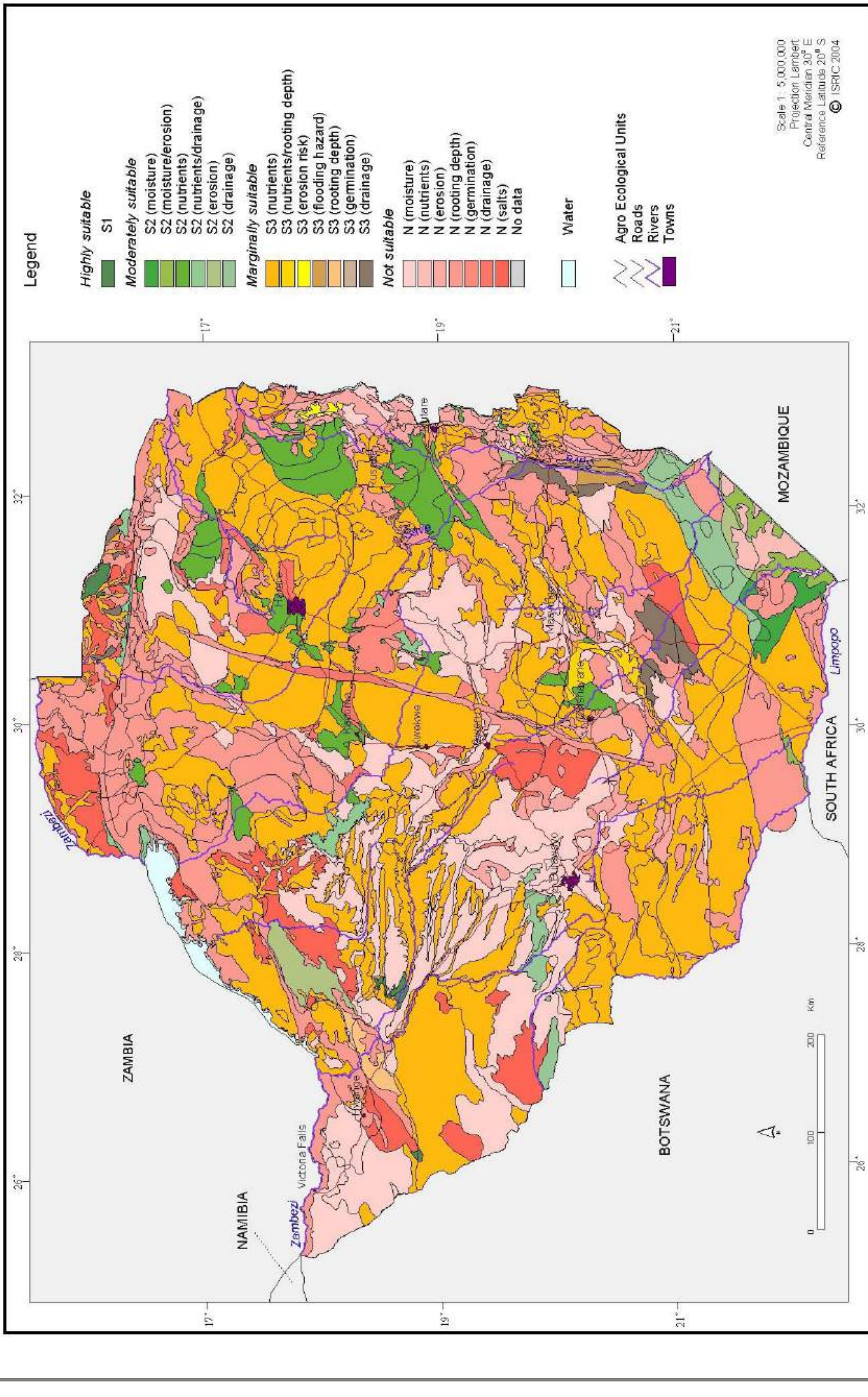

Figure 13. Suitability for maize cultivation under low inputs and technology

Annual variation in maize production is large (see statistics in Figure 8) due to the rainfall variability. The reliability of rainfall is generally of greater importance for rain-fed maize growing than the annual average, as the variation from year to year is large. In the assessment on the suitability for maize growing long-term averages of monthly rainfall values have been used.

4.2 Erosion hazard

The erosion risk is generally low to very low for those areas that are evaluated to be physically suitable for growing maize under low inputs and technology level (Table 2 and Figure 14). This is mainly determined by the low relief of those zones. Medium to high risk (11% of the total suitable area) are present in the northeast of the Highveld where rainfall intensities are high and relief is more expressed. The soils developed on the acid igneous rocks (granites and gneisses) have a sandy topsoil, and a low organic C content. This results in a weak structure that, under cultivation, easily disintegrates and is very susceptible to erosion.

There are certainly areas within Zimbabwe with high to very high erosion risk, but they almost exclusively have soils that are too shallow for sustainable cultivation of low-input maize (and therefore labeled unsuitable).

Table 2. Extent of erosion risk

Erosion risk class	Extent (km^2)
Very low	73,779
Low	107,723
Moderate	20,636
High	3,199
Very high	2,172
Not applicable	181,125

*Note: the erosion risk is only reported for those areas that are considered suitable for the defined LUT.

Figure 15 shows the erosion risk under current land use. A comparison between this map and Figure 14 reveals some significant points between the areas classified as cultivation (communal/commercial) in the first map and suitable for maize in the second. Erosion risk under maize is not always the same as the risk under actual land use.

Areas with an erosion risk on Figure 14 (considered suitable for maize) do not differ from the same zones on Figure 15 when the land use is communal cultivation, except the sandy soils in the western part of the country where the land use maize classifies with a slightly higher risk than the land use communal cultivation. In the erosion model, crop parameters for the land use communal cultivation are generic (field crops) and do not take into account specific maize parameters.

The erosion risk for low-input grown maize under low technology is only calculated for those areas that can support sustained use of this LUT. Actual land use and management is determined by social factors, economic considerations, and land property history. It means that people are not always in the best place to grow what they grow and to manage the land in the way they do. The poor often have limited possibilities to change their situation.

4.3 A scenario for 20 years prolonged sheet erosion

Since most of the erosion (risk)-prone areas have severe limitations for low-input maize, the extent of the area with a scenario for loss of topsoil over 20 years is limited (Table 3). No land within the areas assesses as suitable, had an erosion risk that translated to loss of 50 cm topsoil (most severe scenario); a limited area in the north east was associated with a topsoil loss scenario of 25 cm over 20 years; and a 10 cm topsoil loss scenario was found in some units in the eastern part of Zimbabwe (see Figure 16).

Table 3. Extent of erosion scenario classes

Topsoil loss class	**Extent (km^2)**
0 cm	201,556
10 cm	5,100
25 cm	851
50 cm	0
Not applicable	181,125

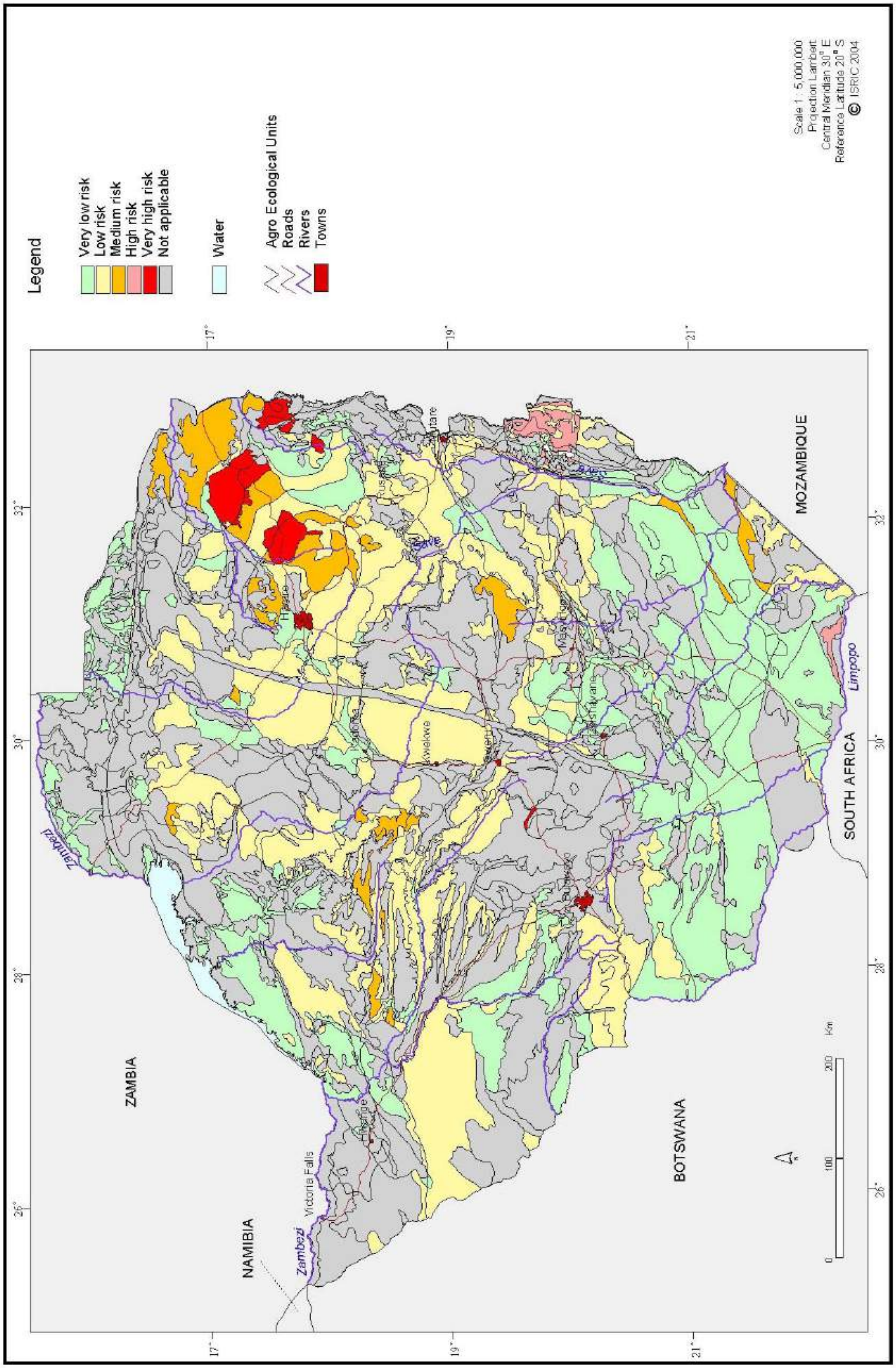

Figure 14. Erosion risk under land use rain-fed maize with low inputs and technology

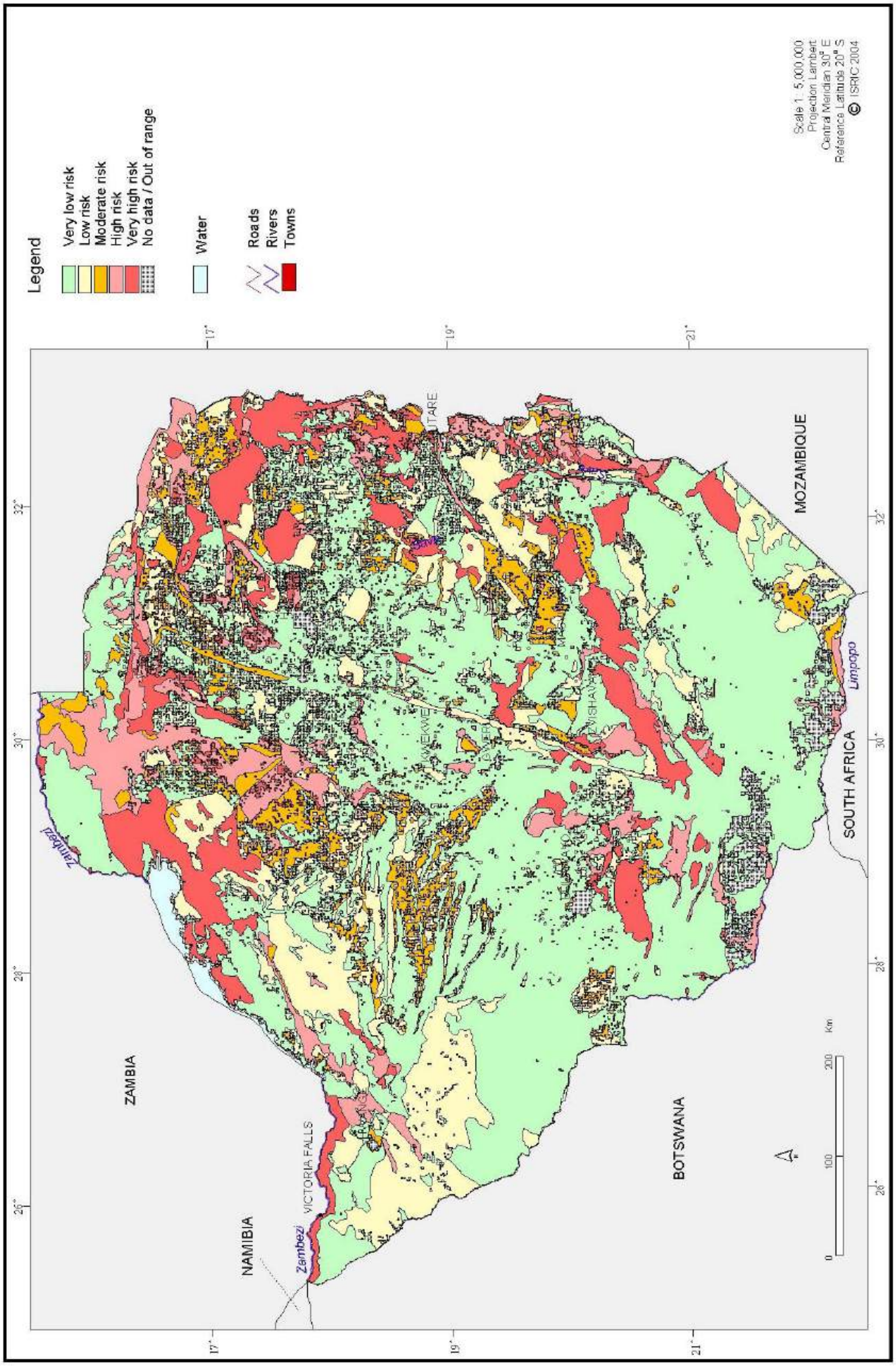

Figure 15. Erosion risk under current land use

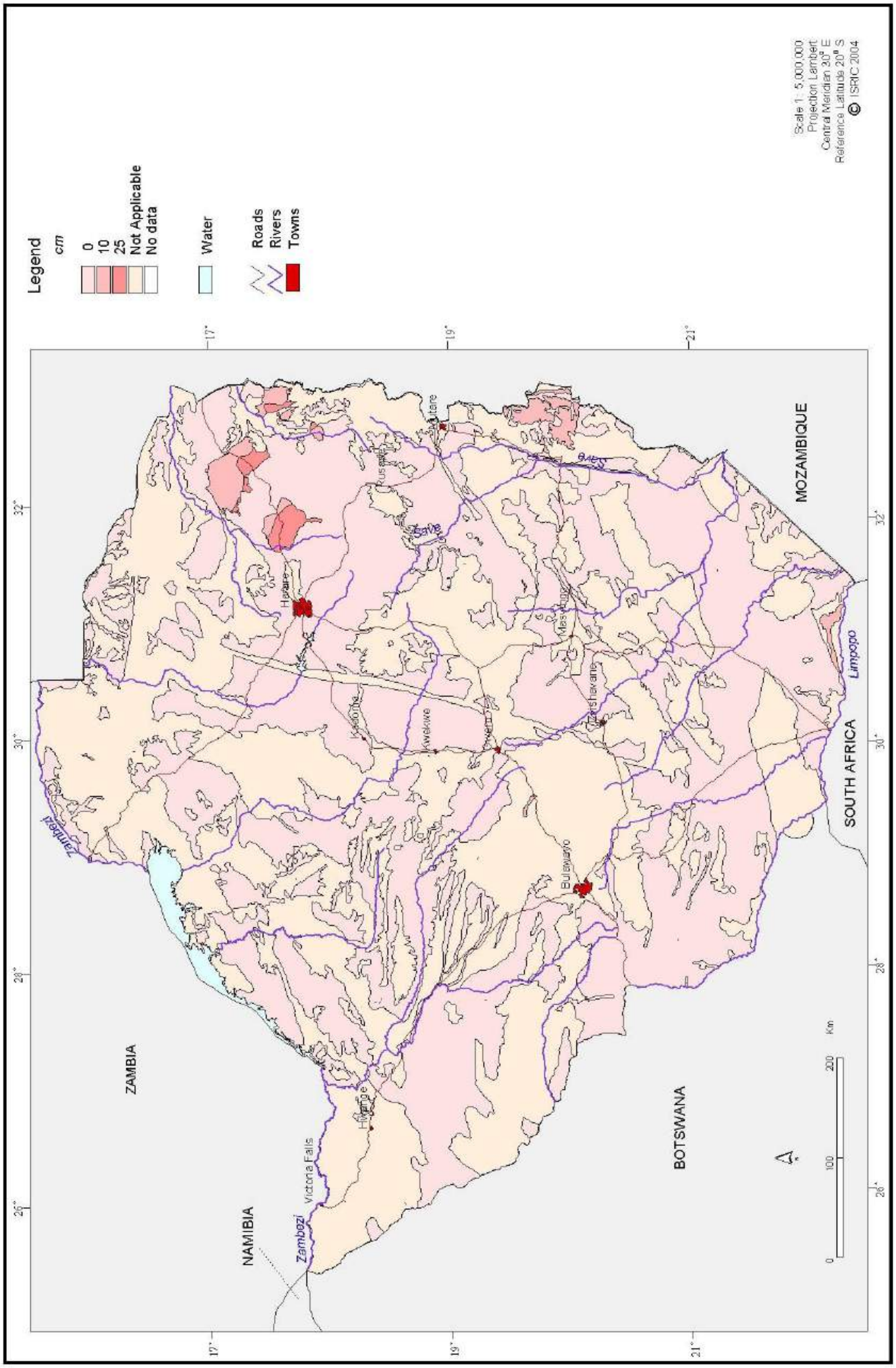

Figure 16. Loss op topsoil after simulated 20 years of soil erosion

4.4 Analysis of crop growth for different production situations

The constraint-free yield is the bio-physical production ceiling: the maximum production attainable when moisture, nutrients, weeds and pests are not limiting, and crop production is influenced only by solar radiation (cloudiness) and temperature.

Constraint-free yield (CFY)
The potential for maize production in Zimbabwe is high (Table 4). Solar radiation and temperatures are conducive to maize growth. Calculated constraint-free yields are between 9228 kg ha^{-1} (Chirundu Sugar Estate) and 14 243 kg ha^{-1} (Inyanga experimental station). Only in the extreme northwest (Binga, Chirundu Sugar Estate) and south (Beitbridge) the average constraint-free yield is less than 10 t ha^{-1} (see Figure 17). Higher average minimum and maximum temperatures explain the lower ranges of constraint-free yields in these areas, causing a shorter growing period and, consequently, less grain filling.

Table 4. Constraint-free yield (CFY) by climate station

Station name	CFY (kg ha^{-1})
Chirundu Sugar Estate	9228
Mount Darwin	11313
Karoi	11980
Umvukwes	12789
Trelawney Research Station	12160
Binga	9951
Harare	12755
Victoria Falls Airport	11608
Gokwe	12250
Inyanga Exp. Station.	14243
Gatooma Cotton Res. Institute	11679
Wankie Main Camp	11465
Kwekwe	12375
Grand Reef	11861
Chivhu	13504
Gwaai	11134
Nyanda	12260
Bulawayo	12691
Chipinge	12637
Triangle Hill	10777
West Nicholson	11466
Beitbridge	9888

Water-limited yield (WLY)

The central core of Zimbabwe, around the Great Dike, has a water-limited yield potential that is close to optimum; 27% of the total *suitable* area (see Figure 18 and Table 5). The area bordering the central core has a high water-limited yield potential, between 7.5 t ha^{-1} to 10 t ha^{-1} (28% of the total *suitable* area). To the southeast, the water-limited yield potential decreases from 5 to 7.5 t ha^{-1} (21%) to 2.5 to 5 t ha^{-1} (14%) and even lower (9% of the total *suitable* area). Figure 18 shows that in the extreme southeast (AEZ V-4/5) moisture conditions are much less than optimal, leading to water-limited yield gaps (difference between water-limited yield and constraint-free yield expressed in % of constraint-free yield) of over 75%, meaning that WLY is 25% or less relative to the CFY. Other areas that have high yield gaps (>75%) include the agro-ecological units north of the cities Harare, Bulawayo, Kadora, and east of Kwekwe.

Table 5. Extent (km^2) of maize yield classes within suitable AEUs for different production situations

Low-input maize yield class ($kg\ ha^{-1}$)	Constraint-free yield (CFY)	Water-limited yield potential (WLY)	Nutrient-limited yield potential (NLY)
0-2500	0	19,018	207,266
2500-5000	0	29,235	241
5000-7500	0	43,665	0
7500-10000	26,784	58,944	0
10000-15000	180,724	56,646	0
No data/not appl.	181,125	181,125	181,125

Nutrient-limited yield (NLY)

In Zimbabwe, paucity of crop nutrients is the major limitation in subsistence agriculture. This was highlighted by the qualitative land evaluation assessment and is confirmed in the quantified analysis. Nutrient-limited yield gaps (the gap between constraint-free yield and nutrient-limited yield) are high, without exception. Table 5 clearly shows that nutrient-limited yields are low all over Zimbabwe for this LUT and the yield gaps with water-limited and constraint-free yields are high. The lowest constraint-free yield is about 9 t ha-^{1} and the highest nutrient-limited yield is less than 3 t ha^{-1} (<1% of the total area). Most of Zimbabwe has a nutrient-limited yield potential less than 1.5 t ha^{-1} (see Figure 20). In the extreme north, southeast, and southwest, nutrient-limited yields are even below 0.5 t ha^{-1}. Phosphorus is the most limiting nutrient (dominantly below 10 kg extractable P_2O_5 ha^{-1} and often even less than 5 kg P_2O_5 ha^{-1}); nitrogen is also consistently low for most Zimbabwean soils (ranging between > 10 and 146 kg ha^{-1}). The nutrient-limited yield gap with potential water-limited yield (which can be considered the maximum attainable yield for rain-fed maize) is shown in Figure 21.

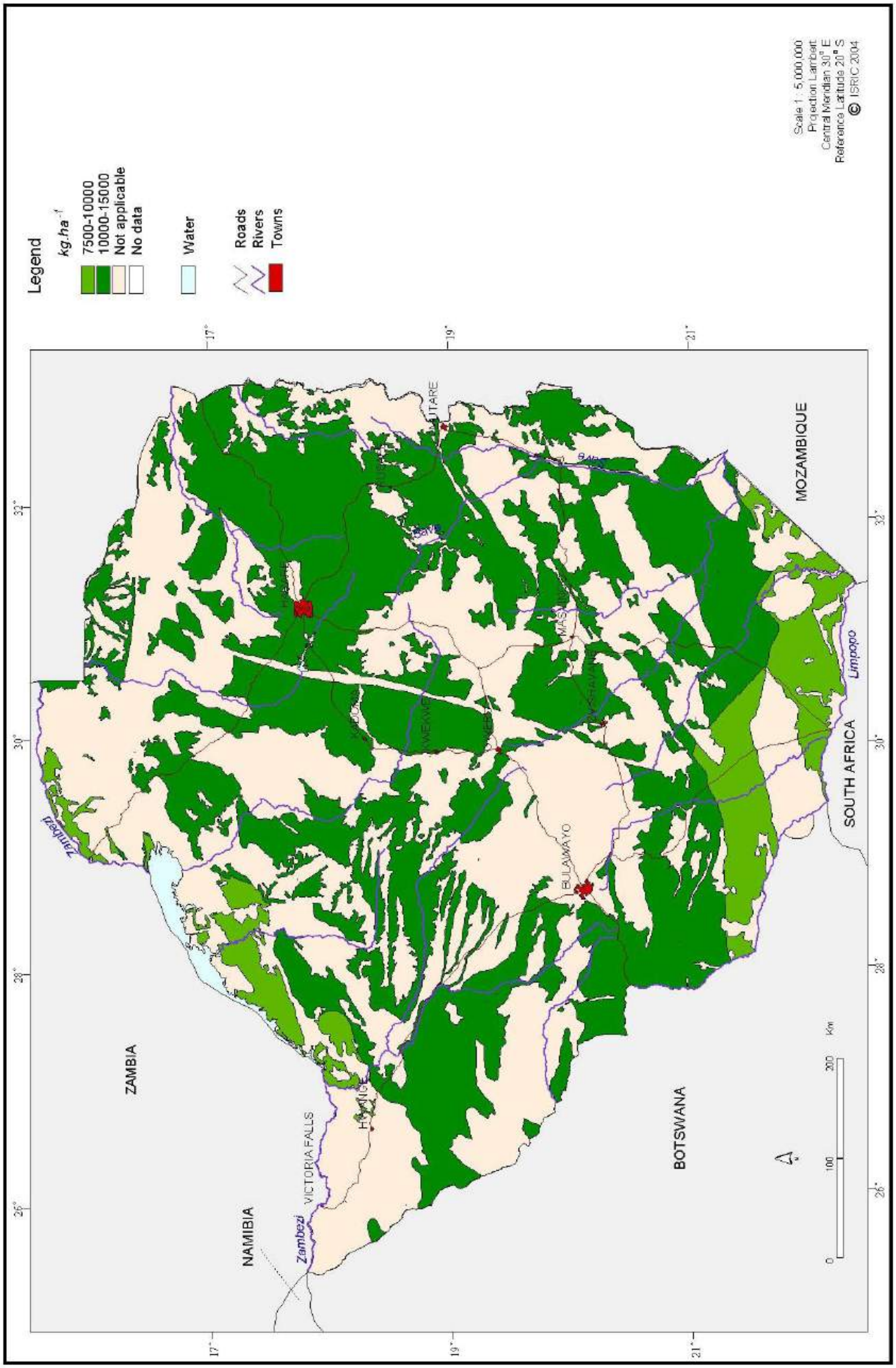

Figure 17. Constraint-free maize yield

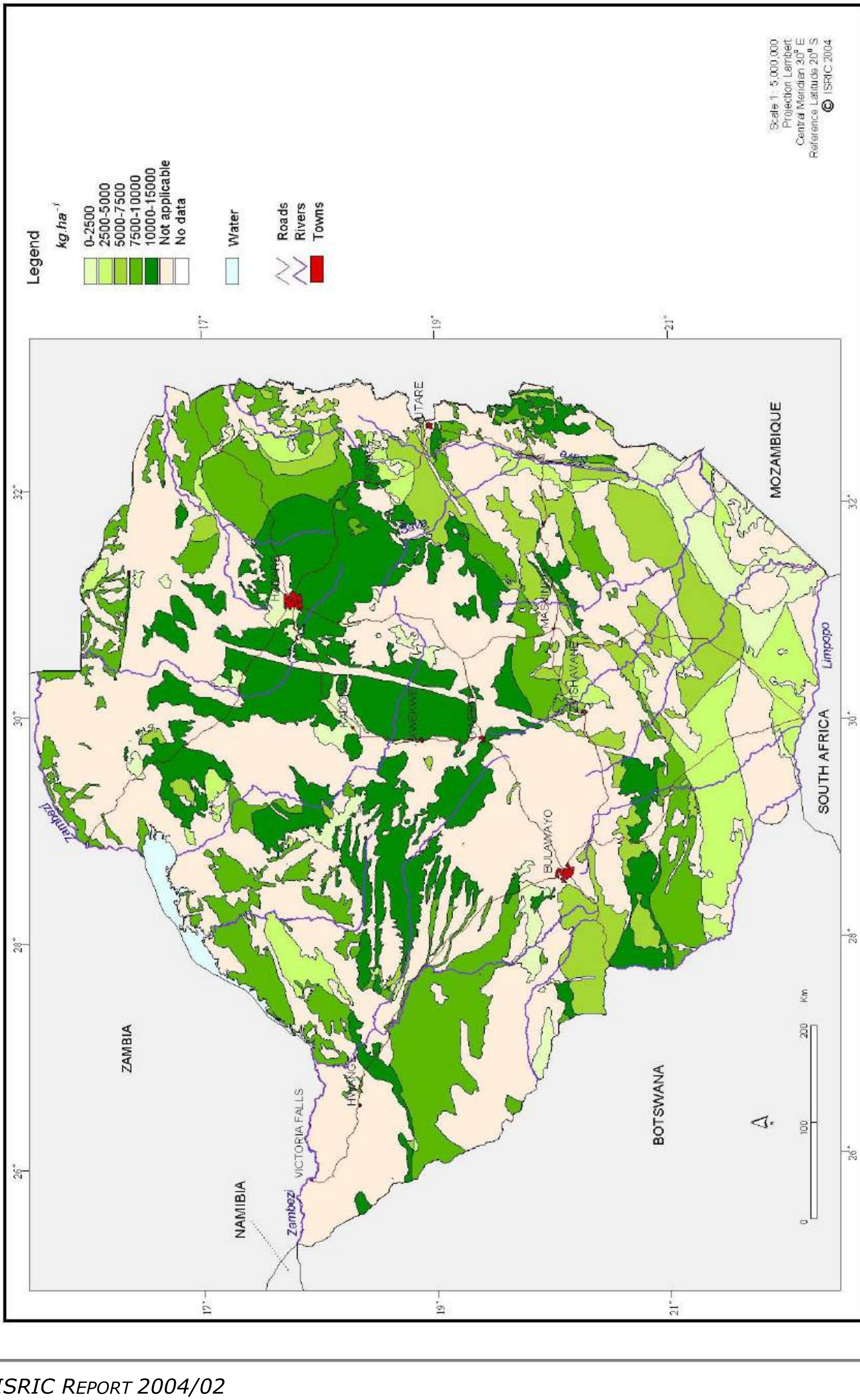

Figure 18. Potential water-limited maize yield

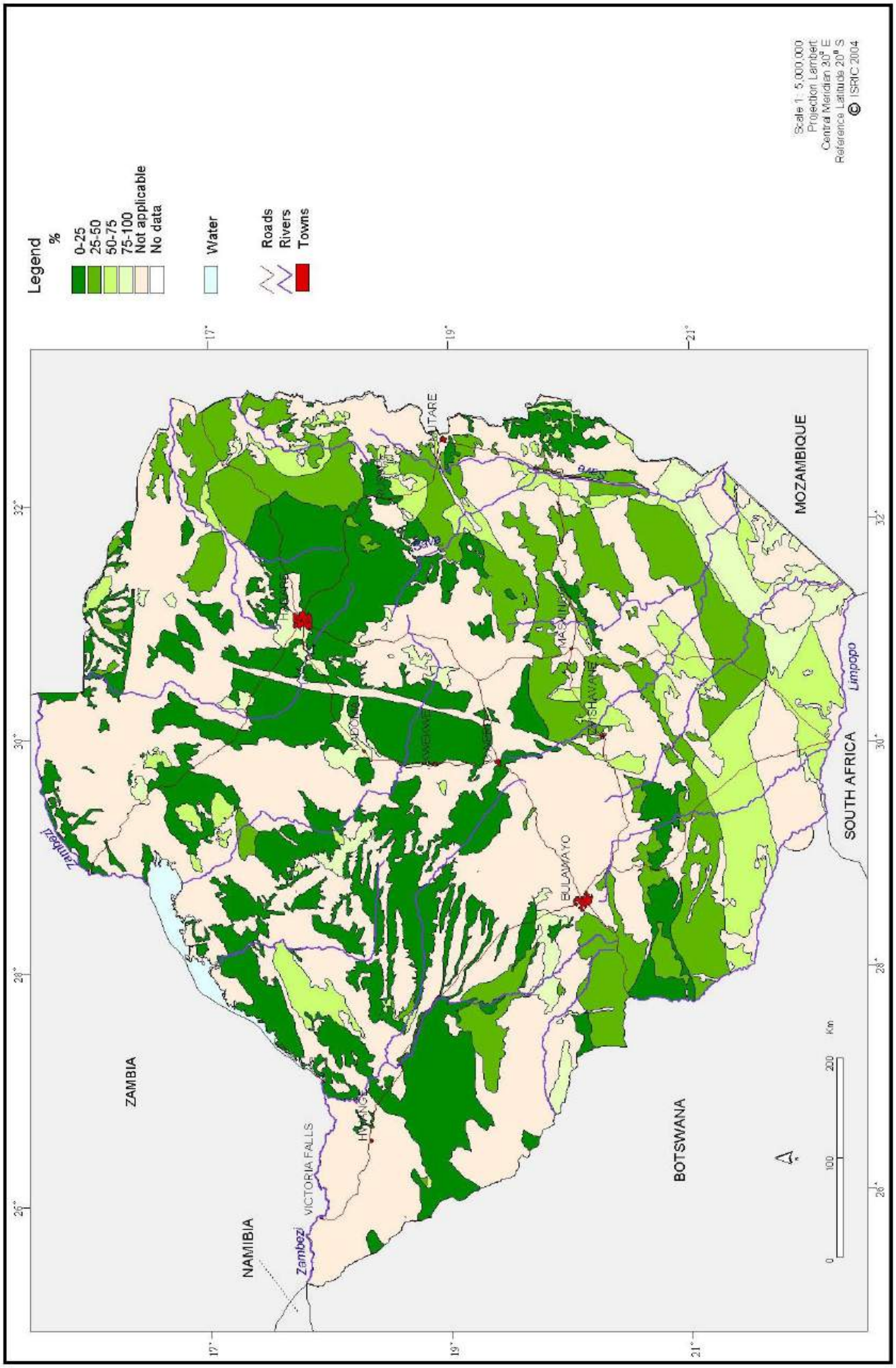

Figure 19. Potential water-limited maize yield gap

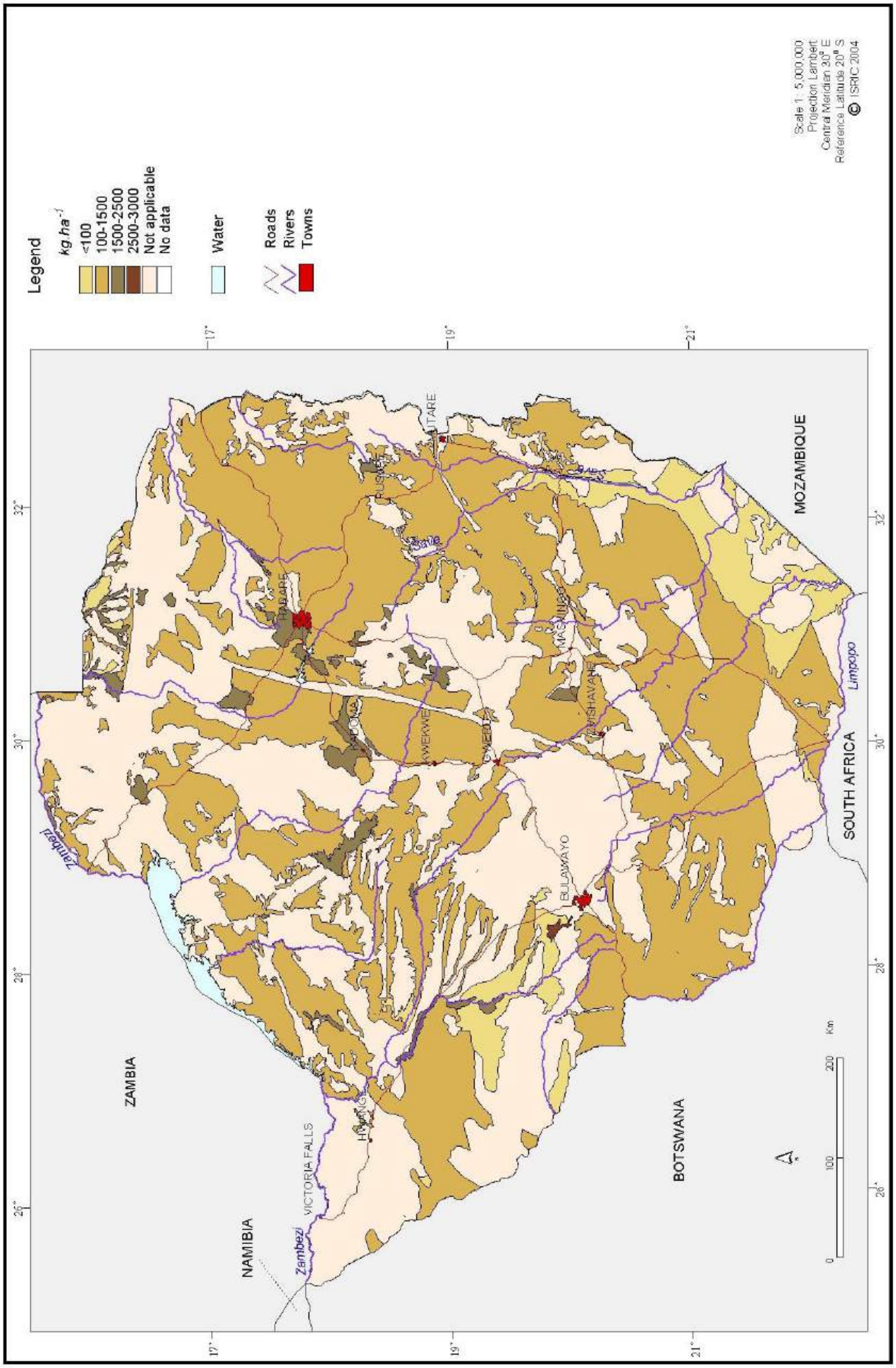

Figure 20. Potential nutrient-limited maize yield.

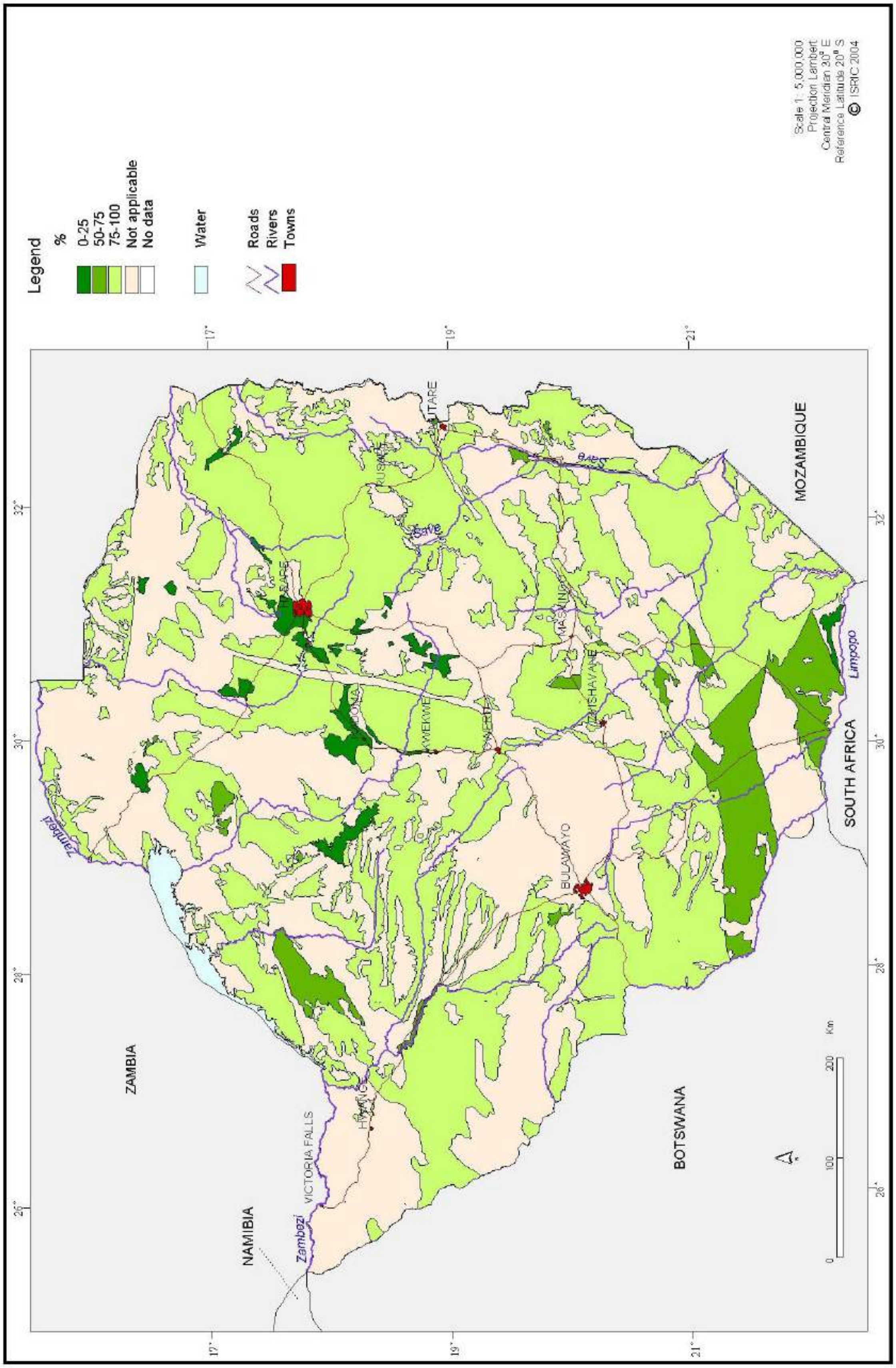

Figure 21. Potential nutrient-limited maize yield gap relative to potential water-limited yield

A caveat must be applied to the data: the lack of measured P-Olsen data (creating the need for PTF-generated figures); the high spatial and temporal variability of the soil fertility parameters and their questionable adequacy for assessing the availability of nutrients; and the fact that the QUEFTS-model was calibrated for Kenya means that the figures related to the nutrient-limited scenarios should be interpreted qualitatively (that is, relative to other scenarios) and not quantitatively.

4.5 Crop growth analysis for an erosion scenario

Water-limited yield decline

Erosion-induced alterations of soil hydraulic characteristics and soil thickness may lead to changes in water-limited crop yield. No measured data on soil moisture retaining and conducting capacity were available in this study. Soil hydraulic parameters were estimated on the basis of dominant texture (see Appendix 3). Therefore, changes in hydraulic parameters are only reflected when dominant texture changes class due to topsoil loss. In the limited area with a scenario for loss of topsoil (5,952 km^2, which is only 3% of the total suitable area for low-input and low-technology maize) little yield impact was predicted. Yield decline is forecast for only 4% of the area with an erosion scenario (10 or 25 cm topsoil loss) (Table 6). Some soils within the erosion scenario area show little texture differentiation in the profile; therefore hydraulic parameters are the same throughout the profile. Consequently, with soil profile decapitation (simulating loss of topsoil due to sheet erosion) no change in hydraulic parameters occurs and no yield impact is forecast.

Table 6. Extent (km^2) relative water-limited yield decline (%) by topsoil erosion class

Erosion scenario (cm topsoil loss)	Yield decline (%)			
	1-10 %	10-25 %	25-50 %	>50%
0	0	0	0	0
10	0	98 (2%)	146 (2%)	0
25	0	0	0	0

Note: the figures between brackets represent the extent of yield decline class relative to the total suitable maize area under an erosion scenario (total area with erosion scenario of 10 or 25 cm is 5,952 km^2).

Nutrient-limited yield decline

For the limited area with a scenario for loss of topsoil (only 3% of the total *suitable* area), a high yield impact was predicted. More than half of the area (58%) with an erosion scenario has a yield decline of 25% or more. For 93% of the area with simulated erosion, an impact on yield is predicted. Tropical soils often have a high within-profile differentiation of nutrient status. For most soils (with possible exceptions of soils on base-rich parent rock and young soils), nutrient status is highest in the topmost layers– related to organic matter turnover- and there is a sharp gradient to lower depths. A loss of the top 10 or 25 cm of the soil profile can have a huge impact on soil fertility, especially in poor and shallow soils. Table 6 shows that the 10 cm topsoil loss scenario impacts on 44% of the total area under an erosion scenario with a yield decline of 25 - 50%.

Table 7. Extent (km^2) relative nutrient-limited yield decline (%) by topsoil erosion class

Erosion scenario (cm topsoil loss)	**Yield decline (%)**			
	1-10 %	10-25 %	25-50 %	>50%
0	0	0	0	0
10	2,101 (35%)	359 (6%)	2,640 (44%)	0
25	0	0	0	851 (14%)

Note: the figures between brackets represent the extent of yield decline class relative to the total suitable maize area under an erosion scenario (total area with erosion scenario of 10 or 25 cm is 5,952 km^2).

In some cases, the texture shift as a consequence of simulated loss of topsoil caused the forecast yields to be higher than before erosion. In those cases, the units in the yield decline map were set to zero yield decline (instead of increase). An incidental yield increase would not be completely unrealistic, but the overall picture would be less clear with more classes added to the legend.

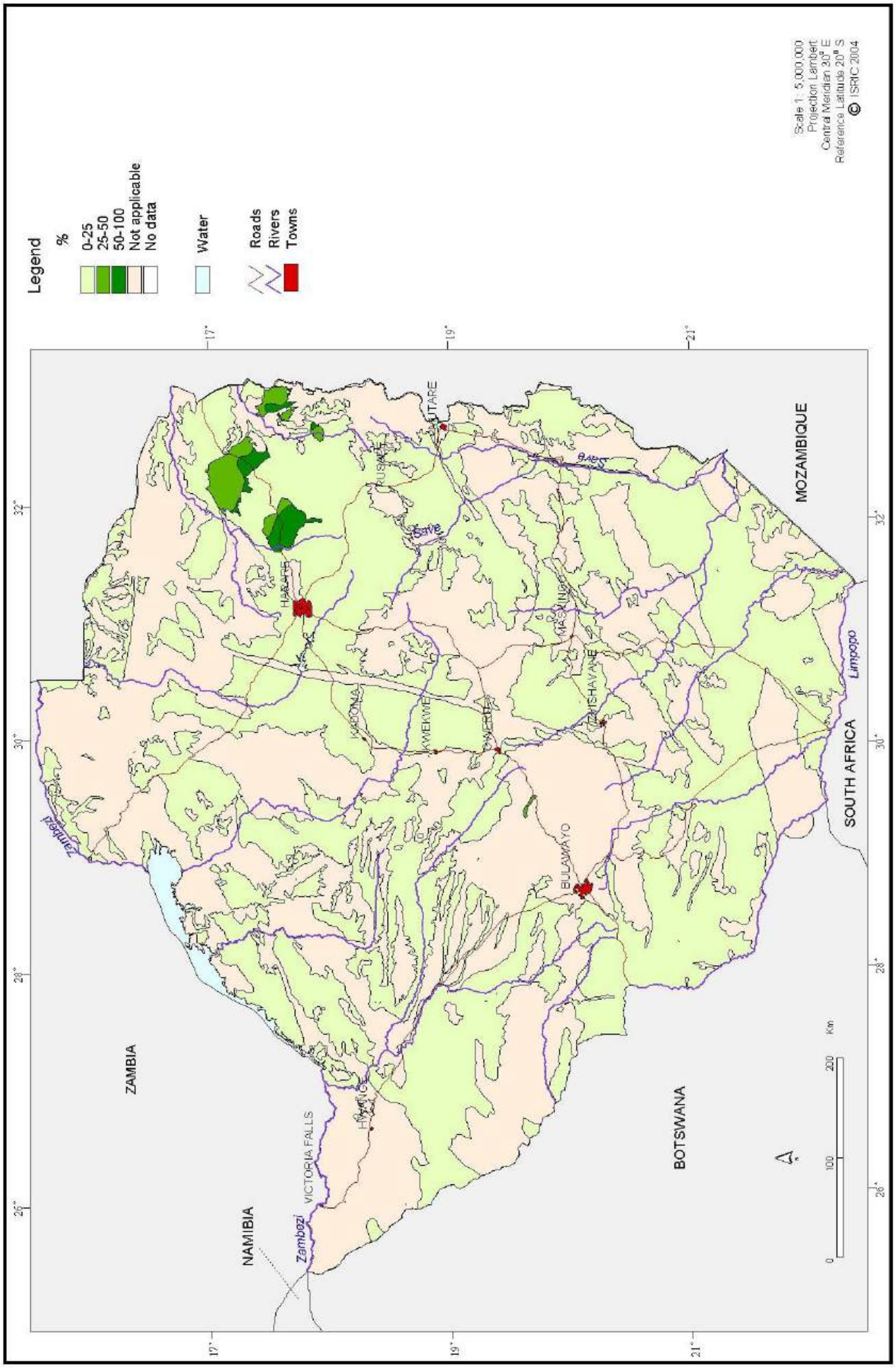

Figure 22. Nutrient-limited maize yield decline after simulated 20 years of erosion

5 Discussion and conclusions

5.1 Land suitability for maize

FAO (2000) reports three major production constraints for Zimbabwe: low and erratic rainfall, inherently low nutrient status (sandy topsoil of soils derived from granite and gneiss) and limited inputs, and lack of appropriate technology.

The land evaluation shows that low nutrient status is the principal physical constraint on maize production for the land suitability classes *moderately-* and *marginally suitable*. All other physical constraints (erosion, availability of moisture, etc.) are of less importance for these suitability classes. Soil moisture shortage is the dominant constraint for the class *not suitable*. This class occurs in areas with low rainfall and shallow soils. It is remarkable that moisture shortage does not rank equally in the classes *moderately-* and *marginally suitable*, as might be expected from the often-reported low yields or harvest failure in the region due to insufficient rainfall. This might be explained by our use of monthly average rainfall data, interpolated into daily data, that mask periods of drought that occur in some years.

Field observations by Vogel (1994) on farms of the Communal Lands with soils derived from granite and gneiss, reveal that rooting of maize is generally not deeper than 30 cm. The observed maize roots used only a quarter of the soil volume of the soils for which a deeper rooting should be attainable. Such shallow rooting does not draw upon the soil moisture and nutrients stored in the subsoil. This shallow rooting depth contrasts strongly with the 120 cm rooting depth given for more than 50 percent of the soils in the database. This depth was used in the WATSAT moisture sufficiency assessment.

In sloping areas prone to erosion, rainfall loss through runoff is a major factor reducing the soil moisture availability to the crop. In the Communal Land areas, runoff loss can reach up to 30 percent of the total rainfall (FAO 2000). Combining these effects of reduced rooting depth and rainfall loss through run-off, one has to conclude that less soil moisture is available than assumed in the WATSAT moisture sufficiency assessment.

It is evident that rooting depth for maize is restricted on soils developed on acid igneous rock. Vogel (1994) reported a number of impediments on these soils: low nutrient status; compaction of the subsoil; and high mechanical resistances for root penetration in these sandy soils. In order to increase crop yields, attention must be given to measures improving rooting depth. This is not easy for farmers lacking input resources and technology. Measures to improve the soil fertility by increasing the organic matter content of the topsoil and a dose of basic fertilizer will play a crucial role to reverse the present trends. Deeper rooting of the crop will improve moisture and nutrient availability, resulting in higher yields. Increase yields will not only supply more food and cash crops to farmers but, also are a means to improve the soil, reversing nutrient depletion and soil degradation. The question remains: How to start the virtuous cycle?

5.2 Erosion hazard

The USLE model predicts soil losses in t ha^{-1}. The adaptation of the model, in particular the slope factors, and the lack of calibration of the model for the range of conditions as represented by the databases, do not permit a quantification of soil loss in t ha $^{-1}$ (Mantel *et al.* 2000). The presentation of the results is, therefore, made in qualitative terms: erosion hazard units (EHUs).

Visual comparison with the SLEMSA model results for the Communal Land area (Grohs and Elwell 1993) show a great deal of overlap, even in quantitative classes shown on both maps. Vogel (1994) observed a same order of magnitude between measured erosion plots in the granite area north of Harare and the SLEMSA estimates.

The Universal Soil Loss Equation has several limitations: it has been developed for prediction of soil erosion loss on agricultural lands in the USA with slopes less than 20%; it predicts the amount of soil that moves on a field, not necessarily the amount of soil removed from the field (Trimble and Crosson 2000) – and local deposition, on the slope itself or in the catchment will certainly take place and might improve soils locally.

5.3 Yield gap analysis for different production situations and scenarios

Constraint-free maize yields are high, because for most areas the amount of solar radiation and temperature is adequate. The length of the growing cycle (crop development) is a function of temperature. Yet, only slightly increased temperatures (2 ^{0}C), as foreseen in climate change studies, will be too high, and have a dramatic impact on maize yields and on the total arable areas.

Water-limited yields are high, in some areas close to the constraint-free yield under the assumption of unrestricted rooting depth – as discussed in the previous section (5.2). Broadly speaking, water-limited yield gaps increase to the southeast (AEZ V-4/5), where moisture conditions are constraining. This study used averaged climate data that were manipulated using a rainfall generator, so as to simulate rainfall distributions. Extreme dry and wet years are not considered in the analysis. Yet, the droughts recurring with an interval of several years and related to El Niño, Southern Oscillation (ENSO), cause negative yield impacts and associated food security crises. The present methodology should be repeated using actual daily climate data and for future climatic scenarios, to make the effort of quantification of land degradation under climate change and the impact on productive capacity of land.

Nutrient-limited maize yields are extremely low for the whole of Zimbabwe, when no input is assumed, due to low inherent soil fertility. From this analysis, it is clear that nutrients are the overriding constraint to low input farming

The erosion risk *for the areas suitable for low-input maize under low technology* is low. Predicted erosion losses over a scenario of 20 years are limited and so is the impact on yield. The few AEUs (Eastern Highlands and some AEUs east of Harare) with high erosion risk were translated into an erosion scenario of 10 or 25 cm topsoil loss over 20 years. The impact of water erosion on nutrient-limited yield is high. The extremely low nutrient-limited yields further decline when topsoil is lost. This effect will be magnified where the land utilization type is applied to areas assessed as *not suitable.*

The water-limited yield in this study is hardly affected by the erosion scenario. This is partly explained by the homogeneity in soil texture of the soil units affected by the scenario; no texture change follows from loss of topsoil, therefore no change in soil water conditions and, therefore, no yield impact results. On generally deep soils the decrease of soil thickness did not lead to yield declines. Whether topsoil loss leads to actual decline in soil physical properties depends much on: the organic matter content in the remaining soil, the clay type (determining aggregate stability and the sensitivity to slaking and crusting), biological activity (creation of pores), and land management (soil tillage and soil cover management).

This study considered only those areas assessed as *suitable* for sustained application of the defined land use. In reality, cultivation extends to ecologically fragile areas or areas unfit for sustained cultivation. Not only are those areas more vulnerable to degradation, they require - if cultivated at all - adapted management and inputs. Figure 23 shows the cultivated areas in the Communal Lands together with the land suitability for rain-fed maize (low input and technology). There is a clear overlap between Communal Lands and areas unsuitable for cultivation. It is questionable whether for many of those areas it is possible (technically or financially) to alleviate the severe limitations for use. Erosion risk under actual land use (shown in Figure 15) is considerably higher than the erosion risk under low inputs and technology grown maize in the suitable areas. Figure 24 shows the population density and the suitability for rain-fed maize (low inputs and technology); it shows that many people are living in marginal lands. It is mostly the poor who are condemned to the marginal lands, and their resources are too limited to allow intensification of crop and land management.

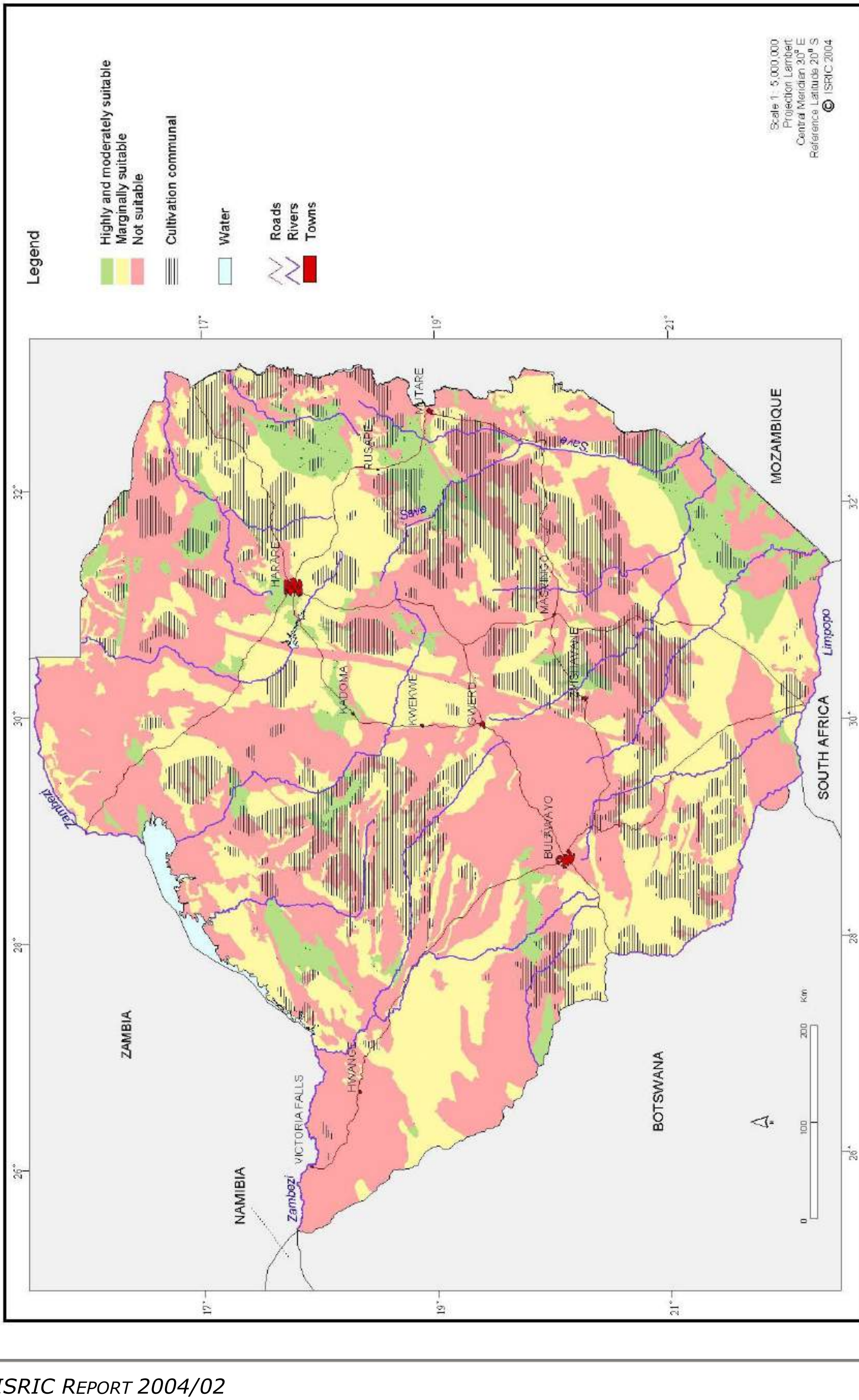

Figure 23. Cultivated areas in the Communal Lands and suitability for rain-fed maize (low inputs and technology)

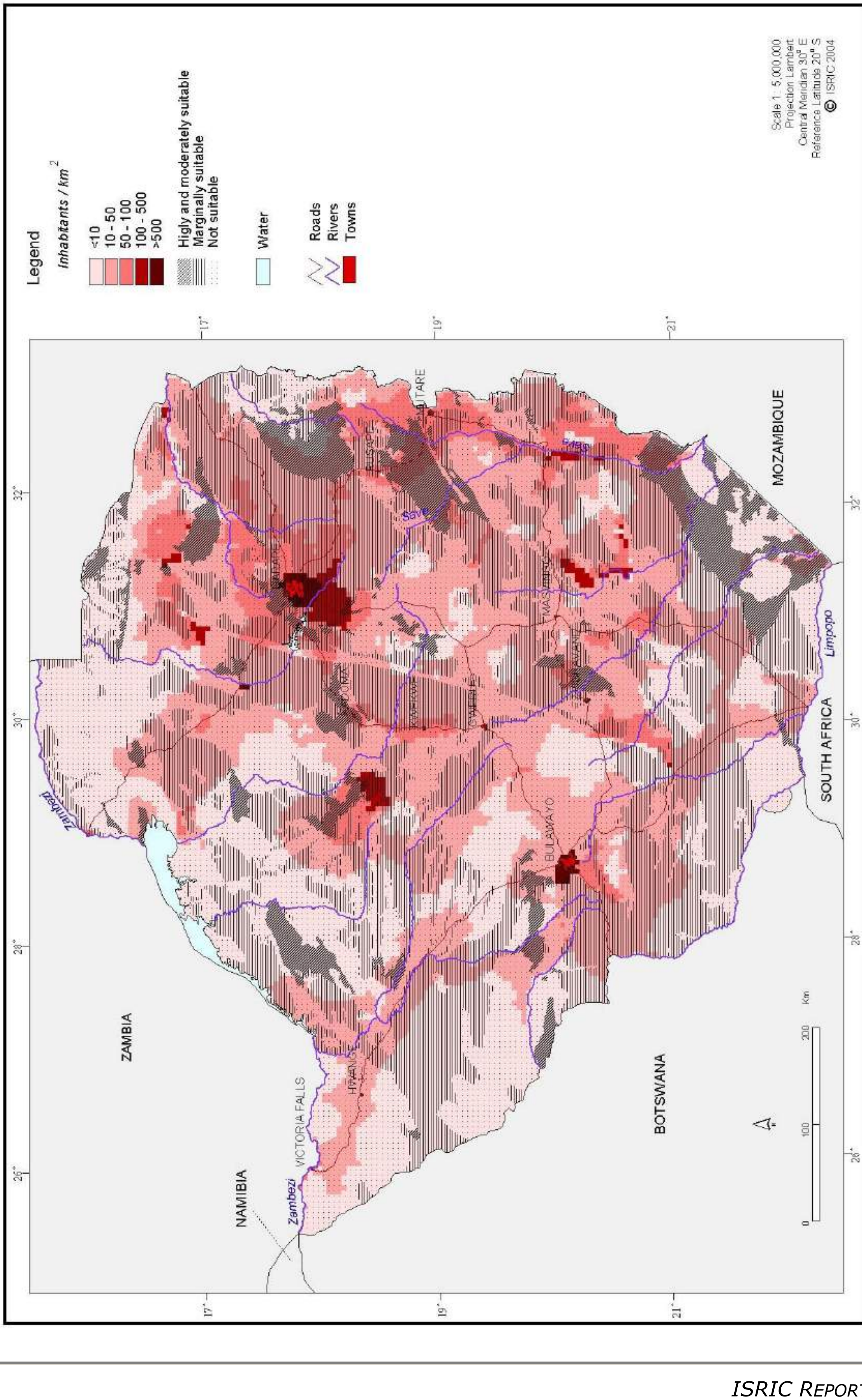

Figure 24. Population density and suitability for rain-fed maize (low inputs and technology)

Crop production and climate change

In this study we analyzed the effects land degradation (prolonged sheet erosion) under a constant climate. Climate changes however, and Sub-Saharan Africa is frequently hit by droughts. If climatic change results in increasing frequency and intensity of drought; and significantly higher temperatures, than the food security in Zimbabwe will worsen. Papaioannou (1999) reviewed studies on the impacts of climate change on agricultural production; he states that the potential for increases in drought frequency and severity with climate change is of special concern for Sub-Saharan Africa, since droughts in the current climate cause severe disruptions to regional food supplies. Schulze *et al.* (1993) emphasize the importance of intra-seasonal and inter-annual variation of rainfall for crop yields in southern Africa. Sivakumar (1993) has documented that recent droughts had shortened the current crop growing seasons by 5 to 20 days.

With an average temperature rise of 2 ^{0}C, simulated maize yields in Zimbabwe decrease dramatically (Muchena 1994); in some cases up to 30 percent, even under full irrigation conditions (Matarira *et al.* 1995). This is explained by the shortening of the crop growth period, particularly the grain-filling period. Increased CO_2 on plant physiology only partly offsets the negative yield impact. Downing (1992) used a simple index of the atmospheric water balance to assess how agricultural land use may be affected by changes in water resources: with a temperature increase of 2 °C the zones of Zimbabwe with a water surplus decrease by a third (from 9 per cent to about 2.5 per cent); the drier zones will double in area. A further increase in temperature to +4 °C reduces the summer water-surplus zones to less than 2 per cent of Zimbabwe, approximately corresponding to the 1991-92 drought. In addition to shrinkage of the agricultural area, crop yields in marginal zones would become more variable.

Several potential adaptation strategies might offset the negative impacts of climate change: these include switching to drought-tolerant small grains and maize varieties, and appropriate management practices. Zimbabwe does not have the option to shift or extend agricultural zones to higher altitudes as temperatures rise, as proposed for Kenya (Fischer and van Velthuizen 1996). Fertilization and irrigation will be only partly counterbalance the effects of predicted climate change and for many farmers, such options are not realistic: even under current conditions the expenditure on such inputs is beyond their means.

Discussion

Water sufficiency in Africa is under stress because of population growth, changes in land use and, probably, climatic change. The productive flow of rainwater - that fraction of water that is ultimately transpired by crops for production - dubbed green water (Ringersma *et al.* 2003; Rockström and Falkenmark 2000), is low in dryland systems in Sub-Saharan Africa and is estimated as 5-15% (Stroosnijder 2003). Adaptive land management strategies that combat the effects of drought and degradation, and increase food security are urgent, considering the projected climate changes for Zimbabwe. These could include the use of drought-tolerant small maize varieties, alternative crop selection (e.g. sorghum), varying plant density, soil and water conservation practices, and integrated nutrient management. Water conservation cannot be effective without improved nutrient management: policy and research priority should be put on the green water use efficiency. Research at the basin and regional level is required to quantify the potential of water use efficiency increasing technologies and the implications for different land uses and users. The inventories from the World Overview of Conservation Approaches and Technologies (WOCAT) may help to select appropriate conservation strategies for specific land use systems and soil and terrain units.

Most soils in Zimbabwe have a low inherent fertility, which is the overriding constraint for sustained agriculture. Yields are low and, without appropriate management, soils will be further degraded by soil nutrient mining and loss of nutrients through erosion. Economically viable and sustainable maize production in Zimbabwe requires nutrient amendments. Most farmers do apply some chemical fertilizer (northern provinces), and in the southern and eastern provinces cattle manure is mainly used. Soil quality needs to be maintained, at the least, and in many cases soils require reclamation. AEU-specific recommendations on integrated nutrient management strategies require further developed and application in extension; multi-purpose legumes could be an important component of integrated nutrient management strategies to reclaim unproductive lands (Giller 2003). One year natural grass-maize fallows proved to be effective in sustaining organic matter levels in a study on long-term organic matter dynamics in Zimbabwe (Zingore 2002) – but adoption of these practices must depend on the development of economic attractive packages.

This study shows that the nutrients status of the soils severely limits crop production in Zimbabwe. The nutrient-limited yield declines after simulated sheet erosion. There is a clear overlap of Communal Lands with areas *unsuitable* for rain-fed maize (low inputs and technology). Such ecologically fragile areas are more vulnerable to degradation, and require - if cultivated at all - adapted management and inputs. These *unsuitable* areas were not considered in this study. The possible effects of climate change - that will lead to a decrease in the *suitable* area and a decline in yield potential - combined with the scenario of soil degradation, makes the picture even bleaker. This calls for priority on land use policies that stimulate or facilitate the application of integrated crop management practices that aim at increased water use efficiency and balanced nutrient management.

In this study, Zimbabwe is taken as a case for the Southern African region, having similar natural resources and land use types. The conclusions that are valid for Zimbabwe can therefore, also be applied to the surrounding countries.

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Appendix 1. Climate data

Growing period and starting dates of planting

The growing period is defined as the period in which: 1) the soil moisture, from rainfall, is available to the crop, and 2) temperature is high enough for growth (FAO 1984).

For all listed climate stations of Zimbabwe the start of the growing period has been taken from *Agro-climatological Data of Africa* (FAO 1984) which distinguishes three periods in the rainy season; the pre-humid, humid and post-humid:

- The start of the growing period was set when mean rainfall (P) exceeds half the potential evapotranspiration (PET) - the pre-humid period (PET> P>0.5 PET);
- In the humid period, on average, rainfall exceeds the potential evapotranspiration (P>PET). In this period, rainfall is stored as soil moisture and excess recharges the ground water;
- Growth ceases at the end of the post-humid period when the potential evapotranspiration is much larger than the precipitation and soil moisture reserves are exhausted.

The agro-climatological tables give information on the variables for each station as monthly means. Potential evapotranspiration has been calculated according to the Penman method (FAO 1984). For this study, the growing period has been established through comparison between interpolated 10-day amounts of rainfall and potential evapotranspiration. The date of the start of the growing period has been given in Table 8. On basis of this date the Julian day of the year (365 days) was determined.

The agro-climatological data indicate that the border area with South Africa (Beitbridge, climate station ZW0035) is dry all the year round. However, the water balance model WATSAT (Mantel 1995) indicated a start of a maize growing period on December 1st, with full moisture sufficiency for the first month then moisture stress over all subsequent months. This may be explained by the method of averaging out the monthly data to daily data where no clustering in more rainy or drier spells occur. It is to be noted that maize is not grown in the area; sorghum is the major field crop.

Table 8. Climate stations data and their approximate start date of planting period

Station code	Station name	Latitude	Longitude	Altitude (m)	Start planting date	Start planting day (Julian day)
ZW0001	Chirundu Sugar Estate	-16.00	28.90	392	24 Nov	328
ZW0002	Kariba Airport*	-16.52	28.88	518	21 Nov	325
ZW0003	Karoi	-16.84	29.61	1344	10 Nov	314
ZW0004	Harare	-17.84	31.01	1472	6 Nov	310
ZW0005	Mount Darwin	-16.79	31.58	966	16 Nov	320
ZW0006	Umvukwes	-17.04	30.85	1481	6 Nov	310
ZW0007	Trelawney Res. St.	-17.59	30.33	1326	2 Nov	306
ZW0008	Henderson*	-17.59	30.96	1292	5 Nov	309
ZW0009	Binga	-17.62	27.33	617	27 Nov	331
ZW0010	Victoria Falls Airport	-18.10	25.85	1062	20 Nov	324
ZW0011	Wankie*	-18.37	26.49	782	3 Dec	337
ZW0012	Chibero*	-18.10	30.66	1335	1 Nov	305
ZW0013	Marandellas Res.St.*	-18.17	31.49	1646	30 Oct	303
ZW0014	Inyanga Exp. St.	-18.29	32.75	1878	27 Oct	300
ZW0015	Gatooma Cott. Res. St.	-18.32	29.88	1157	11 Nov	315
ZW0016	Wankie Main Camp	-18.74	26.94	1077	18 Nov	322
ZW0017	Gokwe	-18.22	28.93	1282	5 Nov	309
ZW0018	Kwekwe	-18.94	29.83	1215	6 Nov	310
ZW0019	Gweru*	-19.46	29.85	1429	8 Nov	312
ZW0020	Tjolotjo*	-19.76	27.76	1100	22 Nov	326
ZW0021	Nyanyadzi*	-19.76	32.41	530	28 Nov	332
ZW0022	Nyamandhlovu Exp. St.*	-19.95	28.18	1219	15 Nov	319
ZW0023	Grand Reef	-18.99	32.45	1018	4 Nov	308
ZW0024	Umtali*	-18.97	32.66	1119	6 Nov	310
ZW0025	Chivhu	-19.04	30.88	1459	5 Nov	309
ZW0026	Makoholi*	-19.84	30.78	1204	7 Nov	311
ZW0027	Gwaai	-19.29	27.70	999	27 Nov	331
ZW0028	Bulawayo	-20.15	28.61	1344	8 Nov	312
ZW0029	West Nicholson	-21.06	29.36	861	21 Nov	325
ZW0030	Nyanda	-20.07	30.86	1095	12 Nov	316
ZW0031	Chipinge	-20.21	32.61	1132	31 Oct	304
ZW0032	Sabi Valley Exp. St.*	-20.35	32.33	448	28 Nov	332
ZW0033	Motopos Nursery*	-20.39	28.49	1347	7 Nov	311
ZW0034	Triangle Hill	-20.95	31.36	421	15 Nov	319
ZW0035	Beitbridge	-22.22	30.00	457	1 Dec	335

* not used for the assessment of moisture sufficiency using the WATSAT model

Agro-Ecological Zones

The location of climate stations was plotted on the revised AEZ map (Venema 1998). Details of the AEZ are given in Table 9. The climate station best fitting in the AEZ was assigned as representative, while AEZ units without station were assigned a best-fit station according to the AEZ. In case of more than one climate station within one AEZ, further subdivisions were made using natural boundaries that more-or-less coincided with equal distance lines between the locations concerned (see Figure 25).

Table 9. Characteristics of the revised Agro-Ecological Zones. Source: Venema (1998)

N.R. (1)	AEZ (2)	Area (3)	Probability of receiving > 500 mm (%) (4)	Probability of receiving > 750 mm (%) (5)	LGP_ days (6)	Soil_Code (7)	Soil_Description
I	I	0.63	> 90	80 - 90	170 - 200	7M	Red loams
IIa	II a	4.07	> 90	60 - 70	140 - 170	5G/E,5AE,6G	Greyish brown sands/sandy loams derived from granites
IIb	II b	1.99	80 - 90	50	120 - 150	5/6/7G	As above
III	III(1)	0.60	70 - 90	40 - 50	100 - 130	1,5M	Deep Kalahari Sand
III	III(2)	1.25	70 - 80	40	110	2,5M	Very shallow
III	III(5)	5.30	70 - 80	30 - 40	120 - 150	5G/M,6G,4E	Greyish brown sands/sandy loams derived from granites
III	III(7)	0.26	70 - 80	40	130	7G	Red loams
IV	IVy(1)	1.07	60 - 80	20 - 40	110 - 130	1,(2)	Deep Kalahari Sand
IV	IV(2)	1.65	55 - 70	10 - 20	100 - 130	2,(5M)	Very shallow
IV	IV(3)	0.11	30 _ 40	10	70 - 90	3B	Vertisols
IV	IV(4)	2.34	60 - 70	20 - 40	100 - 130	4/5M,1,4C,8	Brown loamy sands and loams
IV	IV(5)	7.68	40 - 65	10 - 30	100 - 135	5G,(4M/S/E)	Greyish brown sands derived from granitic rocks
IV	IVz(1)	2.87	50 - 65	10 - 20	90 - 115	1,(4M,3B)	Deep Kalahari Sand
V	Vx(4)	2.77	< 30	< 10	< 70	2,4P,1,4M	Variable
V	V(2)	0.64	60	20	100 - 130	2,(1)	Very shallow
V	V(3)	0.42	30 - 40	< 10	70 - 100	3B,2	Vertisols
V	V(4)	1.51	70 - 80	30	100 - 130	4M,2,(1,8)	Brown loamy sands and loams
V	V(5)	3.57	40 - 60	< 15	70 - 100	5G,4P,2,4M	Sands & sandy loams derived from granite and gneiss
		0.27†					
	Total	39.00					

Notes:
(1) Natural Regions (Department of the Surveyor General 1984)
(2) Agro-Ecological Zones (Venema 1998)
(3) Approximate area in 10^6 ha using lat/long projection
(4) Probability of receiving more than 500mm rainfall during the period October to April
(5) Probability of receiving more than 750mm rainfall during the period October to April
(6) Length of Growing Period (number of days that Precipitation exceeds half Potential Evapotranspiration)
(7) Provisional Soil Map of Zimbabwe at scale 1:1,000,000 (Department of Research and Specialist Services 1979)
† No data for AEZ

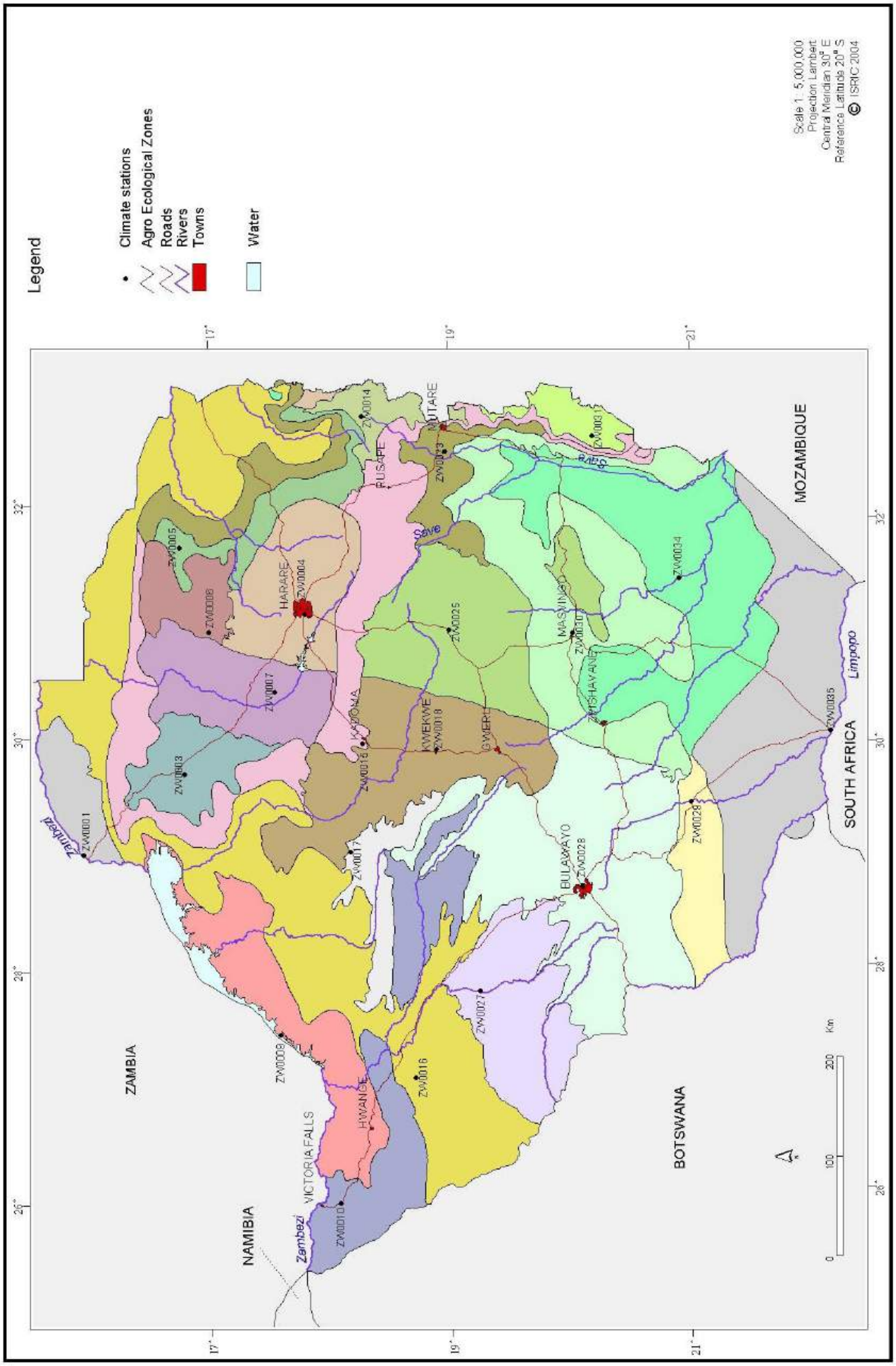

Figure 25. Modified agro-ecological zones

Estimation of number of rainy days for crop growth modelling

Models for simulation of crop growth and erosion processes often require data on rainfall intensity and patterns. Apart from mean monthly rainfall, WOFOST requires the number of rainy days in a month. From those parameters the rainfall distribution is estimated with a rainfall generator module. The number of rainy days per month is rarely available in meteorological databases: a regression analysis was based on 160 data pairs with average monthly rainfall data and number of rain days in the month to derive a formula with which the number of rainy days can be estimated from the mean monthly rainfall**.** Regression is used to derive a functional relation between two variables that are thought to be related and where one variable is known.

Linear regression uses the following formula:

Y = a + b.X

Where by:
Y = the dependent variable
a = the intercept
b = the slope of the fitted line, or average rate of change. It is the expected change in the dependent variable when the explanatory variable changes with one unit.
X = the explanatory variable

The 160 data pairs were obtained from stations in East-Tanzania (n=64) (Myaka *et al.* 2000) and from Kenya (n=96).

Table 10. Unweighted least squares linear regression of number of rainy days

Explanation Variables	**Coefficient**	**Std Error**	**T**	**P**
Constant	2.06953	0.34261	6.04	0.0000
PREC	0.05922	0.00308	19.23	0.0000

R-Squared	0.7007	Resid. Mean Square (MSE)	8.53085
Adjusted R-Squared	0.6988	Standard Deviation	2.92076

Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	1	3155.50	3155.50	369.89	0.0000
Residual	158	1347.87	8.53		
Total	159	4503.37			

Cases Included 160 Missing Cases 0

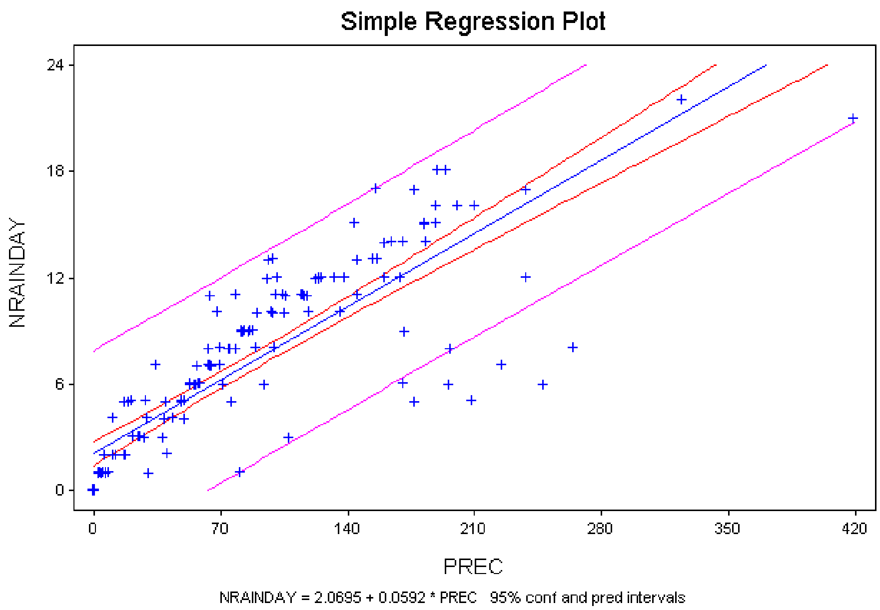

Figure 26. Simple regression plot for estimation of number of rainy days

The formula for predicting number of rain days based on this linear regression is:

Number of rain days = 2.06953 + 0.05922 * mean monthly rainfall

Appendix 2. Soil and terrain data

SOTER concepts

The SOTER methodology (van Engelen and Wen 1995) resembles physiographic or land systems mapping. It identifies areas of land with a distinctive, often repetitive pattern of landform, lithology, surface form, slope, parent material and soils. Areas of land distinguished in this manner are called SOTER units; they are unique combinations of land pattern.

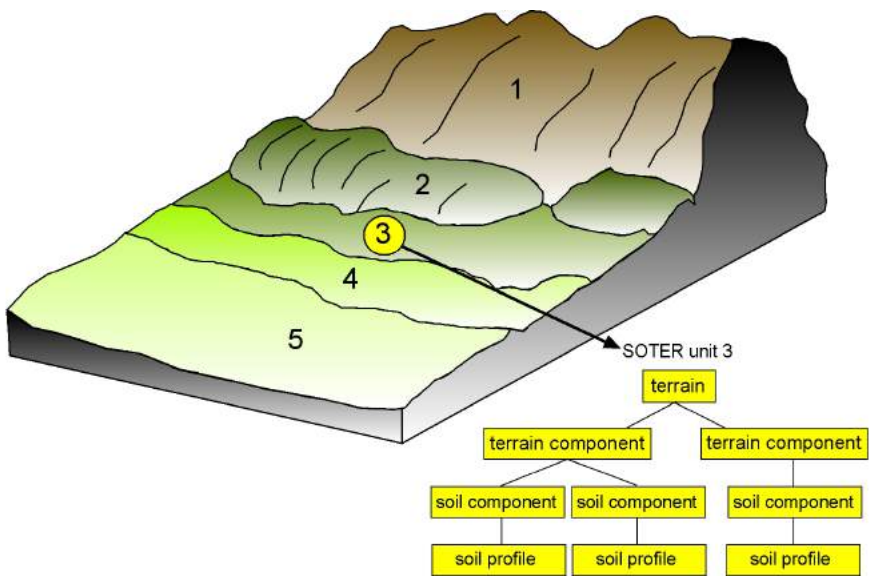

Figure 27. SOTER units in the landscape and composition of their constituents

Each SOTER database consists of two elements: a geographical part and an attribute data part; the first managed by a Geographic Information System (GIS) and the second by a Relational Database Management System (RDBMS). The attribute data of all components of a SOTER unit are stored in a database model of which Figure 28 gives the structure. A total of 118 attributes are allowed in the database.

The SOTER attributes are hierarchically described in terrain units and terrain components, the latter subsequently in soil components (see Figure 27). The SOTER database can generate thematic maps of various attributes or can be used for assessments. Results of attributes directly obtained from the database are e.g. landform, lithology, hypsometry, soils. Other results obtained after assessments can be displayed using the same SOTER base map.

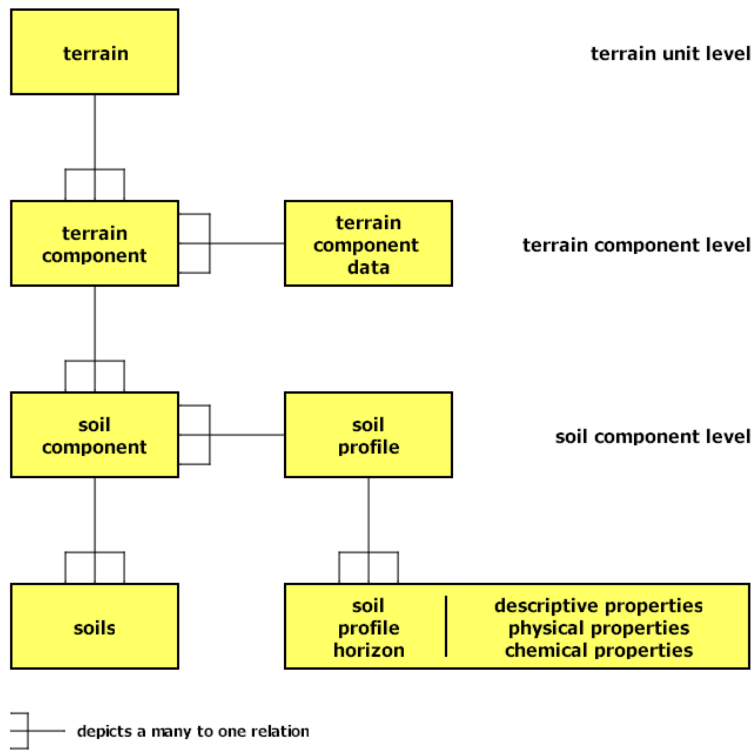

Figure 28. Structure of the SOTER database. Source: Tempel (2002)

The terrain and soils attribute data for the Zimbabwean case study have been published in the SOTER Database for Southern Africa (FAO-ISRIC 2003). This database contains the information of eight Southern African countries. The Pedology and Cartography Section of the Chemistry and Soil Research Institute, Harare, compiled the national SOTER database for Zimbabwe at 1:1M scale in the framework of the UNEP project *The Impact of Desertification on Food Security in Southern Africa: a Case Study in Zimbabwe*.

Additional information has been derived from a 1x1 km Digital Elevation Model (USGS 1997) that has been analyzed by van Engelen and Huting (2004) improving the delineation of the units. A slope map derived from this DEM is shown in Figure 29.

Table 11. Composition of the SOTER database of Zimbabwe

SOTER units	Terrain components	Soil components	Profiles	Horizons
145	198	295	218	702

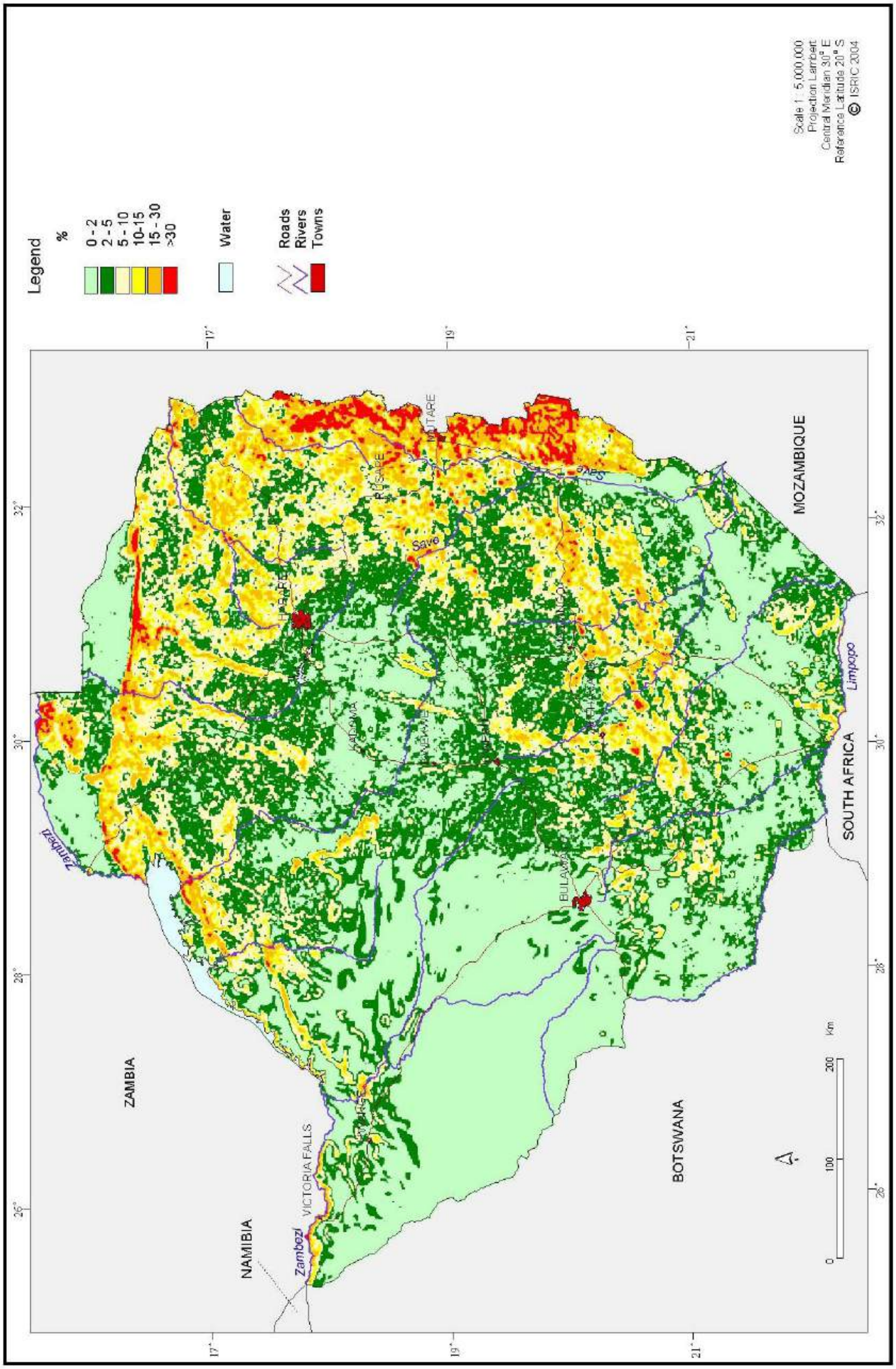

Figure 29. Slope gradient classes derived from a 1 x 1 km DEM

Quantitative data on the SOTER database of Zimbabwe are given in Table 11. In the 702 horizons some mandatory attributes were missing: bulk density was given only for 31 and pH_{H2O} for none of the samples (standard analysis at CSRI comprises pH_{CaCl2} only). High and low pF values were measured for 25 samples. Missing mandatory attributes have been completed using varying methods (Appendix 3).

Landforms

SOTER landform units are characterized by the dominant slope, the slope length and the relief intensity. For this reason, the landform map deviates from the traditional division of the country in six broad physical regions (Anderson *et al.* 1993). See also Chapter 2.

Landforms with slopes less than 10% (plains, plateaus, valley floors and footslopes) cover about 80 percent of the country (see Figure 3). Further divisions can be made according to the hypsometric level of the plains.

Sloping and steep land comprise the rest of the country: the Eastern Highlands along the border with Mozambique with mountainous and hilly ranges; the western hilly areas and the northern escarpment bordering the Zambezi gorge; and the central, southeastern range of medium gradient mountains and hills, bordering to the Lowveld and Save Valley. The central part of the country, composed of the Middleveld and Highveld areas with the Central Dyke, is characterized by undulating plains, alternating with hilly areas. In the southwest, relief turns flat to gentle undulating into the Kalahari Sandveld.

The landform units as defined in the SOTER database have been slightly modified with the help of the digital elevation model (DEM) by classifying slopes, relief intensity and potential drainage density (van Engelen and Huting 2004).

Soils

A soil map with the WRB classification (IUSS *et al.* 1998) at the second level is given in Figure 30. Only the classification of the dominant soil of the SOTER units is given. Areas for all soils in the database are shown in Table 12.

Table 12. Area of soil types (first level of WRB)

Soil type	Area (10^3 ha)	%
Acrisols	1,030	2.6
Arenosols	7,125	18.3
Calcisols	101	0.3
Cambisols	3,313	8.5
Fluvisols	265	0.7
Ferralsols	556	1.4

Gleysols	435	1.1
Leptosols	7,837	20.1
Luvisols	9,161	23.5
Lixisols	4,624	11.9
Nitisols	264	0.7
Phaeozems	334	0.9
Regosols	124	0.3
Solonchaks	369	0.9
Solonetz	1,654	4.2
Vertisols	1,189	3.1
Water	1	0.2
Σ	38,948	98.7

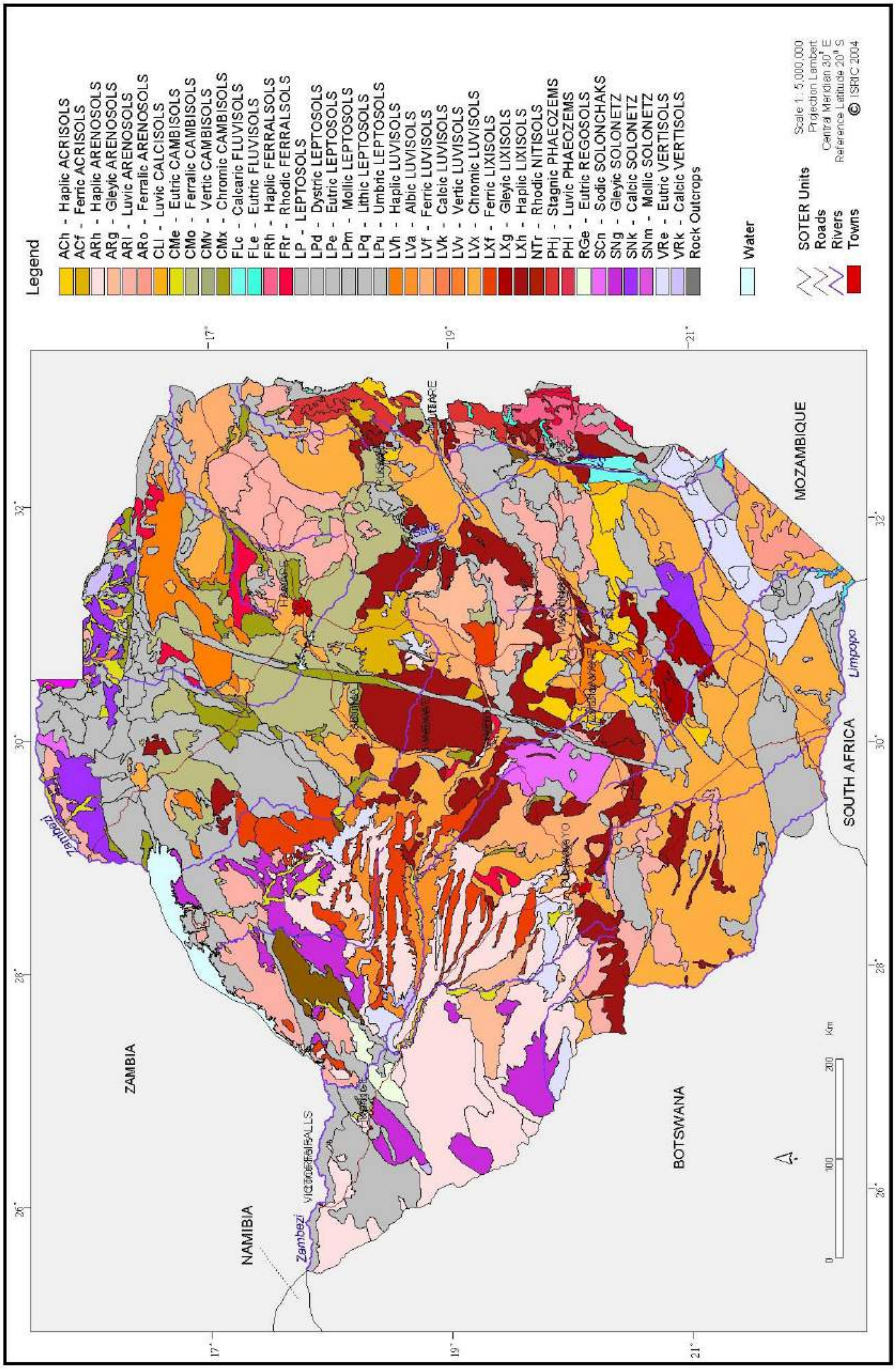

Figure 30. Dominant soils (2nd level of WRB)

Appendix 3. Estimation of missing soil attributes

Several of the interpretations presented in this report required soil parameters that are not part of the standard soil analytical methods that are used at CSRI. The following soil characteristics were not or only partially available in the original database: organic carbon percentage, very fine sand (as defined by Soil Survey Staff (1951) and pH water; while site characteristics like stoniness and rockiness were not always complete.

Missing values were inferred as much as possible from data already in the database. Missing soil depth, rock outcrop and surface stoniness data were taken from the same profile that had been described earlier. We presumed that when a profile is chosen as representative for another soil component that for both soil depths are similar. The same holds for stoniness and rockiness. If not available, soil depth can partly be inferred from the horizon data.

Missing organic carbon values have been estimated using median values for the taxonomic soil subgroup according to the Revised Legend (FAO-Unesco 1988). These median values are derived from the WISE database (Batjes 2002) and calculated for two depths: topsoil (0-30 cm) and subsoil (30-100 cm). The subgroup levels are further subdivided in three textural classes: coarse, medium and fine (FAO-Unesco 1971-1981). The values for each horizon are interpolated from their position within the top 30 cm or the subsoil at 70 cm, assuming an organic carbon content declining with depth.

Sand fractions as defined by CSRI in Zimbabwe differ from those defined by SOTER (that follows the international class boundaries as defined by Soil Survey Staff (1951). Table 13 shows the two systems.

Table 13. Class boundaries in µm of the sand fractions used by CSRI and USDA

Fraction name	CSRI	USDA
very fine sand	-	50-100
fine sand	20-200	100-250
medium sand	200-500	250-500
coarse sand	500-2000	500-1000
very coarse sand	-	1000-2000

The fine sand class of CSRI contains the silt, very fine sand and a part of the fine sand fraction of USDA. As only a few samples have been analyzed according to the internationally accepted standard classes for sand fractions and no regression could be established between the two methods, an expert estimation has been used: one third of the CSRI fine sand fraction (20-200 µm) is considered as the USDA very find sand fraction (50-100 µm).

The measurement of pH water (1:2.5 soil-water) is not standard practice in Zimbabwe. Instead, all samples have pH values measured in 1:2.5 soil : $CaCl_2$ suspension. Based on these pH values and applying a pedotransfer function: $pH_{H2O}=(pH_{CaCl2} + 0.9262)/1.01157$ the corresponding pH_{H2O} values have been calculated (Batjes 2000).

Input files for Crop growth modelling

WOFOST – crop growth model, version 4.3, runs with a climate input file, a soil input file containing soil physical characteristics, and a crop file that contains the crop characteristics by crop species or variety for crop growth modelling. In a batch file, specific data on the land units are specified - such as soil depth, soil type (linked to the soil file), climate station, soil fertility parameters.

Selected parameters required for the WOFOST batch file:

Crop type
Climate station number
Dominant texture (0-50 cm)
Rootable depth
Number of years simulated with the rainfall simulator
Non-infiltrating fraction of rain (set to 10%)
Maximum water storage on the soil after rain
Initial soil moisture conditions
Start of growing season
Maximum allowable duration of crop growth
Potential soil supply of nitrogen during the growing season
Recovery fraction of nitrogen (set to 40%)
Potential soil supply of potassium during the growing season
Recovery fraction of phosphorus (set to 20%)
Potential soil supply of phosphorus during the growing season
Recovery fraction of potassium (set to 50%)

Hydraulic parameters

Soil hydraulic parameters and key soil fertility characteristics are often not available. In this study, we used pedotransfer functions (PTFs) whereby missing data items were inferred from standard measured characteristics (e.g. (Bouma and van Lanen 1987; Tietje and Tapkenhinrichs 1993; Wagner *et al.* 1998), and model input requirements could be satisfied. A function was used that predicts soil moisture characteristics from total pore fraction and soil texture (Danalatos *et al.* 1994; Driessen 1986; Driessen and Konijn 1992). Hydraulic conductivity parameters required for crop growth simulation, were estimated using class PTFs proposed by Driessen (1986). Two K_{sat} values per soil type are needed in WOFOST, one for the topsoil and one for the subsoil. The subsoil value of K_{sat} was set at 70% of the topsoil value. The subsoil value (20-100 cm) of K_{sat} was set at 70% of the topsoil value (0-20 cm).

Nutrient input parameters
The soil fertility information required as input for the crop growth model was averaged over the top 20 cm in which maize nutrient-feeding roots concentrate. The required input parameters for the nutrient-limited crop growth simulation, the QUEFTS module in the WOFOST crop growth model, are potential nitrogen supply, potential potassium supply, and potential phosphorus supply. The potential supply of available nutrients was calculated using the QUEFTS regression equations. Soils with pH > 7.5 and < 4.5, and TOTC > 30 $g.kg^{-1}$ (boundary conditions QUEFTS methodology) are excluded from calculations.

Measured data on P_2O_5, an essential input parameter in the QUEFTS module of WOFOST, were not available from the ZILRIS database. To be able to satisfy model input requirements, P_2O_5 was estimated using a taxo-transfer rule derived from the WISE database (Batjes 1997). Median values of topsoil (<20-<50 cm) P_2O_5 (P-Olsen) from WISE by first and second level soil unit of FAO 1974 classification were taken for representative profiles of the same taxonomic classification. The subsoil was set arbitrarily set at 20% of the topsoil value.

Bulk density
Nutrients are mostly presented in soil analysis as a percentage of the mass of the sieved and dried sample, and not on a volumetric basis. To convert figures of soil fertility indicators and water content based on mass percentage to figures on a volumetric basis, bulk density values are needed Bulk density values were not available from the Zimbabwe database; they were estimated using a taxo-transfer rule derived by Batjes (2003) applied to the WISE global pedon database. Median bulk density values from WISE were organized by second level soil unit of FAO 1988 classification and soil textural class and available by soil depths of 20 cm interval.

Appendix 4. Conversion of SADC land cover classes into SOTER land use classes

The SADC land cover map (CSIR 2002) has been overlaid by the following maps:

- Communal Lands from Anderson *et al.* (1993)
- National Parks and other nature conservation areas from the *General Map of Zimbabwe* (Department of the Surveyor General 1997)

The resulting combination contained land cover classes for the communal areas and for the commercial farming areas, and a separate land use for the National Park areas. The land cover classes have been transformed into the existing SOTER land use classes according to the scheme in Table 14.

Table 14. Conversion SADC land cover classes and SOTER land use

SADC land cover	Communal Lands	Commercial lands	SOTER land use code	SOTER land use
Bare ground	X		AA4	Rain-fed arable cultivation
Bare ground		X	AA2	Fallow cultivation
Built-on	X	X	S	Settlement
Bushland	X		HE2	Semi-nomadism
Bushland		X	HE3	Ranching
Cultivation	X		AA4	Rain-fed arable cultivation
Cultivation		X	AA2	Fallow cultivation
Forest	X	X	FN1	Selective felling
Grassland	X		HE2	Semi-nomadism
Grassland		X	HE3	Ranching
Low shrubland	X		HE2	Semi-nomadism
Low shrubland		X	HE3	Ranching
Plantation	X	X	FP	Plantation forestry
Woodland	X		HE2	Semi-nomadism
Woodland		X	HE3	Ranching

Open water has been maintained as a separate class. The SADC class *wetland* occupied only minimal areas (≤ $1km^2$) and has been merged with the surrounding land use classes.

The transformation of the SADC vegetation types of the National Parks into SOTER vegetation types that follow the Unesco system (Unesco 1973) created difficulties for the land cover classes woodland and bushland. Woodland in the SADC system (wooded areas with 20-80% tree canopy cover) is different from woodland in the Unesco system (>40%). Bushland in Zimbabwe according to SADC contains woody plants 1 - 5 m high covering > 20% of the surface. This definition can be considered more or less equal to the scrub terminology of Unesco although the latter lacks a canopy cover percentage.

Appendix 5. Availability of moisture calculated with the WATSAT model

The moisture sufficiency of the crop for the land quality *availability of moisture* in the ZIMALES model has been estimated using WATSAT, a simple water balance model (Mantel 1995). WATSAT runs on the basis of an interpolation of monthly rainfall and evapotranspiration averages into daily moisture gains and losses. Specific soil, crop and climatic parameters are used for the calculation of the water sufficiency, taking into account the actual rooting depth of the soil. When no limitation on rooting depth was indicated, the calculation was made over 120 cm depth. This might be optimistic; most of the time rooting is shallower and the crop does not extract all the soil moisture stored to this depth (see Chapter 4). WATSAT gives the results (the moisture sufficiency) as a ratio between actual and maximum transpiration rate of the crop. This serves as input in the ZIMALES model to convert this figure into a sufficiency rating of the land quality availability of moisture.

Early maturing hybrid seed is available and used by communal farmers in low rainfall areas with short growing season. Most hybrids mature in 110 in the Middleveld and 130 days in the Highveld (Anderson *et al.* 1993). Very short-season hybrids with 80-110 days maturity provide better opportunities for areas of low and erratic rainfall.

There is a large annual variation in production (see Figure 8) due to the rainfall variability. The reliability of rainfall increases with elevation and from south to north (Anderson *et al.* 1993). Rainfall reliability is generally of greater importance to farming than the annual average, because variation from year to year is large.

WATSAT was run under the following assumptions:

- Daily rainfall figures have been linearly interpolated from monthly average values. These values are easily obtained (FAO 1992) and probably more reliable for all stations; but this interpolation does not take into account the large variation and erratic occurrence of rainfall over the growing season;
- Rooting depth has been set at 120 cm, unless otherwise indicated in the database;
- Weighted average soil texture of the profile has been calculated over 120 cm depth. Often, the topsoil is sandier than the subsoil, so the available moisture capacity may be overestimated.

The result of the WATSAT assessment is shown in Figure 32. The moisture availability shows a strong correlation with the soil thickness (Figure 31) and less with differences in the average rainfall. Only in the southeastern and southwestern part of the country is the influence of low rainfall shown in lower moisture availability. Although the soils of that area are generally deep to very deep, the moisture availability for the unit as a whole shows severe moisture limitations (>80 percent of the unit).

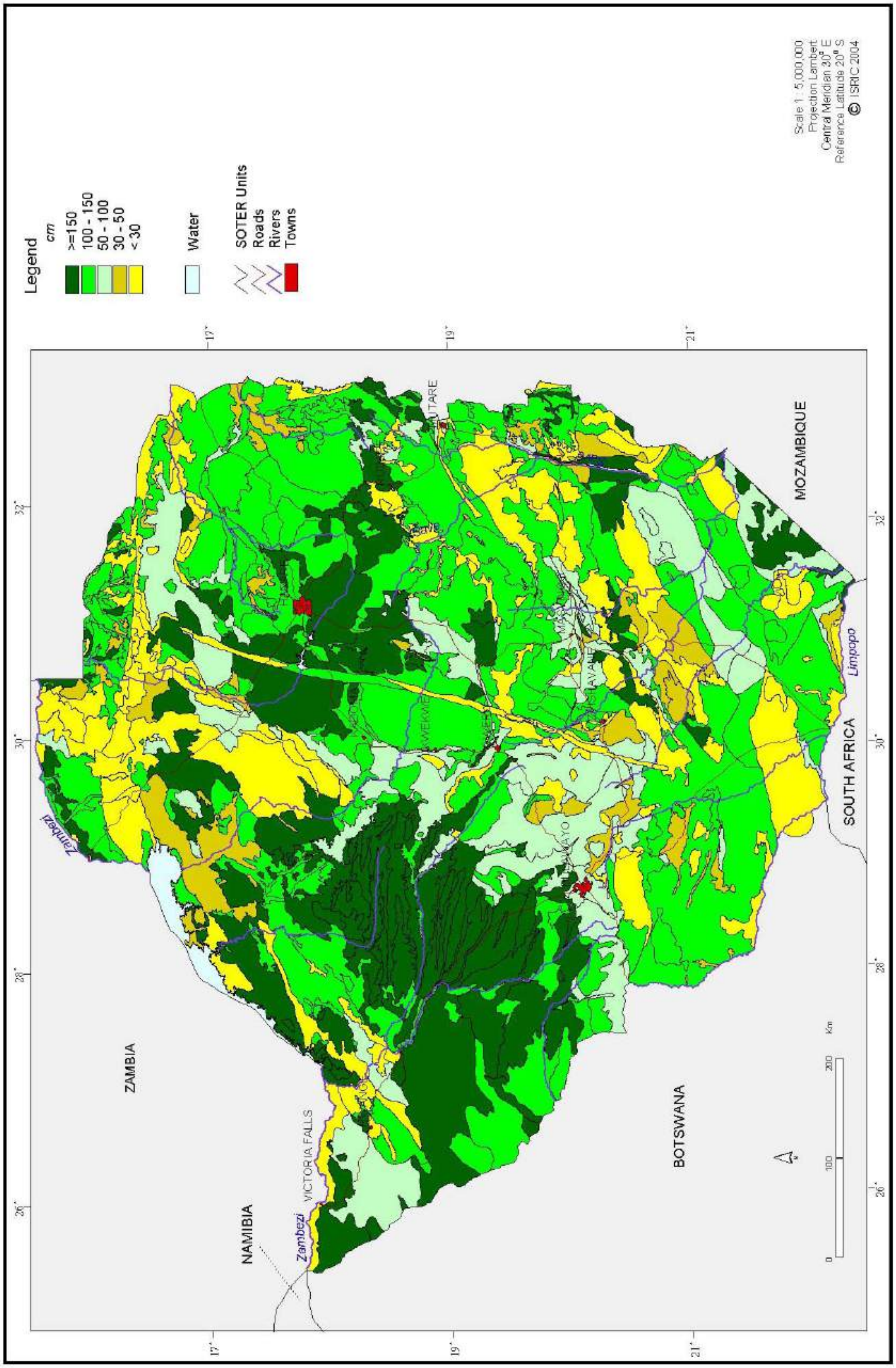

Figure 31. Depth of dominant soils

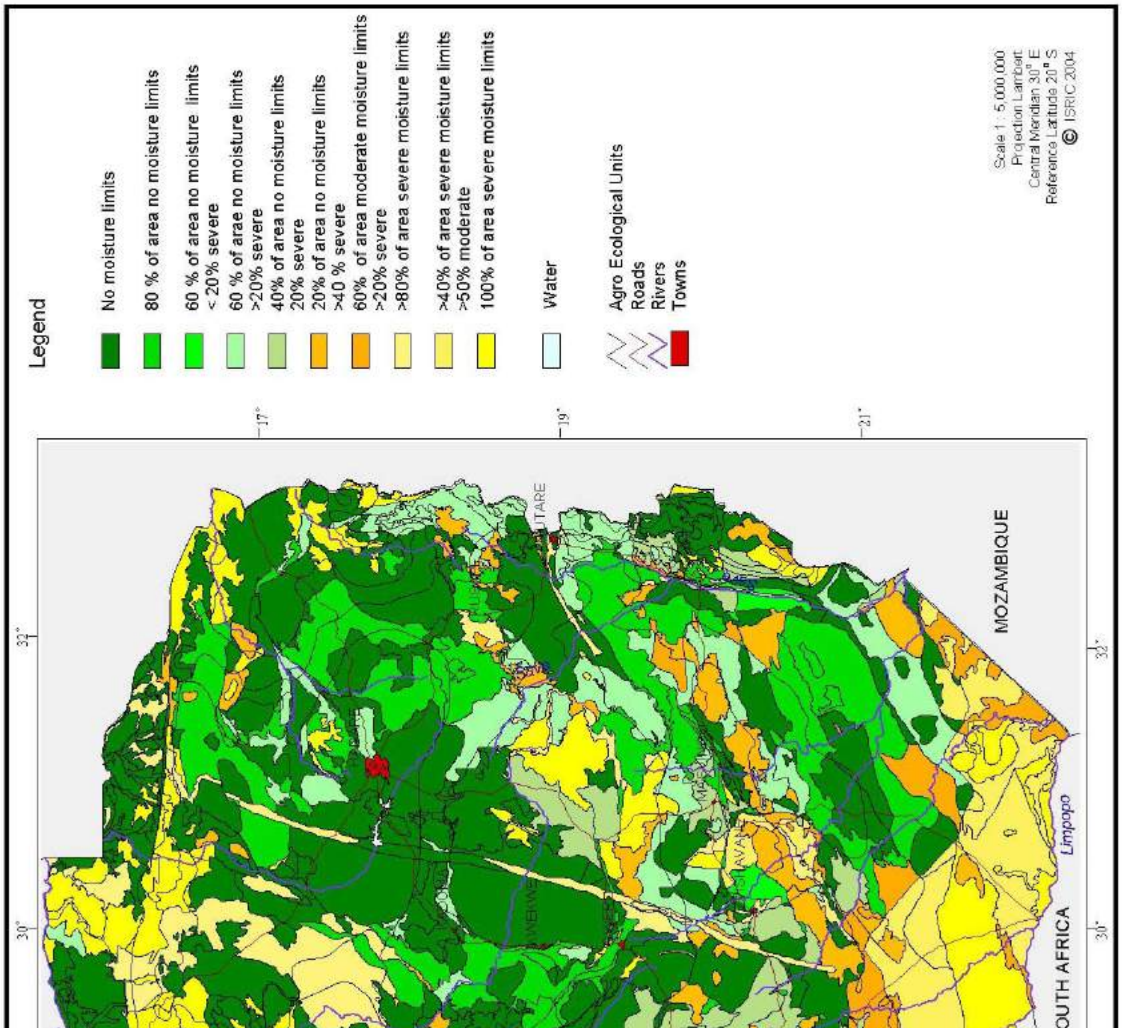

Figure 32. Soil moisture availability

Appendix 6. Land suitability figures

The land suitability assessment followed the methodology as described in the *Framework for Land Evaluation* (FAO 1976). The framework defines the land utilization type (LUT) as a kind of land use for which a set of technical specifications

Table 15. Extent of suitability for maize cultivation and their limitations

Suitability class	Dominant limitation	Extent (km^2)	Extent (%)
Highly suitable S1	no limitations	2585	0.7
Moderately suitable S2	all limitations	37978	9.7
	availability of nutrient	21490	5.5
	erosion hazard	6965	1.8
	availability of oxygen for root growth	5131	1.3
	availability of moisture	3063	0.8
	availability of nutrients and oxygen	1329	0.3
Marginally suitable S3	all limitations	166945	42.9
	availability of nutrients	142070	36.7
	availability of oxygen for root growth	14851	3.8
	erosion hazard	4968	1.1
	available foothold for roots	4173	1.1
	other (flooding hazard or conditions for germination)	883	0.2
Not suitable N	all limitations	177791	45.6
	availability of moisture	138567	35.6
	erosion hazard	10865	2.8
	excess of salts (salinity and sodicity)	11085	2.8
	availability of nutrients	6820	1.8
	availability of oxygen for root growth	4695	1.2
	available foothold for roots	2506	0.6
	flooding hazard or conditions for germination	3252	0.8
No data	insufficient data for evaluation	1184	0.3

is described in a given physical, economic and social setting. In the present case study this is defined as rain-fed maize cultivation with low inputs and low technology (see Chapter 3.2.1).

Insufficient soil data on salinity and sodicity has resulted in unsatisfactory discriminating results for the land quality *excess of salts*. A correction has been made to qualify as *not suitable* (N) all those soils that are classified as Solonchaks and Solonetz in the SOTER database of Zimbabwe.